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Research Article

Flexural Fatigue Behaviors of Silicon Carbide Recycled Concrete in Corrosive Environments

Jinzhi Zhou[1] **Tiantian Fu**[1] **Chuheng Zhong**[1] **Kun Peng**[2] **and Ziyang Shuang**[3]

[1]*College of Civil Engineering Architecture and Environment, Hubei University of Technology, Wuhan 430068, China*
[2]*The Third Construction Co., Ltd. of China Construction Third Engineering Bureau, Wuhan 430068, China*
[3]*The First Company of China Eighth Engineering Bureau Ltd., Guangzhou 510700, China*

Correspondence should be addressed to Chuheng Zhong; chuheng.zhong@hbut.edu.cn

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An experimental study on the flexural fatigue behaviors of recycled concrete (RC) and silicon carbide recycled concrete (SiCRC) was conducted. The immersion time was 0 d, 30 d, 60 d, and 90 d in 5% NaCl solution for these two kinds of recycled concrete specimens, respectively, and then, four-point flexural fatigue tests were performed by MTS fatigue testing machine. The fatigue life for varying stress levels ranging from 0.9 to 0.6 was obtained. The fatigue life was given considering the failure probability according to the fatigue life and stress level of the specimen via the logarithmic normal distribution and Weibull distribution, respectively. The relationship between fatigue life and failure probability was also obtained. The fatigue life with failure probability of 1% and 50% was further predicted. The results showed that the fatigue life of RC and SiCRC increased in corrosive environments. The fatigue life of SiCRC is higher than that of RC, and the incorporation of SiCRC can improve the fatigue life of recycled concrete.

1. Introduction

With the development of the city, construction waste is growing. It is conservatively estimated that, over the next 10 years, China will produce more than 1.5 billion tons of construction waste per year, reaching 7.3 billion tons in 2030 [1]. At present, the construction waste are mainly brick and concrete, which are treated as recycled aggregate and prepared as inorganic mixture for road pavement base. Considering environment and economy, replacing nonrenewable natural aggregate with renewable construction waste, construction waste recycling can not only reduce carbon emissions but also lower costs [2, 3].

Many scholars at home and abroad have studied the mechanics and durability of recycled concrete [4–10]. Ramesh et al. [11] found that the split-tensile strength, the compressive strength, and the elastic modulus of recycled concrete with substitution rate of 30%, 50%, 70%, and 100% were lower than that of natural concrete, and the splitting tensile strength can be increased by 0.7% after incorporation of steel fiber. Aref et al. [12] showed that it was feasible to build self-compacting concrete with a 100% replacement rate of recycled aggregate. Rahal [13] found that the compressive strength and indirect shear strength of 28-day cube and cylinder of recycled aggregate concrete were 90% of natural aggregate concrete under the same mix proportions. Thomas et al. [14] discussed the effect of recycled aggregate on concrete under the same w/c ratio by partially and completely replacing natural aggregate. The durability of recycled aggregate concrete was poor due to the porosity of recycled aggregate itself. Subsequently, Pinghua Zhu et al. [15] reported the durability of recycled concrete with different substitution rates under the coupling of freeze-thaw cycle and chloride erosion.

However, many engineering structures such as bridge decks, piers, offshore structures, highway pavements, and railway sleepers are more vulnerable to fatigue loading [16]. Therefore, scholars have also carried out studies on the fatigue properties of recycled concrete. Singh and Kaushik [17] found that steel fiber recycled concrete statistical distribution of equivalent fatigue life at a given stress level S, approximately, submitted to the two-parameter Weibull distribution. Cusson et al. [18] mentioned that because of the increase of traffic load and the change of environmental conditions, deterioration will affect the service life of the bridge; the use of deicing salt on the road in winter will lead to more serious corrosion deterioration and reduce its durability. The test under the coupled action of freezing-thawing cycles and chloride attack was completed by Hao et al. [19] The results showed that the bending stress had significant negative effect on the frost resistance of RATIC. Wang et al. [20] found that silicon carbide concrete had better working performance on compressive and flexural strength than that of ordinary concrete. Silicon carbide can be used as wear-resistant floor in logistics workshop and distribution workshop to enhance the wear resistance of pavement [21].

In conclusion, the flexural fatigue performance of common recycled concrete and silicon carbide recycled concrete in corrosion environment will be studied by experiments in this paper in order to obtain useful conclusions.

2. Experimental Program

2.1. Materials. In this experiment, constituents of silicon carbide recycled concrete (SiCRC) are Ordinary Portland Cement, coarse aggregates, river sand, manufactured sand, silicon carbide, and admixtures. Ordinary Portland Cement has been obtained from the local supplier. Coarse aggregates have NA and RA two types. Particle size of NA and RA of is 5–30 mm, whose physical properties are given in Table 1. The RA used in this study was completely wetted by spraying water. Fine aggregate was river sand and silicon carbide. The fineness modulus of river sand is 2.8, which belongs to medium sand in II area, with mud content of 0.7%. The size of silicon carbide is 1190 μm. Admixtures are polycarboxylic acid. The water-reduction rate of that is 30%, and the gas and solid content is about 4.7% and 8.8%. Fly ash and slag as materials were mingled to improve the performance of specimens. Chloride containing environment is 5% NaCl solution.

