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Research paper

Preparation and performance of steel slag and recycled brick aggregate modified concrete under the background of solid waste application

Lili Wei[1]

Abstract: Permeable concrete has the characteristics of breathability, permeability, and high heat dissipation. To improve its mechanical and frost resistance properties, this study optimized the preparation and performance of permeable concrete by adding materials to improve its performance. The performance analysis validate that epoxy resin owns a filling effect on the pores of permeable concrete. The internal curing agent, high water absorbent resin, has a good water absorption effect. The synergistic effect of these two increases the density and compressive strength of permeable concrete. When the two contents are 0.5%, the maximum compressive strength of modified permeable concrete at 7 and 28 days was 15.62 and 17.97 MPa, respectively. Under the action of freeze-thaw cycles, its mass loss rate show an upward trend By comparison, epoxy resin and high water absorbent resin are beneficial for improving the frost resistance of permeable concrete. The minimum value of relative dynamic modulus of elasticity remains stable at over 80%, and the loss rate of dynamic modulus of elasticity is all below 0.4. However, the influence of epoxy resin and SAP on the mass loss rate is relatively small, and the mass loss of all experimental groups is controlled below 2.5%. The binomial Fourier function model is the best predictive model for permeable concrete under freeze-thaw cycles. This study has positive significance for improving the performance of permeable concrete and maintaining the sustainable development of ecological cities.

Keywords: frost resistance, mechanical properties, permeable concrete, recycled brick aggregate, solid waste resources, steel slag

[1]Associate Professor, PhD., School of Resources Environment and Architectural Engineering, Chifeng University, Chifeng 024000, China, e-mail: weilili913@163.com, ORCID: 0009-0008-8829-6585

1. Introduction

Permeable Concrete (PC) is a kind of porous lightweight concrete made by mixing aggregates, cement, reinforcing agents, and water. It is the core element of building a sponge city [1,2]. As a new type of pavement material, PC has uniformly distributed surface pores and a honeycomb like structure, which has the characteristics of breathability, water permeability, and lightweight. Therefore, it can effectively absorb rainwater, disperse the impact of urban water logging, and solve the problem of urban flooding. However, PC belongs to a non dense structure, and its strength and frost resistance durability still need to be further improved [3,4]. At the same time, at present China's waste construction waste exceeds 2 billion tons, and the accumulation of solid waste in the metallurgical industry exceeds 1 billion tons, but the comprehensive utilization rate is only about 5%. Improving the utilization level of solid waste resources (SWR) is an urgent problem that needs to be solved in society [5,6]. Therefore, this study combines the utilization of solid waste such as SS and recycled brick aggregate (RBA) with the improvement of PC performance to explore the preparation and performance of SS and RBA modified concrete. The research mainly consists of four parts. The first part is a review of the present research status of SS modified concrete at home and abroad. The second part elaborates on the preparation and performance testing analysis methods of SS concrete. The third part analyzes the performance test results of modified SS concrete. The final section summarizes and summarizes the research experimental results. This study hopes to improve and expand the application range of PCs.

