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Damage prediction and long-term cost performance analysis of glass fiber recycled concrete under freeze-thaw cycles

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ABSTRACT

This paper establishes a freeze-thaw cycle damage model by analyzing the changes in mass, relative dynamic elastic modulus and compressive strength of glass fibers (0 %, 0.5 %, 1.0 %, and 1.5 %) recycled concrete after the freeze-thaw cycle (0, 50, 100, and 150) tests. Meanwhile, the antifreeze life of concrete is predicted based on the Weibull distribution model. The study show that glass fiber can reduce the deterioration of recycled concrete specimen surfaces result from frozen-thaw environment. After 150 freeze-thaw cycles, the specimens with 0.5 %, 1.0 %, and 1.5 % glass fiber content showed a reduction in mass loss of 0.405 %, 1.100 %, and 0.725 %, and an increase in compressive strength of 8.19 %, 21.35 %, and 17.79 %, respectively, when compared with the specimens without glass fiber. Fiber can provide tension when recycled concrete is compressed, thus improving compressive strength, and the optimum glass fiber content is 1.0 %. After 150 freeze-thaw cycles, the freeze-thaw damage of recycled concrete specimens with 1.0 % glass fiber content was the smallest. Compared with that before freeze-thaw, the mass of the specimens only decreased by 2.128 %, and the compressive strength decreased by 35.2 %. Finally, the long-term cost-effectiveness of Recycled Aggregate Concrete (RAC) is analyzed based on the predicted life, and the performance optimization and economic benefits are comprehensively considered. Therefore, the appropriate volumetric admixture of glass fiber can be selected according to the actual situation in different regions, considering the cost-effectiveness of glass fiber recycled concrete to provide suggestions for related research.

1. Introduction

The demolition of old buildings and road reconstruction generate large amounts of construction waste, and the reuse of waste aggregates is the main effective ways to realize green buildings [1–3]. Alqarni [4], Kou [5], and Gao [6] found that recycled concrete prepared under different conditions (such as recycled aggregate replacement rate, crushing index, and treatment method) can improve

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environmental benefits to varying degrees, but will reduce the performance of concrete. Compared with natural coarse aggregate, recycled coarse aggregate has the disadvantages of low apparent density, high porosity, and water absorption, and the surface of recycled coarse bone is attached to old cement mortar, which has poor bonding performance with new cement mortar, resulting in the mechanical properties of recycled concrete inferior to ordinary concrete [7,8]. At the same time, recycled coarse aggregate in the crushing and processing process, the surface will produce micro-cracks, increasing the water absorption of recycled concrete [9,10] and providing a channel for the solution to intrude into the interior of the recycled concrete [11,12], which leads to the recycled concrete frost resistance is inferior to that of ordinary concrete, and is more prone to freeze-thaw damage. Adding high-performance chopped fibers can improve the internal structure and the physical-chemical properties of RAC [13–15]. Mahakavi et al. [16] considered that mixing glass fiber at two volume fractions of 0.5 % and 1.0 % could optimize the mechanical properties of RAC. Ahmad et al. [17] found that compared with nylon fiber, the addition of glass fiber can significantly improve the mechanical properties of peach shell concrete. Wu et al. [18] found that when the fiber volume ratio was 0.25 %, 0.50 %, and 0.75 %, the mechanical strength of RAC with glass fiber is better than that with polypropylene. The results show that glass fiber, polypropylene fiber, and nylon fiber all delayed the micro-cracks propagation to some extent. Among them, adding glass fiber ameliorate the compression resistance and tensile properties of RAC best.

In addition, environmental factors also have a significant impact on the performance of concrete. In regions such as Northeast China and North China, the effects of freeze-thaw cycles on concrete structures are more serious. Under freeze-thaw cycles, concrete structures may incur damage, leading to reduced performance and service life. Relevant research [19–21] shows that the freeze-thaw cycle causes slag drop or erosion of building surfaces, and even the mortar falls off. The regenerated aggregate showed worse physical properties after a long-term freeze-thaw environment. Consequently, frozen-thaw cycle has more severe adverse effects on the performance of RAC [22]. Richardson [23], Ding [24] and Ding [25] believed that incorporating polypropylene and basalt fiber improved the bearing capacity of RC, significantly improved the appearance damage and elastic modulus loss of specimens, and RAC exhibited better frost resistance. Moreover, Fan et al. [26] evaluated the stability level of concrete durability in a single environment based on Analytic Hierarchy Process (AHP). Guo et al. [27] proposed a comprehensive probability assessment framework for the durability of reinforced concrete structures in marine atmospheric environments. The results show that the inhomogeneity of corrosion, the erosion of chloride ions, and climate change can be evaluated by probability. However, the research on the glass fiber ratio's influence on RAC's durability under freeze-thaw cycles was insufficient. Mastali et al. [28] analyzed the eco-efficient and cost-effectiveness of partially replacing industrial fibers with recycled steel by Global Warming Potential (GWP). Syed et al. [29] believed that the use of recycled steel fibers was helpful for the development of environmentally friendly concrete through carbon footprint analysis. However, the optimal balance between the performance optimization and economic benefit of glass fiber RAC remains to be further explored. Therefore, the value engineering analysis method is introduced in this paper to seek the optimal cost-effective fiber content for glass fiber RAC.

The current research results [16–18,23–25] show that the incorporation of fibers mainly aims to inhibit micro-cracks extension in the internal structure. However, the freeze-thaw cycle accelerates internal crack expansion in concrete components in the actual environment. Therefore, this paper studies the effect of different volume content of glass fiber on the performance improvement of recycled concrete under the freeze-thaw cycle. The test measure mass/dynamic elastic modulus after every 25 freeze-thaw cycles and compressive strength after every 50 times. According to the loss rate of compressive strength, mass, and dynamic elastic modulus, the damage model of various properties of RAC with different fiber contents was established. The damage phenomenon in different regions of China was predicted based on the Weibull distribution model. In addition, scholars at home and abroad highly value the environmental protection, performance and comprehensive economic benefits of fiber-recycled aggregate. Based on the predicted minimum life, this article analyzes the long-term behaviour of RC with different fiber content in each region, quantifies the cost-performance ratio of RC according to the calculated cost impact factor, and finally guides the practical application of fiber RC in each region. In order to clearly express the research progress of related topics, the comparison is summarized, as shown in Table 1.

Table 1
The research points of related literatures and research goal.

No.	Opinion of the references	Literatures	Research goals
1	The application of recycled concrete is one of the effective methods for recycling construction waste and alleviating environmental pollution and resource loss.	[1–3]	In order to solve the environmental and resource problems caused by excessive construction waste, this study selected recycled concrete as the research object. Glass fiber incorporation is used to improve the performance of recycled concrete under freeze-thaw cycling. To investigate the improvement effect of glass fiber admixture on the properties of recycled concrete under the freeze-thaw cycles. A damage deterioration model for glass fiber recycled concrete (GFRC) under freeze-thaw cycles was established. At the same time, the life prediction of GFRC was carried out based on the Weibull distribution model. Finally, the performance improvement effect and economic cost of GFRC are comprehensively analyzed. It provides a theoretical basis for the application of GFRC in practical engineering.
2	Recycled aggregate has the disadvantages of low apparent density, high porosity, and water absorption, resulting in recycled concrete being inferior to ordinary concrete.	[7–12]	
3	Under the influence of freeze-thaw cycles, the concrete structure will be damaged and deteriorated, the mechanical properties and durability will be reduced, and the service life will be shortened, thus causing safety hazards.	[19–22]	
4	Adding fiber is the most direct and effective method to improve the performance of recycled concrete. At the same time, incorporating fiber can alleviate the adverse effects of the environment on the performance of concrete.	[23–25]	

