Hindawi
Advances in Civil Engineering
Volume 2022, Article ID 6287810, 10 pages
https://doi.org/10.1155/2022/6287810

Research Article

Durability Evaluation of Concrete in Cold and Arid Regions Based on Grey Relational Theory

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Received 10 May 2022; Revised 19 September 2022; Accepted 7 October 2022; Published 21 October 2022

Academic Editor: Paul Awoyera

Aiming at the outstanding problem of concrete durability in cold and arid regions, the Datonghe-Qingwangchuan Diversion Project in Gansu Province, China, was used as a typical research area, and erosion products were determined by field sampling and laboratory XRD analysis. Three durability evaluation indices, namely, the mass loss rate, relative dynamic elastic modulus (RDEM), and compressive strength loss rate, were measured via indoor accelerated testing. Based on grey relational theory, a concrete durability evaluation model was constructed. The critical failure values of the three evaluation indices were introduced as a set of data to optimize the model and determine the grey relational degree of each group of concrete specimens under different working conditions. The results show that using the test results and the optimized grey relational analysis evaluation model, the concrete specimens mixed with an air-entraining agent have strong resistance to composite erosion. The durability of concrete specimens with an air-entraining agent content of 0.016% and fly ash content of 15% is better, and a high content (30%) of fly ash accelerates the damage of concrete specimens. The model calculations are consistent with the test results. This method can solve the problem of the durability of concrete specimens in the whole test cycle not being fully evaluated. The results of the study provide useful references for concrete mix proportion optimization and durability evaluation problems.

1. Introduction

With the massive use of concrete in hydraulic engineering, its service safety and durability have become a hot issue of the general concern in the engineering community [1–3]. Concrete structure projects in cold and arid regions are in special environments for an extended period of time, and their concrete structures are affected by external environmental factors such as dry and wet cycles, compound salt erosion, and freeze-thaw damage. The surface layer of the structure is prone to corrosion and cracking, which makes the structural load-bearing capacity decrease, and the durable service life often fails to reach the structural design requirements life [4–6]. In the actual service process, the type of concrete itself and the mixing amount of different mixtures will also have an impact on the durability of the concrete [7]. The erosion of the external environment and the deterioration of concrete properties can deteriorate the durability of concrete. Therefore, the study of concrete durability evaluation models for cold and arid regions is of practical and positive significance for the operational safety and life maintenance of concrete structures [8].

There have been many studies on the durability evaluation of concrete. Katpady et al. [9] measured the air permeability and its index to evaluate the durability of concrete. Qin et al. [10] evaluated the durability of concrete specimens with durability values and predicted the changing pattern of concrete durability values. Li et al. [11] used posable set theory to analyze and calculate the weights of the factors affecting durability and combined it with a fuzzy evaluation method to establish a durability assessment element model and correlation function for cross-sea tied arch bridges. Chen et al. [12] evaluated the durability of in-service concrete bridges using an improved three-scale hierarchical analysis method and fuzzy topology theory. Cai et al. [13] evaluated the durability of concrete bridge structures in a chloride ion attack environment by a fuzzy integrated evaluation method. The above evaluation methods have contributed to the evaluation of concrete durability, but the factors affecting concrete durability are complex, numerous, and interrelated. Grey relational theory [14] takes the sequence of each index as the research object and characterizes the closeness of the relationship by the grey correlation degree, which can better solve the complex problem of a lack of information. Prusty et al. [15] used Taguchi-Grey relational analysis to obtain the optimum ratio of geopolymer concrete. Cui et al. [16] predicted the compressive strength of concrete specimens with added metakaolin and slag based on grey relational analysis (GRA) with extreme gradient boosting (XGBoost). Xu et al. [17] applied the hierarchical analysis method to determine weights and constructed a durability assessment model of concrete materials by grey relational theory. Feng et al. [18] predicted the endurance life of concrete for three mix ratios under two damage conditions based on grey system theory. Li et al. [19] predicted the law of concrete acidification depth based on grey theory. The above scholars established durability evaluation models for concrete through grey relational theory. However, the existing evaluation model of grey relational analysis has algorithmic problems and fails to adequately evaluate the durability of concrete specimens during the whole test cycle. In addition, most of the existing studies are limited to the analysis of a single or a small number of influencing factors. There are fewer studies that consider the effect of multiple factors on the durability of concrete. In particular, it is difficult to effectively guide engineering practice because of the lack of relevant theoretical results for the reference of concrete durability design and construction in cold and arid regions.

In summary, for this paper, we selected the Datonghe-Qingwangchuan Diversion Project, which is located in the cold and arid region of the northwest China, as a typical study area. We added three evaluation indices critical damage values (5% critical value of mass loss rate damage, 25% critical value of compressive strength loss rate damage, and 60% critical value of RDEM damage) based on the test data obtained from indoor accelerated tests [20], introduced them into the grey relational analysis evaluation model. Based on the accelerated indoor test and concrete durability evaluation model, the evolution process and characteristics of concrete durability evaluation indices under complex environment were analyzed. This method provides a new idea for the evaluation of the operation of concrete structures in cold and arid regions and also provides a reference for the optimal design of concrete mix proportion in this environment.