2. Related works

The comprehensive utilization of SWR such as SS has become one of the hot issues of global concern. Numerous scholars have conducted a series of studies on the preparation and macroscopic properties of SS modified concrete. In order to develop high-performance concrete thermal energy storage media, Boquera et al. designed four different proportions of concrete. The thermal mechanical properties of concrete were studied using cement and aggregate types as research variables. It was found that ordinary Portland cement and calcium aluminate cement (CaC) combined with steel slag aggregate (SSA) concrete have good stability during thermal cycling. However, the microscopic results show that the bonding force between SSA and cement slurry is weak [7]. Rosales et al. developed a low cement content binder that replaces 50% of cement. They mixed 35% alkali activated stainless SS with 65% fly ash and hydroxide activated solution to form a binder when manufacturing concrete. This study indicates that this type of self compacting concrete has good mechanical properties and durability, while reducing cement consumption and improving the utilization rate of solid waste, e.g. SS [8]. To alleviate the environmental problems caused by natural river sand mining, deal with the accumulation of large amounts of SS, and fill the research gap, Ho et al. and Zhuang et al. prepared five types of concrete using SS instead of crushed granite natural coarse aggregate. This study investigated the heating behavior, residual compressive strength (CS), weight loss, surface texture effects, and chemical degradation behavior of concrete. Experiments have shown that partially or completely replacing crushed granite with SS can enhance the insulation capacity of concrete. After the replacement rate of natural coarse aggregate reaches 75%, the residual strength of concrete is still at a high level when exposed to high temperatures between 600 and 800°C [9, 10]. Piro et al. collected and processed 338 data points to construct a strength prediction model for SS concrete using multiple logistic regression models, artificial neural networks, full quadratic models, and interactive models. The results prove that an increase in the volume fraction of SS can increase the concrete strength. According to the evaluation of statistical tools such as objective functions, scatter plots, and Taylor plots, the artificial neural network model outperforms other models in predicting CS [11, 12]. In summary, there have been many studies on SSA concrete, and the high strength and toughness characteristics of SSA have been confirmed. However, there is relatively little study on the application of SS concrete in PC modification. This study has conducted relevant discussions on solid waste and PC.

3. Preparation and properties of PC modified with steel slag RBA

To achieve a balance between the permeability and mechanical durability of PC, SS and RBAs are used instead of natural sand and gravel aggregates in PC. Modified reclaimed brick aggregate pervious concrete was prepared by epoxy resin and superabsorbent resin.

3.1. Experimental materials and forming technology of PC modified with SS–RBA

PC is mainly composed of cement, aggregates of the same particle size or intermittent grading, and water in a certain mix ratio [13]. PO42.5 ordinary Portland cement is selected as the cement. The cement has a loss on ignition of 3.10, an initial setting time of 150 min, a final setting time of 250 min, and a flexural strength of 28 d. The CS is 7.8 MPa and 45.8 MPa respectively. The coarse aggregate used in the preparation of PC is a mixture of RBA and SSA [14]. Table 1 shows the basic physical properties of aggregates. SS is the waste formed during the separation of molten steel and impurities during the steelmaking process, and is a solid waste substance cooled by silicate and oxide solutions [15, 16]. This study uses SSA after stacking and aging treatment for the preparation of PC.

For improving the mechanical properties of SS–RBA, water-based epoxy resin (WES) and super absorbent polymer (SAP) are introduced. WES and SAP have the advantages of solvent-free, low volatility, and environmental friendliness, and are often used to improve the performance of concrete. SAP, as an internal curing agent, is commonly used to alleviate early cracking and shrinkage of concrete and improve its durability. It fills the micro pores in concrete through water absorption and expansion, improving the impermeability of concrete. It can also lift the CS and flexural strength of concrete [17].

This study used E-44 type WES and matched it with 650 polyamide resin curing agent. The surface of WES is free of mechanical impurities and appears transparent. The quality index

Table 1. SS–RBA modified PC coarse aggregate

Aggregates	Particle size (mm)	Density (kg/m^3)	Bulk density (kg/m^3)	Compact density (kg/m^3)	Loose accumulation voids (%)	Tightly packed voids (%)
RBA	3–5	2485	1060	1185	57.5	52.0
	5–8	2480	1055	1150	58.0	53.5
	10–13	2475	1040	1150	58.0	53.4
Slag aggregate	3–5	3190	1680	1850	47.5	42.0
	5–8	3180	1670	1830	47.2	42.3
	10–13	3160	1680	1820	46.8	42.5

test results show that the epoxy equivalent is 214.2 g/eq, the softening point is 15.7°C, the volatile content is 0.378%, the hydrolyzable chlorine is 0.2098%, and the inorganic chlorine is 0.0008. SAP uses polyacrylic acid sodium salt SAP. The water absorption rate is 498, the absorption rate of 0.9% NaCL is 87, the water content is 4.8%, the bulk density is 0.74 g/ml, and the pH value is 6 at 25°C. The water cement ratio of the PC prepared in the experiment is set to 0.29, and the collection cement ratio is 3.8. Table 2 shows the modified PC mix ratio parameters carried out.

