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Life Prediction of Hydraulic Concrete Based on Grey Residual Markov Model

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Abstract
Hydraulic concrete buildings in the northwest of China are often subject to the combined effects of low-temperature frost damage, during drying and wetting cycles, and salt erosion, so the study of concrete deterioration prediction is of major importance. The prediction model of the relative dynamic elastic modulus (RDEM) of four different kinds of modified concrete under the special environment in the northwest of China was established using Grey residual Markov theory. Based on the available test data, modified values of the dynamic elastic modulus were obtained based on the Grey GM(1,1) model and the residual GM(1,1) model, combined with the Markov sign correction, and the dynamic elastic modulus of concrete was predicted. The computational analysis showed that the maximum relative error of the corrected dynamic elastic modulus was significantly reduced, from 1.599% to 0.270% for the BS2 group. The analysis error showed that the model was more adjusted to the concrete mixed with fly ash and mineral powder, and its calculation error was significantly lower than that of the rest of the groups. The analysis of the data for each group proved that the model could predict the loss of dynamic elastic modulus of the deterioration of the concrete effectively, as well as the number of cycles when the concrete reached the damaged state.

Keywords
Durability, Grey Residuals, Hydraulic Concrete, Lifespan Prediction, Markov

1. Introduction

In the northwest of China, it is cold in winter and hot in summer, with large annual and seasonal temperature differences, low rainfall, high evaporation, and large areas of salinization due to overirrigation. The durability of hydraulic concrete buildings in this region is affected to a great extent by the long-term multi-factor coupling damage due to drying and wetting cycles, freezing and thawing, salt intrusion, and carbonization [1]. According to the relevant data published by the Ministry of Water Resources, the damage to hydraulic concrete structures in the northwest of China is very serious. More than 70% of damage is caused by the harsh natural environment. Affected by this environment, hydraulic concrete structures are greatly influenced by the coupling action during wet-dry cycles, freeze-thaw cycles, and other factors. The damage rate is considerably higher than in coastal areas, resulting in a much shorter service life of hydraulic concrete structures than in other areas, seriously restricting economic development in the northwest of China. Life-span predictions of the residual durability of hydraulic

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concrete buildings under the action of the above factors are essential for performance assessment, which is helpful for making reasonable decisions in concrete selection.

Studies of lifespan predictions of concrete durability have long been of great interest in a wide range of fields. Scholars around the world have conducted much research on this using different methods. Lei et al. [2] proposed a fatigue lifespan prediction method for concrete based on energy dissipation, and the concrete lifespan prediction results were compared with the experimental results to verify the validity of the proposed prediction method. Li et al. [3] studied the prediction of the residual behavior of a post-earthquake damaged reinforced column. The results showed that the residual behavior of the damaged RC column with the proposed damage distribution model could be predicted more accurately than with the ASCE-41 model. The proposed model enables accurate prediction for the residual behavior of damaged RC columns and provides a reference for reconstruction decisions. Nguyen et al. [4] measured the service lifespan of steam-cured concrete using the method of field permeability measurement, and the results of the study could contribute to the establishment of appropriate in situ air permeability measurement procedures for normal-cured concretes or in the cases of expansive concrete with normal-cured and steam-cured mixture. In practice, this approach can be used to assess the quality of precast concrete affected by casting direction and workmanship during construction. Kang et al. [5] used a Grey residual GM(1,1) Markov model to predict the deterioration of hydraulic concrete on the basis of concrete compressive strength and mass loss data.

Currently, most of these studies have generally been limited to the analysis of durability damage prediction models for concrete under single conditions, while there are fewer studies on hydraulic concrete in the special northwestern environments. Furthermore, in recent years, many experts have proposed the prediction method of combining the residual model and Markov theory on the basis of Grey theory [6]. Therefore, the author used the Markov model of Grey residual GM(1,1) after combining the two models, applied it to the prediction of deterioration tests of hydraulic concrete buildings in the northwest of China, and verified the applicability of this prediction model using the method of indoor accelerated tests. The Grey residual Markov model was applied to predict the relative dynamic elastic modulus (RDEM) of concrete specimens for subsequent tests and to predict the number of test cycles required to achieve damage to the concrete. This was applied to provide a theoretical basis for predicting the lifespan of concrete specimens in the salty dry cold region of the northwest.