2. Experimental program

2.1. Material properties and mix designs

The mixtures comprised cement, fly ash, aggregate, water, water-reducing agent, and glass fiber. Cement chose P.O 42.5 grade general silicate cement its performance index is shown in Table 2. Fly ash adopted the grade I with a density of 2.55 g/cm^3, a burning vector of 2.8 %, and a fineness modulus of 16 %. Aggregate includes fine aggregate and coarse aggregate. The fine aggregate is natural river sand, and the fineness modulus is 2.63. Coarse aggregate includes natural coarse aggregate and recycled coarse aggregate. The natural coarse aggregate is natural gravel with a particle size of 5–20 mm and a crushing index of 9.6 %. The recycled coarse aggregate is taken from the waste concrete in a road reconstruction project in Nanchang Economic Development Zone. A jaw crusher is used to crush the waste concrete, and the recycled coarse aggregate with continuous grading of 5–20 mm is obtained through screening and other processes. The basic performance parameters of aggregate are shown in Table 3. The recycled coarse aggregate is shown in Fig. 1 and Fig. 2. The recycled coarse aggregate replacement rate in this study is 25 %. All the water from the laboratory tap. The water reducer selected polycarboxylate-based Super Plasticizer (SP) with a water reduction rate of 35 %. To avoid the additional influence of material variable factors such as glass fiber length and aspect ratio on the experimental results, the fibers selected for this study had a length of 14 mm and a diameter of 12 μm. The alkali-resistant short-cut glass fibers are demonstrated in Fig. 3, and the chemical-physical properties are shown in Table 4.

Relevant studies have shown that when the replacement rate of recycled aggregate is 25 %, the 7-day strength of RAC is slightly higher than that of ordinary concrete, and its average elastic modulus decreases less, which has little effect on the working performance of concrete [30,31]. Therefore, the replacement rate of recycled aggregate in this study is selected as 25 %. Referring to the “Specification for mix proportion design of ordinary concrete” (JGJ 55-2011), the RAC mix for this test is shown in Table 5 [32].This project takes recycled concrete as the object, focusing on the loss rate of mass, compressive strength and dynamic elastic modulus of RC with different glass fiber contents under freeze-thaw damage. According to the volume ratio of glass fiber (0 %, 0.5 %, 1.0 %, 1.5 %) and freeze-thaw time (0, 50, 100, 150), a total of 16 groups of specimens (3 in each group) were set up, as shown in Table 6.

2.2. Experimental method

In this study, the freeze-thaw cycle test is carried out on the specimens by the quick freezing method according to the standard of “Standard for Test Methods for Long-term Performance and Durability of Ordinary Concrete” (GB / T50082-2009) [33]. When the specimens were cured under standard conditions for 24 d, the specimens were taken out and immersed in water at (20 ± 2) ℃ for 4 d. The specimens were put into the freeze-thaw testing machine for a freeze-thaw cycle test after 28 d of age. A freeze-thaw cycle time of 4 h, freezing process temperature control at (-18 ± 2)℃, melting process temperature control at (5 ± 2) ℃. Mass loss rate and relative dynamic elastic modulus tests were performed on specimens at 25 freeze-thaw cycle intervals. Stop the test when one of the following conditions occurs in the freeze-thaw cycle:

1) To achieve the specified number of freeze-thaw cycles 150 times.
2) The relative dynamic elastic modulus of the specimen is reduced to less than 60 %.
3) The mass loss rate of the specimen reaches 5 %.

When the number of freeze-thaw cycles is 0, 50, 100, and 150 times, refer to the “Standard for Test Methods of Mechanical Properties of Ordinary Concrete” (GB/T 50081-2002) [34] to test the compressive strength of the specimen.

3. Analysis of test results

In a harsh service environment, the materials that makeup concrete will inevitably deteriorate due to environmental corrosion. As a result, the overall bearing capacity of the concrete specimen is reduced. Therefore, studying the improvement rule of RAC mechanical properties under different influence factors is essential.

The authors have extensively researched fiberglass materials, considering the effects of multiple factors, including steam curing, alkaline erosion, pre-cracks, and sustained loading on GFRP-reinforced concrete beams. Zhang et al. [35] proposed the semi-reliability probability damage assessment. Wu et al. [36,37] analyzed the microscopic degradation mechanism and macroscopic strength attenuation rule of GFRP bars in alkaline and established the reformative tensile strength and degradation prediction model for up to 8 years. Yang et al. [38,39] combined experimental data and prediction results to analyze the evolution law of crevice destroy and energy consumption of concrete beams.

The text explored the overall component properties of RAC with glass fiber. The loss rate of mass, dynamic elastic modulus and

Table 2
Cement performance index.

Cement kinds	Ignition loss	Initial setting time	Final setting time	28 d compressive strength	28 d flexural strength
P.O 42.5	4.21 %	165 min	225 min	49 MPa	7.7 MPa

Table 3
Basic performance parameters of aggregate.

Type of aggregate	Size grading	Bulk density	Apparent density	Soil content	Crush index
Natural coarse aggregate	5–20 mm	1520 kg/cm^3	2897 kg/cm^3	1.5 %	9.6 %
Recycled coarse aggregate	5–20 mm	119 2 kg/cm^3	2624 kg/cm^3	4.5 %	7.3 %
Fine aggregate	< 0.5 mm	-	2620 kg/cm^3	1.0 %	-

Fig. 1. Recycled concrete and its crushing.

Fig. 2. Regenerated coarse aggregate.

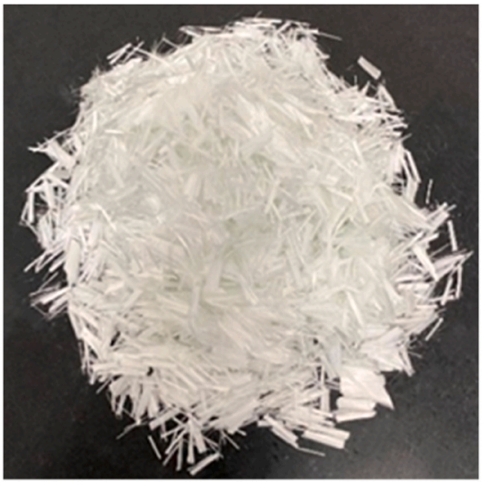

Fig. 3. Glass fiber.

Table 4
Performance index of glass fiber.

Tensile strength	Elongation at break	Modulus of elasticity	Density	Linear density	Length	Diameter
1700 MPa	3 %	70 GPa	2.5 g/cm^3	8.12 dtex	14 mm	12 μm

Table 5
Proportions of recycled concrete (kg) [32].

Concrete number	Cement	Sand	Gravel	Recycled aggregate	Water	Fly ash	Water reducer	Glass fiber
RC	420	720	744	248	175	87	1.26	0
GFRC0.5	420	720	744	248	175	87	1.26	4.55
GFRC1.0	420	720	744	248	175	87	1.26	9.1
GFRC1.5	420	720	744	248	175	87	1.26	13.65

Notes: RC represents recycled concrete, GFRC0.5 represents RAC with a glass fiber volume content of 0.5 %.

Table 6
Grouping design of specimens.

Concrete number	Number	Glass fiber mix amount/%	The number of freeze-thaw cycles/times
RC	F-0-0	0	0
	F-50-0		50
	F-100-0		100
	F-150-0		150
GFRC0.5	F-0-0.5	0.5	0
	F-50-0.5		50
	F-100-0.5		100
	F-150-0.5		150
GFRC1.0	F-0-1.0	1.0	0
	F-50-1.0		50
	F-100-1.0		100
	F-150-1.0		150
GFRC1.5	F-0-1.5	1.5	0
	F-50-1.5		50
	F-100-1.5		100
	F-150-1.5		150

Notes: F indicates the freeze-thaw environment. 0, 50, 100, and 150 indicate the number of freeze-thaw times. 0, 0.5, 1.0, and 1.5 indicate glass fiber volume rate. For example, F-100-1.0 indicates glass fiber recycled concrete with a volume ratio of 1.0 % after 100 freeze-thaw cycles.

compressive strength of specimens were tested to obtain the corresponding degradation attenuation model, further predicting the life of glass fiber recycled concrete. The data are shown in Table 7.

