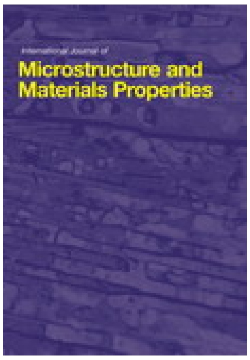

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Optimisation method for durability of recycled concrete based on nano strengthening technology

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Abstract: Studying the durability optimisation problem of recycled concrete can extend the service life of concrete structures and reduce maintenance costs. Therefore, the paper proposes a durability optimisation method for recycled concrete based on nano strengthening technology. Firstly, select experimental materials for recycled concrete, analyse the factors affecting the strength of recycled coarse aggregate concrete, and determine the design scheme of recycled concrete mix proportion. Then, the recycled coarse aggregate was modified by soaking in nano SiO_2 dispersion, and dispersed for 20 minutes using YM-060S ultrasonic dispersion machine before being placed in a container to optimise the durability of recycled concrete. The results show that the improved recycled concrete in this paper has increased its water resistance by more than 16% compared to RAC, and its quality loss rate does not exceed –0.21%, indicating that the method proposed in this paper can effectively improve the durability of recycled concrete.

Keywords: nano strengthening; dispersion immersion method; frost resistance test; water penetration resistance test; concrete mix design.

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1 Introduction

Recycled aggregate is a new type of green and energy-saving material made from construction waste that has been thoroughly crushed, graded, and reprocessed. It is a sustainable and reusable recycled concrete made from it. The utilisation of recycled concrete can not only improve the environmental problems caused by construction waste, but also alleviate the shortage of non-renewable resources such as sand and gravel in a short period of time, which is in line with the green and sustainable development goal advocated by China's construction industry (Li et al., 2022a; Wang and Li, 2022). The durability of recycled concrete refers to its ability to maintain its original performance and structural integrity under different conditions (such as long-term wetting, high temperature, freeze-thaw cycles, etc.). Usually, when evaluating the durability of recycled concrete, it is necessary to consider its impermeability and freeze-thaw resistance. Generally speaking, improving the durability of recycled concrete helps to extend its service life, reduce its impact on the environment, and reduce waste of funds and resources, achieving sustainable development. Durability is an important indicator for measuring the service life of concrete. Due to the high content of crushed stone and low cement in recycled concrete, it is prone to problems such as voids and cracks, which can affect the durability of concrete. Durability issues not only exist in recycled concrete itself, but also in the interface between recycled concrete and traditional concrete structures. Therefore, conducting research on the durability optimisation of recycled concrete is of great significance for promoting its application in practical engineering and ensuring the service life of concrete structures.

Relevant scholars have conducted research on this issue and made certain progress. Ding et al. (2022) proposed a study on the durability optimisation of fibre reinforced recycled concrete, and found that compared to ordinary concrete, recycled concrete has poor frost resistance, sulphate resistance, and chloride salt resistance. After sulphate attack, the quality and dynamic elastic modulus of recycled concrete decrease significantly. The effect of adding auxiliary cementitious materials such as fly ash and silica fume on recycled concrete was tested, and it was found that they can significantly improve the mechanical properties and durability of recycled concrete. And compared the effect of adding low calcium bentonite on the performance of ordinary concrete and recycled concrete, it was found that low calcium bentonite contributes more to the durability and later strength of recycled concrete. Hou et al. (2021) proposed the research on durability optimisation of recycled concrete corroded by composite salt, replacing cement with fly ash, slag, silica fume, metakaolin and other active mineral admixtures, and studying the impact of mineral admixtures' mix on the durability of recycled concrete. XRD, FTIR, TG-DSC, SEM, EDS and other characterisation methods were used to analyse the mineral composition, content and microstructure changes of erosion products, and study the damage process of recycled concrete corroded by composite salt, and evaluated the durability performance of recycled concrete under different recycled cement ratios and water cement ratios. It was found that thermal activation has a higher activity of recycled cement at 650°C, and the durability of recycled concrete made from it is equivalent to that of ordinary Portland concrete. Zhang (2021) proposed a study on the optimisation of the durability of recycled concrete under the improvement of admixtures. A numerical model for the compressive strength and elastic modulus of recycled coarse aggregate concrete was established by organising a large amount of literature data. The durability of recycled concrete was improved by adding admixtures, and several parameters for the treatment and modification methods of recycled coarse aggregate were added to the model, Obtain a strength model for the corresponding modified recycled coarse aggregate concrete. The above methods can improve the compressive strength of recycled coarse aggregate concrete, but their effectiveness in resisting water penetration is not satisfactory.

Nano strengthening technology can effectively improve the mechanical properties and durability of recycled concrete, which helps promote the application of recycled concrete in engineering. Recycled concrete is a new type of building material made from recycled waste concrete, which has advantages such as environmental protection and resource conservation. However, due to the presence of a large number of old concrete particles in recycled concrete, its compressive strength and durability are poor, seriously affecting its use in practical engineering. Therefore, studying how to improve the durability of recycled concrete through nano strengthening technology and better utilise its advantages has high theoretical research value and practical application prospects. In response to the issue of poor resistance to water permeability, this article proposes a durability optimisation method for recycled concrete based on nano strengthening technology. The specific research ideas are as follows:

Firstly, analyse the factors affecting the strength of recycled coarse aggregate concrete, obtain the significance analysis results of each factor through orthogonal experiments, and determine the design scheme of recycled concrete mix proportion;

Secondly, based on the above analysis results, the experimental materials for recycled concrete were selected, and the recycled coarse aggregate was modified by soaking in nano SiO_2 dispersion. The silica sol with a solid content of 30% of nano SiO_2 was diluted into a water dispersion by mass ratio.