2. Grey Residual Markov Model

2.1 Grey Residual Model

The GM(1,1) models represent a differential equation model of order 1 and one variable. Its first step is to generate a cumulative series of accumulation of the RDEM change process of concrete. This series is then processed mathematically to obtain the prediction model, and the prediction value can be calculated by a cumulative reduction of the prediction model [7]. $X^{(0)}(k)$ denotes the original data series of the concrete RDEM.

$$X^{(0)}(k) = \{x^{(0)}(1), x^{(0)}(2), \ldots, x^{(0)}(n)\} \tag{1}$$

Conducting a cumulative addition to the above sequence yields the following cumulative series:

$$X^{(1)}(k) = \{x^{(1)}(1), x^{(1)}(2), \dots, x^{(1)}(n)\} \tag{2}$$

The rest of the calculation process reference [5] will not be repeated here.

$\hat{\varepsilon}^{(0)}$ correcting the reduced values with the resulting residual corrections $x^{(0)}$ gives.

$$\begin{aligned} \hat{x}^{(0)}(m+1) &= \hat{x}^{(0)}(m+1) \pm \hat{\varepsilon}^{(0)}(m+1) = (1-e^{a})\left(x^{(0)}(1)-\frac{\beta}{\alpha}\right)e^{-\alpha m} \\ &\pm (1-e^{a_{\varepsilon}})\left(\varepsilon^{(0)}(2)-\frac{\beta_{\varepsilon}}{\alpha_{\varepsilon}}\right)e^{-\alpha_{\varepsilon} m}, m = 2,3,\dots,n \end{aligned} \tag{3}$$

2.2 Symbolic Corrections for Markov Processes

The relative error between the original and predicted values is largely due to the elimination of sensitive data or correction, and the residual sequence often appears to alternate between positive and negative, which means that the sign of the residual predicted value is uncertain. Therefore, the improvement of the Grey residual model is essential, and the Markov model has a beneficial effect on the prediction of the state of the process; thus, this paper combines the Grey residual and the Markov model to improve the accuracy of the prediction model.

The specific steps for determining the positive and negative signs of the residual corrections at a future moment using a Markov process are as follows:

Specify state 1 as the residual positive value and state 2 as the residual negative value. The frequency of the positive and negative values in the statistics $\varepsilon_1^{(0)}$, and the state transfer probability matrix P are obtained as follows:

$$P = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \tag{4}$$

where s_{ij} is the number of state i transfers to the state j, and S_i is the number of times the state i appears.

The rest of the calculation process reference [5] will not be repeated here.

The relative error is calculated from the following equation:

$$\Delta_k \varepsilon = \left|x^{(0)}(k) - \hat{x}^{(0)}(k)\right| / x^{(0)}(k), \quad k = 1,2,\dots,n \tag{5}$$

3. Accelerated Indoor Tests

3.1 Test Materials and Ratio Design

The cement used was ordinary P.O42.5 silicate cement produced by Gansu Province Qilianshan Cement Group Co., and had a flexural strength of 7.6 MPa and a compressive strength of 48.7 MPa at 28 d. The indices of each parameter are shown in Table 1.

The fine aggregate was made from river sand in the Anning district, Lanzhou City. Its apparent density was 2,580 kg/m^3, its fineness modulus 2.78, and its water content 3.3%. Coarse aggregates used were from Lanzhou Hualong Commercial Concrete Company, and they had an apparent density of 2,660 kg/m^3, moisture content of 0.15%, and mud content of 0.15%.

Table 1. P.O42.5 cement quality parameters

Quality parameter index	Detection value	standard value
Specific surface area (m^2/kg)	348	≥300
Initial setting time (min)	145	≥45
Final setting time (min)	220	≤600
Safety and security	qualified	qualified
Chloride ion (%)	0.012	≤0.06
Loss on burn (%)	1.6	≤5.0
Magnesium oxide (%)	2.0	≤5.0
Sulphur trioxide (%)	2.4	≤3.5

Xie [8] found, through sampling and analysis of water and soil samples at the Jingdian project site, that concrete in the cold and arid regions of northwest China was mainly subjected to compound erosion by sulfate and chloride salts; therefore, according to the actual engineering situation, in this study a sodium sulfate-sodium chloride compound salt solution with a mass fraction of 5% was selected, and a clear water control group was established. The concrete specimens were selected with a water/cement ratio of 0.45 and were mixed with fly ash, mineral powder, and air-entraining agent to form four different kinds of modified concrete; the numbers and details of the ratios are shown in Table 2.