3.1. *Comparative analysis of the specimen surface damage phenomenon*

The apparent texture of RAC changed significantly after freeze-thaw damage, and the mixing amount of glass fiber influenced the surface change of RAC. After 150 times, the specimen's surface morphology changes are shown in Fig. 4.

Fig. 4 showed that the specimen surface aggregate was damaged to a varying extent after freeze-thaw damnification. The surface of unmixed glass fiber tests was more seriously damaged than that of mixed glass fiber tests, and the phenomenon of the thin layer of "peeling" occurred. Specimens mixed with glass fiber showed less apparent damage. The damage to the specimen's surface was the smallest when the volume incorporation of glass fiber valued 1.5 %. From the surface morphology observation, adding glass fiber can effectively reduce the damage resulting from the freeze-thaw environment, which is consistent with the research results of Lei et al. [40].

3.2. *Loss of mass after freeze-thaw damage*

The frozen-thaw cycles broke the specimen's surface, with the increase in the times, the situation gradually aggravated, resulting in a loss of specimen quality. After every 25 times, specimens were weighed. According to the formula, the loss rate of prismatic specimens mass was calculated. These data are shown in Table 7. The mass loss of glass fiber RC with different volume rates changed with frozen-thaw times, as shown in Fig. 5.

$$\Delta W_n = \frac{m_0 - m_n}{m_0} \times 100\% \quad (1)$$

Where, ΔW_n and m_n indicate the mass and their loss rate after n freeze-thaw cycles.

Table 7
Experimental data of glass fiber regenerated recycled concrete after freeze-thaw damage.

The number of freeze-thaw cycles	Mix designation	Mass loss rate/%	Dynamic elastic modulus loss rate/%	Compressive strength/ MPa	Compressive strength loss rate/%
0	RC	0.000	0.0	47.3	0.0
	GFRC0.5	0.000	0.0	49.8	0.0
	GFRC1.0	0.000	0.0	52.6	0.0
	GFRC1.5	0.000	0.0	51.8	0.0
25	RC	0.262	7.3		-
	GFRC0.5	0.178	6.6		-
	GFRC1.0	0.115	4.7		-
	GFRC1.5	0.114	5.4		-
50	RC	0.566	13.8	39.2	17.1
	GFRC0.5	0.430	11.8	42.3	15.1
	GFRC1.0	0.214	9.5	45.9	12.7
	GFRC1.5	0.280	10.4	45.0	13.1
75	RC	0.807	18.1		-
	GFRC0.5	0.588	15.1		-
	GFRC1.0	0.356	12.3		-
	GFRC1.5	0.436	13.6		-
100	RC	1.205	24.2	35.3	25.4
	GFRC0.5	0.976	20.6	37.5	24.7
	GFRC1.0	0.608	17.0	40.8	22.4
	GFRC1.5	0.696	18.1	39.8	23.2
125	RC	2.212	33.4		-
	GFRC0.5	1.858	29.8		-
	GFRC1.0	1.310	27.0		-
	GFRC1.5	1.682	30.0		-
150	RC	3.228	38.3	28.1	40.6
	GFRC0.5	2.823	35.6	30.4	39.0
	GFRC1.0	2.128	30.9	34.1	35.2
	GFRC1.5	2.503	33.5	33.1	36.1

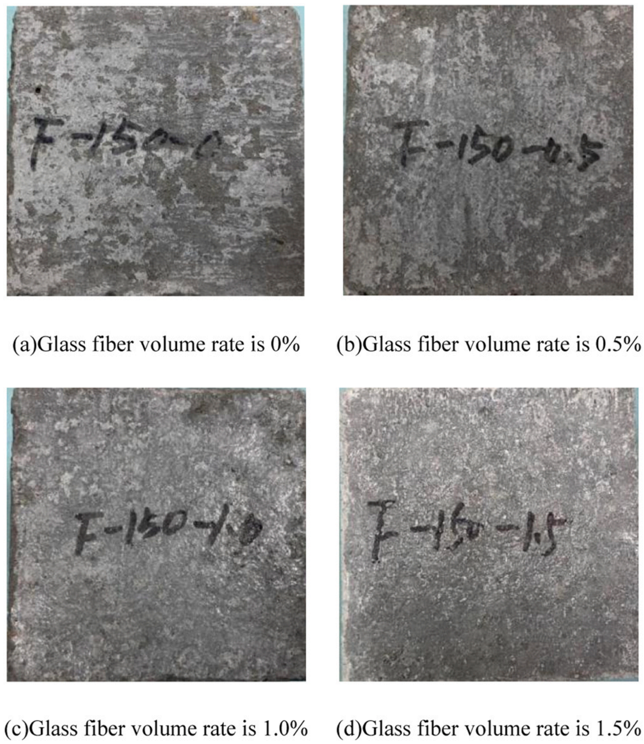

Fig. 4. Surface texture of specimens after 150 freeze-thaw cycles.

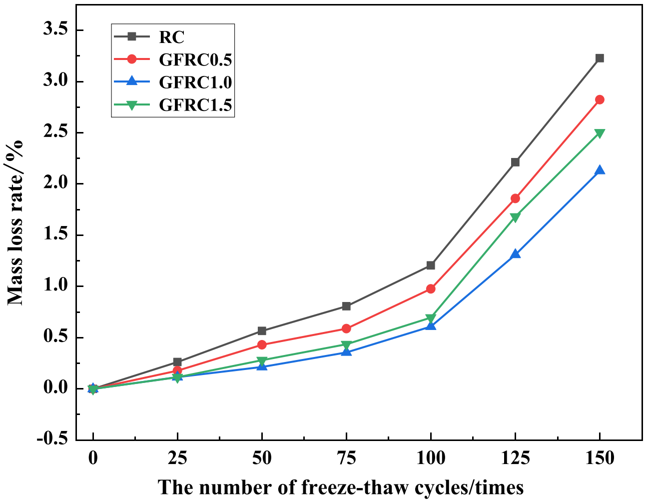

Fig. 5. The mass loss rate changes with the number of freeze-thaw cycles.

Fig. 5 shows that the mass loss rate of glass fiber recycled concrete is associated with freeze-thaw tines, and the rate of change in mass loss also increases with time's increase. The specimen mass loss rate increased slightly before 100 times and increased rapidly after 100 times, and the value reaches the maximum after 150 times. Moreover, the mass loss rate of unmixed fiber RC is the largest simultaneously. The mass-loss of specimens with a glass fiber content of 0 %, 0.5 %, 1.0 %, and 1.5 % is 3.228 %, 2.823 %, 2.128 %, and 2.503 %, respectively, still in line with the specification requires that the value is less than 5 %. With the incorporation of glass fiber (0.5 %, 1.0 %, and 1.5 %), the mass loss rate decreases by 0.405 %, 1.100 %, and 0.725 %, respectively. The reduction of the mass loss rate is the largest as glass fiber content values 1.0 %.