Table 2. Experimental mix proportion of SS brick aggregate modified PC

Group	Epoxy resin	SAP	Material usage (kg/m^3)						
			Water	Cement	Slag	Recycled aggregate	Water reducing agent	Epoxy resin	SAP
1	0	0	128	440	835	835	1.13	0	0
2	0	0.5	128	440	835	835	1.13	0	2.2
3	0	1	128	440	835	835	1.13	0	4.4
4	0.5	0	128	440	835	835	1.13	2.2	0
5	0.5	0.5	128	440	835	835	1.13	2.2	2.2
6	0.5	1	128	440	835	835	1.13	2.2	4.4
7	1	0	128	440	835	835	1.13	4.4	0
8	1	0.5	128	440	835	835	1.13	4.4	2.2
9	1	1	128	440	835	835	1.13	4.4	4.4

This study used the feeding and stirring method. Firstly, mix the cement, SSA, recycled aggregate, and SAP dry for two minutes until uniform. Add half the quantity of water and stir with polycarboxylic acid water reducer (PAWR) for two minutes. After wetting the surface of the aggregate and powder, add the remaining water and mix it evenly with a PAWR. The minimum particle size of the modified PC prepared in this study is between 3–5 mm, and there is almost no fine aggregate with a particle size below 4.75 mm. The traditional vibration forming method is not applicable. In response, this study designed an improved vibration forming device for forming surfaces based on a drop hammer device. The molding process diagram of modified PC is shown in Fig. 1. In Fig. 1, the threaded connecting rod of the new drop hammer device is equipped with a scale to control the height of the drop hammer. The bottom is equipped with three different types of detachable base plates. These two technological improvements have solved the problem of adjusting and controlling impact energy and impact area, avoiding the harm of aggregate fragmentation. Finally, use a manual press to hold the PC template lightly pressed by the hammer at a pressure of 1 MPa for 20 seconds.

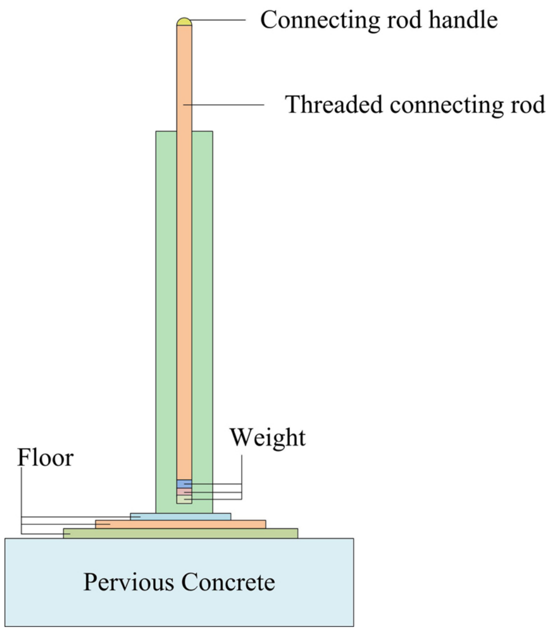


Fig. 1. Improved drop hammer device for modified PC

3.2. Performance testing methods and mechanical property decay model construction for PC

The performance tests conducted in this study include continuous porosity testing, strength testing, permeability coefficient testing, and dynamic elastic modulus (DEM) testing of PC under freeze-thaw cycles (FT-C). Refer to CJJT253-2016 Technical Specification for Application of Recycled Aggregate PC for continuous porosity testing of PC. The quality testing process of fully immersing PC in water is shown in Fig. 2.

Refer to the GB/T25993-2010 standard for permeable pavement bricks and panels to conduct permeability coefficient tests on modified PC, and the permeability device is shown in Fig. 3.