Table 2. Concrete mix ratio

Number	Clinker (kg/m^3)	Water (kg/m^3)	Fine aggregates (kg/m^3)	Coarse aggregates (kg/m^3)	Fly ash (%)	Mineral powder (%)	Aspirant (%)
S2	411	185	595	1209	0	0	0
F1	349	185	595	1209	15	0	0
K1	329	185	595	1209	0	20	0
Y1	411	185	595	1209	0	0	0.008

3.2 Test Methodologies

Xie [9] found that the test scheme developed in his study on the method to assess the resistance the concrete to sulfate erosion under the action of the freeze-thaw and wet-dry cycles was basically consistent with the actual situation. Therefore, the test regime developed according to the Standard for Long-Term Performance and Durability Test Methods of Ordinary Concrete (National Standard of the People's Republic of China, GB/T50082-2009) combined with the literature is shown in Fig. 1.

The "wet" in the wet-dry cycle test and the "thaw" in the freeze-thaw cycle test were carried out in either clear water or a compound salt solution, depending on the grouping. In this method, one wet-dry/salt attack/freeze-thaw cycle took one week, and a total of eight cycles was performed. At the end of each cycle, the RDEM of the specimen was measured and the data recorded, for a total of nine times.

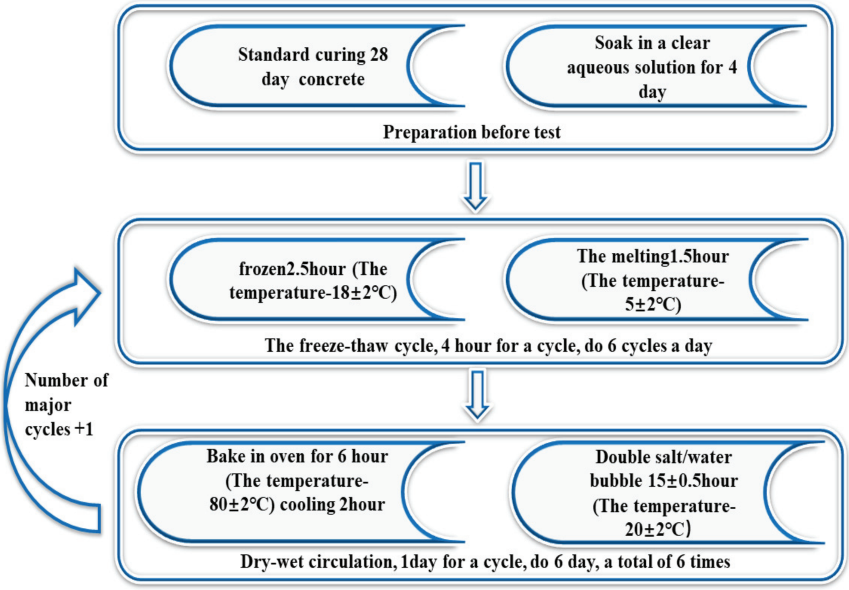


Fig. 1. Freeze-thaw and wet-dry cycle test regime.

4. Performance Analysis

4.1 Data Source

In this paper, statistics on the RDEM loss of specimens from four sets of tests in clear water and compound salt, respectively, were taken for calculation, and the detailed data are shown in Fig. 2.