Then, the YM-060S ultrasonic disperser was used to disperse for 20 minutes and placed in a container to achieve durability optimisation of recycled concrete based on nano strengthening technology.

Finally, the durability performance of recycled concrete after nano strengthening technology was evaluated through water permeability and frost resistance tests, and conclusions were drawn.

2 Material selection and mix design of recycled concrete

2.1 Selection of test materials

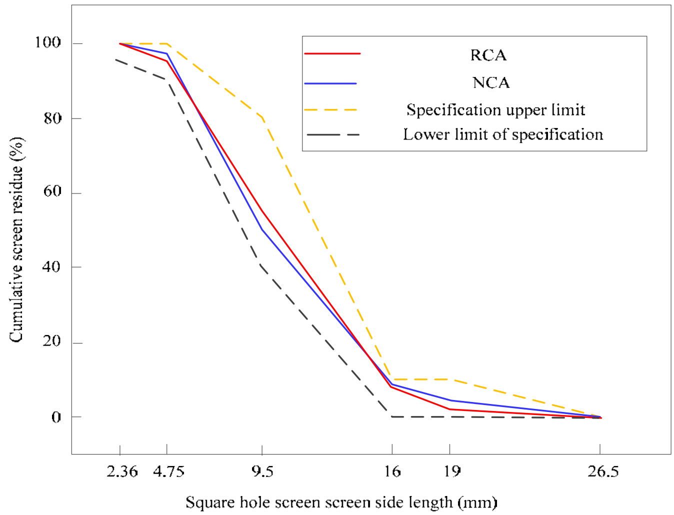
The cement adopts Yatai Group Swan brand P.O. 42.5 R grade ordinary Portland cement, and the basic parameters and indicators of cement are shown in Table 1.

Table 1 Basic parameters and indicators of cement

0.08 mm sieve residue/ %	*Requirement of normal consistency/ %*	*Stability*	*Setting time/min*		*Compressive strength/MPa*		*Flexural strength/MPa*	
			Initial setting	*Final set*	*3 d*	*28 d*	*3 d*	*28 d*
1.8	27.6	Qualified	135	217	24.6	48.5	4.2	8.2

Coarse aggregate is selected from concrete test blocks with strength grade C40 abandoned in the laboratory and an age of over one year. First, small blocks with a width of less than 100 mm are split by a universal testing machine, and then crushed twice by a jaw crusher (Chen et al., 2022). After sieving, RCA with a particle size range of 5–20 mm was obtained. Due to the large amount of mortar powder remaining on the surface of RCA after being crushed by the jaw crusher, it was washed with tap water and dried. The final grading curve is shown in Figure 1.

Figure 1 Grading of coarse aggregate particles (see online version for colours)



According to the provisions of 'recycled coarse aggregates for concrete' (GB/T25177-2010), the performance test of recycled aggregates is conducted. The performance indicators of recycled coarse aggregates and non-recycled coarse aggregates used in the test are shown in Table 2.

Table 2 Aggregate performance indicators

Aggregate type	*Bulk density/ kg•m^3*	*Density/ kg•m^3*	*Crushing index/%*	*Water absorption rate/%*
Non-recycled coarse aggregate	1,440	2,760	14.2	1.7
Recycled coarse aggregate	1,283	2,680	22.4	6.6

The fine aggregate is naturally extracted river sand, with an apparent density of 2,742 kg/m^3 and a fineness modulus of 2.8, belonging to the category of medium sand. The silica sol adopts Gulf Group JN-01 alkaline silica sol, with a solid content of 30% and an average particle size of SiO_2 of 20 nm. The water reducing agent adopts polycarboxylic acid high-efficiency water reducing agent (Liu et al., 2021). In the sulphate resistance test, analytical grade anhydrous sodium sulphate white crystalline powder produced by Tianjin Bodi Chemical was used, with a purity of ≥99%. The specific parameters are shown in Table 3.

Analyse the factors affecting the strength of recycled concrete based on Table 3 materials.

Table 3 Anhydrous sodium sulphate parameter indicators

Parameter	*Index*
pH value (50 g/L, 25℃)	5.0–8.0
Clarification test/number	≤3
Water insoluble substance, w/%	≤0.005
loss on ignition, w/%	≤0.2
Chloride (Cl), w/%	≤0.001
Chloride (Cl), w/%	≤0.001
Phosphate (PO_4), w/%	≤0.001
Total nitrogen content (N), w/%	≤0.0005
Potassium (K), w/%	≤0.01
Calcium (Ca), w/%	≤0.002
Cutter (Fe), w/%	≤0.0005
heavy metal (calculated in Pb), w/%	≤0.0005

2.2 *Analysis of factors influencing the strength of recycled concrete*

In order to explore the comprehensive impact of nano strengthening technology and other influencing factors, a cube compressive strength orthogonal experiment with four factors and three levels was conducted before the final mix design in this article, including the replacement rate of recycled coarse aggregate, water cement ratio, sand ratio, and mortar adhesion rate. The factors with significant effects were selected from the four factors for the final mix design (Zhang et al., 2022; Wei et al., 2021b; Wu et al., 2022b). The orthogonal experimental plan is shown in Tables 4, 5, and 6.