According to the data obtained from the test, the regression analysis was performed on the mass-loss rate of glass fiber RC under freeze-thaw cycles, the relationship between it and different glass fiber contents was obtained in Fig. 6. The mass-loss rate of glass fiber RC increases non-linearly with freeze-thaw times, on the contrary, it demonstrates an exponential function relationship as shown in following equation. The parameters obtained by the regression are shown in Table 8. This correlation coefficient R^2 is relatively high, and the test value of each specimen's mass loss rate ΔW_n is relatively evenly distributed on the fitting curve. The figure shows that the mass decreases sharply as the freeze-thaw times exceed 100.

$$\Delta W_n = ae^{bn} \times 100\% \tag{2}$$

Regression analysis was carried out on the mass loss attenuation coefficients a and b of different fiber admixture, and the unary cubic function of glass fiber content can express the mass loss attenuation coefficients. The expressions are shown as follows, the regression curves are shown in Fig. 7.

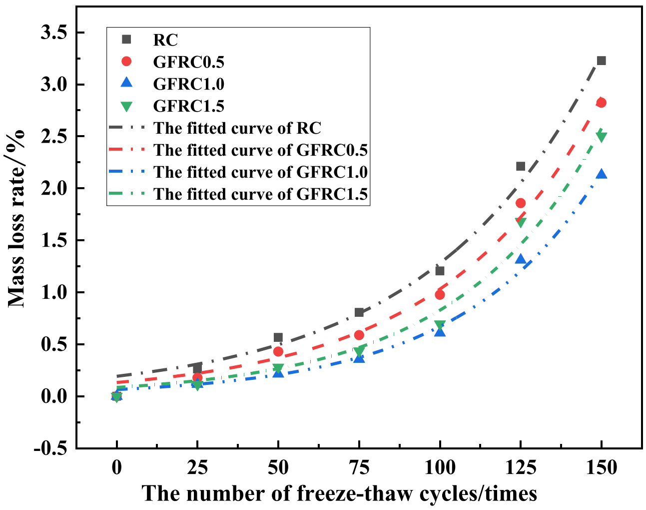

Fig. 6. Regression curve of mass loss rate under different freeze-thaw cycles.

Table 8
Regression parameters of mass loss under freeze-thaw cycle.

Concrete number	Coefficient *a*	Coefficient *b*	R^2
RC	0.19287	0.01892	0.98808
GFRC0.5	0.13261	0.02051	0.9907
GFRC1.0	0.06473	0.02339	0.99307
GFRC1.5	0.08558	0.0227	0.98112

$$a = 0.12847x^3 - 0.2794x^2 - 0.04867x + 0.19287 \tag{3}$$

$$b = -0.00648x^3 + 0.0123x^2 - 0.00135x + 0.01892 \tag{4}$$

3.3. Loss of compressive strength after freeze-thaw damage

The compressive strength loss rate of glass fiber recycled concrete test piece after the following formula calculates the freeze-thaw cycle. The calculation results are shown in Table 7. The value changes with the freeze-thaw times shown in Fig. 8.

$$\Delta f_c(n) = \frac{f_{c,0} - f_{c,n}}{f_{c,0}} \times 100\% \tag{5}$$

Where, $\Delta f_c(n)$ indicates the compressive strength loss rate after n freeze-thaw cycles (%), $f_{c,n}$ indicates the compressive strength value after n freeze-thaw cycles (MPa).

In Fig. 8, the compressive strength loss rate of glass fiber RC increases gradually with the freeze-thaw times. At the same times, the loss rate of compressive strength without fiber recycled concrete is the largest, and the minimum loss rate is glass fiber ratio values 1.0 %. The incorporation of glass fiber into RC plays the connection between the recycled concrete aggregate to bear the tensile force for the compression cracking of RC to improve the compression resistance, which is consistent with the research results of Ali et al. [41]. After 50 freeze-thaw cycles, the compressive strength of RC with 0.5 %, 1.0 %, and 1.5 % is 7.91 %, 17.09 %, and 14.80 % higher than RC without mixed fiber, respectively. After 100 freeze-thaw times, they are 6.23 %, 15.58 %, and 2.75 % higher than RC. After 150 freeze-thaw times, they are 8.19 %, 21.35 %, and 17.79 % higher than RC. Therefore, as the freeze-thaw times are coincident, the compression resistance of glass fiber RC is better than that of unmixed fiber RC, meanwhile, the best glass fiber mix is 1.0 %.

According to the obtained data, the regression analysis of the compressive strength loss rate and freeze-thaw times of glass fiber RC is conducted. The relationship curve of different glass fiber mixtures is shown in Fig. 9. The compressive strength loss rate of glass fiber RC increase linearly with the freeze-thaw times, the correlation formula is as follows. The parameters obtained by the regression are shown in Table 9. The correlation coefficients of the model R^2 are all higher.

$$\Delta f_c(n) = dn + c \tag{6}$$

From the regression analysis of the loss decay coefficients *c* and *d* of different glass fiber incorporation resistance strengths, the mass loss decay coefficients can be expressed by the unary cubic function of glass fiber incorporation. The expressions are shown as follows, the regression curves are shown in Fig. 10.

$$c = 0.49333x^3 - 0.5x^2 - 0.97333x + 1.26 \tag{7}$$

$$d = 0.0592x^3 - 0.12x^2 + 0.0312x + 0.2602 \tag{8}$$

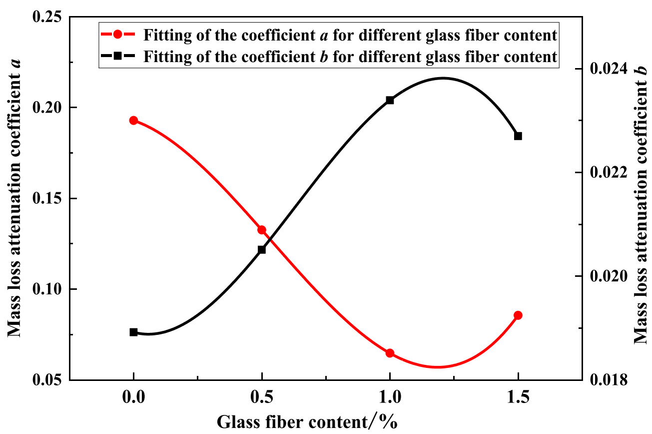

Fig. 7. Mass loss attenuation coefficient.

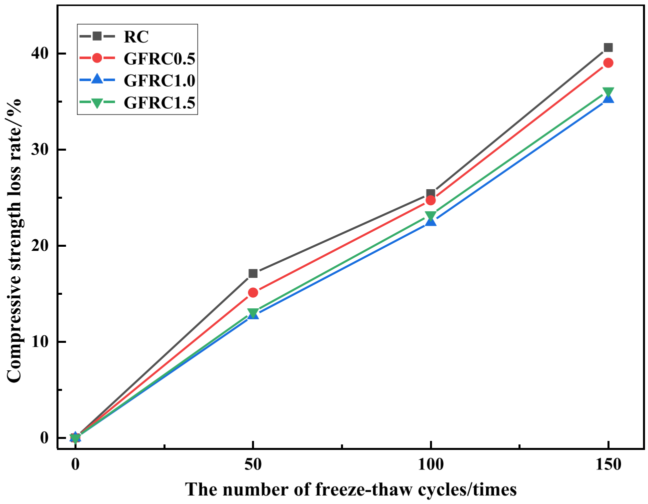

Fig. 8. Relationship between the number of freeze-thaw cycles and the loss rate of compressive strength.

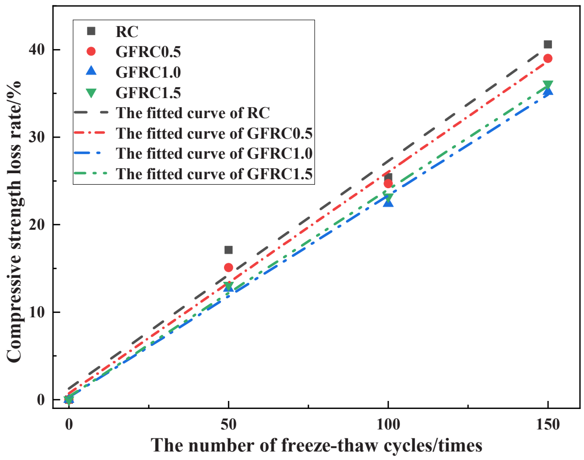

Fig. 9. Regression curve of compressive strength loss rate under different freeze-thaw cycles.