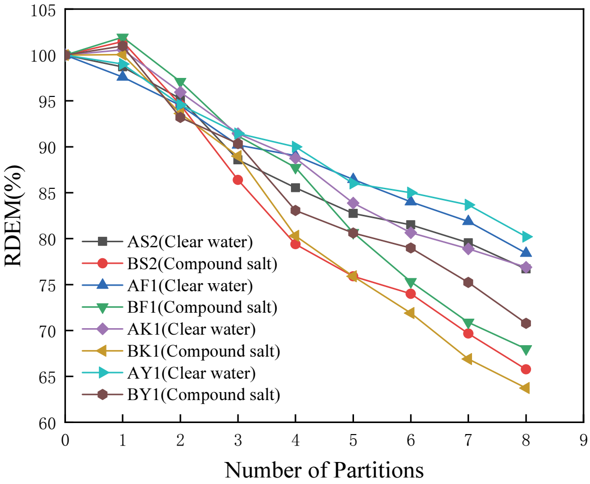


Fig. 2. Raw data RDEM.

It can be seen in Fig. 2 that the RDEM law for each group showed the following situation. The hydraulic concrete under the action of clear water had the most serious loss of dynamic elasticity in the group of ordinary concrete S2, with a loss rate of dynamic elastic modulus reaching 23.3%, while the Y1 group with the air-entraining agent incorporated had the least elastic loss with a loss rate of dynamic elastic modulus of only 19.79%. Under the action of the compound salt, the elastic loss of the K1 group doped with mineral powder reached 36.27%, which was much higher than that of the other group. Like the clear water group, the Y1 group with the air entrainment agent had the smallest elastic loss of 29.22% under the action of the compound salt. The experimental results showed that the RDEM of clear water samples decreased with the test. After the first large-cycle test, the RDEM of four groups of samples under the action of compound salt increased to varying degrees and then decreased with the test, and the decreasing range was greater than that of the same modified concrete in clear water. When comparing the results of the eighth large cycle, the dynamic elastic modulus in the clear water group was higher than that of the compound salt group, and the Y1 group outperformed the rest of the groups in both clear water and compound salt, indicating that the modified concrete with an air-entraining agent was more suitable for the dry cold region of saline in the northwest.

4.2 Data Processing

Based on the test results, the experimental data for the S2 group were predicted. The RDEM of 0–5 large cycle tests was used as the original value to build the model, and the data of 6–8 major cycle tests were predicted and compared with the original value. The calculation results are shown in Table 3.

Table 3. Simulation results of RDEM of specimens in group S2 from 0 to 5 large-cycle tests

Group	Number of cycles	Original value (%)	Grey simulated value (%)	Residual series	Residual simulated values	Correction result (%)	Relative error (%)
AS2	0	100.00	-	-	-	-	-
	1	98.71	98.70122	0.00878	-	-	-
	2	95.24	94.22611	1.01389	1.14764	95.37375	0.140
	3	88.59	89.95390	-1.36390	0.93520	89.01870	0.484
	4	85.54	85.87539	-0.33539	0.76209	85.11330	0.499
	5	82.74	81.98181	0.75819	0.62102	82.60283	0.166
BS2	0	100.00	-	-	-	-	-
	1	101.47	101.34180	0.12825	-	-	-
	2	94.58	93.89700	0.68299	0.62419	94.52120	0.062
	3	86.40	86.99916	-0.59916	0.79160	86.20756	0.223
	4	79.39	80.60805	-1.21805	1.00391	79.60414	0.270
	5	75.90	74.68644	1.21357	1.27316	75.95960	0.079

Table 3 shows the raw RDEM values of concrete samples from group S2 in clear water and compound salt of test 0-5 with the corrected results after data processing. In clear water, the maximum error was 0.499%, the minimum error was 0.140%, and the average error was 0.322%. In compound salt, the maximum error was 0.270%, the minimum error was 0.062%, and the average error was 0.158%. The error in the compound salt was less than that in the clear water, either in terms of maximum error, average error, or minimum error.

The remaining datasets could be predicted accordingly. Due to space limitations, detailed processes are not listed one by one. The maximum error, minimum error, and average error of the data of other groups are shown in Fig. 3 that the 0–5 errors of each group presented the following situation. The largest maximum error of 1.073% occurred in the BK1 compound salt group, and the smallest minimum error of 0.062% occurred in the BS2 and BY1 compound salt groups. The relatively large errors that occurred could be found in the simulation results of the Grey GM(1,1) model before residual correction; whether in clear water or compound salt solution, the errors were large (e.g., the maximum relative errors of 1.540% and 1.599% for AS2 and BS2, respectively), but in the Grey residual GM(1,1) model after residual correction, the relative errors were significantly reduced (e.g., the maximum relative errors of AS2 and BS2 had maximum relative errors of 0.499% and 0.270%, respectively), which made the simulations more closely resemble the original data of the RDEM of concrete.

