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Research Article

Degradation Resistance and Reliability Analysis of Recycled Aggregate Concrete in a Sulfate Environment

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Resistance to sulfate degradation is an important index used to measure concrete's durability. In this study, recycled aggregate concrete (RAC) with a 0%, 30%, and 50% recycled coarse aggregate substitution rate and a 0% and 15% recycled fine aggregate replacement rate was used as the research object, and its degradation resistance was evaluated by the mass loss rate and the relative dynamic modulus of elasticity. The degradation products were studied and analyzed with SEM scanning electron microscopy and XRD phase analysis. The relative dynamic modulus of elasticity was selected as the degradation index, the RAC concrete's degradation resistance was modeled by Wiener, and the reliability curve was obtained. The results showed that expansion products, such as gypsum and Ettringite, were produced in RAC concrete in a dry-wet sulfate cycling environment, and such defects as pores and voids were filled in the initial stage. The stress the expansion products exerted in the later stage caused the concrete to crack and peel, which demonstrated that the fluctuation law of mass and the dynamic elastic modulus increased first and then decreased. The recycled coarse aggregate substitution ratio's effect on RAC concrete is higher than that of recycled fine aggregate. The reliability curve established by the Wiener model can reflect the reliability of RAC concrete under different cycles well and can obtain RAC concrete's sulfate degradation resistance life with different aggregate substitution rates.

1. Introduction

Because of China's rapid urbanization in recent decades, urban construction is increasing with each passing day, which at the same time leads to a series of problems, such as environmental degradation and resource depletion. The "China Resources Comprehensive Utilization Annual Report" (2014) the China Development and Reform Commission issued pointed out in detail that in 2013 alone, China produced approximately 1 billion tons of construction waste, while only approximately 50 million tons of the waste were used, which equates to a utilization rate of only 5%. In contrast, Germany, the United States, Japan, and other countries already have implemented relevant regulations that can guide China's efforts to recycle waste concrete [1–3]. These countries' construction waste utilization rate far exceeds that of China, and their utilization rate of recycled aggregates is shown in Figure 1. Based on the total annual output of cement in China, Shi et al. predicted that by 2020, China will generate 63.8 billion specimens of waste concrete per year, an average annual increase of 8% [4]. Thus, it is urgent to improve the reuse of waste concrete, and recycled aggregate concrete (RAC) was developed to do so. RAC is a concrete prepared by recycling or processing waste concrete to replace natural aggregate completely or in part [5], and its promotion can reduce the exploitation of natural sand and gravel greatly. Further, it can realize the recycling of waste concrete and meet the requirements of "green sustainable development."

Scholars from various countries have conducted rich research on RAC's mechanical properties. Luisa et al. [6] studied recycled coarse aggregate's (RA) effect on concrete's mechanical properties when different replacement ratios of natural aggregates were used and indicated that the concrete's compressive and tensile strength and elasticity were prepared regardless of the amount of natural aggregate RA

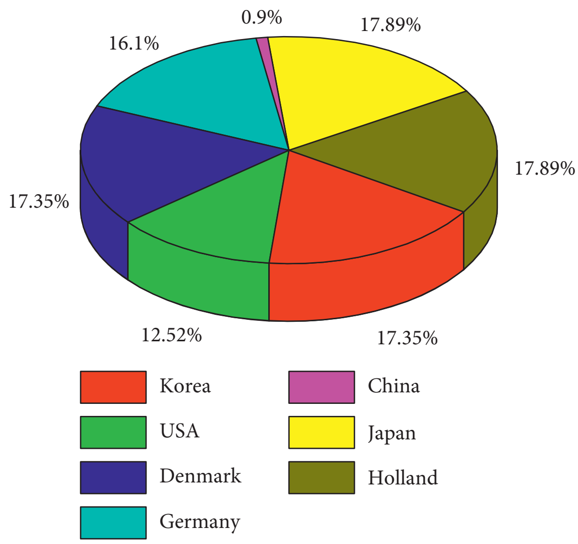

Figure 1: Construction waste utilization rate (year 2014).

replaced. However, the modulus is lower than that of ordinary concrete, and the greater the percentage of RA replaced, the greater the decrease in the indicators above. Luo et al. [7] studied the effects of different RA replacement rates and different mineral admixtures on RAC's tensile and creep properties at an early age. The results showed that the RA replacement rate was 50%~100% during the RAC's tensile and creep phases, which is 8%~31% higher than that of ordinary concrete; further, its tensile creep increased with the increase in mineral admixture. However, there is less research on RAC's durability, and according to Thomas, the most unknown aspect of RAC is its durability in different adverse environments [8].

Therefore, RAC prepared by mixing different amounts of recycled coarse and fine aggregates was taken as the research object. In the case of sulfate attack, the RAC's quality loss rate and relative dynamic elastic modulus were studied macroscopically. The degradation law and microscopic analysis of RAC's microstructure and chemical elements were evaluated with XRD and SEM, and the data were processed by the Wiener probability distribution method to predict RAC's life.

2. Materials and Test Plan

2.1. Materials. The cement selected was P.O42.5 ordinary Portland cement that China Qilianshan Cement Plant produces. A commercial company in Lanzhou provided the gravel and the sandstone, which was river sand. The water reducing agent used was the UNF type naphthalene series a commercial mixed company produces. Tap water was selected as the water reducing agent. Recycled coarse and fine aggregates were crushed with C30 waste concrete and sieved. 5 mm~31.5 mm gravel was recycled coarse aggregate, and 5 mm or less was recycled fine aggregate. The aggregate modulus was 3.34, which corresponds to coarse sand, the various properties of which are shown in Table 1. The difference in particle size distribution from natural river sand is shown in Figure 2.

2.2. Test Plan. The concrete mix ratio followed the relevant provisions of "Test methods for long-term performance and durability of ordinary concrete" [9], and is shown in Table 2. The replacement ratio of recycled coarse aggregate and fine aggregate was based on the mechanical properties test described in [10]. In Table 2, recycled coarse aggregate replacement rate is abbreviated as RCARR, recycled fine aggregate replacement rate is abbreviated as RFARR, recycled coarse aggregate is abbreviated as RCA, and recycled fine aggregate is abbreviated as RFA.