2. Grey Relational Analysis Evaluation Model

In grey system theory, people usually refer to the data sequences of the factors constituting the system as the basic behavior factor sequences and the artificially set sequences as the primary behavior sequences. Its main task is to analyze and determine the correlation between the sequences of basic behavioral factors and between the sequences of basic behavioral factors and the sequences of primary behaviors. The closer the two compared sequences are, the larger the correlation degree is, and the inverse also holds [21]. In this paper, Dunn's correlation degree model is used, and the expression [22] is

$$\mathbf{R} = \mathbf{W} \cdot \mathbf{E}, \tag{1}$$

where $\mathbf{R}$ is the matrix of r_{ij} values, the comprehensive assessment results of the ith evaluation object; $\mathbf{W}$ is the matrix of w_{ij} values, the weights of each indicator of the ith evaluation object; and $\mathbf{E}$ is the matrix of e_{ij} values, the correlation coefficients of each indicator of the ith evaluation object with regard to the main behavior sequence.

2.1. Durability Index Judgment Matrix Determination. With m evaluated objects and the existence of n evaluation indices for each evaluated object, the steps of establishing the model are as follows:

(1) The original index judgment matrix is established as

$$\mathbf{A} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{bmatrix}. \tag{2}$$

(2) The indicator master behaviors sequence is determined as: $\mathbf{A}_* = (a_{*1}, a_{*2} \cdots a_{*n})$, where $a_{*j}\,(j = 1, 2 \cdots, n)$ represents the optimal reference value of the jth index.

(3) Standardization of evaluation indicators: assuming that the allowable variation range of the jth indicator is $[a_j^{\min}, a_j^{\max}]$, the following three types of indicators can be standardized:

$$x_{ij} = \begin{cases} \dfrac{a_{ij} - a_j^{\min}}{a_j^{\max} - a_j^{\min}}, \\[2ex] \dfrac{a_j^{\max} - a_{ij}}{a_j^{\max} - a_j^{\min}}, \\[2ex] 1 - \dfrac{\left|a_{ij} - \gamma\right|}{a_j^{\max} - a_j^{\min}}, \end{cases} \tag{3}$$

where a_{ij} is the standardized index value; γ is the fixed value of an indicator.

The standardized index matrix is represented as

$$\mathbf{X} = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix}. \tag{4}$$

2.2. Grey Correlation Coefficient. The grey correlation coefficient is obtained as

$$e_{ij} = \frac{\min_i \min_j \left|x_{ij} - x_{*j}\right| + \rho \max_i \max_j \left|x_{ij} - x_{*j}\right|}{\left|x_{ij} - x_{*j}\right| + \rho \max_i \max_j \left|x_{ij} - x_{*j}\right|}, \quad i = 1, 2, \cdots, m, \quad j = 1, 2, \cdots, n, \tag{5}$$

where is a resolution coefficient within the value range [0, 1], generally taken as 0.5.

*2.3. Determining the Weight of Each Index. G*1 method is a subjective weighting method, which can fully and effectively reflect the knowledge and experience of various experts. The entropy weight method is an objective weighting method, which is mainly calculated by mathematical methods on the raw data and objectively reflects the effective information of the data itself.

2.3.1. The G1 Method

(1) The order of importance of the indicators is determined as follows: When the order of the relationship between each evaluation index $x_1, x_2, \cdots, x_n$ and the relevant evaluation objective $x_1 > x_2 > \cdots > x_n$ is determined through consultation with experts, it is indicated that the importance among $x_1, x_2, \cdots, x_n$ is determined in this order.

(2) The relative importance of evaluation indicators x_{j-1} and x_j is evaluated, and the ratio of their importance γ_j is expressed as follows:

$$\frac{x_{j-1}}{x_j} = \gamma_j, \quad j = n, \quad n-1, \quad n-2, \cdots, 3, 2. \tag{6}$$

A classification of γ_j values is shown in Table 1 below.

(3) The weight coefficient w_j is calculated as follows: Based on the rational assignment of γ_j given by the expert, the following equations can be used to calculate the weighting factors w_j and w_{j-1}

$$w_j = \left(1 + \sum_{j=2}^{n} \prod_{i=j}^{n} \gamma_i\right)^{-1}, \tag{7}$$

$$w_{j-1} = \gamma_j w_j, \quad j = n, \quad n-1, \cdots, 3, 2. \tag{8}$$

2.3.2. The Entropy Weight Method

(1) A judgment matrix $\mathbf{A} = (a_{ij})_{mn}$, $(i = 1, 2, \cdots, m, j = 1, 2, \cdots, n)$ is construct, where m is the number of evaluation objects, and n is the evaluation index.

(2) The judgment matrix is normalized to form a new judgment matrix $\mathbf{X} = (x_{ij})_{mn'}$ $(i = 1, 2, \cdots, m, j = 1, 2, \cdots, n)$.