Table 4 C30 mix ratio orthogonal design

Scheme number	*Water-cement ratio/%*	*Cement/ kg•m^3*	*Water/ kg•m^3*	*Non-recycled coarse aggregate/ kg•m^3*	*Recycled coarse aggregate/ kg•m^3*	*Sand/ kg•m^3*	*Sand rate/%*	*Mortar adhesion rate/%*
1	0.43	360	155	799	342	642	36	4.8
2	0.43	360	155	570	571	670	37	5.6
3	0.43	360	155	342	799	699	38	6.7
4	0.45	360	162	799	342	670	37	6.7
5	0.45	360	162	570	571	699	38	4.8
6	0.45	360	162	342	799	642	36	5.6
7	0.47	360	169	799	342	699	38	5.6
8	0.47	360	159	570	571	642	36	6.7
9	0.47	360	169	342	799	670	37	4.8

Using Design expert to establish a univariate significance analysis of the influencing factors in the orthogonal experiment of design, calculate the sum of squares, mean square, and significance coefficient of data type III. The results are shown in Tables 7, 8, and 9.

Table 5 C40 mix ratio orthogonal design

Scheme number	*Water-cement ratio/%*	*Cement/ kg•m³*	*Water/ kg•m³*	*Non-recycled coarse aggregate/ kg•m³*	*Recycled coarse aggregate/ kg•m³*	*Sand/ kg•m³*	*Sand rate/%*	*Mortar adhesion rate/%*
1	0.38	420	160	788	338	633	36	4.8
2	0.38	420	160	563	563	661	37	5.6
3	0.38	420	160	338	788	690	38	6.7
4	0.4	420	168	788	338	661	37	6.7
5	0.4	420	168	563	563	690	38	4.8
6	0.4	420	168	338	788	633	36	5.6
7	0.42	420	176	788	338	690	38	5.6
8	0.42	420	176	563	563	633	36	6.7
9	0.42	420	176	338	788	661	37	4.8

Table 6 C50 mix ratio orthogonal design

Program	*Water-cement ratio/%*	*Cement/ kg•m³*	*Water/ kg•m³*	*Non-recycled coarse aggregate/ kg•m³*	*Recycled coarse aggregate/ kg•m³*	*Sand/ kg•m³*	*Sand rate/%*	*Mortar adhesion rate/%*
1	0.34	470	169	756	324	662	36	4.8
2	0.34	470	160	540	540	608	37	5.6
3	0.34	470	179	324	756	634	38	6.7
4	0.36	470	160	756	324	634	37	6.7
5	0.36	470	179	540	540	662	38	4.8
6	0.36	470	169	324	756	608	36	5.6
7	0.38	470	179	756	324	608	38	5.6
8	0.38	470	160	540	540	662	36	6.7
9	0.38	470	169	324	756	634	37	4.8

Table 7 Significance analysis of various factors in C30 orthogonal experiment

	Type III sum of squares	*df*	*Mean squared*	*F*	*Significance*
Model	44.5	8	2.34	45.7	0.0014
Water-cement ratio	4.68	2	19.765	19.23	0.0118
Substitution rate	39.53	2	0.14	162.39	0.0002
Sand rate	0.28	2	0.0025	1.16	0.3426
Mortar adhesion rate	0.005	2	2.34	0.022	0.8899
Total after correction	45.47	8			

When the significance in the table is less than 0.05, the larger the F-value, the more important the influence of this factor on the dependent variable. The significance analysis of the impact of four factors on compressive strength and the replacement rate of recycled coarse aggregate, water cement ratio, sand ratio, and mortar adhesion rate shows that among the three strength orthogonal tests, the compressive strength is influenced by the four factors, and the replacement rate of recycled coarse aggregate is the highest, followed by the water cement ratio. The significance of the sand ratio and mortar adhesion rate in the orthogonal test jointly designed with these two factors is greater than 0.05, and the relative influence is not significant.

Table 8 Significance analysis of various factors in C40 orthogonal experiment

	Type III sum of squares	*df*	*Mean squared*	*F*	*Significance*
Model	75.75	8	5.335	24.96	0.0043
Water-cement ratio	10.67	2	32.34	14.06	0.02
Substitution rate	64.68	2	0.07	85.24	0.0008
Sand rate	0.14	2	0.13	0.18	0.6949
Mortar adhesion rate	0.26	2	5.335	0.35	0.5872
Total after correction	78.78	8			

Table 9 Significance analysis of various factors in C50 orthogonal experiment

	Type III sum of squares	*df*	*Mean squared*	*F*	*Significance*
Model	117.77	8	3	0.0003	
Water-cement ratio	6	2	54.615	18.91	0.0122
Substitution rate	109.23	2	0.215	244.17	0.0001
Sand rate	0.43	2	1.06	1.34	0.3108
Mortar adhesion rate	2.12	2	3	6.67	0.0611
Total after correction	119.04	8			

Therefore, based on the above research, this article chooses to use the substitution rate of recycled coarse aggregate and water cement ratio as variables in the mix design to design a modification scheme with nano SiO_2.

