Research Article

Research on the Fatigue Properties of High Strength Concrete after Exposure to High Temperature under Low Cyclic Compressive Loading

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By using an electrohydraulic servo fatigue testing machine, fatigue tests were performed on C60 high strength concrete (HSC) under low cyclic compressive loading after undergoing normal temperature, 200°C, 400°C, 600°C, and 800°C. Failure patterns of high strength concrete under low cyclic compressive loading were observed. The influence of the high temperature process on the static elastic modulus of high strength concrete was analyzed. By studying the development law of fatigue strain, regression equations of fatigue strain after different high temperatures were established. Furthermore, the fatigue deformation modulus ratio was defined as the damage variable and the relationship models between the high temperature process and the fatigue damage were established. It provides the experimental foundation for fatigue damage analysis of high strength concrete in objective working conditions, which includes repeated loading and different high temperature processes.

1. Introduction

High strength concrete (HSC) has been widely used with the increasing complex structures of modern architecture. For instance, the Petronas Twin Towers in Kuala Lumpur City Centre, Malaysia, used C80 HSC. 311 South Wacker Drive in Chicago, USA, used C95 HSC. Two Union Square Building in Seattle, USA, used C135 HSC, Television Culture Center of China (TVCC), Shanghai World Financial Center (SWFC), adopted C60 HSC. In practice, concrete structures not only undertake static loading and the cyclic loading (vehicle loads, wind loads, wave loads, etc.), but also may suffer high temperature processes caused by fire or other reasons, which further results in serious damage of its structural properties.

At present, researches on mechanical properties of HSC after exposure to high temperature have been deeply carried out worldwide. Most studies [1–10] focused on the basic properties of HSC, such as appearance, mass, tensile strength, failure pattern, multiaxle strength, and stress-strain curve; those studies established the formula for failure criterion of HSC in

multiaxial stress state. However, the study on fatigue behavior of HSC after exposure to high temperature has not been carried out yet, especially after exposure to different high temperature processes. Several researches were concentrated on uniaxial fatigue behavior of ordinary concrete after exposure to high temperature [11–13]. In those studies, the tensile fatigue behavior of concrete under constant amplitude cyclic load after 100°C and 200°C has been investigated, the static performance of concrete has been analyzed, and the relationship between total strain growth rates at the second stage and fatigue life has been given. Nevertheless, the relationship model between the high temperature process and the fatigue damage of HSC failed to be established, and huge gap in the fatigue damage evaluation of fire-damaged HSC structure remains.

This paper presents the variation discipline of appearance, static elastic modulus, fatigue strain, residual strain, and fatigue deformation modulus of C60 HSC structure which was tested at various stress ratios after suffering room temperature, 200, 400, 600, and 800°C. The static load test and

fatigue test were performed with electrohydraulic servo pressure machine and electrohydraulic servo fatigue machine, respectively. And the relationship models between the high temperature process and the fatigue damage are established, those provide reference to fatigue damage assessment of high strength concrete subjected to different high temperature processes.

2. Materials and Experimental Procedures

2.1. Materials and Mix Proportions. The materials used in this investigation are standard cube specimens, as shown in Figure 1(b), which are made of C60 concrete (the matching ratio is shown in Table 1). Heating temperature was room temperature (20°C), 200°C, 400°C, 600°C, and 800°C respectively. Each set of specimens are constantly heated for 0.5 h, 1 h, 2 h, and 3 h after reaching the specified temperature.

2.2. Apparatus and Testing Methods. The high temperature test was carried out in a box-type resistance furnace, as shown in Figure 1(a), whose size is 300 mm × 500 mm × 200 mm. The maximal permitted temperature of resistance for furnace is 1000°C, and the temperature control precision is $\pm 1^\circ\text{C}$. After specimens were put into the resistance furnace, the temperature gradually rose from the room temperature to the preset temperature in a rate of $10^\circ\text{C}/\text{min}$ [14], and the temperature was maintained constantly for a certain time. In order to prevent the specimens from bursting during heating process, the specimens were wrapped around with high temperature barbed wire.

