Fatigue Life Prediction Model of Pavement Cement Concrete under Multi-field Coupling Condition

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Abstract: Research on the residual flexural strength and fatigue life of pavement cement concrete in Guang Xi region under loading-high temperature-wetting-drying cycle condition to obtain the pavement concrete fatigue strength damage and the residual life prediction model. Based on defining fatigue strength damage variable and constructing residual flexural strength model, the nonlinear mathematical equation between residual flexural strength and such parameters as number of loading, placing time in high temperature and wetting-drying environment is established. Results showed that it can better reflect the decreasing process of pavement cement concrete strength after fatigue damage. The S-N curvilinear equation and failure probability were introduced to analyze the fatigue life of pavement cement concrete, results indicated that the single logarithmic equation can be used to predict the fatigue life accurately with different probability, and it accord with the Weibull distribution. the specific double parameters in Weibull distribution function was given for pavement concrete fatigue life in this multi-field environment.

1 INTRODUCTION

Cement concrete pavement isa linear structure exposed to traffic loading and atmospheric environment. The performance variation of pavement during used has important reference significance for the pavement maintenance, and the durability of concrete pavement under long term fatigue is a problem that people pay close attention to all the time, for example Baluch(2002) et al.[1],Shi (1990)[2],Li(2002)[3]. The United States has set up a special committee to study the problem of concrete fatigue in 1947.Shortly thereafter, China Academy of Railway Sciences Li and Che(1999)[4], Harbin Institute of TechnologyJia(2009)[5], Dalian University of TechnologyMeng(2006)[6] and other units Pan and Qiu(2006)[7],Meng and Song(2009)[8],JOAN and CESAR[9],Chen et al.(2005)[10],Zheng et al.(2007)[11]also carried out a series of experimental research on concrete fatigue. In recent years, it has become a mature method to study the evolution of fatigue damage of concrete by using damage mechanics theory. On the basis of the theory that the damage of concrete is assumed to be the progressive accumulation of damage, the damage variable is introduced to quantify the damage degree of concrete.

Guangxi is located in the subtropical monsoon climate zone, the cement concrete pavement is subjected to the fatigue failure of the loading, high temperature and wetting-drying cycle for a long time. The study on fatigue performance of cement concrete pavement in high temperature and humid area under loading, high temperature and wetting-drying cycle has not been reported. In this paper, the fatigue performance of pavement cement concrete under loading, high temperature and wetting-drying cycle is studied. Based on continuum medium damage mechanics theory, the damage degree of the concrete is evaluated by defining damage variable. The fatigue damage evolution model to reflect the damage degree of concrete and the residual flexural tensile strength, and the prediction model of fatigue life of cement concrete pavement under three factors are established. These models provide the basis for evaluating the fatigue damage mechanism and predicting the remaining life of concrete pavement.

2 EXPERIMENTAL RAW MATERIALS AND CONCRETE MIXTURE RATIO

2.1 Raw Material

The experimental raw materials are Qinling P.O 42.5R, YaozhouChangcheng S95 powder, DatangHancheng first grade fly ash, Chuangqi crushed stone which maximum nominal size is 19mm, Kaidi SDSP-1 high performance water reducer (26% water reduction rate), municipal tap water..

2.2 Concrete Mixture Ratio

According to the design of the two kinds of traffic grade pavement, the concrete with 28 day flexural tensile strength of not less than 4.5 MPa and 5.0MPa was prepared in this experiment. The concrete mix ratio data through endurance performance optimization is list in the Table1.

Table1: Optimum mix proportion of concrete based on durability.