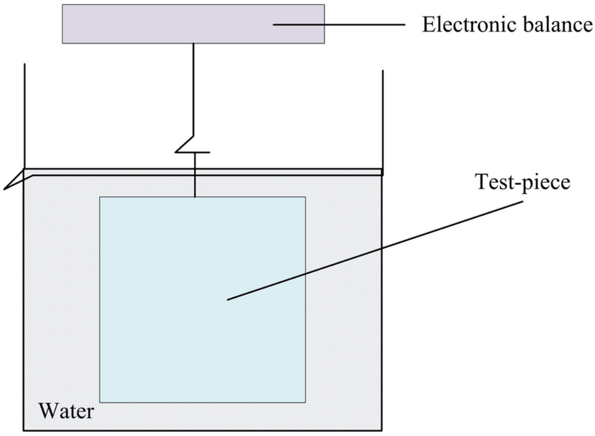


Fig. 2. Schematic diagram of water testing of specimens

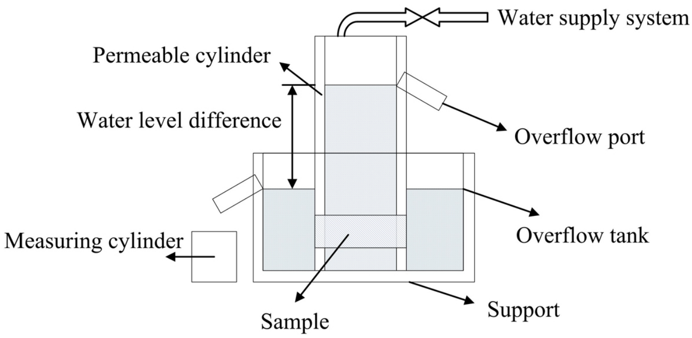


Fig. 3. Schematic diagram of permeability coefficient test device

The calculation process of permeability coefficient is shown in Eq. (3.1). k_T represents the permeability coefficient at temperature T. Q represents the amount of water that seeps out within the specified time of t. G and B represent the thickness (cm) and upper surface area (cm^2) of the specimen, respectively. H represents the water level difference (cm).

$$k_T = \frac{QG}{BHt} \tag{3.1}$$

To calculate the relative DEM (RDEM) loss under FT-C, the expression for the RDEM defined in this study is shown in Eq. (3.2). P represents the RDEM of PC (%). E_i represent the dynamic elastic modulus of pervious concrete after i cycles; E_0 represent the initial dynamic elastic modulus. f_i and f_0 represents the initial FFVF after i cycles, respectively.

$$P = \frac{E_i}{E_0} = \frac{f_i^2}{f_0^2} \tag{3.2}$$

For the attenuation of FFVF and DEM under FT-C, this study defines the loss expressions of frequency and DEM. D_f and D_E represent the loss rates of fundamental frequency vibration and DEM, respectively (see Eq. (3.3)).

$$\begin{cases} D_f = 1 - \dfrac{f_i}{f_0} \\ D_E = 1 - \dfrac{E_i}{E_0} \end{cases} \tag{3.3}$$

To investigate the mechanical property degradation of modified PC under FT-C, the least squares fitting method and DEM test data were used to establish a mechanical property degradation model. This study constructed three functional models. The optimal degradation prediction model was selected based on the fitting test results during use. The construction of the first model is based on the proportional relationship between P and the quantity of FT-C, and the basic model is constructed using the Curve Fitting toolbox of MATLAB. Eq. (3.4) is derived from the calculation process of DEM loss rate. $E(x)$ represents the differentiable function of the DEM, and a is a constant.

$$E(x) = e^{ax} \tag{3.4}$$

The calculation model for RDEM can be obtained by combining Eq. (3.4) and (3.2), as shown in Eq. (3.5).

$$P = \frac{e^{ax}}{E_0} \tag{3.5}$$

The second model considers the deterioration of mechanical properties under FT-C as a deterioration problem under the action of multiple factors. Therefore, using the DEM as the damage variable and using the Gaussian function to construct a mechanical performance attenuation model, Eq. (3.6) is obtained. a_1, b_1 and c_1 are undetermined parameters.