Table 9
Regression parameters of compressive strength under freeze-thaw cycle.

Concrete number	Coefficient *c*	Coefficient *d*	R^2
RC	1.26	0.2602	0.97692
GFRC0.5	0.71	0.2532	0.99003
GFRC1.0	0.28	0.2306	0.99581
GFRC1.5	0.34	0.2368	0.99639

3.4. Loss of dynamic elastic modulus after freeze-thaw damage

According to the mechanical damage theory, the dynamic elastic modulus loss rate of glass fiber RC D_n after the following formula defines frozen-thaw damage, the calculated values are shown in Table 7. The change of dynamic elastic modulus loss rate of glass fiber RC with the frozen-thaw times in Fig. 11.

$$D_n = \left(1 - \frac{E_{dn}}{E_{d0}}\right) \times 100\% \tag{9}$$

Where, D_n and E_{dn} are the dynamic elastic modulus and their loss rate after n frozen-thaw cycles.

As shown in Fig. 11, the dynamic elastic modulus loss rate of glass fiber RC increases with the frozen-thaw times. According to the

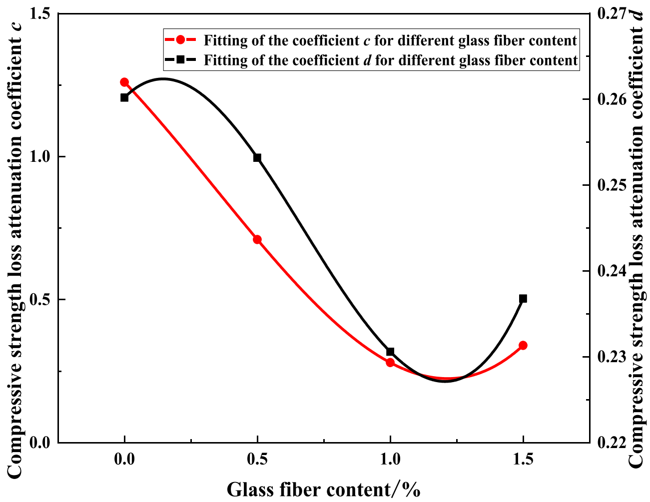

Fig. 10. Compressive strength loss attenuation coefficient.

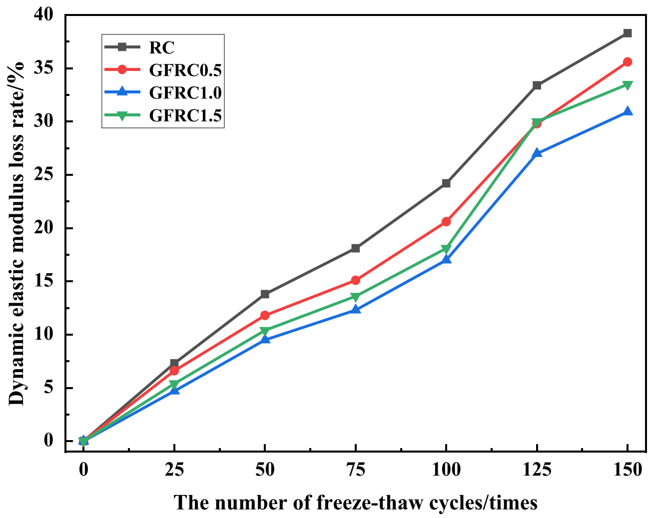

Fig. 11. Relationship between the number of freeze-thaw cycles and the loss rate of dynamic elastic modulus.

figure curves, incorporating glass fiber into RC can reduce the frozen-thaw environment damage to RC's dynamic elastic modulus. When the frozen-thaw less than 25 times, the difference in dynamic elastic modulus of each glass fiber mixed RC is small. The difference in the dynamic elastic modulus loss rate gradually increases with the increasing number of times. After 150 times, the dynamic elastic modulus loss rate of the glass fiber mixing amount of 0.5 %, 1.0 %, and 1.5 % was reduced by 2.7 %, 7.4 %, and 4.8 % compared with the unmixed glass fiber recycled concrete, respectively. Therefore, as the freeze-thaw times are coincident, the frost resistance of RC with glass fiber is better than that without fiber, the best-mixed amount of glass fiber is 1.0 %.

3.4.1. Dynamic elastic modulus loss decay model based on the Weibull distribution model

The Weibull distribution model is a function pattern of random distribution, and the experiments proved that the Weibull distribution could be applied to the concrete frost life prediction [42–44]. Therefore, the dynamic elastic modulus damage attenuation model of glass fiber RC under the freeze-thaw environment was established based on it.

According to the two-parameter Weibull distribution model, it can be assumed that $f(n)$ represents the density function of n times of the freeze-thaw cycles, as shown in the following formula:

$$f(n) = \frac{\beta}{\eta}\left(\frac{n}{\eta}\right)^{\beta-1}\exp\left[-\left(\frac{n}{\eta}\right)^{\beta}\right] \tag{10}$$

Integrating the above equation, the corresponding failure probability function is shown as the following equation:

$$F(n) = 1 - \exp\left[-\left(\frac{n}{\eta}\right)^{\beta}\right] \quad (11)$$

Then, the failure probability expression of glass fiber recycled concrete after n frozen-thaw times are as follows:

$$P_f(n) = 1 - \exp\left[-\left(\frac{n}{\eta}\right)^{\beta}\right] \quad (12)$$

where, β is the Weibull shape coefficient, η is the dimension parameter.

According to the above equation, the failure probability of the Weibull distribution function is an increasing function, when the number of glass fiber recycled concrete cycles n increases, the failure probability also increases accordingly. At the failure probability $P_f(n) = 1$, N is the number of failures of the frozen-thaw damage of specimens. It is assumed that after the glass fiber recycled concrete passes through n frozen-thaw times, the failure probability of specimens is $P_f(n)$, and the depletion variable is $D(n)$. When $n = N$, the glass fiber recycled concrete fails under the freeze-thaw cycle; at this time, $P_f(n) = 1$, $D(n) = 1$. Therefore, the failure probability and depletion variable of glass fiber recycled concrete are treated equivalent, that is, $P_f(n) = D(n)$.

Therefore, $D(n)$ is expressed as:

$$D(n) = 1 - \exp\left[-\left(\frac{n}{\eta}\right)^{\beta}\right] \quad (13)$$

For the convenience of calculation, the constant transformation on both ends of the above formula is:

$$\frac{1}{1 - D(n)} = \exp\left(\frac{n}{\eta}\right)^{\beta} \quad (14)$$

Taking the log on both sides of the upper formula is:

$$\ln\left(\ln\frac{1}{1 - D(n)}\right) = \beta \ln\frac{1}{\eta} + \beta \ln(n) \quad (15)$$

Let $y = \ln\left(\ln\frac{1}{1-D(n)}\right), x = \ln(n), a = \beta, b = \beta\ln(1/\eta)$, then:

$$y = ex + f \quad (16)$$

The x and y are calculated according to the obtained damage amount $D(n)$, and the linear regression of x and y are performed. The parameters of the RC under each glass fiber content are shown in Table 10, the fitting curves are shown in Fig. 12.