The static load test was carried out with the electrohydraulic servo pressure machine, as shown in Figure 1(c). The axis of specimen should be coincident with the axis of the machine panel before test, then repeatedly preloading and unloading the specimen three times with 20% of the upper limit load with 20% of the upper limit load; then pressure was applied at a rate of 0.3 MPa/s–0.8 MPa/s on the specimen until failure, and the ultimate bearing capacity of the specimen was obtained.

The fatigue test was carried out with an electrohydraulic servo fatigue machine, as shown in Figure 1(d). The fatigue load was applied by a 500 kN actuator in the vertical direction; the pressure is monitored by the voltmeter. The GTC 450 full digital electrohydraulic servo controller was used to control and collect data in real time. Cyclic loading waveform was sine wave, the minimum stress level $S_{\min}$ (the ratio of minimum lateral compressive stress $\sigma_{\min}$ and tensile strength f_t) was 0.1, and the maximum stress levels $S_{\max}$ were 0.80, 0.85, and 0.90, respectively. Each principal stress direction must be perpendicular to the surface of the specimen. The deformation was measured with a 50 mm foil resistive strain gauge, which was applied to the two free surfaces of the specimen.

All tests were carried out by using three layers of plastic films spread with butter as the friction-reducing pad to ensure the test was conducted with few friction.

3. Test Results and Discussion

3.1. Experimental Results and Analysis

3.1.1. Apparent Appearance. HSC specimens have a series of apparent characteristics changes during the heating process

from the room temperature (20°C) to the specified temperature, including the color variation, crack propagation, scaling, broken corners, and looseness, as shown in Figure 2 and Table 2. When the temperature exceeded 200°C, irritating odor was generated. When the temperature exceeded 400°C, water mist emitted from the furnace door and irritating odor increased; when temperature reached 600°C, the water mist mostly disappeared and remarkable sound of bursting came out occasionally of box-type resistance furnace. When the heating process finished and the furnace door was opened, there were water droplets on the upper and lower sides of the furnace door.

As shown in Figure 2, the color of cooled specimens had no significant difference between before and after suffering 200°C [14]. The whole or part of specimens appeared rust red after suffering 400°C for one hour, which had a significant contrast with the color of the corresponding specimen at the room temperature. After heating up for 3 hours, the red disappeared and the light gray appeared on the specimen surface. Crack increased, but it did not spread across the entire surface. A small number of specimens had peeled pieces and broken corners, but most of the specimens kept a unbroken appearance. A small number of specimens had burst during the heating process, which caused rough section area, many holes, and cracks. After suffering 800°C, the specimens' appearance turned into offwhite, and some coarse cracks came out, and the overall structure was relatively loose.

It was analyzed that, at 400°C, hydration of calcium ferrite ($\text{CaO}\cdot\text{Fe}_2\text{O}_3\cdot\text{H}_2\text{O}$) in the concrete has a chemical reaction with $\text{Ca}(\text{OH})_2$, which results in reddish-brown $\text{Fe}(\text{OH})_3$ [12]. With 600°C, $\text{Fe}(\text{OH})_3$ was decomposed into iron oxide and the red disappears.

3.1.2. Failure Mode. The failure modes of HSC under low cyclic compressive loading after different high temperature processes are shown in Figure 3. Due to suffering the high temperature, there were already some visible cracks on the specimens surface before loading. During 600°C procedure, some specimens sustained brittle failure and burst with splitting sound. This is because the strength of cement gel is close to the strength of coarse aggregate, which makes the development of cracks unable to be blocked and buffered by coarse aggregate like ordinary concrete. When reaching the peak stress, the energy accumulated inside is released in a rapid and violent manner and it made the specimen burst. It was obvious to see that, under uniaxial compressive stress, the HSC specimen split into multiple small cylinders. The failure surface of HSC was parallel to the compressive stress direction and perpendicular to the free surface, causing formation of one or more failure surfaces, and this phenomenon is called columnar damage. The failure mode of HSC was column-shaped conquassation, and the specific form is related to the applied stress level. Some specimens even show the failure mode of bulk fragments. This conclusion is consistent with the experimental results of Lv [12] and Xu [15].