$$y = a_1 e^{-\left(\frac{x-b_1}{c_1}\right)^2} \tag{3.6}$$

The third model uses the Fourier function to fit the predicted values of DEM. The expression of the monomial Fourier function is shown in Eq. (3.7), a_0 is undetermined parameters.

$$y = a_0 + a_1 \cos(xw) + b_1 \sin(xw) \tag{3.7}$$

The expression of the polynomial Fourier function is shown in Eq. (3.8).

$$y = a_0 + a_1 \cos(xw) + b_1 \sin(xw) + a_2 \cos(2xw) + b_2 \sin(2xw) \tag{3.8}$$

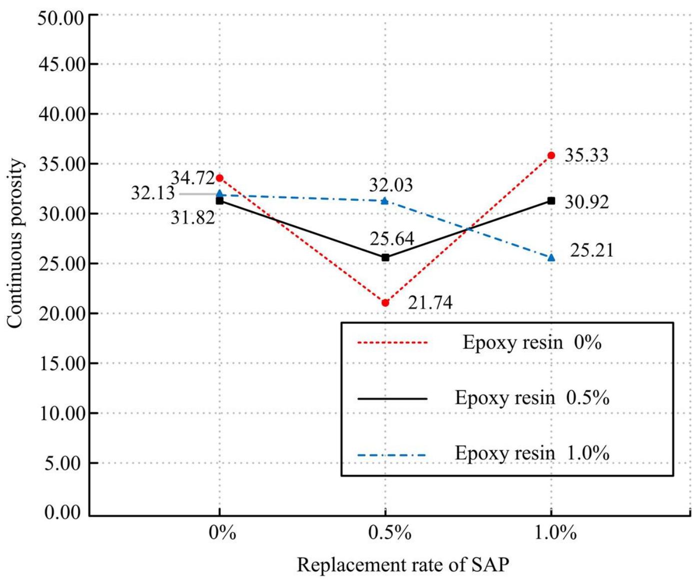
4. Performance testing of epoxy resin combined with SAP modified PC

In order to explore the impact of different WES and SAP dosages on the performance of PC, experiments are conducted to test the basic performance and frost resistance of PC, and the corresponding experimental results are analyzed.

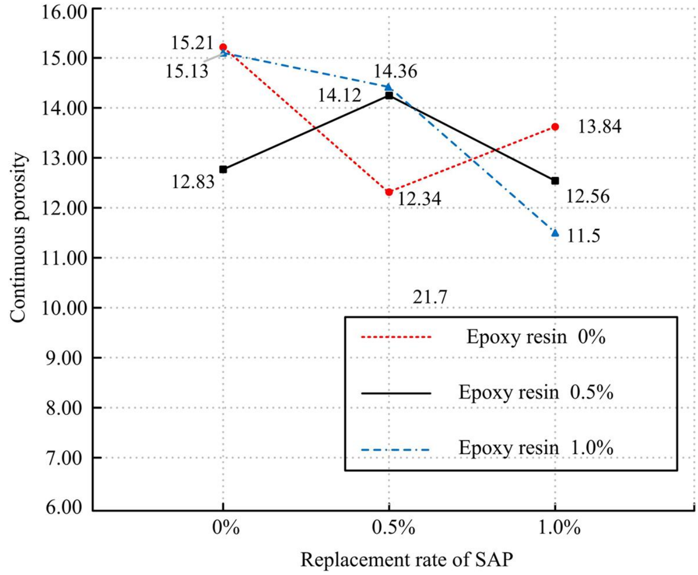
4.1. Basic performance testing of epoxy resin combined with SAP modified PC