Sample number	**Water binder ratio**	**cement**	**Powder**	**fly ash**	**water**	**coarse aggregate**	**sand**	**water reducer**
		Kg/m^3						
C1	0.34	315	63	42	0.8	1114	734	2.52
C2	0.34	285	57	38	129	1185	726	2.28

3 FATIGUE TEST METHOD

The test method based on “highway engineering cement and cement concrete test code”.The flexural tensile fatigue test was carried out for 90 days after the standard maintenance of concrete specimens. The fatigue testing machine is MTS-810 with a maximum range of 10 tons, the loading fatigue level is controlled to be 50% and 80% of the maximum flexural strength, the loading scheme is a sine wave three point loading, the loading frequency is set to 10HZ, the low stress ratio is 0.1, and the number of fatigue cycle were 72 thousand times, 144 thousand times and 216 thousand times respectively. According to the climate zoning which is high temperature and humidity in Guangxi. Select the temperature difference is 32℃-40℃，the Humidity difference is 60%-80%. The high temperature and wetting-drying cycle corresponding to the fatigue loading times were 1 months, 2 months and 3 months respectively. After the fatigue test, the static tensile strength test was carried out on the universal testing machine, and the fatigue damage evolution model of the concrete was established based on the residual flexural strength.

4 ANALYSIS OF RESEARCH RESULTS

4.1 Definition Of Fatigue Damage Variable

Fatigue damage of concrete is quantitatively described by damage variable. In order to reflect the fatigue damage evolution process of concrete strength, the residual strength method is used to define the damage variable, which is used to characterize the residual bearing capacity of concrete after fatigue. Under different conditions of concrete application, Ravindrauses attenuation of splitting strength of concrete under fatigue loading to define damage variable, Lu et al.(2002)[12], Zhao et al.(1999)[13] proposed static compressive residual strength to define the damage variable, but the control index of the mechanical properties of the cement concrete pavement is the flexural tensile strength. the results of the previous tests also confirmed that the residual flexural tensile strength of cement concrete pavement is decreasing under the three factors of loading, high temperature and wetting-drying cycle. Therefore, the residual flexural strength of concrete is introduced as the damage variable, and It is defined as the ratio of the concrete flexural strength attenuation after a certain time to the initial flexural strength of concrete. The formula (1) is as follows:

$$D=\frac{\sigma_{f0}-\sigma_f}{\sigma_{f0}} \tag{1}$$

σ f0: Flexural strength of concrete specimens in initial state

σ f :Residual flexural strength of concrete specimens subjected to damage

4.2 Residual Flexural Tensile Strength Damage Model of Concrete Under Loading ,High Temperature and Wetting-Drying Cycle

4.2.1 Variation of Residual Flexural Strength of Concrete Under Loading, High Temperature and wetting-Drying Cycle

Scattered points distribution in Figure 1（a）-（d）shows the variation law of the residual flexural strength of C1 and C2 concrete under loading, high temperature and wetting-drying cycle. Under this condition, the flexural tensile strength of concrete decreases with the increase of time, 80% stress level significantly accelerated damage to concrete, the lower the strength grade of concrete performance is more significant. Under 50% and 80% stress level, C1 concrete flexural strength decrease by 11.6% and 2.5% respectively, C2 concrete flexural strength by 10.4% and 4.8% respectively, compared with the condition under loading of single factor. C1 concrete flexural strength decrease by 33.4% and 3.4% lower respectively, C2 concrete flexural strength by 31.9% and 4.9% respectively, compared with the conditions under loading and high temperature of double factor. Compare the effects of the three factors, the order of influence degree of concrete flexural tensile strength is loading<high temperature<wetting-drying cycle. When evaluating the mechanical properties value of cement concrete pavement changing with time under the condition of high temperature and wetting-drying cycle,only consider the loading or consider the effect of loading and temperature is not enough. So it is necessary to introduce an influencing factor to consider the humidity factor, and in the existing two factors superimposed wetting-dryingcycle, will produce a doubling damage effect.