β and η can be calculated according to the e and f of each specimen in Table 10 to obtain the freeze-thaw depletion model of glass fiber regenerated concrete under Weibull distribution. The model expression is shown as follows, and the coefficients are shown in Table 11.

$$D(n) = 1 - \exp\left[-\left(\frac{n}{\eta}\right)^{\beta}\right] \quad (17)$$

According to Table 11, the correlation coefficient R^2 of the freeze-thaw damage model based on the dynamic elastic modulus of glass fiber RC under Weibull distribution is all above 0.95. While satisfying the randomness of freeze-thaw depletion of glass fiber RC, the proposed model also meets the boundary condition of freeze-thaw damage $D_n = 0$ when the freeze-thaw cycle is $n = 0$. Therefore, the model is suggested to describe the elastic modulus decay of glass fiber regenerated concrete after the freeze-thaw damage.

3.4.2. Life prediction of recycled concrete based on the Weibull distribution model

The glass fiber recycled concrete specimens freeze and thaw by rapid freezing method, and the test data is obtained through accelerated test. Therefore, the mathematical model combined with the accelerated test measure are used to predict the life of RC in the actual environment. Li [45] had clarified the relationship between the in-service life t of serving the concrete and the number of rapid frozen-thaw times n, as follows. Moreover, the possible frozen-thaw times in the past 50 years in China, Changchun, Beijing, Xining, and Yichang were counted and analyzed. It is concluded that the possible annual average frozen-thaw times in different regions of China are shown in Table 12.

$$t = \frac{kn}{M} \quad (18)$$

Where, t is the component's service life (year), k is the freeze-thaw test coefficient, generally takes 12; n is the indoor rapid freeze-thaw times, and M is the possible freeze-thaw times for the actual environment of the concrete structure in one year.

According to the Weibull distribution model, the freeze-thaw times n at dynamic elastic model loss rate $D_n = 40$ % was calculated, and the life of all kinds of glass fiber recycled concrete in each area was predicted according to the above formula. The prediction results are shown in Table 13.

The above table indicates that the RC's service life gradually increases with glass fiber content. When it reaches 1.0 %, the glass fiber RC's service life is the longest in each region. Therefore, it is suggested that when the concrete structure using 25 % regenerated

Table 10
Dynamic elastic modulus damage fitting parameters under freeze-thaw cycle.

Concrete number	Coefficient e	Coefficient f	R^2
RC	1.02762	− 5.93584	0.98414
GFRC0.5	1.02650	− 6.07949	0.96543
GFRC1.0	1.12678	− 6.72753	0.96600
GFRC1.5	1.10815	− 6.54258	0.95483

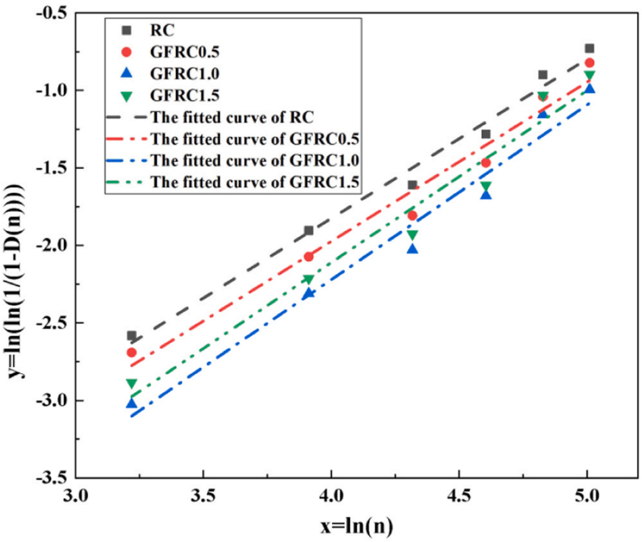

Fig. 12. Dynamic elastic modulus damage fitting curve under freeze-thaw cycle.

Table 11
Parameters of the Weibull distribution model under the freeze-thaw cycle.

Concrete number	Coefficient β	Coefficient η
RC	1.02762	322.5630535
GFRC0.5	1.0265	373.4689527
GFRC1.0	1.12678	391.7327639
GFRC1.5	1.10815	366.5211802

Table 12
Annual average number of freeze-thaw cycles that may occur in different regions of China.

Region (Representative Region)	Average annual freeze-thaw cycles/times
Northeast Region (Changchun)	120
North China Region (Beijing)	84
Northwest Region (Xining)	118
Central China Region (Yichang)	18
Eastern China Region	18–84

Table 13
Frost resistance life prediction of glass fiber recycled concrete (year).

	Fiberglass admixture			
Region	0	0.5 %	1.0 %	1.5 %
Northeast Region	18	19	22	20
North China Region	24	28	31	29
Northwest Region	18	20	22	20
Central China Region	112	129	149	133
Eastern China Region	24–112	18–129	31–149	29–133

aggregate instead in the project, glass fiber should be mixed with a 1.0 % volume rate.

4. Economical analyses

The accelerated carbonization method is widely used to realize the green modification of RAC [46–48]. The carbonization modification method is simple, efficient, economical and environmental. Moreover, the mechanism of action is to dissolve CO_2 and contact with the calcium source in the recycled aggregate adhesion mortar to generate $CaCO_3$ crystal and silicate gel. After carbonization, the solid volume increases, filling the gaps inside RC, making the Interface Transition Zone (ITZ) bond better, thus improving the physical properties of the RC. Zhang et al. [49] believed that carbonation of hydrated calcium silicate could increase solid volume by 23 %.

Compared with natural aggregate, the process of waste aggregate from recovery to carbonization treatment and regeneration significantly reduces the pressure of the system production on the environment. Furthermore, the carbonization of regenerated aggregate and the incorporation of glass fiber optimize the mechanical properties and durability of RC. However, obtaining the high modification result at an extremely high cost in the practical application is not desirable, and the best balance among performance optimization, environmental load, and economic benefit should be sought. The applicable conditions of RAC with different fiber content are adapted to local conditions. This paper mainly conducts an economical analysis of the applicability of glass fiber RAC under the freeze-thaw environment in different regions of China.

4.1. Long-term performance analysis of glass fiber recycled concrete after freeze-thaw damage

According to annual average freeze-thaw cycle number statistics, the number of times in East China should be between the number in Central China and North China; therefore, the predicted life expectancy in East China refers to the average value in Central China and North China for calculation. When the dynamic elastic modulus of glass fiber RC drops to 60 %, the minimum predicted freezing life of glass fiber recycled concrete in each area is 18 years, so 18 is taken as the actual service life of long-term performance analysis. Moreover, as shown in Eq. (18), the freeze-thaw test coefficient k usually takes the value of 12. Therefore, in Northeast China, North China, Northwest China, Central China, and East China, the freeze-thaw cycles were taken 180, 126, 177, 27, and 76 times under the test conditions to calculate the performance impairments. According to the predicted damage model of mass, compressive strength, and dynamic elastic modulus, the residual compressive strength percentage, residual mass percentage, and residual dynamic elastic modulus percentage of RC in different regional freeze-thaw environments and different fiber contents were calculated, respectively. Finally, referring to the importance of each index and giving the corresponding weight, the comprehensive performance evaluation value of RC with different glass fiber content in each region is calculated, as shown in Table 14.

According to the long-term analysis and calculation, the three-dimensional comparison effect of the mass coefficient, compressive strength coefficient, and dynamic elastic modulus coefficient of RC with different glass fiber content in each area is shown in Fig. 13. Horizontal point of view: On the one hand, due to the low number of frozen-thaw times in every year, the mass, compressive strength, and dynamic elastic modulus of glass fiber regenerated concrete in Central China are better than those in other regions. On the other hand, fiber addition improves the properties of regenerated concrete, and the best effect is achieved as the incorporation ratio of fiber values is 1.0 %. Longitudinal point of view: the glass fiber regenerated concrete in the five major regions has minor mass damage and a significant loss of compressive strength and dynamic elastic modulus. Among the properties of glass fiber regenerated concrete, the

Table 14
Performance evaluation of glass fiber regenerated aggregate concrete.