(3) According to the definition of entropy, for m evaluation objects and n evaluation index, the entropy is determined as

$$H_j = -\frac{1}{\ln n}\left(\sum_{i=1}^{m} f_{ij} \ln f_{ij}\right), \quad i = 1, 2, \cdots, m, \quad j = 1, 2, \cdots, n, \tag{9}$$

where $f_{ij} = (1 + x_{ij}) / \sum_{i=1}^{m} (1 + x_{ij})$.

(4) The entropy weight of the evaluation index w_j is calculated as

$$w_j = \left(1 - H_j\right) / \left(m - \sum_{j=1}^{n} H_j\right), \quad \mathbf{W} = \left(w_j\right)_{1\times n}, \quad \sum_{j=1}^{n} w_j = 1. \tag{10}$$

2.3.3. The MIE Method to Determine the Integrated Weights. The MIE method [23] calculates the combined weights via the following equation:

$$w = \frac{\left[w_{1j} w_{2j}\right]^{1/2}}{\sum_{j=1}^{n} \left[w_{1j} w_{2j}\right]^{1/2}}, \tag{11}$$

where w is the comprehensive weight, w_{1j} is the subjective weight, and w_{2j} is the objective weight for $j = (1, 2, ..., n)$.

2.3.4. Grey Correlation. The correlation degree is calculated as

$$r_i = \sum_{j=1}^{n} w_{ij} e_{ij}. \tag{12}$$

We evaluate the evaluated object according to the calculated correlation degree. For this paper, the greater the degree of correlation, the better the durability of the concrete [24].

3. Accelerated Indoor Tests

3.1. Test Materials and Mix Proportions. The environmental characteristics of the Datonghe-Qingwangchuan Diversion project and the influence of the mixtures on the durability of

Table 1: γ_j value reference table.

γ_j	Degree of importance
1.0	Equally important
1.2	Slightly important
1.4	Obviously important
1.6	Strongly important
1.8	Extremely important
	1.1, 1.3, 1.5, 1.7, and 1.9 are between the above situations

concrete were taken into account. Two test environmental conditions and five concrete proportions were designed for comparison testing concerning the JGJ 55-2011 standard [25]. Among them, *S*1 was the reference mix proportion, and the other four mix proportions were different contents of fly ash and air-entraining agent. The test cement was P.O. 42.5 Portland cement. The fineness modulus of fine aggregate was 3.18. The coarse aggregate was 5~20 mm continuous gradation, with a rough surface and hard texture of gravel. Its water content was 0.15%, and its mud content was 0.15%. Fly ash was selected from first-grade fly ash used in the laboratory, and tap water from the Lanzhou area was used for mixing. The main active ingredient of the air-entraining agent was SY-5 powdered air-entraining agent of triterpene saponin. The proportions of concrete are shown in Table 2.

XRD analysis was carried out on the concrete spalling residues from the Datonghe-Qingwangchuan Diversion project. The residues mainly consisted of $3CaO{\cdot}CaCl_2{\cdot}12H_2O$, $3CaO{\cdot}Al_2O_3{\cdot}CaCl_2{\cdot}10H_2O$, $CaSO_4{\cdot}2H_2O$, $3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}32H_2O$, and $CaCO_3{\cdot}CaSO_4{\cdot}CaSiO_3{\cdot}15H_2O$. As shown in Figure 1, it indicates that corrosive ions such as chloride ions and sulfate ions react with hydration products such as $Ca(OH)_2$ inside the concrete to generate chloride salts and sulfate erosion products. Based on the above analysis, sulfate and chloride salts are the main erosion-damage ions in the area of the Datonghe-Qingwangchuan Diversion project. According to the data analysis, we selected a 5% mass fraction of sodium sulfate/sodium chloride compound salt solution (liquid B), with water (liquid A) as the control test.

The test regime was carried out in accordance with GB/T50082-2009 [20] and the dry-wet-freeze-thaw test regime developed in the literature [24] as detailed in Figure 2. Two concrete specimen sizes were selected: $100 \times 100 \times 100\,\mathrm{mm}^3$ and $100 \times 100 \times 400\,\mathrm{mm}^3$. The former was used to test compressive strength, and the latter was used to test mass and RDEM. The test was designed for a total of 8 cycles, and the test blocks were measured at the end of each cycle.

3.2. Analysis of Test Results. According to the SL775-2018 standard [26], three indices were selected in this paper to evaluate the durability performance of concrete. Figure 3 shows the variation process of three durability evaluation indices in water and compound salt solution for test blocks with different fly ash contents (0%, 15%, and 30%). Figure 4 shows the variation process of three durability evaluation indices in water and compound salt solution for test blocks with different air-entraining agent contents (0%, 0.008%, and 0.016%). The results are as follows:

Figure 3 shows that the concrete specimens with low content (15%) of fly ash reduce the rate of decline of the three durability evaluation indices. The concrete specimens with high fly ash content (30%) accelerate the rate of decline of the three durability evaluation indices. Meanwhile, the comparative test data show that the effect of compound salt erosion on the durability of concrete is more obvious.