The concrete test specimens were 100 mm × 100 mm × 400 mm, and there was a total of 6 groups with 3 specimens per group. When the test specimens were prepared and cured for 26 d according to the standard curing conditions, they were taken out in advance and placed in an oven for 48 h to measure their initial quality and the dynamic modulus, and then replaced in the test chamber (as shown in Figure 3). A 5% Na_2SO_4 solution was added such that the liquid covered the top of the specimens (20–30) mm, and the solution was replaced every 30 days after the test began. The test was completed every 23 hours, and the test specimens' dynamic elastic modulus E_{ni} and mass M_{ni} were measured every 10 dry and wet cycles, their appearance was examined, and the relative dynamic elastic modulus P_{ni} and mass loss rate W_{ni} were calculated. The parametric equation used to calculate the test blocks' P_{ni} and W_{ni} is as follows:

$$
\begin{aligned}
P_{ni} &= \frac{E_{ni}}{E_{n0}}, \\
W_{ni} &= \frac{M_{n0} - M_{ni}}{M_{n0}},
\end{aligned}
\tag{1}
$$

in which, E_{n0}, E_{ni}, and P_{ni} are the initial dynamic elastic modulus of the n^{th} test specimen, the dynamic elastic modulus of the n^{th} times test specimen after the i^{th} wet and dry cycle, and the i^{th} dry and wet cycle of the n^{th} test specimen after its relative dynamic modulus. M_{n0}, M_{ni}, W_{ni} are the initial mass of the n^{th} test specimen, its mass after the i^{th} wet and dry cycle, and its mass loss rate after the i^{th} dry and wet cycle.

3. Reliability Evaluation of Residual Life Based on Wiener Theory

Because of concrete's long life and high reliability, it is difficult to collect a sufficient amount of failure data in a short time. Therefore, the traditional probabilistic method is unsuitable to predict concrete's remaining life. The Wiener stochastic process has good statistical properties [11] and is used widely in the fields of machinery and finance [12–14], and according to the literature [15], the process can describe the deterioration trend in concrete's durability effectively. Therefore, measured life data were used to characterize RAC concrete's reliability under different cycles in a sulfate attack environment. As the performance degradation index, the dynamic elastic modulus was used to model the relative dynamic elastic modulus' degradation process and obtain the reliability function of the remaining life.

Table 1: Performance indexes of recycled aggregate.

Types	Void ratio (%)	Moisture content (%)	Water absorption rate (%)	Apparent density (kg/m^3)	Bulk density (kg/m^3)	Crushing indicator (%)
Coarse aggregate	47.25	0.5	5.65	2280	1406	13.3
Fine aggregate	39.78	0.68	6.47	1940	1180	—

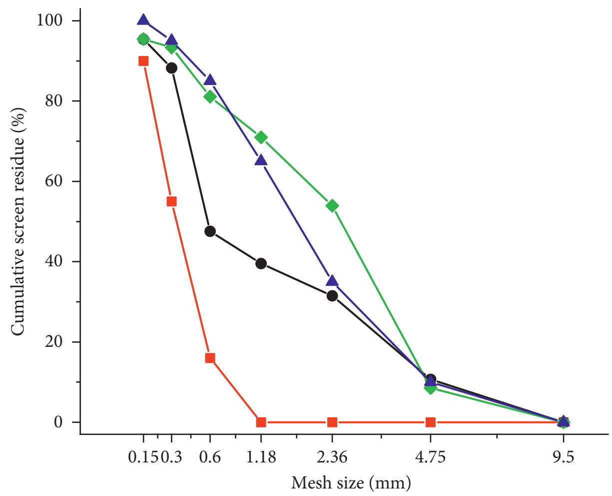

Figure 2: Sieve weight.

Table 2: Recycled aggregate concrete mix ratio.

Number	RCARR (%)	RFARR (%)	Mix ratio (kg·m^{-3})					
			Water	Cement	Coarse aggregate		Fine aggregate	
					Gravel	RCA	Sand	RFA
1	0	0	0.57	1	3.37	0	2.09	0
2	0	15	0.57	1	3.37	0	1.58	0.51
3	30	0	0.57	1	2.36	1.01	2.09	0
4	30	15	0.57	1	2.36	1.01	1.58	0.51
5	50	0	0.57	1	1.69	1.69	2.09	0
6	50	15	0.57	1	1.69	1.69	1.58	0.51

(a)

(b)

Figure 3: Dry and wet concrete test. (a) Dry and wet concrete circulator. (b) Dry and wet cycles.

Assume that the concrete specimen's durability degradation at time t is $D(t)$. When $D(t)$ reaches the failure threshold, D_f, for the first time, the specimen is considered to meet the failure criterion. At this time, the specimen's life, T, satisfies the following formula:

$$T = \inf\left\{t \,\middle|\, D(t) \geq D_f\right\}. \quad (2)$$

From equation (2), lifetime T's distribution can be derived as an inverse Gaussian distribution, and the distribution function and probability density function are as follows:

$$\begin{aligned} F(t) &= p(T \leq t) = p\left(D(t) \geq D_f\right) = p\left(W(t) \geq \frac{D_f - \mu t}{\sigma_W}\right) \\ &= \Phi\left(\frac{\mu t - D_f}{\sigma_W \sqrt{t}}\right) + \exp\left(\frac{2\mu D_f}{\sigma_W^2}\right)\Phi\left(\frac{-\mu t - D_f}{\sigma_W \sqrt{t}}\right), \\ f(t) &= \frac{D_f}{\sqrt{2\pi\sigma_W^2 t^3}} \exp\left[-\frac{\left(D_f - \mu t\right)^2}{2\sigma_W^2 t}\right]. \end{aligned} \quad (3)$$

Its reliability function is as follows:

$$\begin{aligned} R(t) &= 1 - F(t) \\ &= 1 - \Phi\left(\frac{\mu t - D_f}{\sigma_W \sqrt{t}}\right) - \exp\left(\frac{2\mu D_f}{\sigma_W^2}\right)\Phi\left(\frac{-\mu t - D_f}{\sigma_W \sqrt{t}}\right). \end{aligned} \quad (4)$$

In addition, in the life estimation, the parameter estimation method adopted is as follows.