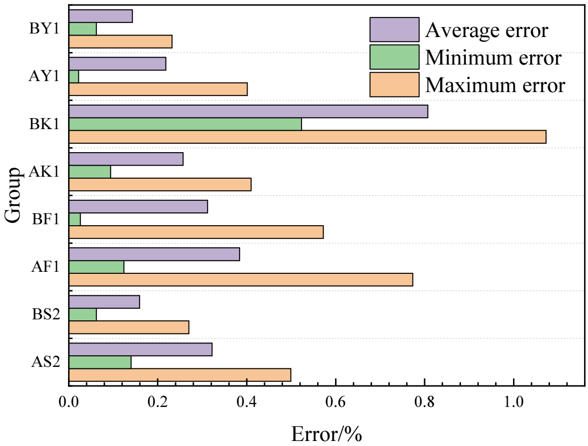


Fig. 3. Error of each group.

The RDEM of the remaining 6th to 8th large-cycle tests was calculated by the Grey residual model, and the accuracy of the model prediction was verified by obtaining the corrected values through sign correction and comparison with the original data as a means of predicting the future lifespan of concrete specimens with different mix ratios.

4.3 Symbol Correction

The Grey residual GM(1,1) model was applied to predict the RDEM of concrete specimens in fresh water and the compound salt solution for the 6th, 7th, and 8th large-cycle tests and to determine the sign of the residual correction.

The prediction and sign correction for the RDEM of the AS2 group, based on the residual series of the AS2 group, showed that the number of residuals shifted from positive to positive was 2, the number of shifts from positive to negative was 1, and the number of occurrences of positive values was 3. Thus, the Markoff state transition matrix P is:

$$\boldsymbol{P} = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} = \begin{bmatrix} 2/3 & 1/3 \\ 1/2 & 1/2 \end{bmatrix}$$

As seen in Table 3, the RDEM residual values of concrete for the 5th large-cycle test were positive, and then the initial vector $s^{(0)} = (1,0)$.

From Eq. (5), the positive and negative results for the residual predictions of the 6th large-cycle test are as follows:

$$\boldsymbol{s} = s^{(0)} \qquad \boldsymbol{P} = (1,0) \cdot \begin{bmatrix} 2/3 & 1/3 \\ 1/2 & 1/2 \end{bmatrix} = \left(\frac{2}{3}, \frac{1}{3}\right)$$

Notably, the probability that the predicted value of the RDEM residual of concrete for the 6th large-cycle test was positive was 2/3, and the probability that it was negative was 1/3; thus, the positive sign was taken. Similarly, using the predicted value of the RDEM residuals of the 6th large cycle test as the initial value, the positive and negative predicted values of the residuals of the 7th and 8th large cycle tests could be calculated.

The prediction and sign correction of the RDEM of the BS2 group is not described in detail since the calculation process is the same as above. The final prediction of the RDEM of concrete is shown in Table 4.

Table 4. Predicted results of RDEM of group S2 specimens for the 6th–8th large-cycle tests

Group	Number of cycles	Original value (%)	Grey predicted value (%)	Residual predicted value	Residual predicted value symbolic	Correction result (kg)	Relative error (%)
AS2	6	81.51	78.26475	0.50606	+	78.77081	3.361
	7	79.55	74.71623	0.41239	+	75.12862	5.558
	8	76.70	71.32860	0.33605	+	71.66465	6.565
BS2	6	73.99	69.19984	1.61463	+	70.81446	4.292
	7	69.66	64.11629	2.04767	+	66.16396	5.019
	8	65.77	59.40619	2.59686	+	62.00305	5.727

Table 4 shows the original RDEM values of concrete specimens from group S2 in clear water and compound salt for the 6th to 8th tests with correction by the Markov model with the maximum error of 6.565%, the minimum error of 3.361%, and the average error of 5.087% in clear water. The maximum error in the compound salt was 5.727%, the minimum error was 4.292%, and the average error was 5.013%. These results infer that the relative error became larger with the increasing tendency in the number of trials, and the variation in the compound salt was lower than that of the clear water, and the results were more closely matched to the original values.