3 Research on durability optimisation of recycled concrete based on nano strengthening technology

Promoting the mix ratio of recycled concrete can help save resources, reduce environmental pollution, reduce costs, and increase the sustainability of building materials, all of which are important basis for its promotion. This article utilises nano strengthening technology to optimise the durability of recycled concrete. The recycled coarse aggregate is modified by soaking in nano SiO_2 dispersion. The silica sol with a solid content of 30% of nano SiO_2 is diluted into a water dispersion by mass ratio, and dispersed for 20 minutes using a YM-060S ultrasonic dispersion machine before being placed in a container. Soak the crushed, screened, cleaned, and dried RCA in a nano SiO_2 dispersion to ensure that the dispersion does not exceed the coarse aggregate (Li et al., 2022b). During the drying process, the oven temperature is controlled at 60℃ and heated for 24 hours to fully evaporate the moisture of the material while avoiding thermal decomposition reactions, in order to better absorb the nano SiO_2 dispersion and fill the cracks with nanoparticles. According to Fick’s second law, concentration and time are important factors that affect the contact and diffusion of two substances. In order to obtain a reasonable range of modification parameters, the recycled coarse aggregate was soaked in SiO_2 dispersion solution with a concentration of 0, 1%, 2%, 3%, 4%, and 5% for 48 hours before formal testing. The recycled coarse aggregate concrete was made under the same mix ratio, and the strength comparison under all concentration conditions was shown in Figure 2, based on the 28 day compressive strength at 0 concentration.

Figure 2 Trend of compressive strength changes under different conditions (see online version for colours)

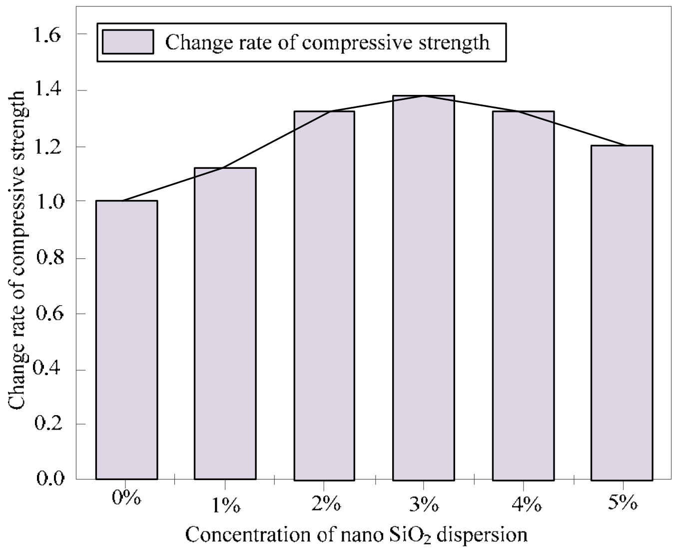
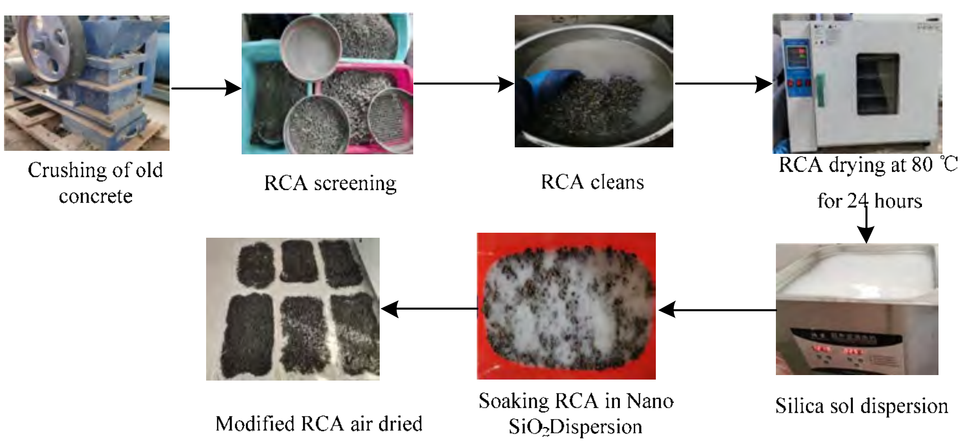
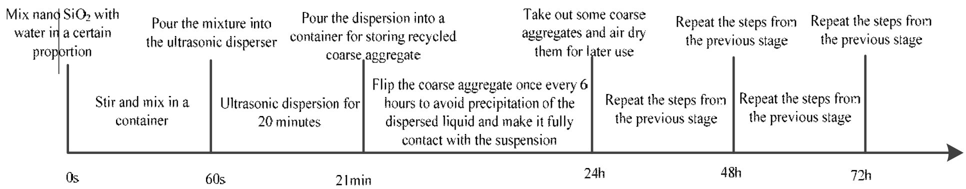


Figure 3 Flowchart of obtaining modified recycled coarse aggregate based on nanostrengthening, (a) aggregate preparation process (b) specific process for modifying recycled coarse aggregate with nano SiO_2 dispersion (see online version for colours)



(a)

Figure 3 Flowchart of obtaining modified recycled coarse aggregate based on nanostrengthening, (a) aggregate preparation process (b) specific process for modifying recycled coarse aggregate with nano SiO_2 dispersion (continued) (see online version for colours)



(b)

From Figure 2, it can be seen that under the 48 hour soaking time condition, the compressive strength first increases and then decreases with the increase of the dispersion concentration, reaching a peak at a concentration of 3%. Therefore, the final setting of nano SiO_2 dispersion concentration is 0, 1%, 2%, and 3%, and the soaking time is 24 hours, 48 hours, and 72 hours. At the same time, soak NCA in water under the same conditions as the control group. After reaching the soaking time requirement, the coarse aggregate is taken out in batches and dried to a saturated surface dry state under natural conditions. The specific modification process is shown in Figure 3.