Regions	Concrete number	Mass	Compression strength	Dynamic elastic modulus	Performance comprehensive evaluation
Northeast China	RC	0.942	0.519	0.577	0.627
	GFRC0.5	0.947	0.537	0.623	0.654
	GFRC1.0	0.956	0.582	0.659	0.688
	GFRC1.5	0.949	0.570	0.635	0.672
North China	RC	0.979	0.660	0.683	0.733
	GFRC0.5	0.982	0.674	0.721	0.754
	GFRC1.0	0.988	0.707	0.757	0.783
	GFRC1.5	0.985	0.698	0.736	0.771
Northwest China	RC	0.945	0.527	0.583	0.633
	GFRC0.5	0.950	0.545	0.628	0.659
	GFRC1.0	0.959	0.589	0.665	0.693
	GFRC1.5	0.952	0.577	0.640	0.677
Central China	RC	0.997	0.917	0.925	0.936
	GFRC0.5	0.998	0.925	0.935	0.943
	GFRC1.0	0.999	0.935	0.952	0.955
	GFRC1.5	0.998	0.933	0.946	0.951
East China	RC	0.992	0.790	0.797	0.833
	GFRC0.5	0.994	0.800	0.823	0.848
	GFRC1.0	0.996	0.822	0.854	0.870
	GFRC1.5	0.995	0.817	0.840	0.862
Weight		0.2	0.4	0.4	1.0

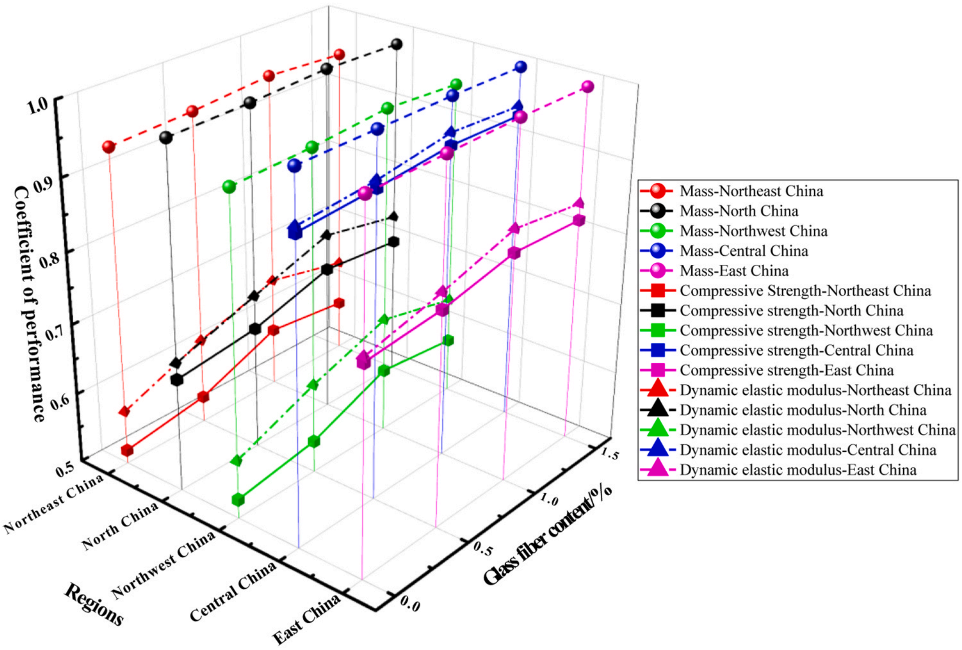

Fig. 13. Performance evaluation of glass fiber regenerated aggregate concrete.

best reservation is mass, followed by the dynamic elastic modulus, and the final is concrete compressive strength. In conclusion, a freeze-thaw environment significantly damages the compressive strength of glass fiber RC, which is the most important mechanical property of concrete components. Furthermore, it shows that the long-term performance analysis of glass fiber RAC under the freeze-thaw cycle is critical. It has a strong practical guiding significance for applying glass fiber RAC in engineering projects.

A comprehensive evaluation of glass fiber RAC performance in Fig. 14 shows that: from different regions, the performance coefficient in Central China is generally reasonable. Because the annual average freeze-thaw times in Central China are small, which has little influence on the life damage of concrete components, its performance evaluation has certain advantages compared with other regions. From the perspective of glass fiber content, glass fiber significantly enhances the freeze-thaw resistance of RC. As the fiber volume ratio reaches 1.0 %, the glass fiber RAC in each area shows optimal performance. In addition, the same fiber incorporation variable significantly optimizes concrete properties in Northeast China and Northwest China with the worst freeze-thaw environment. In contrast, the improvement effect of fiber incorporation in Central China with fewer freeze-thaw cycles is poor. Because of that, the

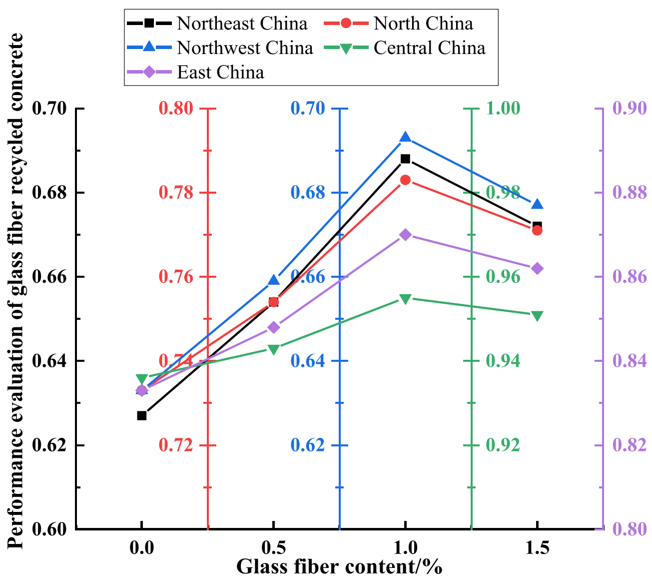

Fig. 14. Comprehensive evaluation of glass fiber regenerated aggregate concrete performance.

glass fiber plays a "micro steel bar" in the concrete matrix and inhibit micro-crack expansion in the freeze-thaw cycle. However, excessive fiber incorporation is easy to cause the "agglomeration" phenomenon, and the fiber agglomeration affects the bridging of the interface transition zone, decreasing the strength of concrete. Therefore, from the long-term performance analysis of glass fiber RAC, the comprehensive performance coefficient of RAC is the largest when the fiber volume admixture values 1.0 %; simultaneously, the RAC exhibits optimal performance. This conclusion is consistent with the short-term trial results: when the fiber content is 1.0 %, the mass, compressive strength and dynamic elastic modulus of the test block are optimal compared with other content.

4.2. Cost analysis of glass fiber recycled concrete after freeze-thaw damage

This test replaces recycled aggregate with natural aggregate by 25 %. Other materials (cement, sand, fly ash, water, and water reducer) are the same except for different fiber content. Therefore, the cost analysis should only consider the price difference caused by different glass fiber content. The comprehensive cost calculation of RAC with different fiber content is shown in Table 15. According to the market cost: C30 natural aggregate concrete is 335 yuan/m^3; C30 RAC is 273 yuan/m^3; glass fiber costs, converted by mass divided by volume, 0.5 % is 11.78 yuan/m^3,1.0 % is 23.56 yuan/m^3, 1.5 % is 35.34 yuan/m^3. Let the cost coefficient of C30 natural aggregate concrete is 1, and the comprehensive material cost of RC with different fiber content is converted into the corresponding cost coefficient.