The final experimental results of the continuous porosity and permeability coefficient of different PC specimens are shown in Fig. 4. In Fig. 4, when the SAP dosage is 0%, the continuous porosity of modified PC tends to first decrease and then increase with the rise of epoxy resin dosage, but it is less than the continuous porosity of 1.0% epoxy resin dosage. This is because a certain amount of epoxy resin can fill the pores inside the concrete. However, as the dosage of epoxy resin continues to increase, the epoxy resin itself will generate larger voids, increasing the continuous porosity of concrete. When the SAP content increases to 1.0%, the continuous porosity decreases with the increase of epoxy resin content. This is because when the epoxy resin dosage increases to a certain value, the SAP filling effect is enhanced, and the continuous porosity decreases more significantly. When the WES content is 0% and 0.5%, the continuous porosity decreases first and then increases with the addition of SAP. However, excessive SAP addition can result in excessive water absorption capacity, leading to an increase in continuous porosity and a decrease in permeability. When the WES addition amount is 1%, the addition of SAP results in a continuous decrease in porosity. WES and SAP collaborate to fill the internal pores at this time, reducing the continuous porosity, the variation law of permeability coefficient is basically consistent with the continuous porosity variation law. However, when the WES content is 0.5%, the permeability coefficient and continuous porosity change in opposite patterns.

The CS test of modified PC are displayed in Fig. 5. The 7d CS of modified PC with different dosage of WES first increases and then decreases with the lifting of SAP dosage. When the



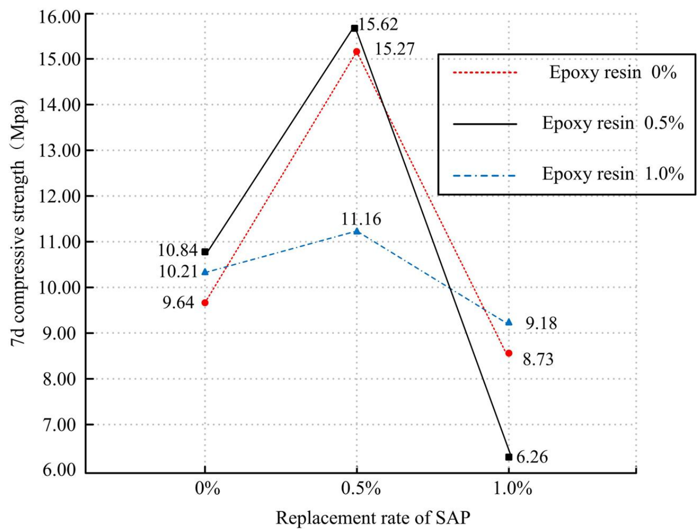
(a)



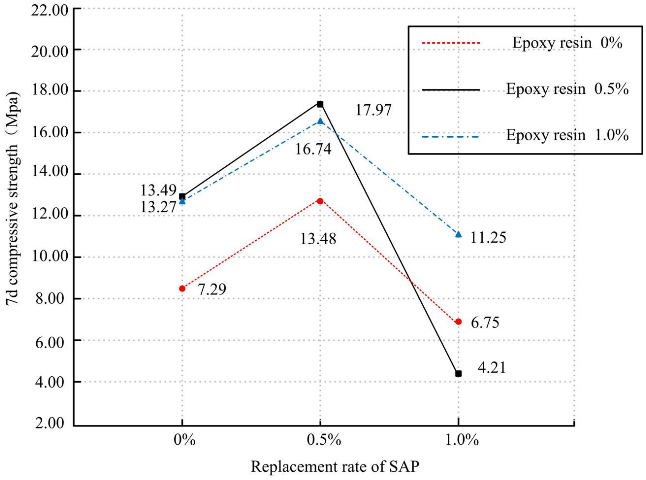
(b)

Fig. 4. Quality variation pattern

SAP content is 0‰ or 0.5‰, WES can fill the pore spaces between cement colloids, enhance the compactness of concrete, and improve CS. However, when the SAP dosage is 1.0‰, the water absorption of SAP is limited due to the effect of WES, and the strength is affected.



(a)



(b)

Fig. 5. Quality variation pattern

4.2. Frost resistance test of epoxy resin combined with SAP modified PC

Fig. 6 is the statistical results of the variation pattern of PC quality. As the FT-C increases, the quality loss rate of PC shows an increasing trend. At the end of the 50 FT-Cs set in the experiment, the quality loss of the 9 mix proportions of PC in the study is all below 2.5%, and the quality loss control was good.