2.2. Specimen. The experiment carries on the mix proportion design of the reference concrete C30 according to the JCJ55-2011 (Specification for Mix Proportion Design of Ordinary Concrete). The substitution rate of recycled aggregate is 20% in RC. Further, based on RC, 10% fine aggregate can be replaced with an equal volume of silicon carbide, which made SiCRC.

There are two kinds of concrete specimens, the mineral powder is 100 kg/m^3, the cement is 210 kg/m^3, the fly ash is 60 kg/m^3, and the water and water reducer are 160 kg/m^3 and 7.4 kg/m^3, respectively. The amount of other materials is given in Table 2. The flexural fatigue test was carried out with 150 mm × 150 mm × 550 mm standard trabecular specimens. It has 2 mix proportion and 8 groups of specimens. The flexural fatigue specimens of each group were 9. The specimens were standard cured for 28 d. Then, specimens' soaking time periods were 0, 30, 60, and 90 d in 5% NaCl solution.

3. Test Methods

Fatigue test was carried out on the MTS in the structure hall of Hubei University of Technology, as shown in Figure 1. Loading mode selected load control, four-point bending method, and sine wave cycle loading mode; loading frequency is 10 Hz; the stress level is 0.6, 0.7, and 0.9; the test flow is shown in Figure 2.

4. Test Results and Analysis

4.1. Experimental Phenomena. The results show that white spots and concave-convex pits are produced on the surface of RC and SiCRC specimens after chlorine salt soaking. With loading, crack gradually appears in the middle of the tension side of the specimen and extends to the compression zone. Due to the weak bond between coarse aggregate and cement gel, when loaded to the ultimate load, the specimen produced brittle fractures, accompanied by the sound of bang. The destroyed image is shown in Figure 3.

4.2. Fatigue Test Data. The results of the fatigue tests as obtained in this investigation are given in Tables 3 and 4. In bending fatigue tests, even with the same batch of raw materials, the produced samples are differences. Because silicon carbide recycled concrete is a composite, it has been treated with chlorine salt soaking. Fatigue failure is more complicated than static load failure. The results of fatigue test are very discrete. *S-N* relation graph is a widely accepted method to evaluate the fatigue life of practical engineering. When considering the effect of minimum stress, constant life fatigue diagram can be used such as Haigh or Smith diagrams to represent. The recycled concrete has a different fatigue life under different bending fatigue stress levels. The relationship between stress level *S* and fatigue life *N* can be described by the rectangular Cartesian coordinate system. The *S-N* curve can clearly and intuitively describe the fatigue characteristics of materials [4]. Figure 4 shows the *S-N* curves of recycled concrete of different types and different immersion ages showing the relationship between fatigue life (*N*) and stress level (*S*), respectively.

It can be seen from Figure 4 that the fatigue life of each group of recycled concrete specimens decreases with the increase of stress level. When the stress level is certain, with the increase of soaking age, the fatigue life of recycled concrete and silicon carbide recycled concrete increases. When the stress level is certain and the soaking age is the same, the fatigue life of silicon carbide recycled concrete under chlorine salt immersion is higher than that of recycled concrete.

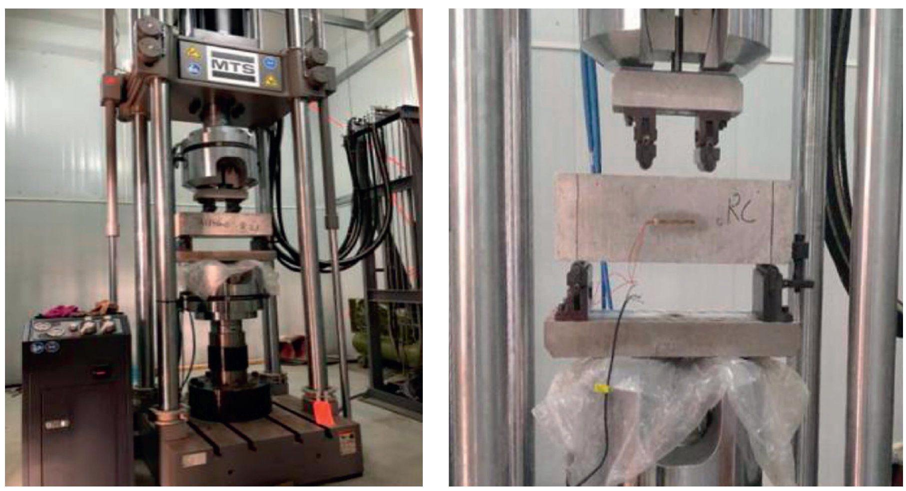
Without the chlorine, due to the higher porosity and lower strength of RC, the size of silicon carbide is small and can be filled between other aggregate gaps, which improves the density of concrete. The addition of silicon carbide and coal fly ash improves the inner capillary structure of concrete and improves the bonding ability of concrete as a whole. Meanwhile, the hydroxyl of concrete admixture and silicon carbide, main components' SiC on the surface, and oxygen

Table 1: Physical properties of coarse aggregate.

Category	Particle size (mm)	Water absorption (%)	Apparent density (kg/m^3)	Crushing value (%)
Recycled coarse aggregate	5~30	9.5	2520	14.9
Natural coarse aggregate	5~30	0.9	2650	9

Table 2: Mixture proportion (kg/m^3).

