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Utilizing Data-Driven Methods to Predict the Fatigue Life of Cement Concrete Considering Corrosive Environmental Factors

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ABSTRACT

The primary objective of this study is to assess the fatigue resistance of cement concrete when exposed to corrosive environments. To achieve this, experimental results from high-cycle fatigue (HCF) and low-cycle fatigue (LCF) tests conducted on cement concrete samples subjected to various corrosive conditions were used. Various data-driven techniques, including multiple linear regression (MLR), Taguchi sensitivity analysis (TSA), and response surface method (RSM) were utilized. The aim was not only to identify the most influential parameter affecting fatigue life but also to offer a simpler and cost-effective alternative to experimental approaches. Consequently, two key parameters related to the corrosive environment: pH value and immersion time, along with the cyclic force applied to the concrete samples as input variables across different approaches were considered. The number of cycles until sample failure regarded as the output variable in all analyses. Furthermore, the analyses were conducted with the assumption that longer fatigue life is preferable. The findings revealed that the fatigue life of Portland cement concrete consistently decreased with increasing immersion time. Notably, the pH value emerged as the most significant parameter, while the other two factors exhibited equivalent impacts.

***doi**:*

1. INTRODUCTION

Corrosion is a chemical phenomenon that occurs in metals and its visible signs are seen as color changes on the surface. This is a general definition for non-porous components. Otherwise, the corrosive substance penetrates the material and causes internal damage that is not visible to the naked eye. On the other hand, in the construction industry, when concrete corrosion is discussed, the most attention is paid to reinforced concrete, as the rebars undergo corrosion phenomena and ultimately lead to the weakening of concrete strength. Therefore, many scholars investigated this issue, including modifying concrete to make it more resistant to corrosion. For example, Glass and Buenfeld investigated corrosion of steel in concrete due to various chlorides [1]. Moreover, Tian et al. studied the corrosion phenomenon in the steel rebar of concrete surrounded by chloride ions [2]. In this regard, accelerated corrosion tests were used. They stated that there is a significant difference between the corrosion mechanisms and the behavior of concrete structures in the vicinity of natural environments. The result of this study showed that in the long term, the natural corrosion rate of steel in concrete decreases with time. In fact, the non-uniform distribution of multi-layer corrosion products at the interface of steel and concrete causes rapid formation of cracks, and this is the main reason for failure. Cao et al. presented an equation to estimate the corrosion of reinforcements in terms of surface crack width in concrete [3]. In this study, three parameters including bar diameter, water-cement ratio, and thickness of concrete protection layer were considered as variables. The most important achievement of this research indicated that by increasing the ratio of water to cement, cracks appear earlier. Also, with the increase in the thickness of the concrete protection layer, the appearance of cracks due to the corrosion of the steel rebar occurs earlier. In addition, the corrosion intensity of the steel rebar decreases with the increase of the bar diameter in a given crack width. Mak et al. presented a new approach to evaluate corrosion of steel rebars in reinforced concrete based on the characteristics of surface cracks [4]. They stated that corrosion

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measurement methods such as mass loss are not good indicator of bond deterioration. However, the average mass loss of more than 25.5% with a significant decrease in bond strength can be considered. Furthermore, they reported that accelerated corrosion using impressed current in the presence of chlorides can lead to non-uniform corrosion along the rod and localized pitting corrosion. Finally, they stated that the geometry and configuration of the samples have an effect on the crack pattern and can be focused on this part to strengthen reinforced concrete against corrosion. Lu et al. collected experimental data related to corrosion rates in reinforced concrete structures [5]. Next, they evaluated seven existing experimental models for corrosion rate prediction and finally presented a new model including various parameters such as concrete strength, temperature, relative humidity, corrosion duration, and chloride content of concrete. In addition, they compared the uncertainty and probability characteristics of different models with the presented model. Finally, they stated that the probability distributions of model errors can be described with good accuracy as lognormal, normal, Weibull, or Gumbel distributions. In addition to the many studies that have been done in this field, some scientists suggested that it is better to use concrete reinforced with polymers, carbon fibers, or natural fibers instead of conventional concrete. Guo et al. investigated the durability of fiber-reinforced polymers (FRPs) exposed to the dual environment of sea water and sea sand concrete [6]. In this research, they used three different fibers including carbon, basalt, and glass. Also, to perform the corrosion test, the samples were immersed in the corrosive environment of sea water for 6 months. They reported that the color and gloss of the carbon fiber-reinforced polymer (CFRP) surfaces remained unchanged, but the other two samples were degraded. Also, the corrosion of polymer concrete samples (reinforced by silica powder) in the vicinity of various corrosive environments, including sodium hydroxide, hydrochloric acid, acetic acid, citric acid, and sulfuric acid has been evaluated [7]. The results of this research indicate that the weight of the polymer concrete sample decreases by 31% in the vicinity of acetic acid, and after that, the reduction of its compressive strength is significant. Moreover, Golestaneh et al. reported that this type of polymer concrete has good corrosion resistance against other corrosive environments .