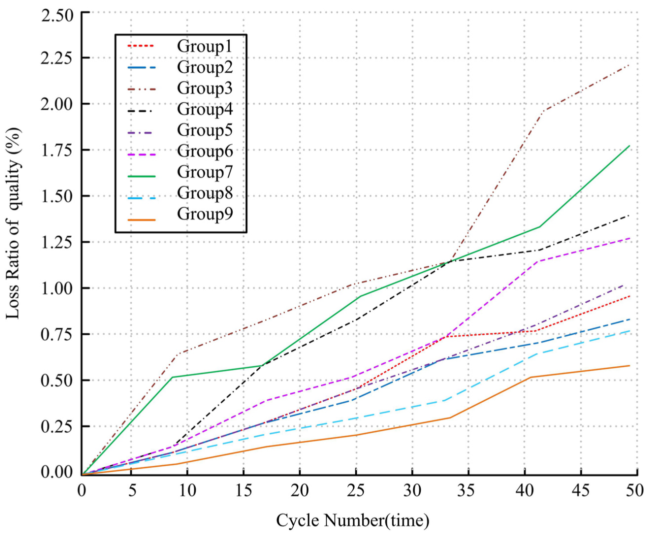
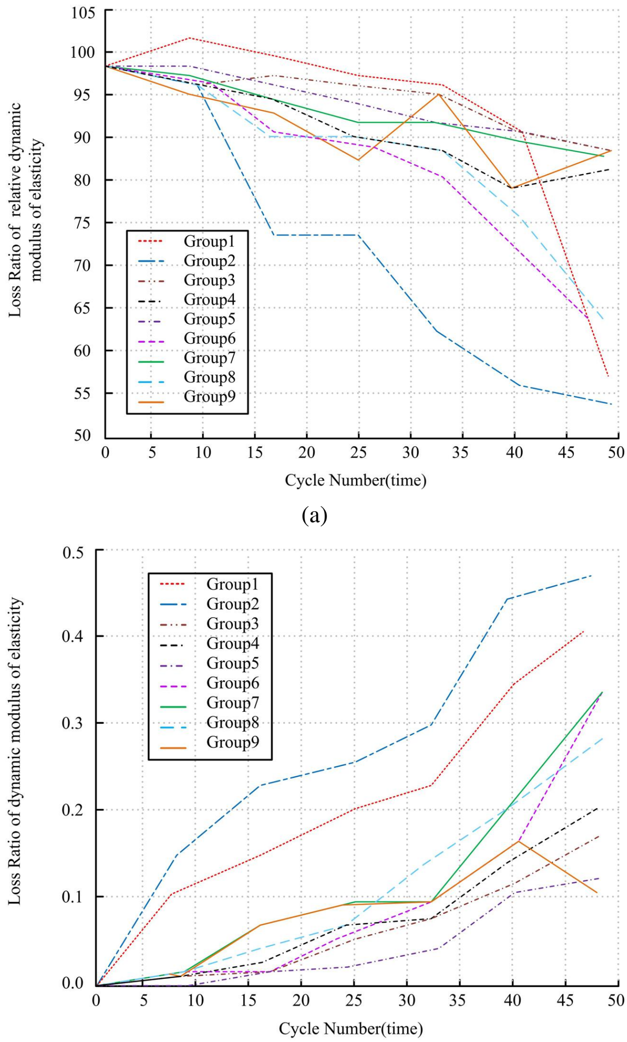


Fig. 6. Quality variation pattern

The RDEM and attenuation law of DEM of PC are listed in Fig. 7. The RDEM of experimental groups 4, 6, 7, and 9 decreased slightly, with the lowest values above 80%, indicating better frost resistance. The RDEM of other experimental groups showed a significant downward trend with the progress of FT-C. Group 1 and Group 2 decreased to below 60% in the later stage, indicating that WES and SAP have significantly improved the frost resistance of PC. The loss rate of DEM of PC shows an upward trend with FT-C. Group 1 and Group 2 have the highest loss rate of DEM, while other experimental groups have smaller loss rates of DEM.