4.2.2 Decreasing Model of Residual Flexural Strength of Concrete Subjected to Loading, High Temperature and Wetting-Drying Cycle

Three variables of loading, high temperature and dry wet cycle are needed in this model. Due to the humidity and temperature have the characteristics of adaptability and simultaneity,therefore, the residual flexural tensile strength damage model of cement concrete pavement is designed as two function combinations: δ=F[f(nh), f(t)],n represents the number of fatigue loading, t represents the time of high temperature wetting-drying cycle.

The modeling idea is as follows: Query existing literature, the concrete strength and the fatigue loading approximate relation of power function. Preliminary test indicates that there is a linear relationship between the strength temperature, humidity and the power exponent of time. Fatigue damage formula under loading, high temperature and wetting-drying cycle is as follows:（2）

$$D=1-\frac{\sigma}{\sigma_f}=a\bullet(1-\frac{n_h}{N_h})^b\bullet(\frac{t}{t_{\max}})^c \tag{2}$$

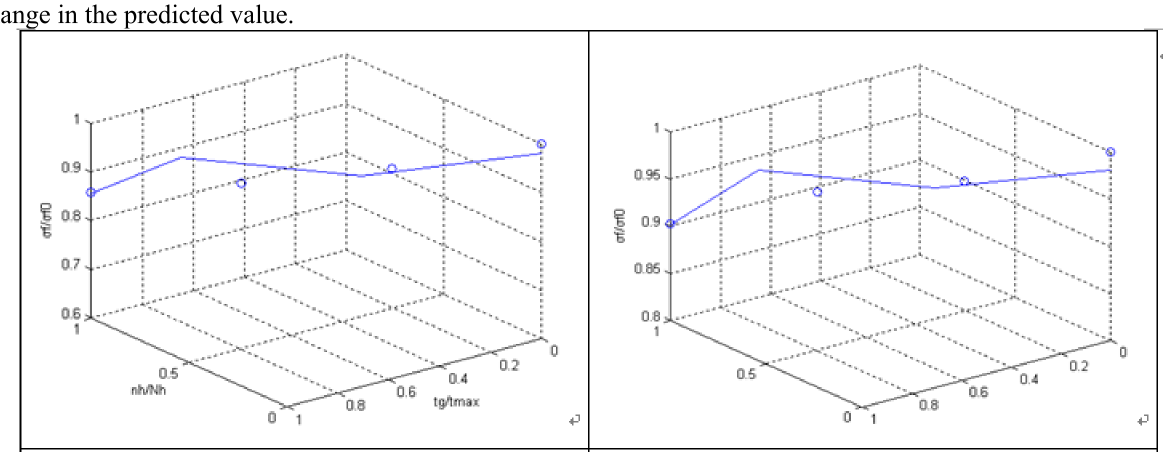
δ /δf: The ratio of residual tensile strength to maximum flexural tensile strength

nh/Nh: The ratio of loading times to fatigue life

t/tma: The ratio of the operating time and the maximum test period under high temperature wetting-drying cycle

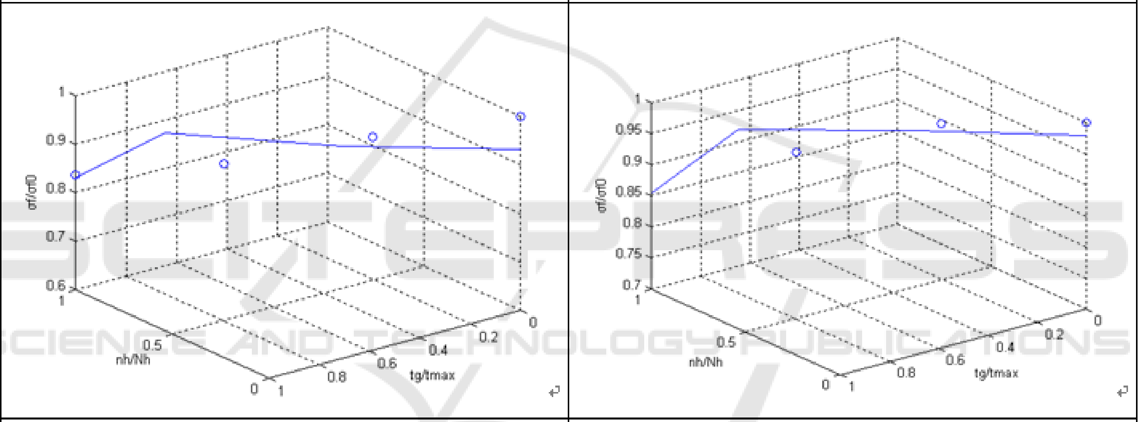
Multiple regression analysis (Formula 3-6) was used to calculate the results, the complex correlation coefficient is above 0.88. Table 2 shows the comparison between the experimental values and the predicted values using regression models, the results show that the maximum prediction error is below