Figure 4 shows that in water, the durability evaluation indices of the three groups of concrete specimens decrease gradually as the test proceeded, but the decrease is slower. In the compound salt solution, the durability evaluation indices of all three groups of concrete specimens experience a slight increase and then a decrease. The concrete specimens with 0.016% air-entraining agent content have the best durability.

4. Test Case Analysis

4.1. Grey Correlation Coefficient. In this paper, we took the S1 group test data as an example for calculation and analysis. To better compare different working conditions, the damage threshold values of the three indicators were added as a tenth set of data to the original data, set as the *X*th cycle as shown in Table 3.

According to (2), the above data were used to construct the original index matrix with group *S*1 as the evaluated object. The primary sequence of the three indices was determined as $\mathbf{A}_* = (1, 1, 1)$. According to equations (3)–(5), the correlation coefficients of each evaluation index relative to the optimal index were calculated for group *S*1 after each macrocycle as shown in Table 4.

4.2. Calculation of the Weight of Each Index

(1) The *G*1 method: The three evaluation indices of mass loss rate (x_1), compressive strength loss rate (x_2), and RDEM (x_3) were compared two by two, and the relative importance of the three evaluation indices was ranked after combining expert opinions $x_3 > x_2 > x_1$.

This gave $\gamma_2 = 1.1$ and $\gamma_3 = 1.4$. Then, $\gamma_2\gamma_3 = 1.54$, and, hence, $\gamma_2\gamma_3 + \gamma_3 = 2.94$.

According to (7), we had $\mathbf{w}_3 = (1 + 2.94)^{-1} = 0.2539$.

According to (8), we had $\mathbf{w}_2 = \gamma_3\mathbf{w}_3 = 0.3553$, $\mathbf{w}_1 = \gamma_2\mathbf{w}_2 = 0.3908$.

Thus, the subjective weights were $\mathbf{W}_1 = (\,0.2539 \quad 0.3553 \quad 0.3908\,)$.

Table 2: Mix proportions of concrete.

Number	Water–cement ratio	Cement ($kg \cdot m^{-3}$)	Water ($kg \cdot m^{-3}$)	Fine aggregate ($kg \cdot m^{-3}$)	Coarse aggregate ($kg \cdot m^{-3}$)	Fly ash ($kg \cdot m^{-3}$)	Fly ash (%)	Air-entraining (%)
*S*1	0.45	411	185	595	1209	0	0	0
*F*1	0.45	349	185	595	1209	62	15	0
*F*2	0.45	288	185	595	1209	123	30	0
*Y*1	0.45	411	185	595	1209	0	0	0.008
*Y*2	0.45	411	185	595	1209	0	0	0.016

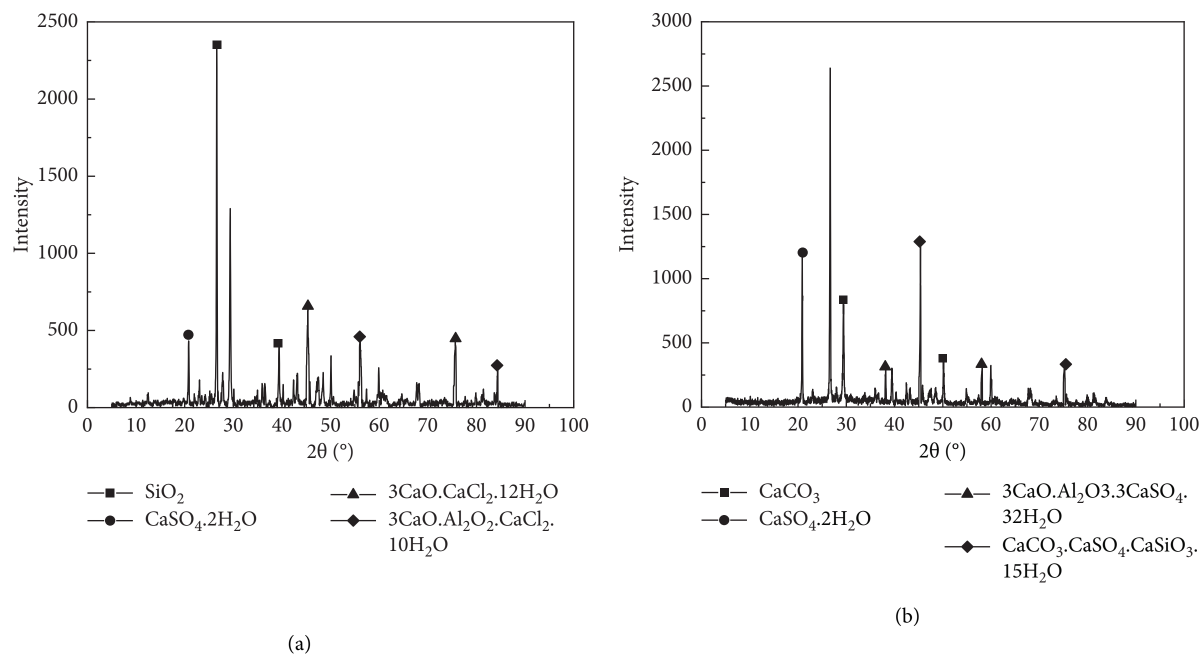

Figure 1: XRD diffraction patterns of the spalling residue of concrete.