Concrete type	Cement	NA	RA	Silicon carbide	Manufactured sand	River sand	Water
RC	210	824	206	—	380	455	160
SiCRC	210	824	206	83.5	342	409	160



(a) (b)

Figure 1: Fatigue test equipment.

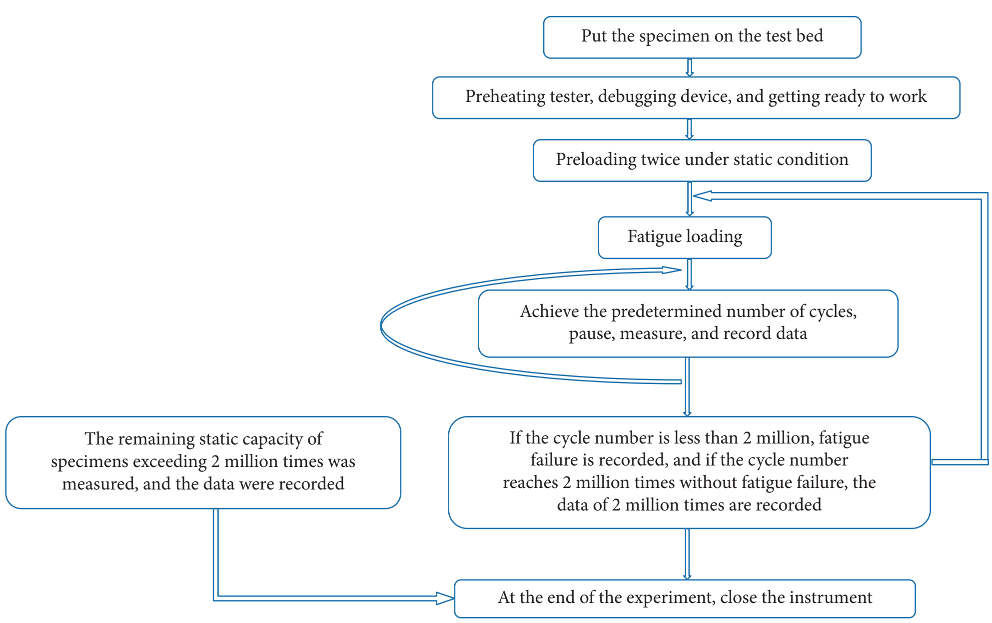
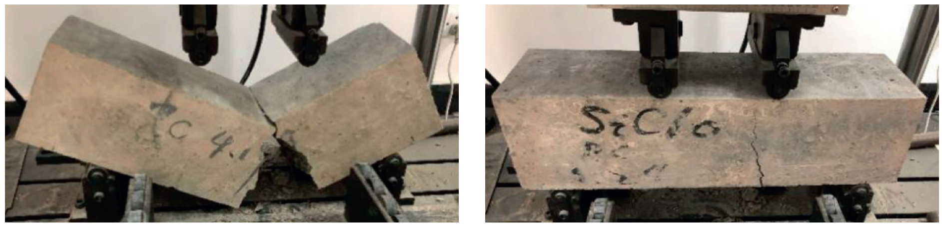


Figure 2: Test procedure for fatigue test.



(a) (b)

Figure 3: Failure morphology of specimens.

Table 3: Fatigue life (*N*) for RC.

Specimen no.	Stress level	Fatigue life data (*N*)		
RC (0 d)	0.9	113	211	319
	0.7	14647	31841	45239
	0.6	57981	106042	148596
RC (30 d)	0.9	125	223	332
	0.7	16135	33855	48271
	0.6	60458	108267	151029
RC (60 d)	0.9	136	236	346
	0.7	17737	35324	50736
	0.6	62549	110749	153773
RC (90 d)	0.9	145	247	357
	0.7	19319	36973	52632
	0.6	64597	112823	156175

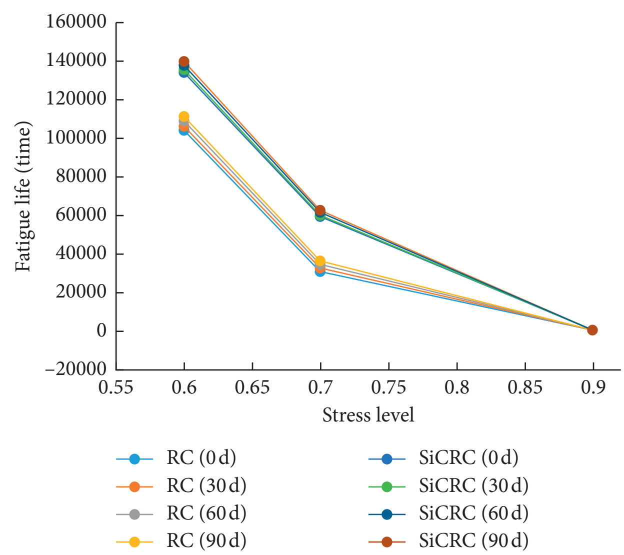


Figure 4: *S*-*N* curves.

Table 4: Fatigue life (*N*) for SiCRC.