(a)

(b)

Fig. 7. RDEM and attenuation law of DEM; (a) Relative dynamic modulus of elasticity, (b) Dynamic modulus of elasticity

Perform least squares fitting based on the RDEM data, and the fitting results of experimental groups 4, and 7 are shown in Fig. 8. The basic model has the worst fit. The goodness of fit of the binomial Fourier function model is higher than that of the monomial Fourier function model. This result has a high degree of fit with the experimental results, making it the optimal model for fitting the mechanical attenuation law of modified PC under FT-C.

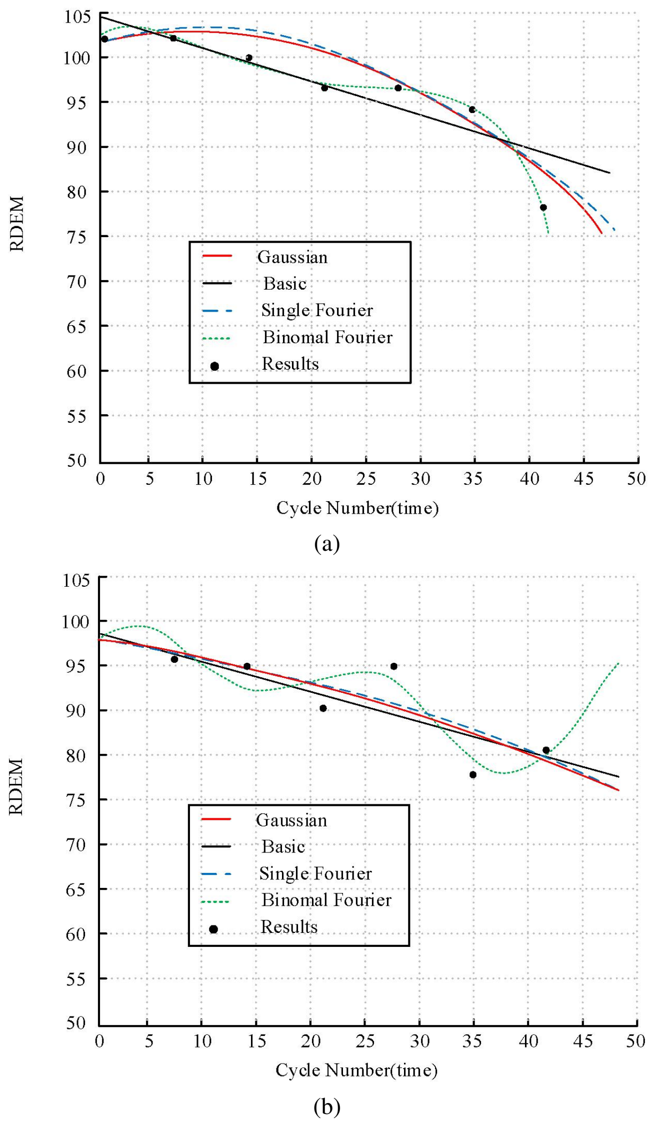


Fig. 8. Mechanical property attenuation model fitting effect; (a) Group 4, (b) Group 7

5. Conclusions

To improve the mechanical properties of PC and reduce the load caused by solid waste accumulation on the environment, this study replaced natural coarse aggregate with SS and waste brick aggregate, and used WES and SAP in the molding of PC. The experimental results showed that epoxy resin had a filling effect on the pores of concrete. The internal curing agent SAP had a good water absorption effect. The combination of the two helped to form a dense structure in PC, which was beneficial for the development of mechanical strength. When the dosage was 0.5%, the CS of modified PC was the highest. The mass loss rate increased with the growth of FT-C, but the mass loss of all experimental groups was controlled below 2.5%. The RDEM of the experimental group without using epoxy resin and SAP decreased to below 60%. The RDEM and the decrease in DEM of other groups were relatively small. Epoxy resin and SAP were beneficial for improving the frost resistance of PC. The binomial Fourier function model was the best predictive model for PC under FT-C. Overall, the PC prepared in this study performs better in terms of mechanical properties and frost resistance, but micro research is still needed to explore the performance of modified PC at the micro level.

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