6.5%. It shows that the model has high prediction accuracy. Figure 2 (a) - (d), the curve indicates the change in the predicted value.



(a)50% loading, high temperature variation ,wetting-drying cycle（C1）

(b)50% loading, high temperature variation , wetting-drying cycle（C2）



(c)80% loading, high temperature variation , wetting-drying cycle（C1）

(d)80% loading, high temperature variation , wetting-drying cycle（C2）

Fig. 1: Effect of loading, high temperature and wetting-drying cycle on the residual flexural tensile strength of concrete

$$D = 1 - \frac{\sigma}{\sigma_f} = 1 - 0.989 \bullet (1 - \frac{n_h}{N_h})^{0.012} \bullet (\frac{t}{t_{\max}})^{0.028} \quad (R^2=0.935)$$

（C1 concrete under 50% loading high temperature difference wetting-drying environment）（3）

$$D = 1 - \frac{\sigma}{\sigma_f} = 1 - 0.975 \bullet (1 - \frac{n_h}{N_h})^{0.017} \bullet (\frac{t}{t_{\max}})^{0.048} \quad (R^2=0.854)$$

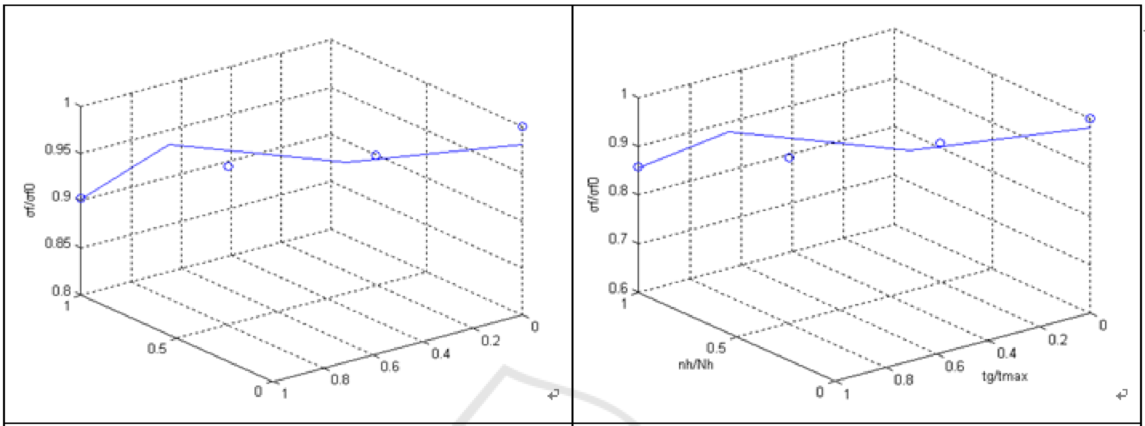
（C2 concrete under 50% loading high temperature difference wetting-drying environment）（4）

$$D = 1 - \frac{\sigma}{\sigma_f} = 1 - 0.983 \bullet (1 - \frac{n_h}{N_h})^{0.018} \bullet (\frac{t}{t_{\max}})^{0.001} \quad (R^2=0.944)$$