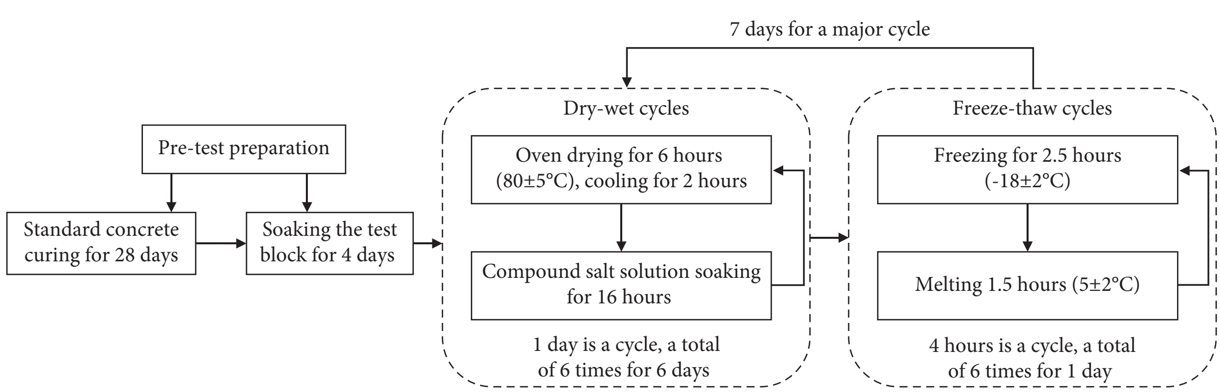

Figure 2: The dry-wet-freeze-thaw cycles test system.

(2) The entropy weight method: In this paper, the *S*1 group test data after adding the *X*th cycle were used as an example for calculation and analysis. The data were constructed as the original judgment matrix according to equation (2). The matrix was standardized according to equation (3), and then the objective weights of each evaluation index of concrete in water and compound salt solution were calculated by equations (9) and (10).

Water (AS1):

$$\mathbf{W}_{A2} = \begin{pmatrix} 0.2702 & 0.4089 & 0.3208 \end{pmatrix}. \tag{13}$$

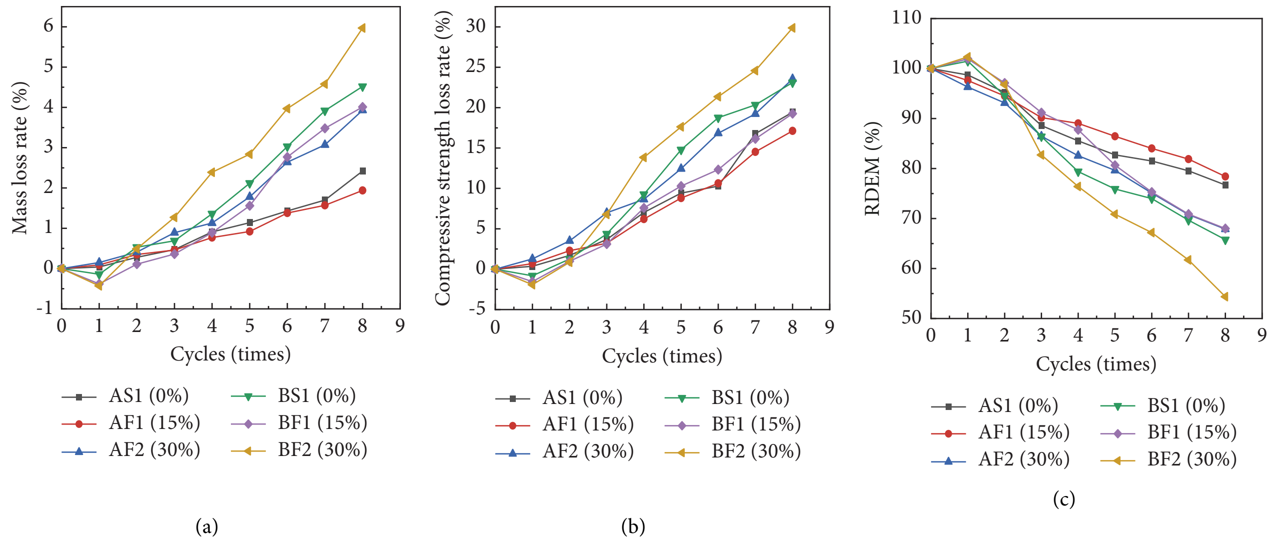

Figure 3: Variation curves of macro-indices of concrete with different fly ash content (A: water; B: compound salt solution). (a) Mass loss rate. (b) Compressive strength loss rate. (c) RDEM.