Figure 4 Aggregate crushing value test (see online version for colours)

To investigate the modification effect of nano SiO_2 pre soaking method on the properties of RCA itself, after modifying RCA using the above method, water absorption test and crushing value test were conducted according to the 'highway engineering aggregate test specification' (JTG-2005). The water absorption test adopts the drying method, and each sample is subjected to two parallel tests to take the average value and record the results. In the crushing value test, three sets of samples with a thickness of 9.5–13.2 mm were taken from each sample, each with a weight of 3,000 grams. Each sample was evenly loaded into the test mould three times and the surface of the sample was made flat. A metal rod was used to evenly compact the sample 25 times and scrape the final surface flat. The experiment was conducted using a 600 KN universal testing machine to uniformly load the test mould to 400 KN in about ten minutes and stabilise for five seconds before unloading, and the sample was taken out. Finally, the sample was sieved using a 2.36 mm standard sieve to obtain the test crushing value. The test process is shown in Figure 4.

4 Experimental results and analysis

Based on the results of mechanical performance tests, the durability test selected the N40 and R40-100 mix ratio scheme, and the nano SiO_2 modification conditions selected the most suitable modification scheme in the compressive strength test results: 1% concentration soaking for 72 hours (RSAC I), 2% concentration soaking for 48 hours (RSAC II), and the modified recycled coarse aggregate concrete was reconfigured. Simultaneously mix non-recycled concrete and unmodified recycled coarse aggregate concrete as control groups for water permeability and frost resistance tests. The durability of recycled concrete refers to its ability to maintain its original performance and structural integrity under different conditions. Usually, evaluating the durability of recycled concrete mainly requires consideration of its impermeability and freeze-thaw resistance. Therefore, this article verifies the durability performance of recycled concrete through water permeability and frost resistance tests. The water permeability test and frost resistance test are based on the ‘test specification for cement and cement concrete in highway engineering’ (JTG3420-2020).

4.1 Experimental design

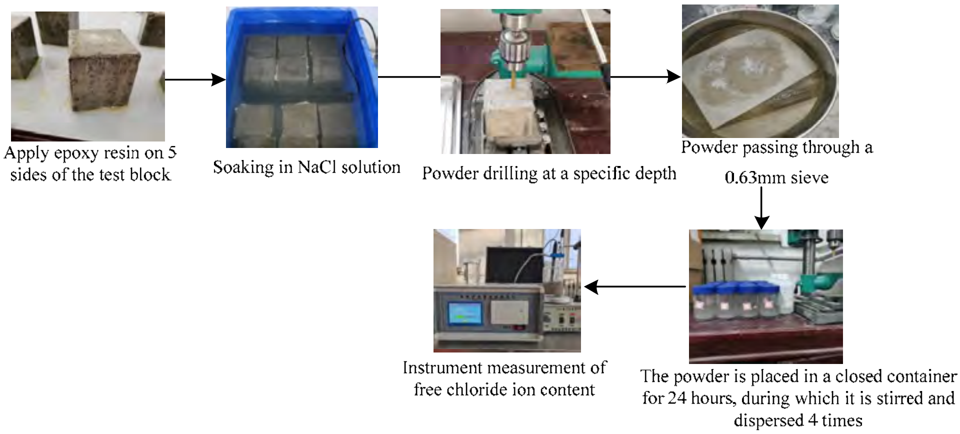
4.1.1 Design of anti-permeability test

The water permeability test is conducted using the step-by-step pressure method, and cylindrical test blocks with a diameter of 150 mm and a height of 150 mm are made, with six blocks in each group. Starting from 0.1 MPa, the water pressure increases by 0.1 MPa every eight hours until the surface of three specimens in each group seeps, and the water pressure at this time is recorded to calculate the impermeability level of the concrete.

The chloride ion penetration test was conducted using the SSWY-820 rapid chloride ion content analyser, and the measured chloride ion concentration was the free chloride ion concentration. Test and make 100 mm × 100 mm × 100 mm cubic specimens, with three pieces in each group. After curing the specimens for two days, wrap five sides of the specimens with epoxy resin, leaving one side exposed and immerse it in a 10% concentration of Na Cl solution to achieve the effect of chloride ion one-sided penetration. To ensure the concentration of Na Cl solution, the solution should be changed every ten days. During the soaking process, the NaCl solution should exceed the surface of the test block by 20 mm. After soaking for five days, ten days, and 30 days, take out the test blocks and use a bench drill to drill concrete powder layer by layer every 5 mm. Drill 10 g of powder through a 0.63 mm sieve from each layer, dry it, mix it evenly in 100 ml of deionised water, and disperse the deposited powder again every eight hours. After 24 hours, conduct the test. The experimental process is shown in Figure 5.

Perform anti-permeability test verification according to the above process.