（C1 concrete under 80% loading high temperature difference wetting-drying environment）（5）

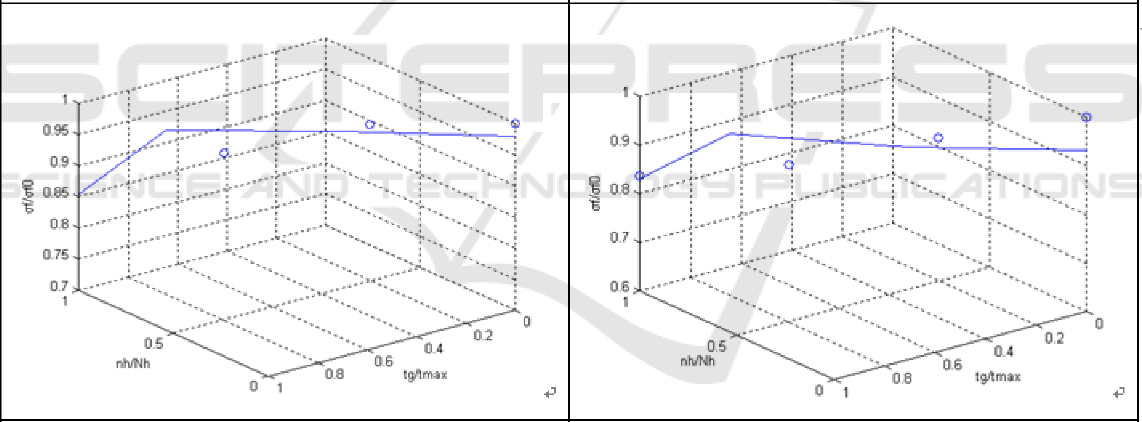
$$D = 1 - \frac{\sigma}{\sigma_f} = 1 - 0.968 \bullet (1 - \frac{n_h}{N_h})^{0.020} \bullet (\frac{t}{t_{\max}})^{0.037} \quad (R^2=0.833)$$

（C2 concrete under 50% loading high temperature difference wetting-drying environment）（6）



(a)50% loading, high temperature variation , wetting-drying cycle（C1）

(b)50% loading, high temperature variation , wetting-drying cycle（C2）



(c)80% loading, high temperature variation , wetting-drying cycle（C1）

(d)80% loading, high temperature variation , wetting-drying cycle（C2）

Fig. 2: The residual flexural tensile strength prediction of concrete underthe loading, high temperature and wetting-drying cycle environment.

Table 2 Under the influence of three kinds of factors, such as loading, high temperature and wetting-drying cycle, the predicted value of the damage model is compared with the experimental value.

combination factors1 / combination factors2			50%loading+ wetting-drying		80%loading+ wetting-drying	
			C1	C2	C1	C2
Fatigue loading times+The cycle time of high temperature and wet	72000 times loading+2 months wetting-drying circulation at high temperature	δs/δf	0.9624	0.9356	0.9875	0.9440
		δy/δf	0.9539	0.9178	0.9747	0.9213
		relative error%	-0.8	-1.8	-1.2	-2.3
	144000 times loading+4 months wetting-drying circulation at high temperature	δs/δf	0.9436	0.8922	0.9310	0.8754
		δy/δf	0.9645	0.9377	0.8560	0.9323
		relative error%	2.2	5.1	3.4	6.5
	216000 times+6 months wetting-drying circulation at high temperature	δs/δf	0.9028	0.8585	0.8574	0.8375
		δy/δf	0.9015	0.8550	0.8560	0.8296
		relative error%	-0.1	-0.4	-1.4	-0.9

Note:δsrepresents the flexural tensile strength of test, δy represents the predicted flexural tensile strength, δf represents the ultimate flexural tensile strength

