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Accelerated life testing of concrete based on stochastic approach and assessment

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Abstract. This study aimed to design the accelerated life testing (ALT) of concrete, which stimulating the special natural environment maximumly. Its evaluation indexes, such as dynamic elastic modulus, mass and ultrasonic velocity were measured, and the variation of relative mass and relative dynamic elastic modulus of concrete were studied. Meanwhile, the microanalysis method was used. Moreover, an exploratory application of the stochastic approach, the Weibull distribution and the lognormal distribution, were made to assess the durability of concrete structures. The results show that the ALT for simulating natural environment is more close to the service process of concrete structure under actual conditions; The relative dynamic elastic modulus can be used as the dominant durability evaluation parameters, because it is more sensitive to the environmental factors compared with the relative quality evaluation parameters; In the course of the concrete deterioration, the destruction of the salt freezing cycle is the dominant factor, supplemented by other factors; Both of those two stochastic approaches can be used to evaluate the reliability of concrete specimens under the condition of ALT; By comparison, The lognormal distribution method is better to describe the reliability process.

Keywords: concrete; accelerated life testing; durability; weibull distribution; lognormal distribution; reliability

1. Introduction

There is a large amount of saline soil in the Western Region of China, and Xining is one of the typical saline soil areas. Saline soil, local sandstorm, dry weather, large temperature difference, radiation intensity and other harsh environment have a serious threat to the durability of concrete structures in Xining. This problem, to a large extent, can be solved by studying the durability of concrete and improving the service life of concrete structures. Previously, we have made field exposure tests of concrete for many years in West China, and collected a lot of life data. The accelerated life testing (ALT) and field exposure testing should be carried out simultaneously during service life prediction, and it is necessary to establish the relationship between indoor and outdoor service life prediction. Therefore, based on the existing test methods, it is very essential to find a suitable and operational concrete ALT method for the study of concrete deterioration process, mechanism of concrete structure, and lifetime prediction under actual complex environments. The design of ALT experiment is very practical, which needs to be noticed when collecting data.

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There're some studies about artificial ALT for concrete: Zhang *et al*. (2015) presented a comprehensive durability test of cement concrete to simulate the natural environment, which consisted of dry and wet cycles, carbonization, freezing and thawing cycles, chlorine ion and so on. Malumbela *et al*. (2012) proposed the standard procedure for accelerating the corrosion of reinforcing steel in concrete, considering the accelerated corrosion technique is not uniform. Chen *et al*. (2015) made an artificial accelerated testing system by simulating coastal climate, and carried out a durability test. Wang *et al*. (2014) established an equivalent relationship between the corrosion rate in the natural environment and that under the standard temperature and relative humidity condition.

However, China has a vast territory, and the climate environment is complex and changeable; environmental factors has complicated and diversified synergistic effect, the macroclimate connected to local microclimate, so the whole country cannot adopt the unified parameter to carry on the accurate comprehensive durability test. Thus, for Xining area, the ALT program should be established according to the actual environment and climatic characteristics.

Besides, during the development of the service life prediction on durability behavior of concrete, concrete lifetime prediction method based on probabilistic reliability is one of the important research directions. Ryan and O'Connor (2013) obtained the probability distribution function of different Self-Compacting Concretes by using the probability regression model. Wang *et al*. (2014)

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Table 1 Mix proportion of concrete

Sample	Cementitious	Sand	Gravel	Fly ash	Water reducing agent	Water
ACC1	1	1.67	2.89	0.25	0.015	0.43
ACC2	1	1.42	2.92	0.23	0.020	0.35
ACC3	1	1.29	2.35	0.15	0.026	0.30

Table 2 Soil analysis report of experimental points

No.	Ion	*n*/mmol	*m*/mg	Mass fraction/%
1	CO_3^{2-}	1.13	68	0.007
2	HCO_3^-	12.48	761	0.076
3	Cl^-	6.42	227	0.023
4	SO_4^{2-}	1.23	117	0.012
5	Ca^{2+}	0.92	37	0.004
6	Mg^{2+}	2.14	51	0.005

Table 3 Salt dosage and solution concentration in compound salt solution

Salt type and mass fraction (%)				Solution concentration
$NaHCO_3$	NaCl	$MgSO_4$	Na_2SO_4	
1.1	2.2	3.2	3.5	10%

obtained the service life of reinforced concrete under a certain degree of reinforcement corrosion probability, by considering two random variables: the chloride diffusion coefficient and the thickness of the protective layer. Strauss *et al*. (2013) introduced a feasible approach to analyze the effects of chloride-induced deterioration on the overall safety level, and incorporated time-varying chloride concentration information into the framework of nonlinear analysis and reliability assessment. Conciatori *et al*. (2015) carried out the estimation of uncertainty on stochastic parameters in a multi-ionic reactive transport model for concrete degradation by using the Rosenblueth point estimator method. Safehian and Ramezanianpour (2015) estimated the corrosion initiation time of coastal RC structures based on a developed probabilistic service life model. Iii (2015) established the random service life model of recycled aggregate concrete based on chloride ion corrosion by using probabilistic method. Cho *et al.* (2015) estimated the remaining service life of reinforced concrete buildings by utilizing a fuzzy theory to consider the effects of multiple influencing factors on the deterioration of durability. In general, it is very necessary to make time-variant reliability assessment for the durability degradation index of concrete based on probabilistic reliability. As a probabilistic reliability method, Weibull distribution and lognormal distribution modeling, which has the characteristics of stability, easy calculation and analysis, has been widely used in the field of product reliability evaluation (Tenemaza and Ortega 2016, Xu and Tang 2015, Singh and Tripathi 2015). However, until recently, little attention of the application of Weibull distribution and lognormal distribution stochastic method has been paid to concrete reliability assessment.