Specimen no.	Stress level	Fatigue life data (*N*)		
SiCRC (0 d)	0.9	255	404	612
	0.7	22716	61953	93326
	0.6	70463	135524	196022
SiCRC (30 d)	0.9	262	408	619
	0.7	23941	63117	94565
	0.6	71926	137033	197576
SiCRC (60 d)	0.9	266	413	623
	0.7	24851	64028	95447
	0.6	73942	139031	199527
SiCRC (90 d)	0.9	272	419	631
	0.7	26044	65238	96646
	0.6	76186	141231	201767

atom with strong negative charge in cement clinker molecules generate a hydrogen bond, which further improves the strength of concrete.

After soaking in chloride, the fatigue life of SiCRC increases as follows. In the long-term immersion of NaCL solution, chlorine salt diffuses into the concrete with the increase of soaking age. Because a large number of chloride ions exist, the crystals of salt are formed in concrete. It is mainly that tricalcium aluminate combines with chloride ion to form "Fessler salt." At the same time, the cement hydration will continue to produce calcium hydroxide and other substances, which will make the interior of concrete more dense. The connection between the aggregate inside the concrete closer and strength of the concrete increases. Silicon carbide is a kind of aggregate with high toughness and hardness, and the SiCRC is a kind of material with good uniformity. The addition of silicon improves toughness and crack resistance of concrete as a whole. The performance of RC under the condition of chlorine salt soaking and the mechanism of chlorine salt erosion are similar to SiCRC, but the fatigue life performance is not as good as that of SiCRC because of the lack of the addition of silicon improves.

5. Numerical Distribution Analysis

On the strength and fatigue life of concrete materials, scholars mostly use the lognormal distribution model and the Weibull distribution model [22–25]. In this section, lognormal distribution and two-parameter Weibull distribution model will be used to analyze the fatigue performance of recycled concrete in chloride immersion.

5.1. Lognormal Distribution. The logarithm of specimens' fatigue life ($S = \lg N$) obeys normal distribution; then, the probability density function is as follows:

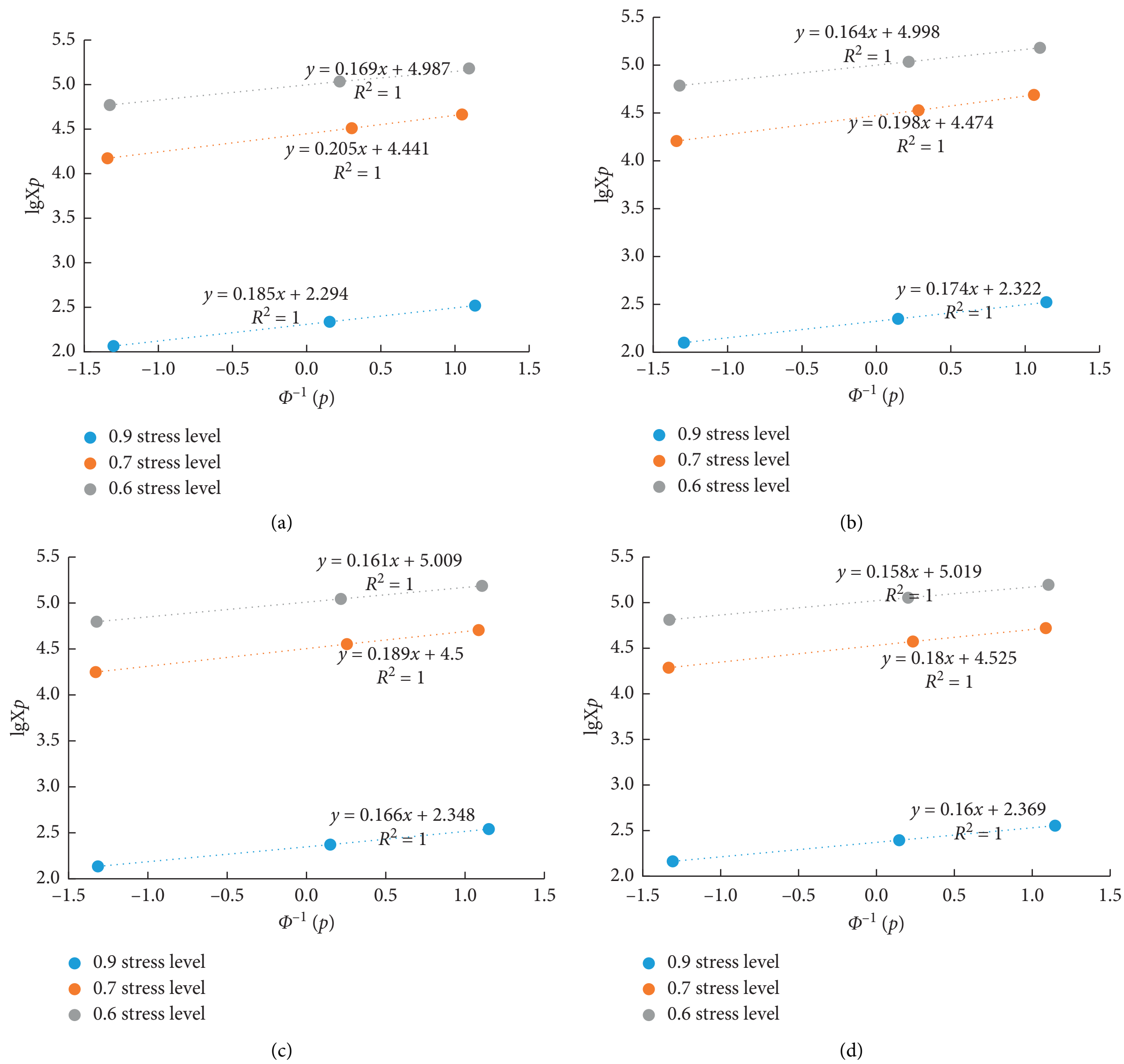


Figure 5: RC linear regression. (a) RC (0 d). (b) RC (30 d). (c) RC (60 d). (d) RC (90 d).