Each of the mixes is assumed to have a total of m test specimens for the sulfate test. For test specimen i, the performance degradation degree at the initial time, t_0, is $D_{i0} = 0$, and the test specimen's performance degradation degree is measured at time t_1, ..., t_{ni}, respectively, and the measured value, D_{i1}, ..., D_{in} is recorded $\Delta x_{ij} = D_{ij} - D_{i(j-1)}$, and is sample i's degree of performance degradation between times t_{j-1} and t_j, which is obtained by the nature of the Wiener degradation process:

$$\Delta x_{ij} \sim N\left(\mu\Delta t_j, \sigma^2 \Delta t_j\right), \quad (5)$$

in which, $\Delta t_j = t_j - t_{(j-1)}$; $i = 1, \ldots\ldots, m$; $j = 1, \ldots\ldots, n$.

The likelihood function obtained from the performance degradation data is as follows:

$$L\left(\mu, \sigma^2\right) = \prod_{i-1}^{m} \prod_{j=1}^{n_i} \frac{1}{\sqrt{2\sigma^2 \pi \Delta t_j}} \exp\left[-\frac{\left(\Delta x_{ij} - \mu \Delta t_j\right)}{2\sigma^2 \Delta t_j}\right]. \quad (6)$$

From equation (6), the maximum likelihood estimate of Wiener's required parameters, μ and σ^2, can be obtained as follows:

$$\begin{aligned} \tilde{\mu} &= \frac{\sum_{i=1}^{m} D_{in_i}}{\sum_{i=1}^{m} t_{ni}}, \\ \tilde{\sigma}^2 &= \frac{1}{\sum_{i=1}^{m} n_i}\left[\sum_{i=1}^{m}\sum_{j=1}^{n_i} \frac{\left(\Delta x_{ij}\right)^2}{\Delta t_{ij}} - \frac{\left(\sum_{i=1}^{m} D_{in_i}\right)^2}{\sum_{i=1}^{m} t_{n_i}}\right]. \end{aligned} \quad (7)$$

4. Results and Discussion

4.1. RAC Quality Loss Rate Analysis. In this study, RAC with a 0%, 30%, and 50% recycled coarse aggregate replacement rate and 0% and 15% recycled fine aggregate replacement rate was taken as the research object. Figure 4 shows the RAC mass loss rate according to the number of dry and wet cycles. In this analysis, RAC includes recycled coarse aggregate instead of concrete (RCAC) and recycled fine aggregate instead of concrete (RFAC).

It can be seen from Figures 4(a) and 4(b) that during 0~40 dry and wet cycles, RFAC's mass increased faster than that of ordinary concrete. The reasons for this are as follows [16–18]: (1) RFA has a higher water absorption rate in RFAC, which reduced the RFAC's effective water-to-binder ratio and resulted in insufficient cement hydration; (2) in the middle of the RFAC's forming vibration process, the moisture attached to the slurry moved to the new interface, which caused the slurry to "bleed" and made the interface loose and porous; (3) the new RFAC interface's local water-to-binder ratio increased, which caused the cement to hydrate to produce more $Ca(OH)_2$, and enriched with $Ca(OH)_2$, attach to the slurry's surface. These three processes above worked together to immerse the RFAC in the sulfate solution, where the porous interface caused the SO_4^{2-} to penetrate the RFAC, and the C_3A and its hydration product, $Ca(OH)_2$, reacted with the SO_4^{2-} in the RFAC to produce gypsum. In expanded substances such as Ettringite, unhydrated cement particles continue to be hydrated to form substances such as C-S-H gel, and the RFAC's quality increased continuously, and the rate of increase exceeded that of ordinary concrete. During 40~80 dry and wet cycles, RFAC had a faster mass loss rate than does ordinary concrete. It is considered that RFAC can absorb more sulfate solution and loose interface because RFA's higher water absorption rate in a wet environment and its porosity are conducive to the sulfate solution's diffusion. The chemical reaction that takes place in RFAC also is more frequent than in ordinary concrete. In a dry environment, because of RFA's higher water absorption, more sulfate solution remains in the RFAC pores. As the water evaporates, it produces a high concentration of sulfate solution more easily, and more salt crystals form, which makes RFAC more susceptible to microcracks than is ordinary concrete. In a wet environment, RFAC produces more expansion products than does ordinary concrete, which causes it to develop microcracks. After evaporation of water in a dry