3.1.3. Relative Compressive Strength. Through the static test, the compressive strength of the specimen after the antifric-tion at room temperature was 49.6 MPa, and the compressive

FIGURE 1: Apparatus and specimens: (a) box-type resistance furnace; (b) specimens; (c) electrohydraulic servo pressure machine; (d) electrohydraulic servo fatigue machine.

FIGURE 2: The apparent changes of HSC after different high temperature processes: (a) P-2-2; (b) P-4-1; (c) P-4-3; (d) P-6-0.5; (e) P-8-3; (f) normal temperature (P-X-X indicates fatigue test, heating temperature ($\times 100^\circ\text{C}$), holding time (h), such as P-2-2 indicates holding 2 h after heating up to 200°C).

TABLE 1: Mix proportions of HSC.

Cement: kg/m^3	Sand: kg/m^3	Gravel: kg/m^3	Water: kg/m^3	Water-reducing agent: kg/m^3	Water-to-binder ratio
510	720	1040	163	11	0.32

FIGURE 3: Failure mode of HSC specimens under uniaxial compression loads after different high temperature processes: (a) P-2-0.5, $S_{\max} = 0.80$, $0.5N_f$; (b) P-2-3, $S_{\max} = 0.85$, $0.5N_f$; (c) P-5-0.5, $S_{\max} = 0.90$, $0.25N_f$; (d) P-6-3, $S_{\max} = 0.85$, $0.75N_f$; (e) P-8-2, $S_{\max} = 0.90$, N_f ; (f) critical failure state of fatigue.

TABLE 2: Appearance characteristics of HSC after exposure to high temperatures and then room temperature cooling.

Temperature: °C	Color	Crack propagation	scaling	Broken edges and corners	Looseness
20	Cinereous	None	None	None	None
200	Cinereous	None	None	None	None
400 (0.5 h, 1 h)	Reddish	Little	Little	Little	Mild
600	Grey	Some	Some	Some	A little heavy
800	Offwhite	Throughout the surface	Mostly	All the cornerS	Heavy

strength of the HSC specimen after different high temperature processes is shown in Table 3.

3.1.4. Fatigue Life. The fatigue life of the HSC specimens under uniaxial compression cyclic loading is shown in Table 4. Since it is generally believed that the fatigue life of concrete material obeys the lognormal distribution [16, 17], the logarithm of the mean value of fatigue life obtained under the same stress level is used as the average fatigue life of specimens under this condition.

3.1.5. Fatigue Deformation. In this experiment, the maximum strain $\varepsilon_{T,\max}$ at the fatigue direction of the HSC was measured, and its relationship with the relative fatigue cycles was shown in Figure 4. It can be seen that when specimens are under fatigue load, the longitudinal fatigue total strain increases with the maximum stress level and fatigue load cycle number and its development can be divided into three stages, which is the same as the fatigue strain behavior of ordinary concrete (Zhao DF, 2002); [18, 19]. The first stage was the crack initiation stage, the fatigue strain increased rapidly from zero to the

TABLE 3: Basic mechanical values of HSC after different high temperature processes.