$$f_N(n) = \frac{1}{\sqrt{2\pi}\ln 10\sigma_0 n}\exp\left[-\frac{(\lg n - \mu_0)^2}{2\sigma_0^2}\right], \tag{1}$$

where μ_0 and σ_0 of $\lg N$ are average value and standard deviation and distribution parameters N is the random variable:

$$F_N(n) = P(N \le n) = \varphi\left(\frac{\lg n - \mu_0}{\sigma_0}\right). \tag{2}$$

The function values to the cumulative distribution function is called cumulative failure probability or unreliable. Then, the reliability function is as follows:

$$R_N(n) = 1 - F_X(x) = 1 - \varphi\left(\frac{\lg n - \mu_0}{\sigma_0}\right). \tag{3}$$

In order to regress the model distribution parameters, the cumulative failure probability is known to be p. Taking $\varphi^{-1}(\cdot)$ on both sides at the same time, reliability life of $(1-p)$ is as follows:

$$\lg n_p = \mu_0 + \varphi^{-1}(p)\sigma_0, \tag{4}$$

When $Y = \lg x_p$, $Z = \varphi^{-1}(p)$, $a = \mu_0$, and $b = \sigma_0$, equation (4) can be transformed into the following primary linear equation:

$$\begin{aligned} Y &= a + bN, \\ \hat{\mu}_0 &= \hat{a}, \\ \hat{\sigma}_0 &= \hat{b}. \end{aligned} \tag{5}$$