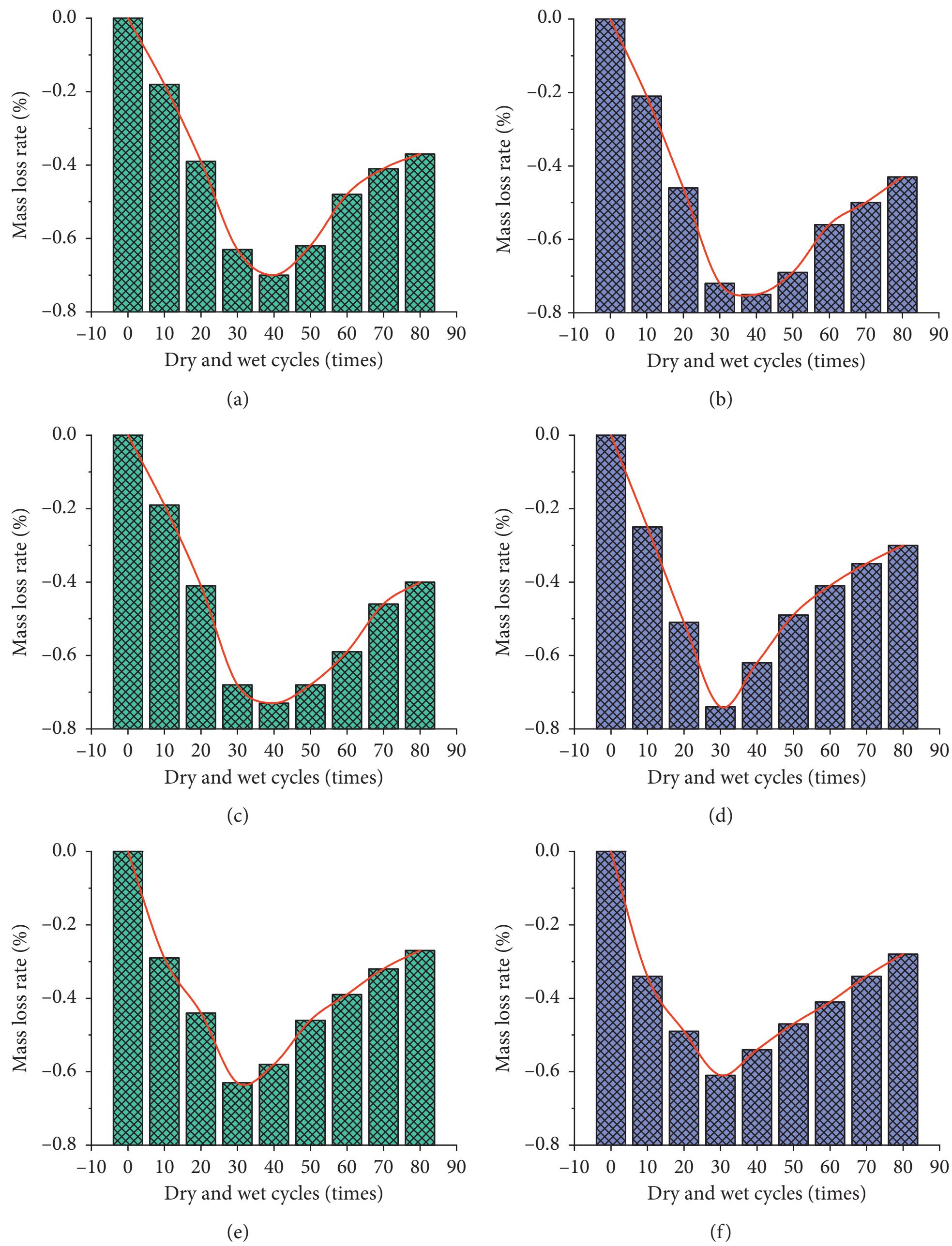

Figure 4: Mass loss rate of recycled concrete. (a) RCA0%–RFA0%. (b) RCA0%–RFA15%. (c) RCA30%–RFA0%. (d) RCA30%–RFA15%. (e) RCA50%–RFA0%. (f) RCA50%–RFA15%.

environment, its quality decreases continuously, and the loss rate exceeds that of ordinary concrete.

As can be seen in Figures 4(c) and 4(d), with the addition of recycled coarse aggregate, RCAC and RAC's mass and loss rate increased compared to the ordinary concrete in Figures 4(a) and 4(b). Further, because RAC not only incorporates RCA, but also RFA, it began to lose mass after the 30th dry and wet cycle. The reason for this is that RAC absorbs more because of RCA and RFA's common water absorption. Because it absorbs sulfate solution more easily, in a sulfate solution in a wet environment, RAC can produce more expansive substances than RCAC can, which produces microcracks in the RAC. In a dry environment, RAC evaporates with water, which causes pores to form. A higher concentration of the sulfate solution, which in turn produces salt crystals, produces microcracks in it, and the above environment continues to circulate, resulting in its faster loss rate compared to ordinary concrete and RCAC.

Figures 4(e) and 4(f) shows that, as the amount of recycled coarse aggregate increased, the two types of concrete in the figure had faster mass increase and loss rates than did the concrete in Figures 4(a)–4(d). However, the concrete's coarse aggregate content was 50%, to which 15% recycled fine aggregate was added, which had little effect on the concrete mass loss rate.

One can see in Figure 4 that all of the test specimens' quality increased first and then decreased as the number of dry and wet cycles increased. After 40 dry and wet cycles, the specimens' quality reached their maximum compared with the initial quality, and the quality increased by approximately 0.7%. As the amount of recycled coarse aggregate increased, its mass loss rate increased. Keeping the amount of recycled coarse aggregate constant, the recycled fine aggregate was mixed with the concrete, and the quality increased and the loss rate accelerated gradually. In general, the RAC concrete and ordinary concrete's change in quality in the dry and wet sulfate environments was similar, but recycled coarse aggregate's replacement rate had less influence on the RAC concrete's sulfate resistance than did the recycled fine aggregate's replacement rate.

4.2. RAC Relative Dynamic Modulus Analysis. The RAC's relative dynamic modulus with the number of dry and wet cycles is illustrated in Figure 5.

As Figures 5(a) and 5(b) show, the two types of concrete's relative dynamic elastic modulus increased during 0~30 dry and wet cycles, but the RFAC's modulus was higher than that of ordinary concrete. First, this result is considered to be attributable to immersion in the sulfate solution, when there are more unhydrated cement particles in RFAC and its hydration product, $Ca(OH)_2$, than in ordinary concrete, as well as RFA, and the RFAC's new interface is loose and porous. The water absorption rate is favorable for the sulfate solution to enter into the expansion product with C_3A and its hydration products. The unhydrated cement particles in the RFAC continue to hydrate to form C-S-H and other substances, which fill the RFAC's pores, while its relative dynamic modulus increases faster than in ordinary concrete. During 30~80 dry and wet cycles, RFAC's relative dynamic elastic modulus showed a more rapid downward trend than does ordinary concrete. It is considered that RFAC can absorb more sulfate solution in a wet environment than can ordinary concrete to produce more expansion. As sexual substances, these swelling substances cause the RFAC to produce microcracks. RFAC has a faster water evaporation rate in a dry environment than does ordinary concrete, which increases the concentration of sulfate solution in its pores, and it is more likely to produce salt crystals, which will cause microcracks in the concrete, which will be repeated and then behave as RFAC. Ordinary concrete's relative dynamic modulus decreases at a faster rate.