Based on the above-mentioned literature review in this field, it is clear that the effect of corrosive environments on the cyclic behavior of concrete (conventional or reinforced by steel rebars or fibers, etc.) has rarely been investigated. In other words, most of the research aims to identify the corrosive effects of different environments on the compressive strength of the sample, or study of the cyclic behavior of concrete in the vicinity of fresh air. Meanwhile, the old buildings are still being serviced, which are made of ordinary cement concrete and are always in the vicinity of various environments, including acid rains, etc. Therefore, knowledge about the cyclic behavior of cement concrete without the presence of reinforcement in the vicinity of different corrosive environments is very important to estimate the remaining life of old buildings. In this regard, the author experimentally investigated, in his previous article, the effect of corrosive environments with different pH values on the high-cycle fatigue behavior of polymer concrete [8]. To this end, five different environments were considered, and polymer concrete samples were immersed in them for one month. Finally, axial fatigue test was performed. Comparison of S-N diagrams showed that the fatigue life of polymer concrete in the vicinity of corrosive environments is much higher than the fatigue life of conventional concrete with similar environmental conditions, and 100% improvement was observed in some tests. In addition, Reza Kashyzadeh stated that the longest and shortest fatigue life of conventional concrete are related to the samples adjacent to fresh air and alkaline environment, respectively. Besides, in the present article, the main goal is to investigate the simultaneous effect of different parameters such as pH value and immersion time on the fatigue life of cement concrete in the range between low cycle and high cycle areas. To achieve this goal, for the first time, data mining techniques and statistical analyzes are used based on the database of experimental results, which is the innovation of the current research.

2. EXPERIMENTAL DATA

2.1. Specimen preparation

To make cement concrete, aggregate as one of the main components of concrete was prepared in round shape and different sizes (fine aggregates with a size of 4.75 and smaller, and coarse aggregates with the size range of 4.75-12.5). In order to classify the aggregates from the viewpoint of appearance and size, it was done according to the relevant standards, i.e., BS EN 13043. More details are given in previous publications [9-10]. The number of 48 cylindrical laboratory samples (diameter: 76 mm & height: 152 mm) were made based on ISO 1920-3 standard [11]. In this regard, Portland cement was used as an adhesive substance and proportions of concrete elements were considered according to ACI-211.1-91 [12]. Table 1 presents the details of cement concrete production.

TABLE 1. The details of cement concrete production

Aggregate	Fine (%)	30
	Coarse (%)	46
Portland cement (%)		17
Water/Cement ratio: W/C (%)		0.42
Curing	Temperature (℃)	20
	Time (day)	28

2.2. Environmental conditions

In this research, to simulate different natural environments, four corrosive solutions including water, sea water, acidic and alkaline, respectively with pH values of 7, 7.25, 2.5, and 12.5 were used. The basis of all solutions is distilled water (pH of 7) and to reach higher and lower pH values, various elements were added with different percentages. Full details can be found in reference 8.