4.3. Analysis of the cost-performance ratio of glass fiber recycled concrete after freeze-thaw damage

Its function and cost factors should be considered the primary evaluation indexes to evaluate concrete use value in a specific area. This paper introduces the value engineering analysis method. According to the following formula, the functional coefficient takes the comprehensive performance evaluation of glass fiber RAC in Table 14, and the cost coefficient comes from the cost conversion of Table 15. The cost performance value of glass fiber RAC in different areas is calculated, as shown in Table 16.

$$V = \frac{F}{C} \tag{19}$$

Where, V is the comprehensive value of concrete, F,C are the function and cost respectively.

The cost performance ratio of RAC without fiber mixed in northeast China is taken as the reference standard, and the change rate of the cost performance ratio of RAC with different glass fiber content in each region is shown in Fig. 15. Regional horizontal comparison is available: the cost-performance ratio of glass fiber RAC is inversely related to the average annual freeze-thaw cycles. The concrete cost-performance ratio is low in northeast and northwest China with more freeze-thaw times; the concrete cost-performance ratio is high in Central and East China with less freeze-thaw times.

In Northeast and Northwest China, RAC has the highest cost-performance ratio when the fiber content amount is 1.0 %. Because of the significant average annual freeze-thaw times, take the long view, the performance improvement effect of fiber on RAC in these two regions is particularly significant. The cost performance value of the RAC in the two areas is arranged from large to small as mixed with 1.0 % glass fiber > unmixed fiber > mixed with 0.5 % glass fiber > mixed with 1.5 % glass fiber. In contrast to the unmixed fiber RC, the modification advantage of adding 1.0 % glass fiber exceeds the cost disadvantage of the fiber material. The annual average freeze-thaw times in Northwest China are slightly less than that in Northeast China, so the improvement effect of fiber in Northwest China is slightly less than in Northeast China.

On the contrary, in Central China, East China, and North China, the cost-performance ratio of RAC is the highest without fiber. Due to the regional annual freeze-melt cycle number being small when the actual service of 18 years is taken as a long-term performance evaluation, the performance improvement of concrete mixed with fiber is not significant enough. The fiber of RAC modification advantage is insufficient to compensate for the increased material cost disadvantage; therefore, in Central China, East China, and North China, the RAC without fiber has the highest cost-performance ratio. However, it can be predicted that: with the increase in concrete service life, the performance advantages of fiber materials will appear later.

5. Conclusion

(1) After freeze-thaw damage, the aggregates on the specimen's surface were damaged to varying degrees, and the surface deterioration degree of the RC without glass fiber was greater than that of the RC with glass fiber. The glass fiber is mixed into the RAC, which plays a role in connecting the aggregates, thereby inhibiting the development of micro-cracks and improving the

Table 15
Comprehensive cost comparison of different types of concrete.

Item	RC	GFRC0.5	GFRC1.0	GFRC1.5	NC
Fiber material (Yuan/m^3)	0	11.78	23.56	35.34	0
Other materials (Yuan/m^3)	273	273	273	273	335
Comprehensive cost of materials (Yuan/m^3)	273	284.78	296.56	308.34	335
Cost conversion coefficient	0.815	0.850	0.885	0.920	1.000

Notes: NC represents natural concrete.

Table 16
Value evaluation of glass fiber recycled aggregate concrete.

Regions	Concrete number	Functional coefficient *F*	Cost coefficient *C*	Cost performance *V*
Northeast China	RC	0.627	0.815	0.769
	GFRC0.5	0.654	0.850	0.769
	GFRC1.0	0.688	0.885	0.777
	GFRC1.5	0.672	0.920	0.730
North China	RC	0.733	0.815	0.899
	GFRC0.5	0.754	0.850	0.887
	GFRC1.0	0.783	0.885	0.884
	GFRC1.5	0.771	0.920	0.837
Northwest China	RC	0.633	0.815	0.777
	GFRC0.5	0.659	0.850	0.775
	GFRC1.0	0.693	0.885	0.783
	GFRC1.5	0.677	0.920	0.736
Central China	RC	0.936	0.815	1.149
	GFRC0.5	0.943	0.850	1.110
	GFRC1.0	0.955	0.885	1.078
	GFRC1.5	0.951	0.920	1.033
East China	RC	0.833	0.815	1.022
	GFRC0.5	0.848	0.850	0.998
	GFRC1.0	0.870	0.885	0.982
	GFRC1.5	0.862	0.920	0.936

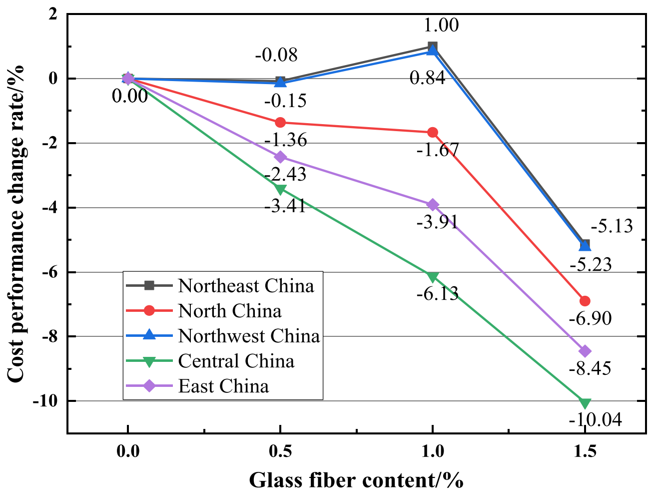

Fig. 15. Change rate of different glass fiber recycled aggregate concrete.

RC's performance. An excessive amount of fibers is easy to agglomerate in the concrete matrix, which reduces the modification effect of fibers on RAC.

(2) The mass loss rate of glass fiber RC is associated with the freeze-thaw times; the change rate of it also increases with the times. After 150 times, when the glass fiber content is 0.5 %, 1.0 %, and 1.5 %, the mass loss rate is reduced by 0.405 %, 1.100 %, and 0.725 %, respectively; the compressive strength of RC is raised to 8.19 %, 21.35 %, and 17.79 %, respectively. Moreover, the performance of RAC is the best as the glass fiber ratio values 1.0 %. Based on the Weibull distribution, the loss attenuation pattern of dynamic elastic modulus of glass fiber RC is established after freeze-thaw damage. The fitting accuracy is more significant than 0.95, which can well reflect the internal freeze-thaw destruction of glass fiber regenerated concrete. Based on the dynamic elastic modulus damage model, the frost-resistant durability life of glass fiber RC is predicted.

(3) The fiber improves the mass, compressive strength, and dynamic elastic modulus of RC in the freeze-thaw environment, based on the long-term performance of components in service for 18 years. Considering the increased material cost of fiber incorporation in the northeast and northwest regions where the freezing and thawing environment is relatively harsh, the RAC mixed with 1.0 % glass fiber is still the most cost-effective. In addition, it is foreseeable that in areas with fewer annual average freeze-thaw cycles, such as Central China, East China, and North China, the performance advantages brought by fiber materials will also appear later as the service life of concrete increases.

CRediT authorship contribution statement

Weiwei Wu: Writing – review & editing, Resources, Methodology. **Yuewen Huang:** Investigation, Supervision, Validation, Writing – review & editing. **Wenrui Yang:** Resources, Project administration, Conceptualization. **Chengwei Li:** Writing – original draft, Formal analysis, Data curation. **Xiaolong Xiong:** Visualization, Software, Data curation. **Jia He:** Writing – review & editing, Supervision, Resources, Conceptualization. **Zhiyi Tang:** Methodology, Investigation, Formal analysis. **Weijie Quan:** Visualization, Software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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