Specimen number	f_c^T : Mpa	E^T : (10^4 N/mm ²)	ε_p : 10^{-6}
P-2-0.5	42.6	3.21	1920
P-2-1	40.1	3.33	1999
P-2-2	41.2	3.59	1948
P-2-3	46.5	3.54	2076
P-4-0.5	45.2	3.44	2515
P-4-1	44.3	3.43	2505
P-4-2	42.4	3.43	2631
P-4-3	39.9	3.37	3056
P-6-0.5	32.5	3.37	3784
P-6-1	30.2	3.11	3101
P-6-2	28.5	3.04	3985
P-6-3	25.9	2.96	3624
P-8-0.5	19.2	2.87	4203
P-8-1	18.0	2.80	4574
P-8-2	15.3	2.72	4799
P-8-3	11.8	2.66	4816

Note. P-X-X indicates fatigue test-heating temperature-holding time, and P-0 indicates HSC at room temperature.

TABLE 4: Test data of fatigue for HSC.

Specimen number	Average fatigue life		
	$0.9f_c^T$	$0.85f_c^T$	$0.8f_c^T$
P-0	4.19	4.83	5.29
P-2-0.5	2.25	3.37	5.08
P-2-1	3.16	4.53	5.01
P-2-2	2.07	4.34	4.91
P-2-3	2.74	3.60	4.74
P-4-0.5	1.83	4.62	5.15
P-4-1	2.80	4.83	4.97
P-4-2	2.09	2.82	3.08
P-4-3	2.37	4.65	5.04
P-6-0.5	3.47	4.87	5.06
P-6-1	3.52	4.74	4.96
P-6-2	3.50	4.80	5.08
P-6-3	1.49	2.32	4.49
P-8-0.5	3.36	4.20	4.83
P-8-1	3.22	4.02	4.820
P-8-2	3.17	3.87	4.73
P-8-3	3.10	3.74	4.60

Note. P-X-X indicates fatigue test-heating temperature-holding time, and P-0 indicates HSC at room temperature.

steady state, the strain growth rate was large, and this stage accounted for about 10% of the whole fatigue life; that is, $N/N_f \leq 0.10$; the second stage was the stable crack expansion stage, the fatigue strain was linearly increasing and the growth rate was relatively stable, and it accounted for about 75% of the whole fatigue life; that is, $0.10 < N/N_f \leq 0.85$; the third stage was the crack instability damage stage, as the fatigue strain suddenly increased, the test block quickly entered the failure

stage, and the ultimate strain during failure was smaller than the ordinary concrete under uniaxle. This law is consistent with the development law given by Holmen [19].

Further analysis of Figure 4 shows that the fatigue strain of HSC was not only related to the heating temperature and holding time duration but also related to the magnitude of the stress level. When the holding time was the same and the heating temperature was different, the fatigue strain growth was small before 400°C but increased rapidly after 400°C, and the fatigue strain at 800°C was quintuple larger than that at 200°C. It can be seen from Figures 4(a)–4(g) showed that the heating temperature had a greater effect on the fatigue strain of HSC than the holding time and stress level. When the heating temperature was the same and the holding time was different, the fatigue strain of HSC increased with the stress level, but the growth trend was not obvious.

The regression equation of the fatigue strain of HSC after different high temperature processes was obtained by nonlinear multivariate regression of the measured strain, the cycle times, and stress levels:

$$\varepsilon_{T,\max} = a \left(\frac{N}{N_f} \right)^3 + b \left(\frac{N}{N_f} \right)^2 + c \left(\frac{N}{N_f} \right) + dT + et + f. \quad (1)$$

In order to facilitate the engineering application and analysis, this paper analyzed the relationship between the strain and the cycle times of the HSC after the high temperature history under various stress levels and put forward a unified formula.

When $S_{\max} = 0.80$, $S_{\min} = 0.10$,

$$\varepsilon_{T,m} = \left\{ 768.45 \left(\frac{N}{N_f} \right)^3 - 1007.02 \left(\frac{N}{N_f} \right)^2 + 1057 \left(\frac{N}{N_f} \right) + 6.91T + 201.55t + 2295.23 \right\} \quad (2a)$$

($20^\circ\text{C} < T \leq 800^\circ\text{C}$) $R^2 = 0.9017$.