2.3. Cyclic compression-compression test

To evaluate concrete behavior under cyclic loading, axial fatigue test was performed. The most common type of fatigue loading is constant amplitude in the form of a zero-mean or fully reversible sinusoidal function [13-15]. In other words, the absolute magnitude of the maximum and minimum loading is equal to each other. However, cement concrete has good compressive strength [16-18] and does not have acceptable tensile strength. Due to this fact, steel rebar is used to increase the tensile strength of concrete. Therefore, in this study, which only conventional concrete without reinforcement is studied, compression-compression loading with a ratio of 0.1 was applied. In all tests, the loading frequency was 3Hz. In addition, St52 plates with a thickness of 100 mm were used at the beginning and end of the samples between the jaws of the testing machine to apply force uniformly on the cross-sectional surface of the samples [8]. Also, in order to evaluate the results repeatability, each test was repeated three times.

3. DATA MINING APPROACHES

3.1. Multiple linear regression

Using this approach, a linear relationship between the independent variables and the variable is obtained [19]. In other words, a function is presented in terms of input parameters considering specific coefficients. One of the advantages of this method compared to other data mining techniques is the simplicity of use to predict other states that a normal user can evaluate the output according to the input parameters in the shortest possible time. In this research, three parameters of pH value, immersion time, and maximum cyclic force were considered as inputs. Also, the number of cycles to failure was considered as an output. Therefore, the first and second order of linear regression approaches are in the following form:

The first order of linear regression approach

$$N = f(pH, t, F) = \alpha_1 \times pH + \alpha_2 \times t + \alpha_3 \times F + \alpha_4 \tag{1}$$

The second order of linear regression approach

$$N = f(pH, t, F) = \beta_1 \times pH + \beta_2 \times t + \beta_3 \times F + \beta_4 pH^2 + \beta_5 t^2 + \beta_6 F^2 + \beta_7 \tag{2}$$

in which, N is number of cycles to failure, and pH, t, and F represent pH value of corrosive environment, immersion time in the corresponding corrosive environment, and the maximum cyclic force applied in axial dynamic test, respectively. Also, $\alpha_i: i = 1, 2, 3$ and $\beta_j: j = 1, 2, \dots, 7$ are constant coefficients. It is necessary to know that in all the analyses, the force has a positive sign, i.e., the absolute value of the compression force was considered.

3.2. Taguchi sensitivity analysis

Taguchi sensitivity analysis was used to check the effect of input parameters on the response. In fact, TSA is one of the most effective methods used in various engineering and industrial issues [20-22]. One of the advantages of this method is the minimum number of tests [19]. However, this method is not able to consider the mutual effects of input parameters.

In the present research, four levels were considered for the pH value parameter and only two levels were considered for the other two parameters. Details are given in Table 2.

TABLE 2. Details of input parameters and their levels in design of experiment (DOE)

Parameter	Levels			
pH value	2.5	7	7.25	12.5
Immersion time (month)	1	6	-	-
Max. cyclic force (ton)	10	9	-	-

Based on the data in Table 2, the mixed mode Taguchi array (L16(4^1 2^2)), i.e., L16 orthogonal matrix, was used. Moreover, based on the nature of the system's response, which the main goal is to increase fatigue life, larger is better was considered for performing TSA, and finally, the most and least effective parameters on the fatigue life of cement concrete were reported.

3.3. Response surface method

As mentined in the previous subsection, one of the weaknesses of Taguchi method is that it examines the effect of one parameter on the response and assumes other parameters to be fixed. Therefore, the response surface method was used to evaluate the two-by-two effects of the parameters on the response [23-24]. Finally, the outputs of this approach are presented in the form of 2D colored contours, and by superimposing the contours and determining the common area, the optimal values for different parameters can be determined.

In short, Figure 1 provides a visual representation of the sequence of steps in this section of the article.

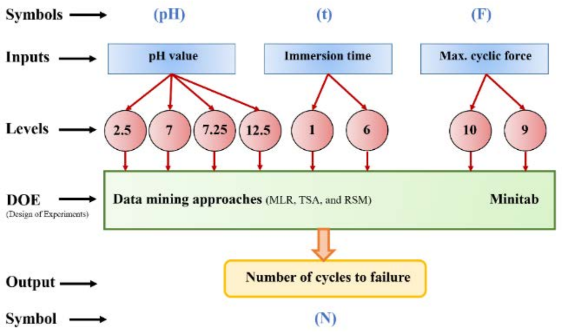


Figure 1. General schematic of the statistical approaches used in this research

4. RESULTS AND DISCUSSION

This section is dedicated to the results obtained from tests and statistical analysis.