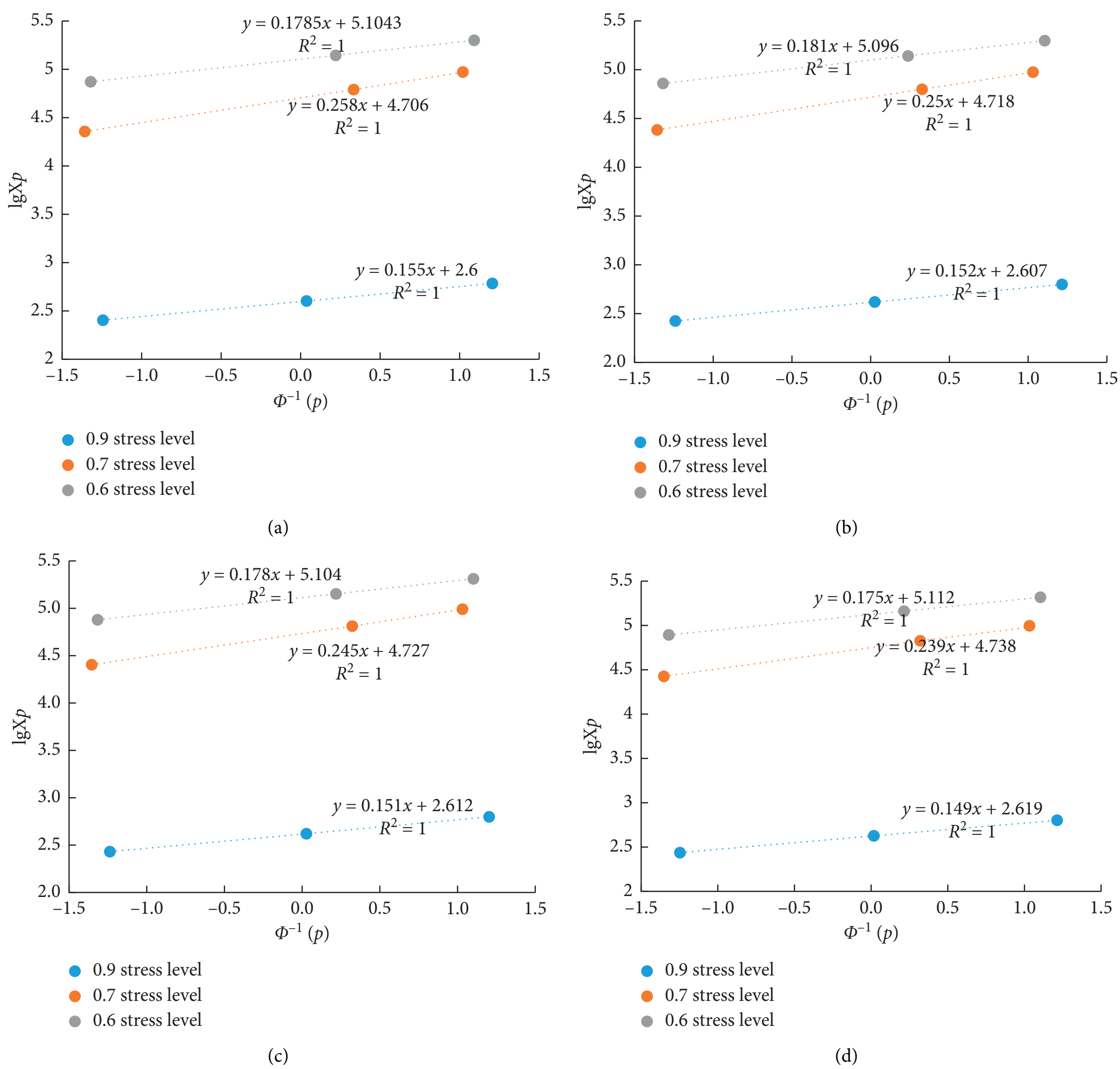


FIGURE 6: SiCRC linear regression. (a) SiCRC (0 d). (b) SiCRC (30 d). (c) SiCRC (60 d). (d) SiCRC (90 d).

a and b can be obtained by regression of test data with formula (5) to determine the distribution parameters μ_0 and σ_0.

Fatigue life of RC and SiCRC in corrosive environments was analyzed by using lognormal distribution theory. The fitting results are shown in Figures 5 and 6.

5.2. Weibull Distribution. According to Weibull distribution theory, the distribution law of fatigue life N of each specimen can be expressed by Weibull function under the same stress level:

$$Y = bX - a, \tag{6}$$

where $Y = \ln[\ln(1/p)]$, $X = \ln N$, and $a = b \ln N_a$.

The data of fatigue life are brought into Y and X, and the data are regressed analysis. The data show a clear linear relationship; then, the results show that the data of four-point bending fatigue test accord with the two-parameter Weibull distribution. On the contrary, the assumption is not tenable.

Fatigue life of RC and SiCRC in corrosive environments was analyzed by using Weibull distribution theory. The fitting results are shown in Figures 7 and 8.

From Figures 5–8 and Table 5, all the correlation coefficient R^2 is 1.0 by using lognormal distribution and R^2 is above 0.95 by using Weibull distribution. The results show that the fatigue life of the two kinds of concrete under the condition of chlorine salt soaking is better from lognormal distribution and Weibull distribution at different ages. Both the lognormal distribution and the two-parameter Weibull distribution , the fatigue life of chloride attack increased to varying degrees compared with that before chloride attack.

For the normal distribution theory, the correlation coefficient R^2 is 1.0, which indicates that it is completely