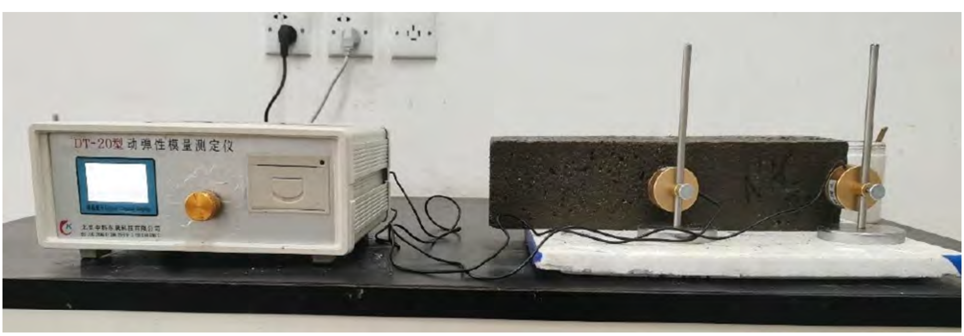
Figure 5 Chloride ion penetration test process (see online version for colours)



4.1.2 Design of frost resistance test

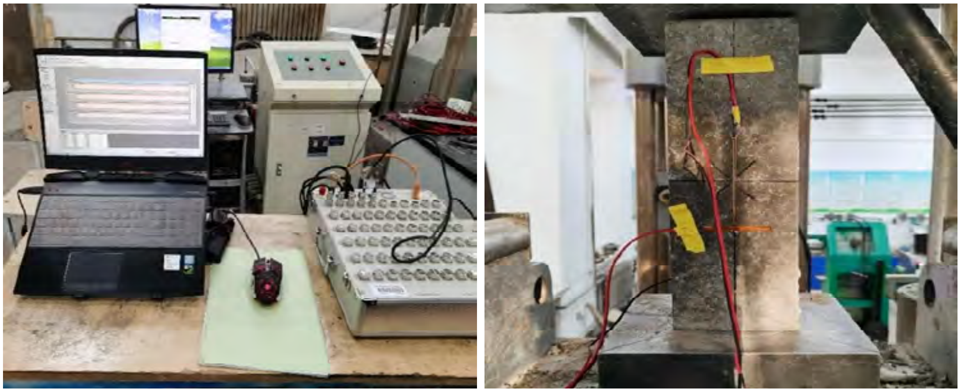
The frost resistance test adopts the fast freezing method, and the concrete specimens are made of 100 mm × 100 mm × 400 mm test blocks with three specimens in each group. Before the start of the test, the 24 day old concrete specimens are soaked in water for four days, and the surface moisture is removed and wiped off to fully absorb water. The centre temperature of the anti-freezing performance testing machine is set to –18°C~5°C, and it is cycled every four hours. After every 50 freeze-thaw cycles, the surface moisture is taken out and wiped dry for mass loss weighing and dynamic elastic modulus testing. The concrete dynamic elastic modulus tester is shown in Figure 6.

Figure 6 Concrete dynamic elastic modulus tester (see online version for colours)



At the same time, 100 mm × 100 mm × 300 mm test blocks are divided into NAC, RAC and RSACII groups, each group has 12 pieces of freeze-thaw cycles under the same conditions. After every 25 cycles, each group takes out three pieces of strain gauge to carry out axial compressive strength test, records the stress and strain values and converts the elastic modulus. The strain box adopts the DH3816 model tested by East China. The test instrument is shown in Figure 7.

Figure 7 Axial compression test of concrete after freeze-thaw, (a) test instruments (b) paste position of strain gauge (see online version for colours)



(a) (b)

Verify the frost resistance test according to the above process. To ensure the reliability and accuracy of experimental results, multiple repeated experiments and cross validation can be conducted, and experimental data can be statistically analysed and compared to obtain more reliable experimental results.

4.2 Result analysis

4.2.1 Analysis of anti-permeability test results

According to the experimental method designed above, the four types of concrete were tested using the N40 and R40-100 mix ratio scheme. Table 10 presents the results of four groups of concrete's water permeability resistance.

Table 10 Results of concrete water penetration resistance test

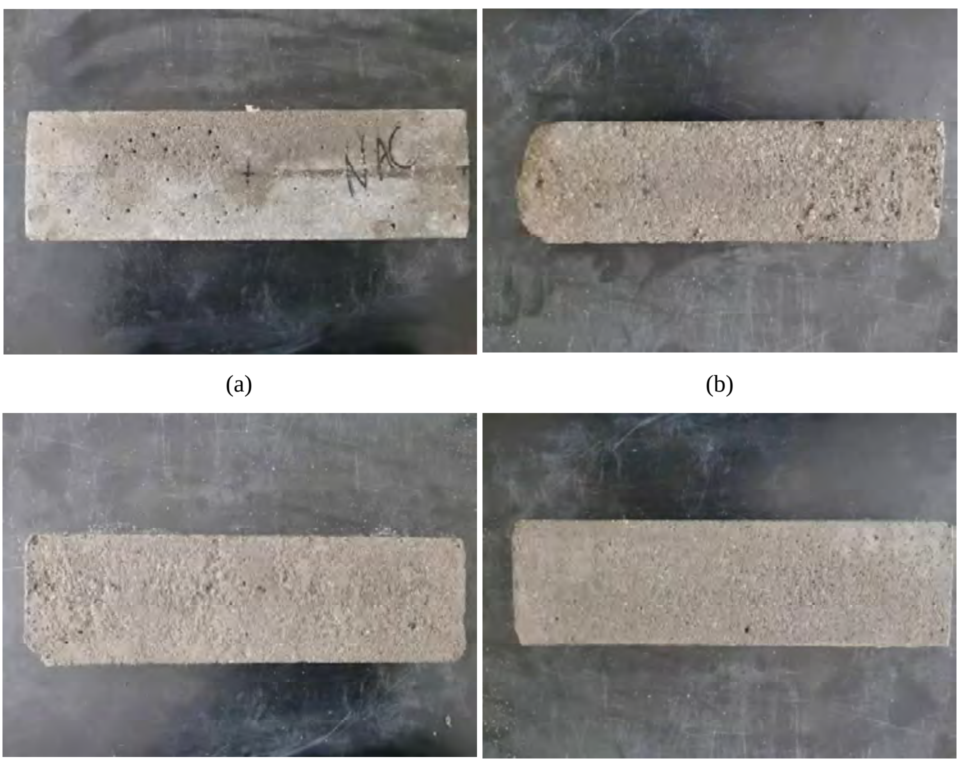
Protocol	*Maximum water pressure/MPa*	*Impermeability level*
NAC	1.1	P10
RAC	0.6	P4
RSAC I	0.7	P6
RSAC II	0.9	P8