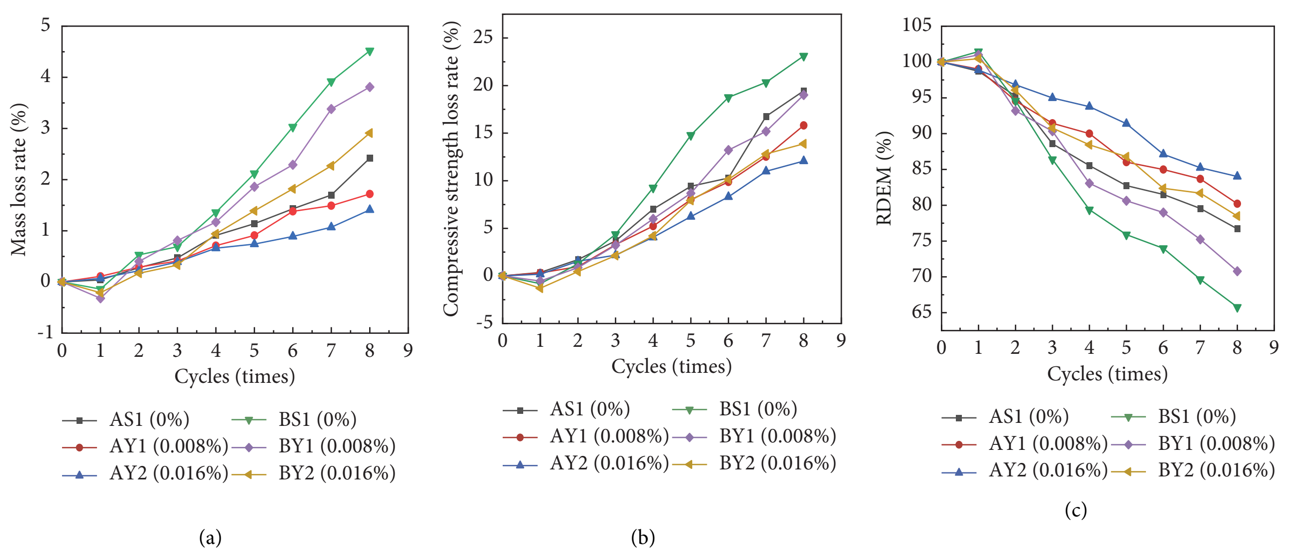

Figure 4: Variation curves of concrete macro-indices with different air-entraining agent dosages. (a) Mass loss rate. (b) Compressive strength loss rate. (c) RDEM.

Compound salt solution (BS1):

$$\mathbf{W}_{\mathbf{B2}} = \begin{pmatrix} 0.3119 & 0.3751 & 0.3130 \end{pmatrix}. \tag{14}$$

(3) The MIE method: From w_1 and w_2, the comprehensive weights could be calculated according to equation (11).

Water (AS1):

$$\mathbf{W}_{\mathbf{A}} = \begin{pmatrix} 0.2627 & 0.3823 & 0.3550 \end{pmatrix}. \tag{15}$$

Compound salt solution (BS1):

$$\mathbf{W}_{\mathbf{B}} = \begin{pmatrix} 0.2825 & 0.3665 & 0.3510 \end{pmatrix}. \tag{16}$$

4.3. Grey Correlation Calculation and Result Analysis. The correlations of group *S*1 in water and compound salt solution after each macrocycle could be calculated according to (12).

Table 3: Group $S1$ test data after adding the Xth cycle.

Cycle	Water (AS1)			Compound salt solution (BS1)		
	Mass loss rate (%)	Compressive strength loss rate (%)	RDEM (%)	Mass loss rate (%)	Compressive strength loss rate (%)	RDEM (%)
0	0.00	0.00	100.00	0.00	0.00	100.00
1	0.04	0.36	98.71	−0.14	−0.82	101.47
2	0.28	1.71	95.24	0.53	1.26	94.58
3	0.47	3.68	88.59	0.69	4.37	86.40
4	0.91	7.02	85.54	1.36	9.26	79.39
5	1.14	9.42	82.74	2.12	14.79	75.90
6	1.43	10.28	81.51	3.03	18.76	73.99
7	1.70	16.77	79.55	3.92	20.34	69.66
8	2.42	19.44	76.70	4.52	23.11	65.77
X	5.00	25.00	60.00	5.00	25.00	60.00

Table 4: Correlation coefficients of evaluation index in group $S1$ after adding the Xth cycle.