As Figures 5(c) and 5(d) show, with the addition of recycled coarse aggregate, RCAC and RAC's relative dynamic modulus increased and decreased, respectively, compared to the ordinary concrete in Figures 5(a) and 5(b) shows. Their relative dynamic elastic moduli increased during 0~30 dry and wet cycles and showed a downward trend thereafter, and together with the recycled fine aggregate, the addition of RAC weakened its resistance to sulfate attack, and its relative dynamic modulus decreased at a faster rate than that of RCAC and its magnitude decreased more as well.

Figures 5(e) and 5(f) show that as the amount of recycled coarse aggregate increased further, RCAC and RAC's relative dynamic moduli increased and decreased compared to the concrete in Figures 5(a)–5(d). When the recycled coarse aggregate was blended with 50%, and 15% recycled fine aggregate was added, its resistance to sulfate attack decreased.

Figure 5 illustrates that all of the test specimens' relative dynamic elastic modulus increased first and then decreased with the number of dry and wet cycles. Compared to their initial value, the specimens' relative dynamic elastic modulus reached its maximum value at 30 dry and wet cycles and increased by approximately 23%. As the amount of recycled coarse aggregate increased, the relative dynamic modulus increased and then decreased, while when the amount remained constant, it was incorporated into the concrete, the relative dynamic elastic modulus increased, and the speed of the subsequent reduction accelerated gradually.

As can be seen in Figures 4 and 5, when the change in the concrete's mass and relative dynamic elastic modulus was small, the ability to resist sulfate attack was better, and the resistance proceeded from strong to weak, as follows: RFA15%C >ordinary Concrete >RCA30%C >RCA30%FA15%C >RCA50%C >RCA50%FA15%C. As the comparison results show, when the amount of recycled coarse aggregate was 30%, and it was mixed with a further 15% of recycled fine aggregate, its resistance to sulfate attack weakened. It was also found that as the amount of recycled coarse aggregate increased, its resistance to sulfate attack decreased.

4.3. RAC Relative Dynamic Modulus Analysis. After the dry and wet cycle test, the concrete test specimens' surface was subjected to scanning electron microscopy (SEM), and XRD analysis was performed on ordinary concrete and RAC (RFA15%–RCA0%) with the best degradation resistance. The test results are shown in Figures 6 and 7.

As Figure 6 shows, ordinary recycled concrete and different coarse and fine aggregates formed degradation products with rod, sheet, and fiber shapes, and iron filings. The degradation products largely formed in the concrete's pores, potholes, and defects, and some also grew from the interior of the concrete's cementitious materials. These degradation products filled the internal pores and voids in the initial stage of degradation, which made the inside of the test pieces more compact, and the external macroscopic performance showed an increase in the dynamic elastic modulus. As the dry and wet cycles continued, more degradation products formed, and some continued to grow out of the interior of the cementitious material, which damaged the original material's composition structure seriously, and degraded the concrete's performance, thereby deteriorating and destroying the specimens. Combined with Figure 7's XRD analysis results, these degradation products largely were crystals, such as Ettringite and gypsum, which caused the volume to expand