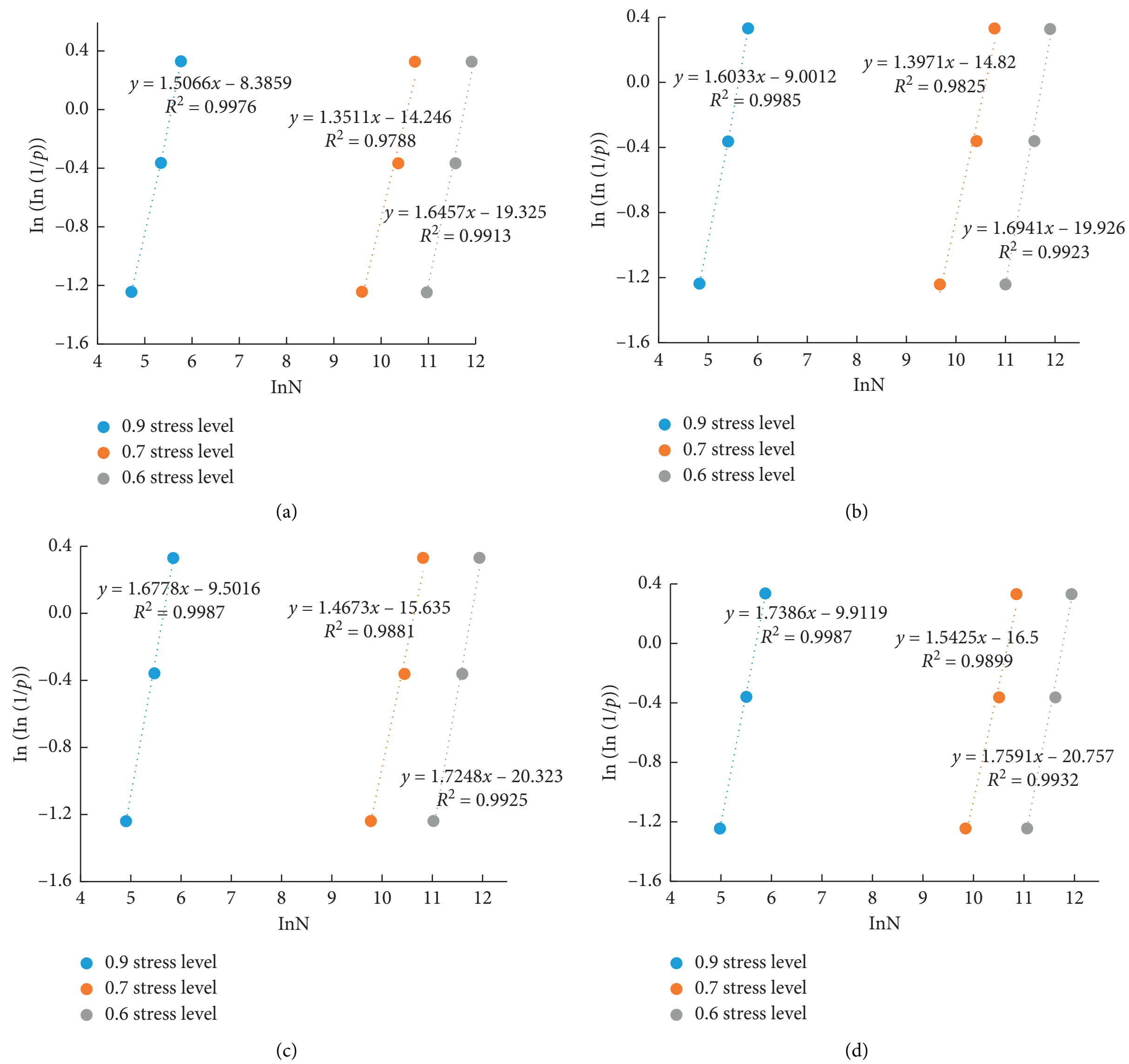


FIGURE 7: RC linear regression. (a) RC (0 d). (b) RC (30 d). (c) RC (60 d). (d) RC (90 d).

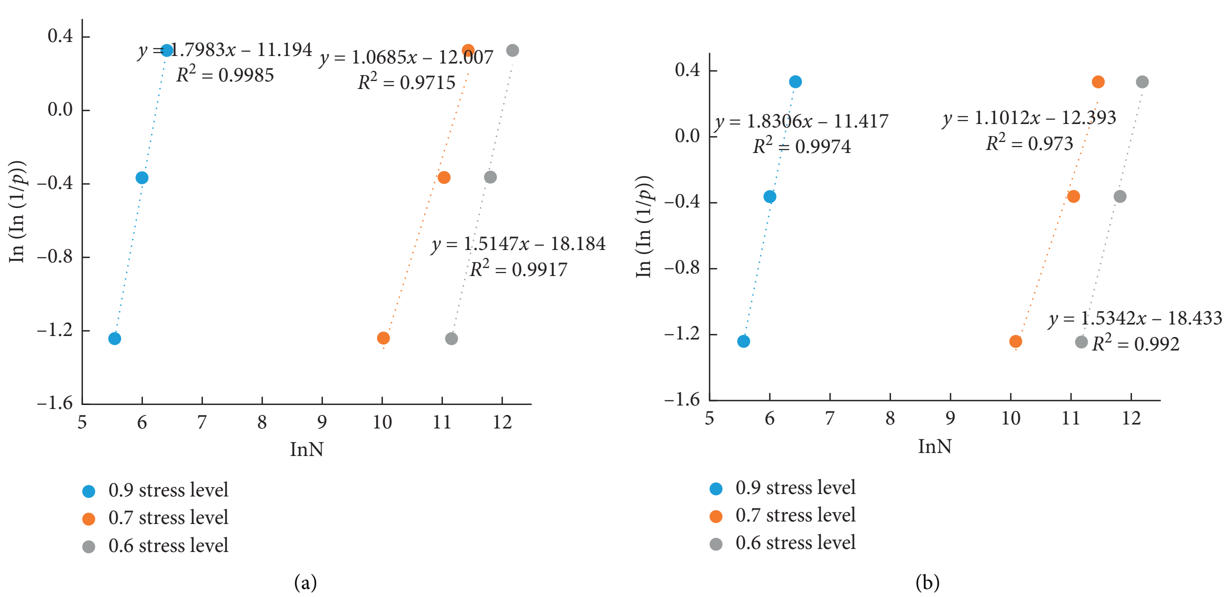


FIGURE 8: Continued.