4.3 Fatigue Life Prediction Model of Pavement Cement Concrete Under Loading High Temperature and Wetting-Drying Cycle.

In the 1850s, the German scholar Whőler put forward the concept of fatigue limit and characterize the s-n curve equation of the fatigue life,. At present, there are two expressions of concrete fatigue equation (7) and (8), and the physical meaning of each parameter is clear, so it is widely used. However, due to the heterogeneity of concrete, the fatigue life of discrete data is very large. In order to model can better reflect the project objective uncertainty, Weibull, a Swedish scholar, proposed a two-parameter Weibull distribution function(9) with a probabilistic physical quantity in 1939.Take double logarithm of either side of the equation, if the linear rule is satisfied, the test data are in accordance with the Weibull distribution.

$$S = a - b\lg N \tag{7}$$

$$\lg S = a - b\lg N \tag{8}$$

$$P(N) = 1 - \exp\left[-\left(\frac{N}{u}\right)^{\alpha}\right] \tag{9}$$

N represents fatigue life, s represents Stress level, a represents Height of fatigue curve (The higher the value, the better the fatigue performance of concrete), b represents the fatigue curve of the speed of change (The higher the value, the more sensitive to the stress level), P (N) Failure probability, α is the slope of the Weibull function at the stress level S, u presents dimension parameters.

In this paper in order to better compare the advantages and disadvantages of the model, regression analysis was performed for each model. At the same time, in order to improve the accuracy of the equation, the experimental test of the three factors condition is added when the level is 0.7, And each condition choose five samples for fatigue test, The formula for calculating the failure probability is P=i/(k+1)（I is the ith failure sample ordinal, K is the total number of samples）.

Table 3 fatigue life equation of concrete under loading high temperature and wetting-drying cycle.

probability P	**grade**	**Single logarithmic equation**		**Double logarithmic equation**	
		$S = a - b\lg N$	**Relevance**	$\lg S = a - b\lg N$	**Relevance**
0.17	C1	S=16.2763-2.5178lgN	0.9642	lgS=10.4700-1.7185lgN	0.9299
	C2	S=9.5621-1.4169lgN	0.9677	lgS=5.8896-0.9674lgN	0.9348
0.33	C1	S=16.2611-2.4899lgN	0.9174	lgS=10.4174-1.6927lgN	0.8690
	C2	S=10.5830-1.5632lgN	0.9476	lgS=6.5733-1.0652lgN	0.9075
0.50	C1	S=15.3497-2.3239lgN	1.0000	lgS=9.9106-1.5977lgN	0.9938
	C2	S=11.3863-1.6802lgN	0.9766	lgS=7.1429-1.1484lgN	0.9477
0.66	C1	S=16.3993-2.4789lgN	0.9810	lgS=10.5757-1.6954lgN	0.9544
	C2	S=11.5624-1.6992lgN	0.9967	lgS=7.2910-1.1657lgN	0.9822
0.83	C1	S=16.7423-2.5259lgN	0.9938	lgS=10.8357-1.7315lgN	0.9760
	C2	S=11.8904-1.7435lgN	0.9865	lgS=7.4985-1.1934lgN	0.9631

Table4. Concrete probabilistic fatigue equation under loading hightemperature and wetting-drying cycle

Stress level	**C1 Probabilistic life equation of concrete**	**Correlation coefficient**	**C2 Probabilistic life equation of concrete**	**Correlation coefficient**
0.5	$P(N)=1-\exp\left[-\left(\frac{N}{2.0859E-16}\right)^{0.179}\right]$	0.963	$P(N)=1-\exp\left[-\left(\frac{N}{3.2603E-20}\right)^{0.146}\right]$	0.994
0.7	$P(N)=1-\exp\left[-\left(\frac{N}{1.9740E-17}\right)^{0.166}\right]$	0.979	$P(N)=1-\exp\left[-\left(\frac{N}{1.1127E-18}\right)^{0.156}\right]$	0.985
0.8	$P(N)=1-\exp\left[-\left(\frac{N}{3.3986E-16}\right)^{0.178}\right]$	0.980	$P(N)=1-\exp\left[-\left(\frac{N}{1.4755E-15}\right)^{0.187}\right]$	0.989