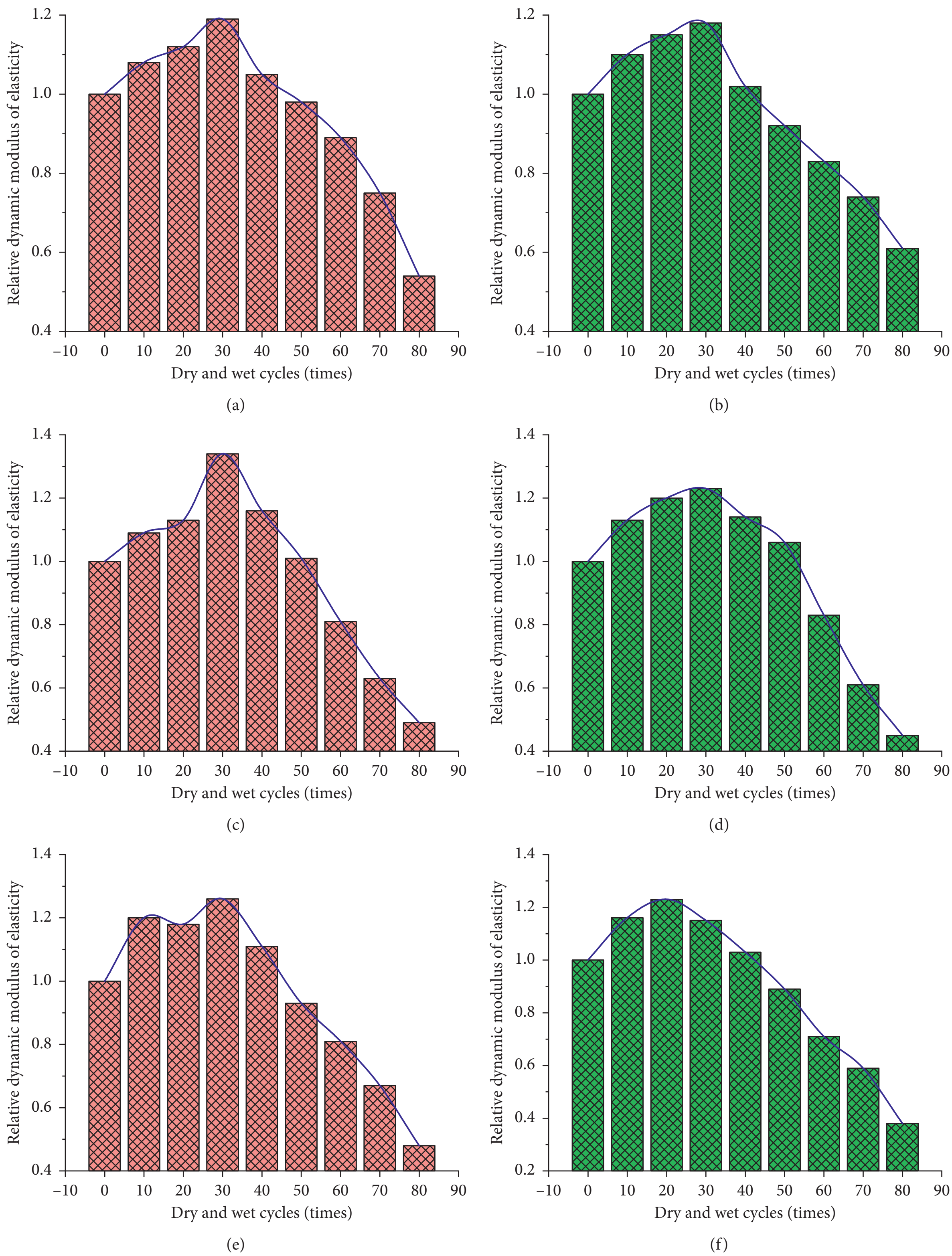

Figure 5: Relative dynamic elastic modulus of recycled concrete. (a) RCA0%–RFA0%. (b) RCA0%–RFA15%. (c) RCA30%–RFA0%. (d) RCA30%–RFA15%. (e) RCA50%–RFA0%. (f) RCA50%–RFA15%.

by 1.2 to 2.5 times. The greater the amount of degradation products formed in the later stage, the greater the expansion stress generated, and the more energy consumed. The hydrated calcium silicate and calcium hydroxide that maintain the stable presence of the cementitious material made the concrete's interior loose, it formed an increasing

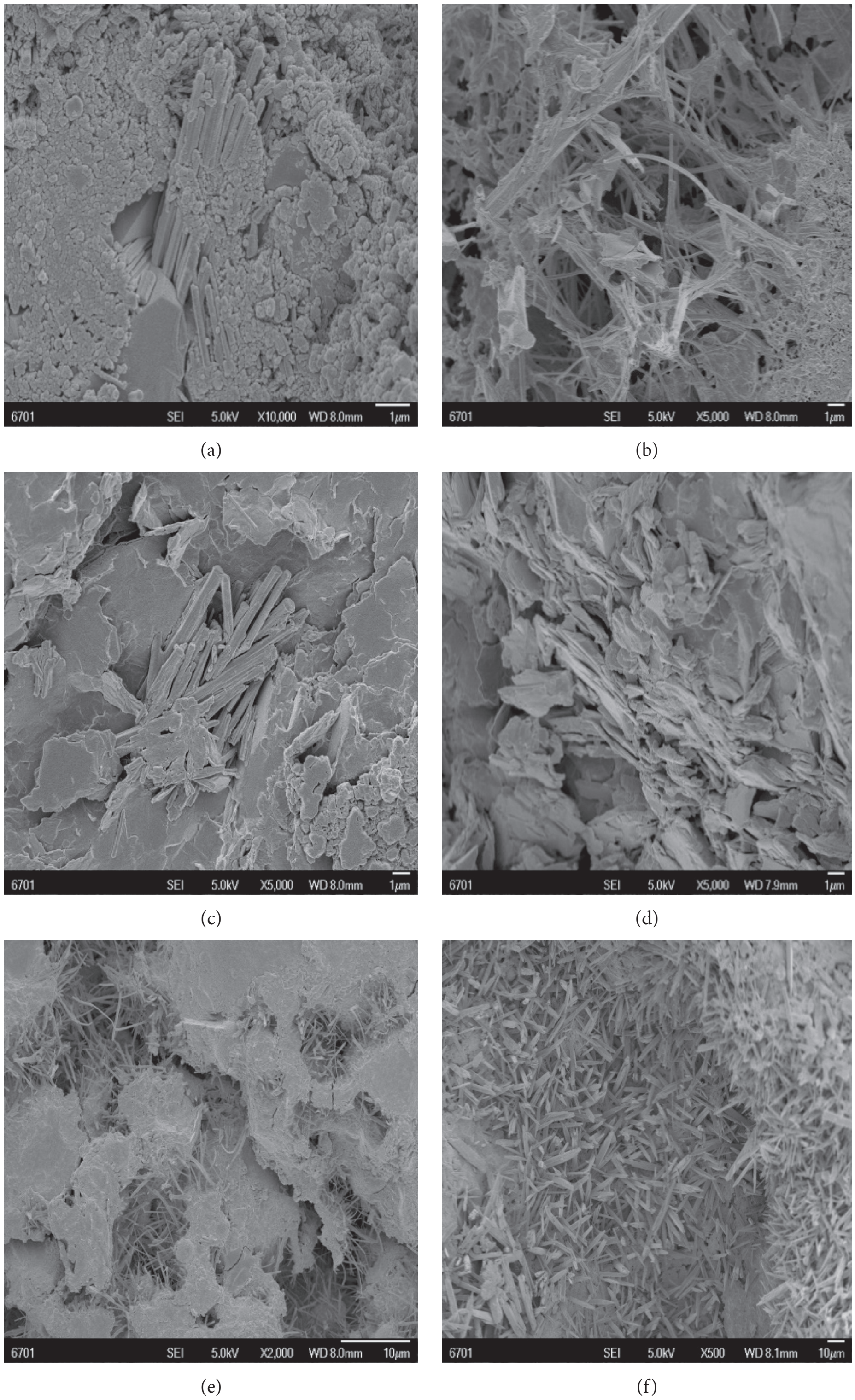

Figure 6: SEM images of degradation of recycled concrete with different proportions. (a) RCA0%–RFA0%. (b) RCA0%–RFA15%. (c) RCA30%–RFA0%. (d) RCA30%–RFA15%. (e) RCA50%–RFA0%. (f) RCA50%–RFA15%.

number of cracks, and its performance degraded further. At the same time, it also was observed that the RAC concrete contained calcium carbonate. The primary reason for this is that the surface of regenerated aggregate was attached with old mortar, and its $CaCO_3$ content was more, also during the dry-wet cycle, part of the CO_2 in the air enters the concrete through the pores on the test pieces' surface, and the coarseness in the RAC concrete. The fine aggregate also showed a considerable degree of carbonization, so calcium carbonate formed in the phase analysis.