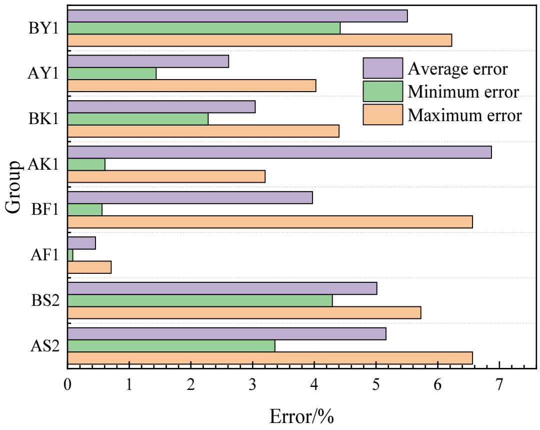


Fig. 4. Correction error result of concrete sample symbol.

Correspondingly, predictions can be made for the remaining sets of data and the original values of RDEM for each group of concrete specimens in clear water and compound salt for the 6th to 8th tests with the corrected results, with the errors shown in Fig. 4, by sign correction of the Markov model.

It can be seen from Fig. 4 that the 6–8 errors of each group presented the following situation. As in the F1 group with mixed air entraining agent, the AF1 group in clear water had the smallest mean error of 0.452%, and the smallest error of 0.559% appeared in the BF1 group with compound salt. The errors were larger before the sign correction, while after the sign correction, the errors in all groups were significantly reduced and the accuracy was improved, with the largest change in the AF1 group in clear water.

The raw values of the RDEM simulated by Grey (0–5 large cycle tests), simulated by Grey residual (0–5 large cycle tests), predicted by Grey (6–8 large cycle tests) and predicted by sign corrected (6–8 large cycle tests) for each group are shown in Fig. 5.

As seen in Fig. 5, the simulated values of the two models of Grey GM(1,1) and Grey residual GM(1,1) were compared with the original data measured by the experiment. For example, the K1 group with mineral powder mixed in the maximum error before residual correction was 0.475%; after residual correction, the error was reduced to 0.085%, by which it could be found that the error of the model after residual correction was significantly reduced and the accuracy was significantly improved. After the sign correction using the Markov model, the prediction results were more consistent with the original data, with a maximum error of 6.565% and an average error of 3.507%. In particular, the AF1 clear water group fit the original values the best, and the BK1 compound salt group was the next best. Therefore, the Grey residual Markov model had a good prediction of concrete durability damage and could predict well the RDEM loss of concrete deterioration, which can be applied to predict the future life expectancy of concrete.

4.4 Life Expectancy Projections

Based on the above model, the RDEM of the concrete specimen for subsequent tests was predicted until the number of test cycles when it reached damage (RDEM dropped below 60%) was predicted.

The prediction and sign correction for the RDEM of the AS2 group, based on the residual series of the AS2 group, showed that the number of residuals shifted from positive to positive was 5, the number of shifts from positive to negative was 1, and the number of occurrences of positive values was 6. Thus, the Markoff state transition matrix P is:

$$\boldsymbol{P}=\begin{bmatrix}P_{11} & P_{12}\\ P_{21} & P_{22}\end{bmatrix}=\begin{bmatrix}5/6 & 1/6\\ 1/2 & 1/2\end{bmatrix}$$