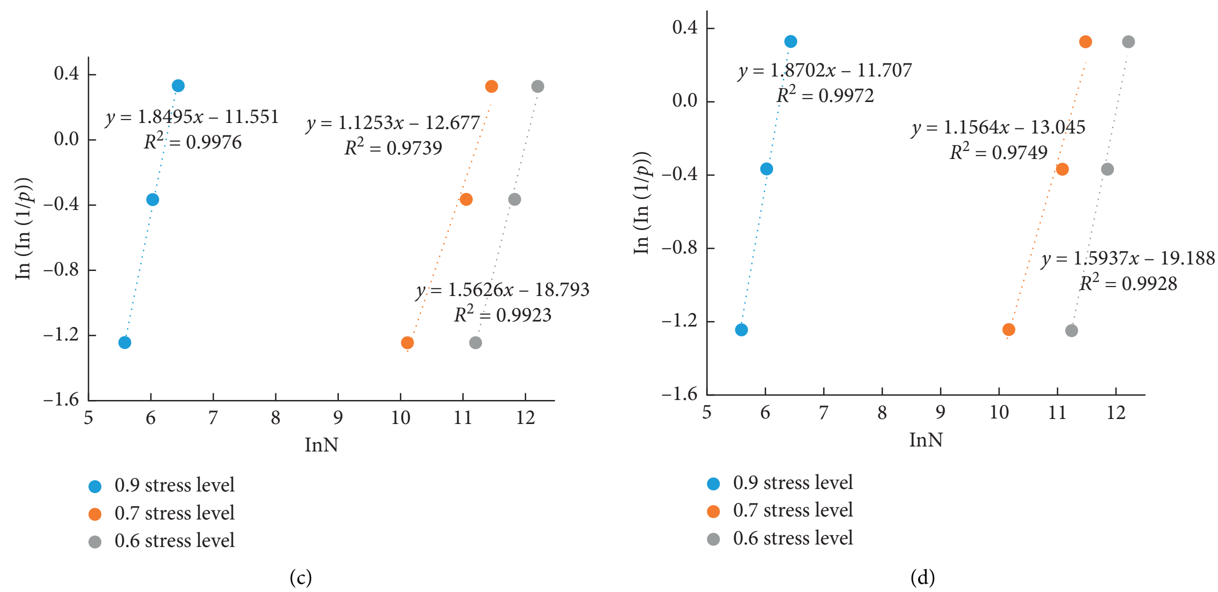


FIGURE 8: SiCRC linear regression. (a) SiCRC (0 d). (b) SiCRC (30 d). (c) SiCRC (60 d). (d) SiCRC (90 d).

TABLE 5: Fitting results of lognormal distribution and Weibull distribution.

Group number	Max stress level	Lognormal distribution					Weibull distribution				
		a	b	R^2	Failure probability 1%	Failure probability 50%	a	b	R^2	Failure probability 1%	Failure probability 50%
RC (0 d)	0.9	2.294	0.185	1.0	73	197	1.5066	8.3859	0.9976	59	205
	0.7	4.41	0.205	1.0	8572	25704	1.3511	14.246	0.9788	7175	28933
	0.6	4.987	0.169	1.0	39250	97051	1.6457	19.325	0.9913	32058	100711
RC (30 d)	0.9	R^2	0.174	1.0	83	210	1.6033	9.001	0.9985	67	218
	0.7	4.474	0.198	1.0	10312	29785	1.3971	14.82	0.9825	8078	31112
	0.6	4.998	0.164	1.0	41350	99541	1.6941	19.926	0.9923	33984	103327
RC (60 d)	0.9	2.348	0.166	1.0	92	223	1.6778	9.502	0.9987	75	232
	0.7	4.5	0.189	1.0	11490	31623	1.4673	15.635	0.9881	9154	33052
	0.6	5.009	0.161	1.0	43098	102094	1.7248	20.323	0.9925	35529	105907
RC (90 d)	0.9	2.369	0.16	1.0	99	234	1.7386	9.9119	0.9987	82	242
	0.7	4.525	0.18	1.0	12771	33497	1.5425	16.5	0.9899	10281	34868
	0.6	5.019	0.158	1.0	44816	104472	1.7591	20.757	0.9932	37068	108167
SiCRC (0 d)	0.9	2.6	0.155	1.0	173	398	1.7983	11.194	0.9985	145	412
	0.7	4.706	0.258	1.0	12758	50816	1.0685	12.007	0.9715	9239	53865
	0.6	5.104	0.178	1.0	48875	127151	1.5147	18.184	0.9917	37024	128418
SiCRC (30 d)	0.9	2.607	0.152	1.0	179	405	1.8306	11.417	0.9974	149	418
	0.7	4.718	0.25	1.0	13690	52240	1.1012	12.393	0.9731	10002	55340
	0.6	5.096	0.181	1.0	47308	124738	1.5342	18.433	0.992	38072	129971
SiCRC (60 d)	0.9	2.612	0.151	1.0	182	409	1.8496	11.551	0.9976	153	423
	0.7	4.727	0.245	1.0	13456	53333	1.1253	12.677	0.9739	10569	56373
	0.6	5.104	0.178	1.0	48968	127057	1.5626	18.793	0.9923	39601	132217
SiCRC (90 d)	0.9	2.619	0.149	1.0	187	416	1.8702	11.707	0.9972	157	430
	0.7	4.738	0.239	1.0	15206	54702	1.1564	13.045	0.9749	11324	57743
	0.6	5.112	0.175	1.0	50686	129420	1.5937	19.188	0.9928	41269	134582

correlated. It does not match the actual situation, and there is a little error.

For the Weibull distribution theory, when the stress level is the same, the correlation coefficient R^2 increases gradually with the increase of soaking age, which shows that the linear relationship is enhanced. When the soaking age is the same, the correlation coefficient of the same type concrete is higher at the stress level 0.9. When the stress level and soaking age are the same, the SiCRC's correlation coefficient R^2 is higher than RC, which indicates that the straight line fitting effect is better. In addition, at the high stress level, the fitting discreteness of fatigue life is large, the fatigue life is 0 when the failure probability is 0, which is wrong with the actual existence.

6. Conclusions

(1) The fatigue life of each concrete specimens decreases with the increase of the stress level, and the fatigue life of both types of concrete increases with the increase of soaking age when the stress level is fixed.

(2) The fatigue life of RC and SiCRC increased in corrosive environments. The fatigue life of SiCRC is higher than that of RC, and the incorporation of SiCRC can improve the fatigue life of recycled concrete.

(3) By both the lognormal distribution and two-parameter Weibull distribution, the fatigue life for chlorine salt erosion increased in varying degrees under the corresponding failure probability.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of Interest.

Acknowledgments

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