When $S_{\max} = 0.85$, $S_{\min} = 0.10$,

$$\varepsilon_{T,m} = \left\{ 829.58 \left(\frac{N}{N_f} \right)^3 - 847.15 \left(\frac{N}{N_f} \right)^2 + 866.41 \left(\frac{N}{N_f} \right) + 6.02T + 481.21t + 2366.90 \right\} \quad (2b)$$

($20^\circ\text{C} < T \leq 800^\circ\text{C}$) $R^2 = 0.8992$.

When $S_{\max} = 0.90$, $S_{\min} = 0.10$,

$$\varepsilon_{T,m} = \left\{ 1321.76 \left(\frac{N}{N_f} \right)^3 - 2178.95 \left(\frac{N}{N_f} \right)^2 + 1695.13 \left(\frac{N}{N_f} \right) + 9.44T + 199.37t + 1698.39 \right\} \quad (2c)$$

($20^\circ\text{C} < T \leq 800^\circ\text{C}$) $R^2 = 0.8346$.

FIGURE 4: Relationship between fatigue strain and relative fatigue cycles: (a) 200°C; (b) 400°C; (c) 600°C; (d) 800°C; (e) 200°C~800°C, $S_{\max} = 0.80$; (f) 200°C~800°C, $S_{\max} = 0.85$; (g) 200°C~800°C, $S_{\max} = 0.90$.

FIGURE 5: Relationship between the fatigue residual strain, holding time t , and high temperature T .

3.2. Fatigue Damage

3.2.1. Fatigue Residual Strain. It is pointed out that, with the increase of fatigue cycle times, the residual strain of concrete in uniaxial stress state was the same with total fatigue strain, which showed a three-stage development law. And the residual strain value under fatigue failure was not affected by the stress level but also had nothing to do with the loading process; it was constant [12, 15, 20]. In this paper, the uniaxial compression fatigue test of HSC after different high temperature process was carried out and the residual strain was measured. The development history is shown in Figure 5, which verifies the above conclusion.

The regression equation of the fatigue residual strain $\epsilon_{r,T}$ of HSC and relative fatigue number N/N_f was obtained by nonlinear regression under the number of cycles and stress levels:

$$\epsilon_{r,T} = a \left(\frac{N}{N_f} \right)^3 + b \left(\frac{N}{N_f} \right)^2 + c \left(\frac{N}{N_f} \right) + dt + e. \quad (3)$$

In order to facilitate engineering application and analysis, this paper analyzed the relationship between the fatigue modulus and the number of cycles of HSC after the different high temperature process under various stress levels and put forward unified formulas.

When $S_{\max} = 0.80$, $S_{\min} = 0.10$,

$$\begin{aligned} \varepsilon_{r,T} = & \left\{ 1061.92 \left(\frac{N}{N_f} \right)^3 - 1686.43 \left(\frac{N}{N_f} \right)^2 \right. \\ & \left. + 1147.08 \left(\frac{N}{N_f} \right) + 2.1855T + 136.5t + 409.28 \right\} \quad (4a) \\ & 20^\circ\text{C} < T \leq 800^\circ\text{C} \quad (R^2 = 0.9017). \end{aligned}$$

When $S_{\max} = 0.85$, $S_{\min} = 0.10$,

$$\begin{aligned} \varepsilon_{r,T} = & \left\{ 696.75 \left(\frac{N}{N_f} \right)^3 - 1165.89 \left(\frac{N}{N_f} \right)^2 \right. \\ & \left. + 975.91 \left(\frac{N}{N_f} \right) + 1.3176T + 197.27t + 376.23 \right\} \quad (4b) \\ & 20^\circ\text{C} < T \leq 800^\circ\text{C} \quad (R^2 = 0.8992). \end{aligned}$$