Cycle	Water (AS1)			Compound salt solution (BS1)		
	Mass loss rate	Compressive strength loss rate	RDEM	Mass loss rate	Compressive strength loss rate	RDEM
0	1	1	1	0.948407	0.940203	0.933881
1	0.984252	0.972006	0.93932	1	1	1
2	0.899281	0.879662	0.807754	0.793147	0.861178	0.750638
3	0.841751	0.772559	0.63678	0.755858	0.713267	0.579106
4	0.733138	0.640369	0.580383	0.631473	0.561545	0.484308
5	0.686813	0.570255	0.536769	0.532085	0.452653	0.447788
6	0.636132	0.548727	0.519642	0.447748	0.397362	0.430071
7	0.595238	0.427058	0.494413	0.387627	0.378931	0.394602
8	0.50813	0.391359	0.461894	0.355467	0.350435	0.367404
X	0.333333	0.333333	0.333333	0.333333	0.333333	0.333333

$$\begin{aligned}\mathbf{R_A} &= (1.0000, 0.9636, 0.8593, 0.7425, 0.6434, 0.5890, 0.5614, 0.4952, 0.4471, 0.3333),\\ \mathbf{R_B} &= (0.9403, 1.0000, 0.8032, 0.6782, 0.5542, 0.4734, 0.4231, 0.3869, 0.3578, 0.3333).\end{aligned} \tag{17}$$

Similarly, the correlation could be calculated for each test group in water and compound salt solution after each macrocycle as shown in Table 5.

The correlation values obtained after excluding the data of the Xth major cycle with regard to the number of major cycles are shown in Figure 5 above. Figure 5 shows that the correlation values indicating the durability performance of concrete in water decreased with increasing number of tests. After three major cycles, the correlation values of all groups except group $F2$ were above 0.7, indicating that the durability of concrete was still at a better level after three cycles of tests. After eight major cycles, the correlation values of concrete specimens in each group showed differences, but they all dropped to their lowest. Among them, group $Y2$ had the largest correlation value of 0.5623 and group $F2$ had the smallest correlation value of 0.3710. The correlation values of the remaining groups (except groups $Y1$ and $Y2$) were reduced to less than 0.5, indicating that the durability of concrete deteriorated after eight cycles. It can be seen that the best durability performance of all the groups was for group $Y2$, and the worst was for group $F2$. After eight major cycles, the correlation values of each group were ranked as follows: $Y2 > Y1 > F1 > S1 > F2$.

In the compound salt solution, the correlation values indicating the durability performance of concrete all underwent the process of increasing and then decreasing. The maximum value of correlation at the end of the first macrocycle indicated that the durability of concrete was improved, which was mainly due to the accumulation of erosion products generated by the compound salt erosion. After two major cycles, the correlation value of each group was above 0.78, and the durability was good. However, after five major cycles, the correlation values of the remaining groups, except groups $F1$, $Y1$, and $Y2$ decreased to below 0.5, and the durability of concrete became worse. Eight major cycles later, the correlation value of group $Y2$ was 0.4670, which was still the maximum among the groups, and the concrete of group $F2$ reached the damage standard. After eight major cycles, the correlation values of the groups that had not yet reached damage failure were in the order $Y2 > Y1 > F1 > S1$.

The correlation values of concrete specimens in water and compound salt solution under the same number of cycles showed that the correlation value of group $F1$ was always the largest among the F groups, and $F1 > S1 > F2$. The incorporation of fly ash with high content (30%) will make

Table 5: Correlation value of each test group in water and compound salt solution.

Number	Correlation value									
	0	1	2	3	4	5	6	7	8	X
AS1	1.0000	0.9636	0.8593	0.7425	0.6434	0.5890	0.5614	0.4952	0.4471	0.3333
AF1	1.0000	0.9329	0.8323	0.7644	0.6862	0.6289	0.5739	0.5256	0.4810	0.3333
AF2	1.0000	0.8947	0.7887	0.6511	0.5969	0.5213	0.4489	0.4129	0.3710	0.3333
AY1	1.0000	0.9624	0.8685	0.7774	0.7113	0.6358	0.5866	0.5526	0.5047	0.3333
AY2	1.0000	0.9681	0.8884	0.8364	0.7677	0.7080	0.6417	0.5948	0.5623	0.3333
BS1	0.9403	1.0000	0.8032	0.6782	0.5542	0.4734	0.4231	0.3869	0.3578	0.3333
BF1	0.8976	1.0000	0.8317	0.7237	0.6195	0.5320	0.4625	0.4139	0.3839	0.3333
BF2	0.8815	1.0000	0.7932	0.5767	0.4646	0.4181	0.3740	0.3429	—	0.3333
BY1	0.9377	1.0000	0.8037	0.7105	0.6095	0.5430	0.4886	0.4375	0.3974	0.3333
BY2	0.9388	1.0000	0.8581	0.7616	0.6739	0.6001	0.5402	0.5041	0.4670	0.3333