Under the three conditions of loading, high temperature and wetting-drying cycle and based on the least square method,the fatigue life equation of concrete is obtained to calculate the failure probability of concrete. The correlation coefficient is between 0.8690-1.0000 shown in Table 3, which has high prediction accuracy and Using single logarithmic equation has higher precision of prediction. Therefore, in this paper, the single log equation is recommended to predict the fatigue life of cement concrete pavement under the condition of loading, high temperature and wetting-drying cycle.

By using the Weibull distribution function for data regression analysis. The mathematical equation between the probability and the fatigue life under different stress levels is shown in Table 4.The linear correlation coefficient is above 0.963. It can be seen that the fatigue life of pavement cement concrete is more consistent with the Weibull distribution function under the conditions of loading, high temperature, dry - wet cycle. In order to evaluate the stress level and fatigue life of concrete under the conditions of loading, high temperature, dry-wet cycle and different failure probability, the drawing of the S-N-P curve is shown in Figure 3.

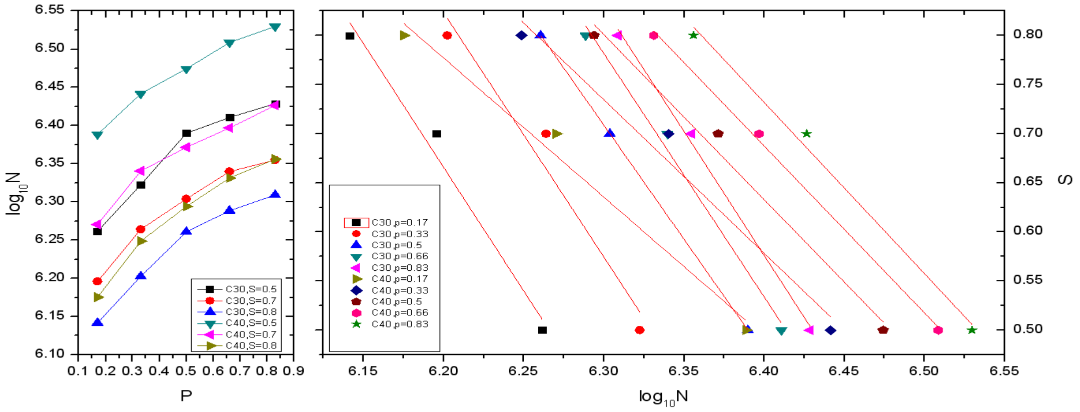


Figure 3 S-N-P curve of pavement cement concrete under loading, high temperature and wetting-drying cycle

5 CONCLUSIONS

Research and analysis of residual fatigue strength model and fatigue life prediction model of cement concrete pavement under under the conditions of loading, high temperature, wetting-drying cycle, the main conclusions are as follows.

(1)It is feasible to use the residual bending strength as a fatigue damage variable to characterize the mechanical properties of pavement cement concrete.The maximum prediction error is less than 6.5% when using the nonlinear equation of fatigue damage of concrete subjected to loading, high temperature and dry wet cycles to predict the residual flexural strength of concrete under fatigue loading. It can better reflect the attenuation law of fatigue strength of cement concrete pavement.

(2)The single-logarithmic S-N curve equation has higher prediction accuracy when calculate the fatigue life of pavement cement concrete under the conditions of loading, high temperature and dry-wet cycle.

(3)The fatigue life of pavement cement concrete under the conditions of loading, high temperature and dry-wet cycle conforms to Weibull distribution. The correlation coefficient of failure probability and fatigue life of concrete under different stress levels is above 0.945.

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