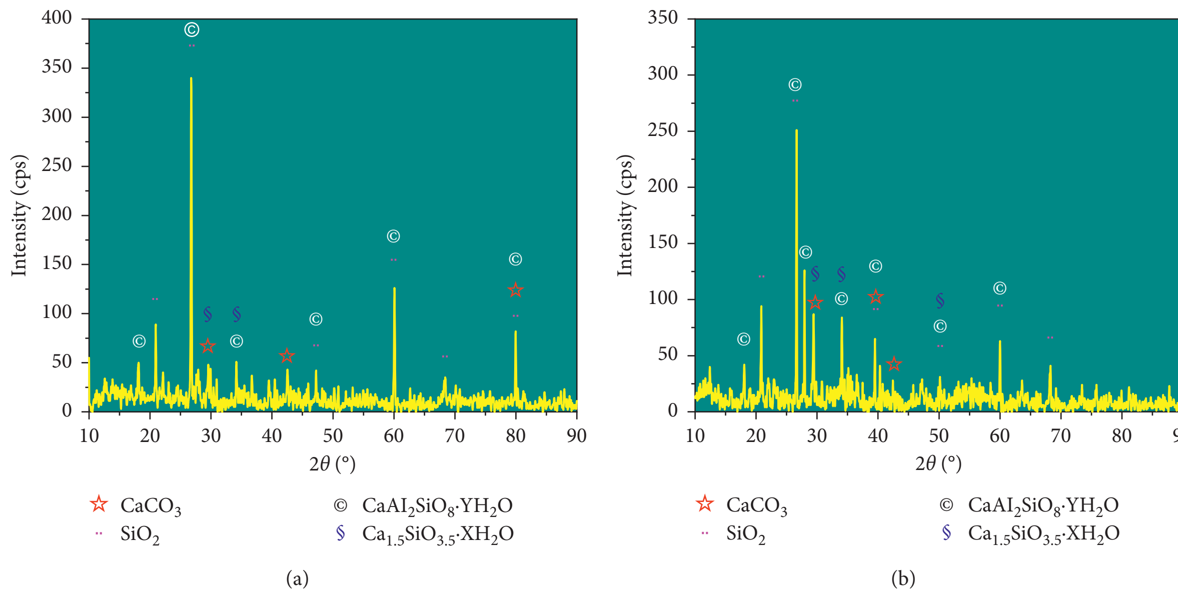

Figure 7: XRD diagram of common concrete and recycled concrete after degradation. (a) Ordinary concrete. (b) RCA concrete.

Table 3: Maximum likelihood estimation parameters of different recycled concrete.

RCARR	0%		30%		50%	
RFARR	0%	15%	0%	15%	0%	15%
μ	0.005750	0.004875	0.006375	0.006875	0.00650	0.007750
σ^2	0.000984	0.000709	0.002007	0.001119	0.00134	0.001257

5. Reliability Analysis of RAC Concrete's Sulfate Resistance

RAC concrete's quality and dynamic elastic modulus changed in a sulfate environment, and the loss in durability increased with the increase in the number of dry and wet cycles. For RAC concrete to have the durability necessary in a corrosive environment, its reliability must be measured in such an environment to ensure that it has the necessary safety and durability in the actual service environment.

According to Section 3, the maximum likelihood estimation method obtains the relevant parameters for concrete mixes' sulfate resistance, as shown in Table 3. The parameters in Table 3 were entered into equation (4) and programmed by MATLAB to obtain the reliability of different mixing ratios of concrete in different cycles of a sulfate degradation environment, as shown in Figure 8.

Figure 8(a) shows that the reliability of RAC concrete that replaces 15% of recycled fine aggregate is higher than that of ordinary concrete throughout the dry and wet cycles, and the amount of time that reliability is 1 is longer than that of ordinary concrete. This shows that 15% RAC concrete has better sulfate resistance than does ordinary concrete. 15%–30% of the RAC concrete was reliable, while the reliability of RAC concrete with 30% recycled coarse aggregate decreased faster than that of the 60% recycled RAC concrete. The reliability decreased rapidly with the same number of cycles when RAC concrete replaced only 30% of recycled coarse aggregate.

As Figure 8(c) shows, the performance degradation began at nearly the same time, but the reliability of the RAC concrete that replaced 50% of the recycled coarse aggregate always was higher than the RAC concrete that replaced only 15% recycled fine aggregate, indicating that 50–0% RAC concrete has better sulfate resistance than 50–15% RAC concrete.

To compare and analyze the effect of recycled coarse and coarse aggregate substitutes on concrete's resistance to sulfate degradation more clearly, each RAC concrete's reliability curve is given in the same figure, as shown in Figure 8(d). As the figure shows, the reliability of 0–15% RAC was significantly higher than that of other coarse and fine aggregates, even ordinary concrete. If the reliability is 0.1, the number of cycles of the concrete test specimen is 0-0% (128 times); 0–15% (146 times); 30–0% (130 times); 30–15% (107 times); 50–0% (118 times), and 50–15% (95 times). Comparing different types of concrete's reliability curves throughout the whole cycle indicated that RFA15%C >Ordinary Concrete >RCA30%C > RCA30%FA15%C > RCA50%C > RCA50%FA15%C, which is the same as the durability index analysis' conclusion. This shows that the relative dynamic elastic modulus can be used as the