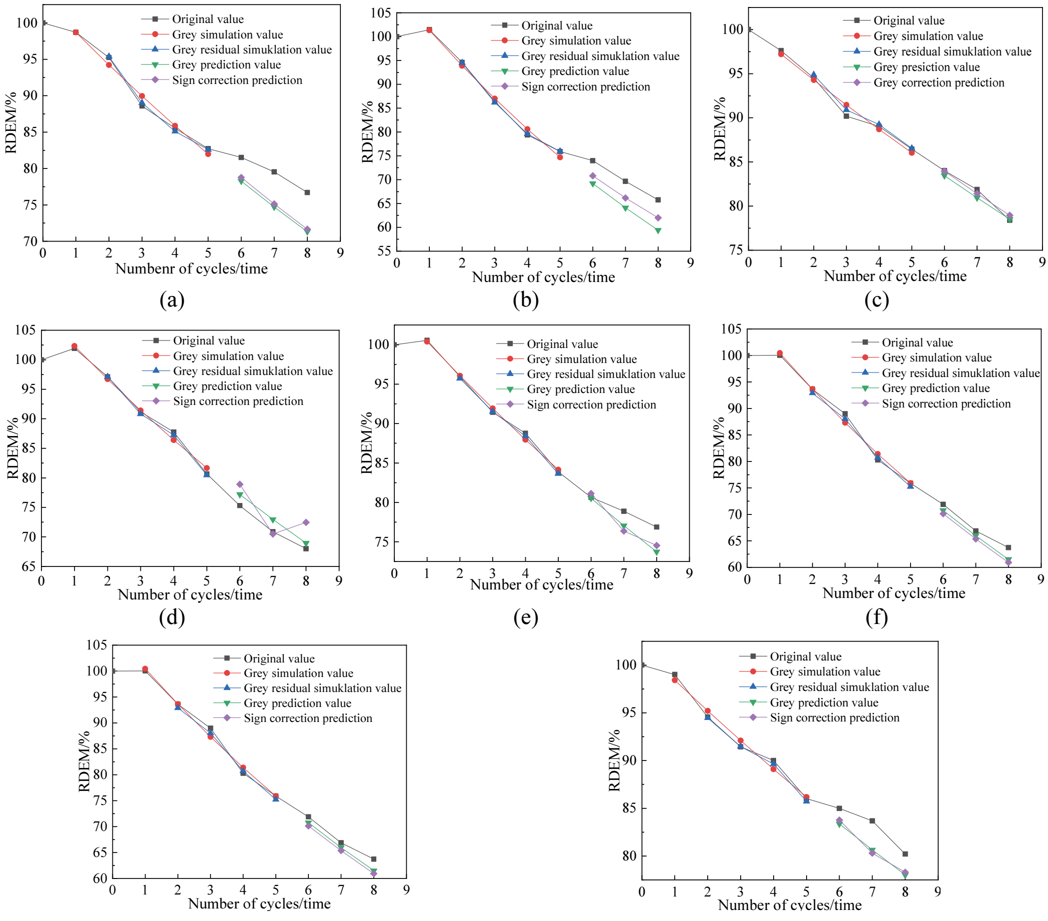
From Table 4, the predicted values of the RDEM residuals of concrete for the 8th large-cycle test were positive, and then the initial vector $s^{(0)}=(1,0)$.

The results of the 9th large-cycle test were obtained from Eq. (5) as:

$$\boldsymbol{s}=\mathrm{s}^{(0)}\quad \boldsymbol{P}=(1,0)\cdot\begin{bmatrix}5/6 & 1/6\\ 1/2 & 1/2\end{bmatrix}=\left(\frac{5}{6},\frac{1}{6}\right)$$

From the above results, it can be seen that the probability that the predicted value of the RDEM residual of concrete for the 9th large-cycles test was positive was 5/6, and the probability that it was negative was

1/6, and thus the positive sign was taken. Similarly, using the predicted value of the residual RDEM for the 9th large-cycles test as the initial value, the positive and negative predicted values of the residuals for the 10th through 12th large-cycles tests could be calculated.



(a) (b) (c) (d) (e) (f) (g) (h)

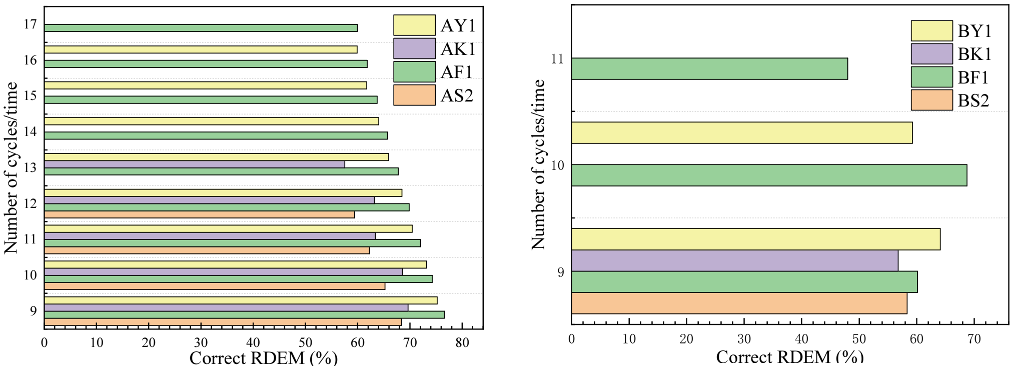
Fig. 5. Comparison of simulation, prediction, and correction for group S2, group F1, group K1, and group Y1: (a) AS2, (b) BS2, (c) AF1, (d) BF1, (e) AK1, (f) BK1, (g) AY, and (h) BY1.