4.1. Experimental results

Table 3 reports the fatigue test results. Assuming the number of 1000 cycles as the boundary between the low-cycle and high-cycle areas for the fatigue behavior of unreinforced concrete, it is clearly evident that by applying the maximum compression load of 10 tons, the concrete shows the low-cycle fatigue behavior (in the fatigue test, plastic deformation, i.e., the state of concrete becoming a paste, was evident). At the same time, by applying the maximum compression load of 9 tons, the concrete shows the high-cycle fatigue behavior and its failure mechanism was brittle in tests. In fact, as mentioned before, it has been tried to consider the fatigue behavior in the transfer range of two different modes, namely LCF and HCF, for comparing the accuracy of the presented models and so that a general statement can be presented for them. In addition, the fatigue test results show that the immersion time in the corrosive environment has a significant effect on the fatigue life of Portland cement concrete. Eventually, if this existing trend between the immersion time of one month to six months and the fatigue life of concrete continues for higher times, it can be expected that after the immersion time of about one year or more, the concrete lacks any resistance against cyclic loading within the range defined in this research.

TABLE 3. Axial fatigue test results of Portland cement concrete under compression-compression load

Sample No.	pH value	Immersion time (hour)	Max. cyclic force (Ton)	Mean number of cycles to failure (N)
1	Acidic environment: 2.5	1	10	1346
2		1	10	
3		1	10	
4		1	9	9144
5		1	9	
6		1	9	
7		6	10	11
8		6	10	
9		6	10	
10		6	9	123
11		6	9	
12		6	9	
13	Water: 7	1	10	69
14		1	10	
15		1	10	
16		1	9	37256
17		1	9	
18		1	9	
19		6	10	3
20		6	10	
21		6	10	
22		6	9	1092
23		6	9	
24		6	9	
25	Sea water: 7.25	1	10	1054
26		1	10	
27		1	10	
28		1	9	24991
29		1	9	
30		1	9	
31		6	10	97
32		6	10	
33		6	10	
34		6	9	791
35		6	9	
36		6	9	
37	Alkaline environment: 12.5	1	10	174
38		1	10	
39		1	10	
40		1	9	5758
41		1	9	
42		1	9	
43		6	10	156
44		6	10	
45		6	10	
46		6	9	219
47		6	9	
48		6	9	

4.2. Results of statistical analysis

4.2.1. Multiple linear regression

Constant coefficients for different orders of linear regression analysis are presented below. For the first order linear regression approach:

$\alpha_1 = -160$

$\alpha_2 = -1932$

$\alpha_3 = -9558$

$\alpha_4 = +103877$

And for the second order linear regression approach:

$\beta_1 = +3507$

$\beta_2 = -1932$

$\beta_3 = -9558$

$\beta_4 = -241$

$\beta_5 = 0$

$\beta_6 = 0$

$\beta_7 = +93005$

The prediction accuracy of the number cycles to failure through input parameters for all test conditions is summarized in Table 4.

TABLE 4. Checking the prediction accuracy of the linear regression method with different orders, only based on the experimental data presented in this research

Input parameters			Output (N)		Regression error compared to reality	
pH	t	F	1st regression	2nd regression	1st	2nd
2.5	1	10	5965	2754.25	343.1649	104.6248
	1	9	15523	12312.25	69.76159	34.6484
	6	10	-3695	-6905.75	33690.91	62879.55
	6	9	5863	2652.25	4666.667	2056.301
7	1	10	5245	8233	7501.449	11831.88
	1	9	14803	17791	60.2668	52.24662
	6	10	-4415	-1427	147266.7	47666.67
	6	9	5143	8131	370.9707	644.5971
7.25	1	10	5205	8251.188	393.833	682.8451
	1	9	14763	17809.19	40.92673	28.7376
	6	10	-4455	-1408.81	4692.784	1552.384
	6	9	5103	8149.188	545.1327	930.2386
12.5	1	10	4365	1674.25	2408.621	862.2126
	1	9	13923	11232.25	141.8027	95.07207
	6	10	-5295	-7985.75	3494.231	5219.071
	6	9	4263	1572.25	1846.575	617.9224