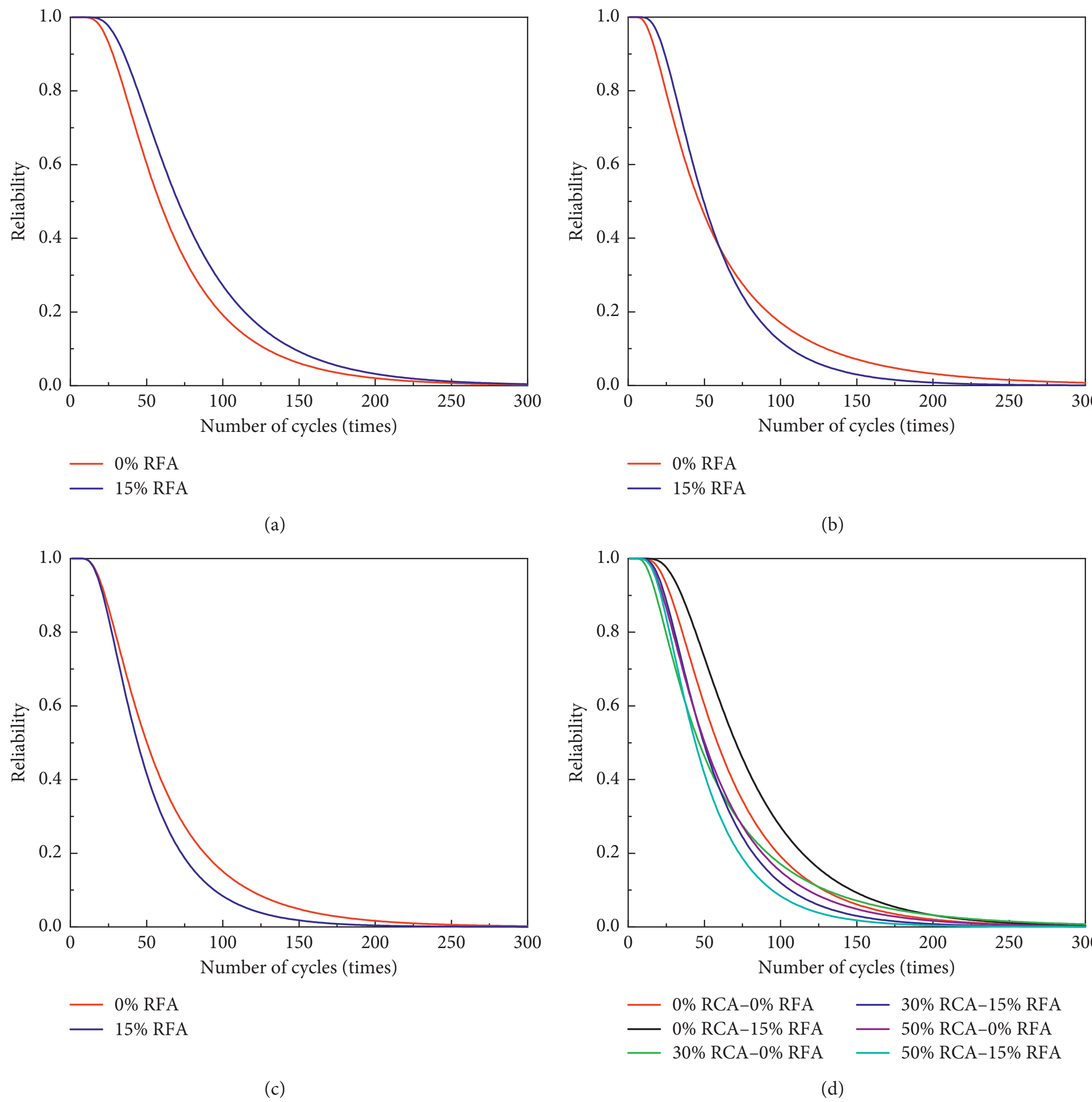

Figure 8: Reliability curve of sulfate resistance of concrete with different mix ratios. (a) RCA0%. (b) RCA30%. (c) RCA50%. (d) Comprehensive.

index of resistance to sulfate attack, and the reliability life prediction analysis the Wiener model established is feasible.

6. Conclusion and Recommendations

(1) In the case of sulfate attack, replacing some fine aggregate with recycled fine aggregate improved RAC concrete's degradation resistance, and the resistance of RAC concrete with 15% recycled fine aggregate substitute was even better than that of ordinary concrete.

(2) RAC concrete's degradation resistance decreased with the replacement rate of recycled coarse aggregate, which had more influence on its degradation resistance than did the replacement rate of recycled fine aggregate.

(3) In the sulfate dry and wet cycle environment, RAC concrete's mass and dynamic elastic modulus showed a trend of increasing first and then decreasing. The greater the recycled coarse aggregate replacement rate, the more severe the mass and dynamic elastic modulus fluctuations.

(4) The relative dynamic elastic modulus was selected as the performance degradation index, and the reliability curve obtained by Wiener modeling reflected RAC concrete's degradation resistance in a sulfate environment and obtained RAC concrete with good reliability. The number of sulfate-wet cycles increased the sulfate resistance and resulted in a

sulfate-resistant life of RAC concrete with different replacement rates.

(5) The recycled coarse aggregate in RAC concrete absorbed more water than did ordinary sand, which caused the local water-to-gel ratio at the interface to increase, such that the interface became loose and porous, and such swelling products as gypsum and Ettringite formed in the sulfate attack environment. These pores filled in the initial stage, and the macroscopic realization was an increase in mass and dynamic elastic modulus. As the degradation continued, the greater the number of expansion products and the greater the stress on the surrounding concrete, which caused the concrete to crack, and produced skin, slag, and so on, and reduced the macroscopic quality performance and the dynamic modulus.

Data Availability

The data used to support the findings of this study have not been made available because the author is still sorting out their doctoral thesis; the relevant test methods and original data need to be kept secret during this period.

Conflicts of Interest

The authors declared there are no conflicts of interest.

Acknowledgments

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