When $S_{\max} = 0.90$, $S_{\min} = 0.10$,

$$\begin{aligned} \varepsilon_{r,T} = & \left\{ 571.91 \left(\frac{N}{N_f} \right)^3 - 887.04 \left(\frac{N}{N_f} \right)^2 \right. \\ & \left. + 725.23 \left(\frac{N}{N_f} \right) + 2.1819T + 171.39t + 471.15 \right\} \quad (4c) \\ & 20^\circ\text{C} < T \leq 800^\circ\text{C} \quad (R^2 = 0.8346). \end{aligned}$$

From Figure 5 and formulas (4a), (4b), and (4c) it can be seen that the residual strain of HSC under fatigue failure is related to the heating temperature and the holding time duration but not related to the magnitude of the stress level and the fatigue cycle times. And it is almost the same with the uniaxial fatigue residual strain development of ordinary concrete. The residual strains of HSC at high temperature from 200°C to 800°C are 471μ , 927μ , 997μ , and 1233μ , which are larger than the uniaxial fatigue residual strain of ordinary concrete. All above can be used as fatigue damage guidelines of HSC after high temperature process.

3.2.2. Fatigue Damage Based on Fatigue Residual Strain. Fatigue damage of concrete is due to its internal microcracks expansion which will lead to an unstable state, so taking the fatigue residual strain as a measure criterion of fatigue damage is scientific and reasonable. According to the basic concepts of damage mechanics, the relative residual strain is defined; that is, the residual strain $\varepsilon_{r,T}$ and fatigue failure ultimate residual strain $\varepsilon_{r,T}^0$ are damage variables; the damage equation is

$$\begin{aligned} D_m &= \frac{\varepsilon_{r,T}}{\varepsilon_{r,m}^0} \\ &= a \left(\frac{N}{N_f} \right)^3 + b \left(\frac{N}{N_f} \right)^2 + c \left(\frac{N}{N_f} \right) + dT + et \quad (5) \\ &+ f, \quad D_m \in (0, 1). \end{aligned}$$

TABLE 5: Fatigue life.

Specimen number	D_m	$N_{e0.9}$	$N_{e0.85}$	$N_{e0.8}$
P-2-0.5	0.835	2.19	4.46	5.20
P-2-1	0.961	2.97	4.87	5.27
P-2-2	0.735	1.88	4.27	5.03
P-2-3	0.686	1.76	4.11	4.96
P-4-0.5	0.770	2.01	4.30	5.11
P-4-1	0.735	1.88	4.27	5.04
P-4-2	0.746	1.92	4.30	5.09
P-4-3	0.739	1.89	4.28	5.06
P-6-0.5	0.415	1.53	3.77	4.62
P-6-1	0.399	1.51	3.74	4.45
P-6-2	0.418	1.53	3.78	4.64
P-6-3	0.402	1.51	3.70	4.60
P-8-0.5	0.394	1.50	3.66	4.39
P-8-1	0.389	1.49	3.62	4.28
P-8-2	0.393	1.50	3.66	4.34
P-8-3	0.395	1.50	3.67	4.33

Note. P-X-X indicates fatigue test-heating temperature- holding time, and P-0 indicates HSC at room temperature.

TABLE 6: Distribution table of relative errors (%).

Specimen number	$E_{0.9}$	$E_{0.85}$	$E_{0.8}$
P-2-0.5	2.667	32.34	2.36
P-2-1	6.01	7.51	5.19
P-2-2	9.18	1.61	2.44
P-2-3	35.77	14.17	4.64
P-4-0.5	9.84	6.93	0.78
P-4-1	32.86	11.59	1.41
P-4-2	8.13	52.48	65.26
P-4-3	20.25	7.96	0.405
P-6-0.5	55.91	22.59	8.70
P-6-1	57.10	21.10	10.28
P-6-2	56.29	21.25	8.66
P-6-3	1.34	59.48	2.45
P-8-0.5	55.36	12.86	9.11
P-8-1	53.73	9.95	11.20
P-8-2	52.68	5.43	8.25
P-8-3	51.61	1.87	5.87

Note. E_{xx} in this table is the absolute value of the relative error.