As it is clear from the analysis, it is not possible to provide an accurate relationship utilizing linear regression that can predict the fatigue behavior of concrete in the vicinity of corrosive environments. On the other hand, in the high-cycle area, the presented models are much better. For example, if we consider only the high-cycle results, i.e., the maximum cyclic force of 9 tons, and the minimum immersion time (one month), the average prediction error of the first and second order of the linear regression analysis is equal to 78.2 and 52.7%, respectively. In the same range, by increasing pH value, i.e., the environment with high corrosiveness, we will have the biggest error. In other words, in this situation, the equations can predict the fatigue behavior of concrete in the vicinity of environment with pH of 12.5 with the least accuracy. And the best prediction accuracy is for the case where the pH of the corrosive environment is 7, i.e., fresh water.

4.2.2. Taguchi sensitivity analysis

It was performed in Minitab software. Figure 2 shows the main effect plot with the aim of comparing the relative fatigue behavior of the effects against other factors. From this figure, the highest fatigue life is related to the state with the lowest immersion time and environment with pH of 7.25. Furthermore, the green graph shows that the number of cycles to failure increases as the loading amplitude decreases, which indicates the correctness of the analysis because the S-N curve introduced by Wohler is based on this fact. In addition, the effect of different parameters on concrete fatigue behavior was extracted in percentage (Figure 3). Form Figure 3, the most effective parameter is the pH value of the corrosive environment. Also, two other parameters, i.e., immersion time and loading amplitude, have a similar effect. They also have similar trends which can be seen in the green and red graphs in Figure 2. The obtained values show that all three parameters are important and cannot be ignored. Hence, there is no idle parameter.

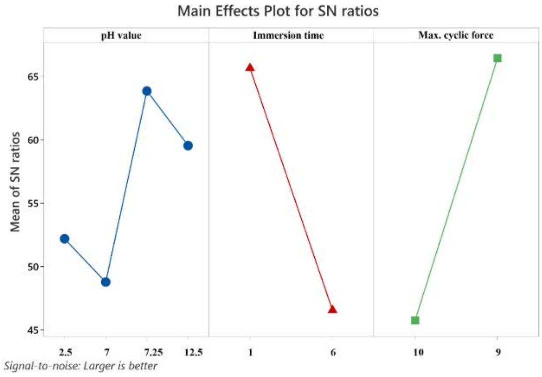


Figure 2. The Main effects plot S/N ratios of Portland cement concrete fatigue life

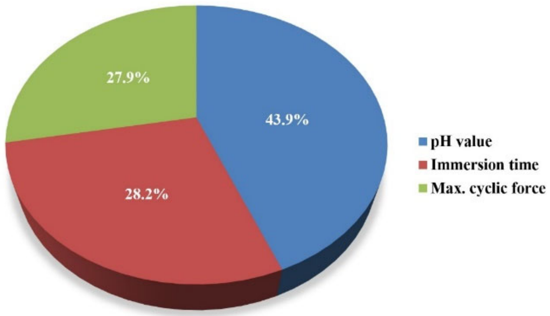
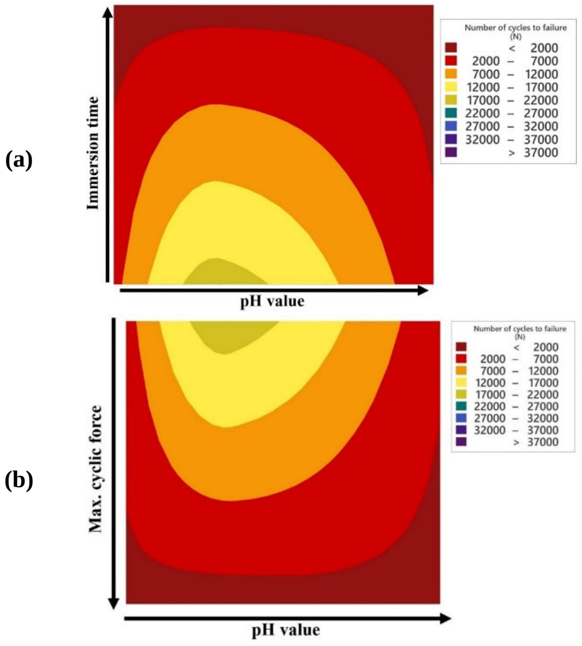