The prediction and sign correction of the RDEM for the BS2 group are not described in detail here, as the calculation procedure is the same as above. The final prediction results are shown in Table 5.

Table 5. Lifespan prediction results of specimens in group S2

Group	Number of tests	Grey predicted value (%)	Residual predicted value	Residual correction value symbolic	Correction result (kg)
AS2	9	68.09456	0.27384	+	68.36840
	10	65.00716	0.22315	+	65.23031
	11	62.05973	0.18185	+	62.24158
	12	59.24595	0.14818	+	59.39413
BS2	9	55.04211	3.29000	+	58.33211

From Table 5, it can be seen that the number of test cycles for concrete specimens in group S2 to reach damage in clear water was 12, and the number of test cycles to reach damage in compound salt was 9. Similarly, the number of test cycles to reach damage for groups F1, K1, and Y1 could be found, and the detailed data and cycle counts for the remaining groups are shown in Fig. 6.



(a) (b)

Fig. 6. Results of the number of cycles in each group: (a) clear water and (b) compound salt.

It can be seen in Fig. 6 that the Grey residual Markov model can calculate the number of coupled wet-dry/salt-erosion/freeze-thaw cycles (large cycles) that each group of concrete specimens can undergo, and the comparison shows that the durability of concrete specimens in the two groups, S2 and K1, was similar. In clear water, the number of test cycles for both were 12 and 13, respectively, and the number of test cycles when both reached damage in compound salt was 9; The F1 and Y1 groups of concrete specimens had the highest durability against erosion and could withstand the number of large cycles. The number of test cycles when both reached damage in clear water was 17 and 16, respectively, and the number of test cycles when both reached damages in compound salt was 11 and 10 respectively. This shows that concrete with low amounts of fly ash and concrete with air-entraining agent resisted the coupling effect of wet-dry/salt attack/freeze-thaw cycles better, and mineral powder dosing was not effective in improving the durability of concrete; the results of their analysis are consistent with the conclusions obtained from the tests.

5. Conclusion

In this paper, the Grey residual GM(1,1) model was combined with the Markov model. Data from four groups of different modified concrete RDEM were verified and the cycle times when they reached failure were predicted. The following conclusions were drawn: (1) The RDEM of the four different types of concrete is taken as the main evaluation index of concrete durability deterioration, and a Grey residual Markov model is established on the basis of the experimental data, which performed well overall, and the errors of most of the correction results are reduced to different degrees. Compared with the original data, the average error is only 3.507%, which verified that the model has a good prediction effect on the RDEM loss of hydraulic concrete deterioration within a certain prediction range. (2) The lifespan prediction of the four different kinds of modified concrete based on the predicted values derived from the Grey residual Markov model is found to be more applicable to the modified concrete mixed with fly ash and mineral powder. A comparison of the calculated results for each group showed that the specimens in groups F1 and Y1 have better durability and their service lifespan is significantly better than the remaining two groups (S2 and K1). This shows that concrete with low fly ash content and concrete with the air entraining agent are more suitable for the dry and cold saline area in northwest China. (3) For the study of service lifespan prediction of actual concrete, there is a lack of lifespan data of concrete specimens of various sample sizes with different water/cement ratios due to various conditions. Further depth is needed in the sign correction, so follow-up work should study a larger sample capacity in order to lay a theoretical foundation for the durability damage and lifespan prediction of hydraulic concrete in the actual northwest service environment.

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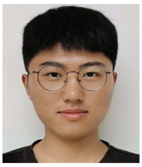

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