Figure 6 shows the relationship between the damage variables of HSC and the relative fatigue cycle times after different high temperature process. The fatigue damage model can be used to analyze the accumulated fatigue damage of HSC under low temperature uniaxial compression after different high temperature processes.

The remaining fatigue life of the HSC under low cyclic uniaxial compression after suffering different high temperature process was predicted, which was shown in Table 5. Compared to the test results in Table 4, the relative error distribution of the fatigue life of HSC under uniaxial compression after suffering different high temperature processes can be obtained as shown in Table 6.

FIGURE 6: Relationship between damage and relative fatigue cycles of HSC with high temperature process.

It can be seen from the calculated results that, among the absolute values of the relative error between predicted and measured values, the values which are less than 30% account for more than 85% of the total. With the huge difficulties in testing, the numerous influential factors, and the big discrepancy of experimental data taken into consideration, the predicted value was satisfactory for the low cyclic uniaxial

compressive fatigue test of HSC after suffering different high temperature processes. Thus, an effective method was developed to predict the fatigue residual life of HSC after different high temperature processes.

The damage equation at different stress levels from formulas (4a), (4b), and (4c) to (5) and Figure 6 was obtained by non-linear regression under the number of cycles and stress levels.

When $S_{\max} = 0.80$, $S_{\min} = 0.10$,

$$D_m = \left\{ 3.3141 \left(\frac{N}{N_f} \right)^3 - 5.6933 \left(\frac{N}{N_f} \right)^2 + 3.2574 \left(\frac{N}{N_f} \right) - 0.001 \left(\frac{T}{100} \right) + 0.0029t + 0.1423 \right\} \quad 20^\circ\text{C} < T \leq 800^\circ\text{C} \quad (R^2 = 0.9027). \quad (6a)$$

When $S_{\max} = 0.85$, $S_{\min} = 0.10$,

$$D_m = \left\{ 3.3604 \left(\frac{N}{N_f} \right)^3 - 6.0469 \left(\frac{N}{N_f} \right)^2 + 3.6014 \left(\frac{N}{N_f} \right) - 0.004 \left(\frac{T}{100} \right) + 0.0038t + 0.1036 \right\} \quad 20^\circ\text{C} < T \leq 800^\circ\text{C} \quad (R^2 = 0.8844). \quad (6b)$$

When $S_{\max} = 0.90$, $S_{\min} = 0.10$,

$$D_m = \left\{ 3.6074 \left(\frac{N}{N_f} \right)^3 - 6.3556 \left(\frac{N}{N_f} \right)^2 + 3.6530 \left(\frac{N}{N_f} \right) - 0.003 \left(\frac{T}{100} \right) + 0.0133t + 0.1152 \right\} \quad 20^\circ\text{C} < T \leq 800^\circ\text{C} \quad (R^2 = 0.8171). \quad (6c)$$

4. Conclusions

The color of HSC turns lighter after the high temperature processes. At about 500°C , the specimens are light gray and parts of them have a serious burst; the cross-section is relatively rough and some holes and cracks exist in the broken specimens. After 800°C , the specimens' appearance are offwhite, some coarse cracks appear, and some even run throughout the specimen. The structure of the specimen is relatively loose.

The maximum longitudinal total strain of the HSC after exposure to high temperature processes under low cyclic uniaxial compressive loading is in accordance with the three-stage development law. The second stage is the stable crack propagation stage, which accounts for about 75% of the whole fatigue life. The formulas to figure out the longitudinal total strains at each stage were given. Compared with the stress level, the effect of high temperature process on the fatigue strain of HSC is more significant, especially the influence of heating temperature.

The relative residual strain was defined as the damage variable, and the fatigue damage model of HSC after different high temperature processes, under low cyclic uniaxial compressive loading, was established. According to the damage

model established by the relative residual strain, the fatigue life of high strength concrete was predicted. More than 85% of the absolute values of the relative error between predicted and measured values are less than 30%, and the result is satisfactory.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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