From Table 10, it can be concluded that under the condition of a water cement ratio of 0.4, the water permeability test of ordinary concrete can withstand the maximum water pressure, reaching 1.1 MPa; the maximum water pressure that can be resisted when the replacement rate of recycled coarse aggregate is 100% under the same conditions is reduced by 45.5%; the modification schemes of RSAC I and RSAC II increased the water pressure resistance by 16.7% and 50%, respectively, compared to RAC. The main reason for this result is determined by the inherent properties of RCA. RCA is obtained by crushing waste concrete. During the crushing process, the aggregate will produce fine cracks due to external forces, and the surface attached mortar structure is looser than the new mortar, with more and larger pores. Under water pressure, these cracks and pores become weak points, providing a channel for water migration in the concrete, reducing the impermeability level. The pores of RCA modified by nano-SiO_2 are filled to reduce its water absorption, and $Ca(OH)_2$ is consumed in the process of participating in the new hydration reaction to generate a compact C-S-H gel. While filling some of the pores of the old mortar, the old mortar and the new mortar are better bonded to prevent the formation of water seepage channels, so it can withstand greater water pressure and improve the impermeability level.

4.2.2 Analysis of frost resistance test results

According to the above experimental plan, concrete specimens were made, and the appearance of the four types of concrete freeze-thaw cycles is shown in Figures 8 and 9. After 150 cycles, one test piece of RAC broke, while one test piece of RSAC I and RSAC II in the test group broke after 175 cycles. Therefore, the mass loss rate and dynamic elastic modulus test and calculation were stopped until 150 freeze-thaw cycles.

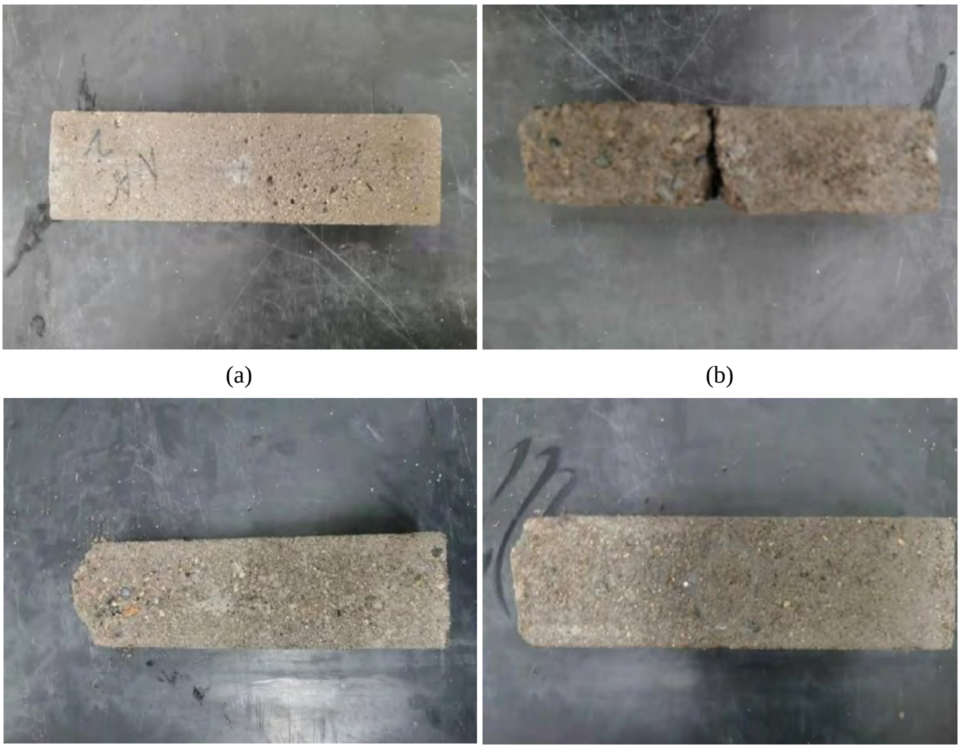
Figure 8 100 freeze-thaw cycles, (a) NAC (b) RAC (c) RSAC I (d) RSAC II (see online version for colours)



(a) (b) (c) (d)

According to the development trend of quality loss rate, whether it is non-recycled concrete or recycled concrete, the quality will increase to varying degrees at the beginning of the freeze-thaw cycle. As the number of cycles increases, the growth rate of concrete quality loss rate gradually accelerates, and the phenomenon of rapid failure of concrete will occur in the later stage of the freeze-thaw cycle. Nano SiO_2 modified recycled coarse aggregate concrete can effectively improve the frost resistance of recycled concrete, but the difference in frost resistance between RSAC I and RSAC II modification schemes is not significant, and the effect in mechanical performance tests has not been achieved.