Figure 3. Prioritizing of parameters based on their effect on concrete fatigue life

4.2.3. Response surface method

The contours extracted from the response surface method are illustrated in Figure 4. From part (a), the fatigue life of concrete always decreases with increasing immersion time. Meanwhile, the maximum fatigue life of concrete is when it is in the vicinity a corrosive environment with a pH in the range of 7 to 7.5. A decrease or increase in the pH value leads to a decrease in the fatigue life of concrete. Although this effect is much greater when the pH increases than when the pH value decreases. For this reason, it can be seen in the contour that there is no symmetry and there are more colors with a red theme on the right side (i.e., higher pH). In part (b), the important point is the similarity of this contour to part (a). This means that the effect of corrosion intensity is replicated. In addition, it is also observed in the status of maximum cyclic force, the fatigue life of concrete decreases as the loading amplitude increases. On the other hand, the pattern of both parts (a and b) is almost the same. This subject indicates that the influence of the two parameters of immersion time and force on the fatigue behavior of concrete is quite similar. This fact was also found in Taguchi sensitivity analysis. Part (c) displays the mutual effects of the two parameters mentioned above. As can be seen, the relationship between these two parameters is in the form of 45 degree areas that change linearly. So that the highest fatigue life of concrete is related to the lowest loading range on the concrete samples that had the shortest immersion time in corrosive environments.



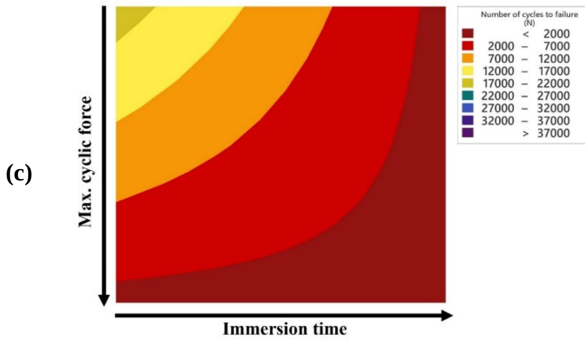


Figure 4. RSM results for fatigue life of Portland cement concrete in terms of different input parameters

5. CONCLUSIONS

This study has attempted to assess fatigue life of Portland cement concrete in the vicinity of various corrosive environments. Also, the effect of different parameters, including pH value and immersion time in the corrosive environment, on the fatigue behavior of the samples was investigated. To achieve this goal, axial fatigue tests were performed, and its results were used in different statistical analysis, including multiple linear regression, Taguchi sensitivity analysis, and response surface method. The most important achievements of this research are:

1- The results of fatigue test indicate that the immersion time in the corrosive environment has a significant effect on the fatigue life of Portland cement concrete, which can change the high-cycle behavior to the low-cycle behavior. In addition, it can be concluded that after one year immersion of conventional concrete in a corrosive environment, its fatigue resistance reaches zero.

2- The results obtained from the linear regression method show that the fatigue behavior of conventional concrete in corrosive environments cannot be predicted using this technique. The main reason is to integrate of low-cycle and high-cycle fatigue data into one analysis. Also, checking the accuracy of this method shows that it has a 52.7% error in approximating the HCF life for samples with minimum immersion time in the corrosive environment.

3- The results of Taguchi sensitivity analysis show that the longest fatigue life is related to the state with the lowest immersion time and corrosive environment with pH of 7.25. In addition, the most effective parameter is the pH value. Also, two other parameters have the same degree of influence.

4- RSM results state that the fatigue life of Portland cement concrete always decreases with the increase of immersion time. In addition, the maximum fatigue life of conventional concrete is when it is in the vicinity of a corrosive environment with a pH in the range of 7 to 7.5.

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