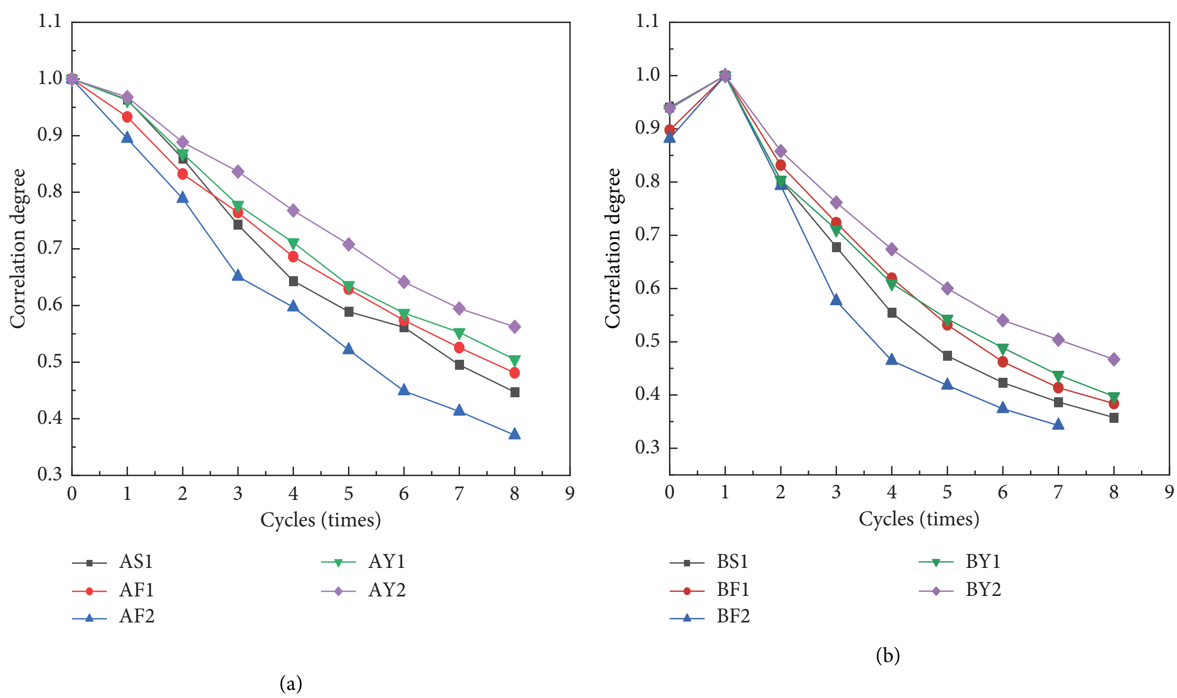

Figure 5: The change process of the correlation values of each test group. (a) Water. (b) Compound salt solution.

the concrete less durable. In group Y, the correlation value order $Y2 > Y1 > S1$ held for any number of cycles. Group Y is the group with the largest correlation value among the test groups at any moment, which means that adding a certain amount of air-entraining agent can improve the durability of concrete.

5. Conclusions

The macro durability degradation law of concrete specimens with different fly ash and air-entraining agent admixtures were studied and analyzed. Based on the grey relational analysis model of concrete durability, the effects of different mixtures on concrete durability were evaluated using mass, compressive strength, and RDEM degradation data. The main conclusions are as follows:

(1) Combined with the environmental characteristics of cold and arid regions, the concrete durability evaluation model is established by the grey relational analysis method. The model is optimized by adding three evaluation indices critical damage values as the data of the Xth major cycle. The problem that the grey relational analysis evaluation model cannot adequately evaluate the durability of concrete specimens during the whole test cycle is solved. The optimized model can qualitatively and quantitatively evaluate the effects of different mixtures on the durability of concrete.

(2) The influence of different service environments on the durability of concrete varies greatly, and the degree of influence of dry-wet-freeze-thaw-compound salt erosion is significantly greater than that of

dry-wet-freeze-thaw cycles. After eight major cycles, the mass loss rate of concrete specimens with 30% fly ash content reached 5.97%, the compressive strength loss rate reached 29.87%, and the RDEM was 54.36%. The maximum decrease reached the damage standard, which shows that fly ash has a more obvious effect on the durability of concrete.

(3) The grey relational analysis evaluation model shows that the concrete specimens mixed with an air-entraining agent have a strong ability to resist compound erosion. The effect of air-entraining agent content on the durability of concrete is in the order $Y2$ (0.4670) > $Y1$ (0.3974) > $S1$ (0.3578); that is, the comprehensive evaluation index is the highest when the air-entraining agent content is 0.016%. The incorporation of high content (30%) of fly ash accelerates the damage of concrete specimens. Mixing low content (15%) fly ash can improve the durability of concrete. This means that concrete mixed with an air-entraining agent and a low amount of fly ash is more suitable for cold and arid regions.

(4) The improved evaluation model is applied to evaluate the durability of concrete in cold and arid regions. The applicability of the model is tested by selecting five types of concrete specimens, and the model calculation is consistent with the test results. The evaluation model overcomes the shortcomings of the existing evaluation methods and enables quantitative description of the degree of influence of each element on its comprehensive durability. It provides useful reference for concrete durability evaluation and optimization of design and construction under similar climatic conditions.

Data Availability

Data and models generated or used in the course of the study are available from the corresponding authors upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

The authors gratefully acknowledge many important contributions from the researchers of all reports cited in our paper. This research was supported by the National Natural Science Foundation of China (No. 51969011), Gansu Provincial Science and Technology Program (Nos. 20JR10RA274 and 21JR7RA301), and Department of Education of Gansu Province: "Innovation Star" Program of Excellent Graduate Student (2021CXZX-640).

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