Figure 9 150 freeze-thaw cycles, (a) NAC (b) RAC (c) RSAC I (d) RSAC II (see online version for colours)



(a) (b) (c) (d)

The mass loss rate of M_{dn} is calculated using the following equation (1):

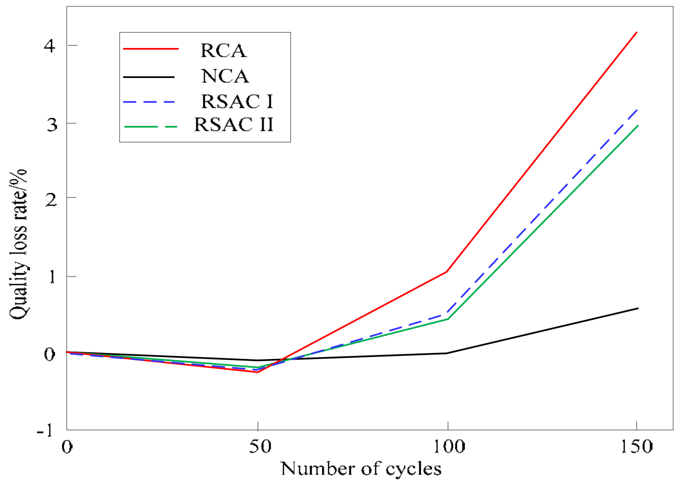
$$M_{dn} = \frac{m_{d0} - m_{dn}}{m_{d0}} \times 100\% \tag{1}$$

In the formula: M_{dn} – mass loss rate of the specimen after n freeze-thaw cycles (%); m_{d0} – mass of the test piece after 0 freeze-thaw cycles (kg); m_{dn} – the mass of the specimen after n freeze-thaw cycles (kg).

According to the calculation method of equation (1), draw the development trend of quality loss rate of four types of concrete after freeze-thaw cycles as shown in Figure 10.

As shown in Figure 10, after 50 cycles, the mass loss rates of the four types of concrete are all negative. The mass loss rates of NAC, RAC, RSAC I, and RSAC II are –0.10%, –0.24%, –0.21%, and –0.18%, respectively, indicating an increase in mass. The reason for this phenomenon is that after 50 freeze-thaw cycles, the surface mortar of the concrete falls off and peels off very little. After water enters the concrete, it freezes and melts, expanding the internal pores of the concrete and increasing the water absorption rate of the concrete. The surface adhesion strength of RAC coarse aggregate to mortar is low, and due to the process of aggregate crushing, there are many microcracks and high porosity. Therefore, after freeze-thaw cycles, the expansion of microcracks and pores is large, resulting in a higher quality increase than NAC. Meanwhile, the data also indicates that the internal structures of modified RSAC I and RSAC II under the same freeze-thaw conditions are more stable and have less freeze-thaw damage compared to RAC.

Figure 10 Mass loss rate after freeze-thaw cycle (see online version for colours)



After 100 freeze-thaw cycles, the mass loss rates of NAC, RAC, RSAC I, and RSAC II were –0.01%, 1.04%, 0.51%, and 0.44%, respectively, indicating a decrease in mass. Among them, the quality of NAC decreased after 50 cycles but was still higher than the quality at the beginning of the freeze-thaw cycle. The quality of recycled concrete has decreased to varying degrees compared to before freeze-thaw. RAC has experienced detachment of column head mortar and a small amount of stones, while RSAC I and RSAC II have only surface mortar detachment.

After 150 freeze-thaw cycles, the mass loss rates of NAC, RAC, RSAC I, and RSAC II were 0.58%, 4.15%, 3.14%, and 2.95%, respectively. The surface mortar of NAC is partially peeled off. One specimen in the RAC group was taken out of the rubber bucket and fractured, with a large amount of coarse aggregate peeling off. The RSAC I situation is due to RAC, but there is also a phenomenon of mortar and aggregate detachment at the column head. The surface mortar of RSAC II is completely peeled off and the aggregate is exposed. After 150 freeze-thaw cycles, the internal damage of the RAC specimen was severe, and although the quality loss rate did not reach the standard limit of 5%, it was no longer possible and meaningless to continue the test due to the fracture of the specimen. During 175 cycles in subsequent experiments, both groups of RSAC I and RSAC II specimens exhibited fracture phenomena.

5 Conclusions

The article proposes a durability optimisation method for recycled concrete based on nano strengthening technology, and evaluates the durability of recycled coarse aggregate concrete after nano strengthening using water permeability and frost resistance as experimental indicators. The following conclusion is drawn:

1 Through water permeability and chloride ion intrusion tests, it is shown that the modification method of nano SiO_2 pre soaking recycled coarse aggregate can effectively improve the ability of concrete to resist water permeability and chloride ion intrusion. The modification schemes of RSAC I and RSAC II have increased the water pressure resistance by 16.7% and 50%, respectively, compared to RAC. This result is attributed to the improvement of concrete compactness and the reduction of internal pores. This result indicates that the durability of recycled concrete has been improved through the method proposed in this paper.

The frost resistance of non-recycled concrete, recycled concrete, and nano reinforced recycled concrete was experimentally studied. The results of quality loss rate indicate that modifying recycled coarse aggregate with nano SiO_2 dispersion is feasible and effective in improving the frost resistance of recycled coarse aggregate concrete. The above results indicate that the durability of recycled concrete is effectively improved after the improvement of the method in this paper.

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