In this study, based on the existing durability test method, the ALT of concrete stimulating natural environment in Xining area was carried out, and the related analysis was given. It is important that this study evaluated the accelerated life reliability based on stochastic method. Furthermore, the stochastic method for modeling the degradation process of the accelerated life was used to obtain the reliability function in order to provide a scientific criterion for the durability design and life prediction of concrete.

2. Experimental program

2.1 Materials and mix proportions

Materials used in this study consisted of ordinary Portland cement (PO.42.5 according to Chinese standard), Coarse aggregate used was a kind of gravel in Lanzhou area with apparent density of 2660 kg/m^3 and mud content of 0.5%. Fine aggregate used was a kind of river sand with fineness modulus of 3.18 and apparent density of 2581 kg/m^3. Class II fly ash (FA) was collected from a local power station. A polycarboxylate-type super-plasticizer with a water-reducing rate of 18% by weight was used, the content of the cementitious materials were 2.0 wt. %, 2.0 wt. % and 1.5 wt. %, respectively. The mixing water used in this work was taken from the general city supply drinking water. Sodium bicarbonate ($NaHCO_3$), sodium chloride (NaCl), magnesium sulfate ($MgSO_4$) and sodium sulfate (Na_2SO_4) were the production of AR grade analytical reagent and mass fraction were 99.5%, 99.5%, 99.0% and 99.0%, respectively.

Three kinds of concrete specimens, approximately prisms 100×100×400 mm, were all cast in steel molds for accelerated life test after 28d standard curing with 23±1℃ and 95% relative humidity. For the sake of comparison, the concrete selected for test were fly ash concrete and ordinary with three different concrete mix ratios, as shown in Table 1. (a) Cement paste at water to binder ratio (*w*/*b*) of 0.43 (denoted as: ACC1), (b) Cement paste at water to binder ratio (*w*/*b*) of 0.35 (denoted as: ACC2), (c) Cement paste at water to binder ratio (*w*/*b*) of 0.30(denoted as: ACC3). There were 66 fly ash concrete specimens in all, with 22 ones in each group. These specimens were numbered in sequence ACC1-1, ACC1-2, ACC1-22, ACC3-1, ACC3-2, and ACC3-22 in each group. Group ACC1, ACC2 and ACC3 represented the specimens corresponding to strength grade C30, C40 and C50 respectively. It should be noted that, the specimens used in this experiment were soaked in water for 2 years after standard curing. So the performance of concrete tends to a steady state.

2.2 Testing plan

Based on the present situation of the climate environment in Xining, the concrete of basic engineering is more susceptible to the effects of complex salt (chloride and sulfate) erosion, solar radiation, dry and wet cycles and freeze-thaw cycles. After field sampling, the results of soil analysis report of experimental points are shown in the Table 2. It is obvious that the saline soil contains HCO_3^-, Cl^-, SO_4^{2-} and Mg^{2+}, and the content of HCO_3^- and Cl^- is high.

According to the report, the corrosion resistance of the soil was designed, in order to speed up the damage failure process, by the stress level, which was that the corrosive ion content in the solution was 5 times as much as that in the soil, along with the salt dosage and solution concentration in compound salt solution showed in Table 3.

Based on the corresponding norms and combined with the natural characteristics of Xining, considering the practical condition of test operation and laboratory, and finally taking into account the operability of the test, relative mass evaluation parameter (ω_1), relative dynamic modulus of elasticity evaluation parameter (ω_2) and relative dynamic modulus of elasticity (E_r) were selected as durability evaluation parameter of concrete. The following formulas

$$\omega_1=(W_r-0.95)/0.05 \tag{1}$$

Where W_r is the relative mass.

$$W_r = \frac{W_t}{W_0} \times 100\% \tag{2}$$

Where W_t is the mass of specimen at time t, W_0 is the initial mass of specimen.

$$\omega_2 = (\frac{v_t^{\ 2}}{v_0^{\ 2}} - 0.6)/0.40 \tag{3}$$

Where v_0 is the initial ultrasonic velocity, v_t is the ultrasonic velocity at time (t).

According to the standard for test methods of long-term performance and durability of ordinary concrete (GB/T 50082-2009) (Chinese Standard 2009), the relation between ultrasonic velocity and relative dynamic modulus (E_r) can be expressed as

$$E_r = \frac{E_t}{E_0} = \frac{v_t^{\ 2}}{v_0^{\ 2}} \tag{4}$$

Where E_0 is the initial dynamic elastic modulus, E_t is the dynamic elastic modulus at time (t).

The mass was measured by electronic balance with an accuracy of 0.01 g and a capacity of 5 kg. Ultrasonic velocity was examined by NM-4A non-metallic ultrasonic testing and analysis instrument, and dynamic modulus of elasticity was measured by STDT-12 concrete dynamic elastic modulus tester. They were all measured in the natural environment. Some factors such as the water content have little effect on the relative value of mass and ultrasonic velocity with time.

The western region of China is rich in solar energy resources, and solar radiation is strong. On the one hand, related literatures about the effect of solar radiation on the performance of concrete are very few; on the other hand, the durability test combined with the factors such as solar radiation, dry and wet, freezing thawing and salt corrosion is also lack of corresponding research.

Considering multiple factors, the deterioration process of specimens in typical saline soil areas of Xining in spring, summer, autumn and winter was simulated. Based on year-round meteorological conditions in Xining areas, for example average sunshine time, average daily sunshine exposure and temperature, the test cycle was shortened on conditions where the same deterioration mechanisms for the specimens were ensured. The testing mechanisms for shortening the service life were as follows:

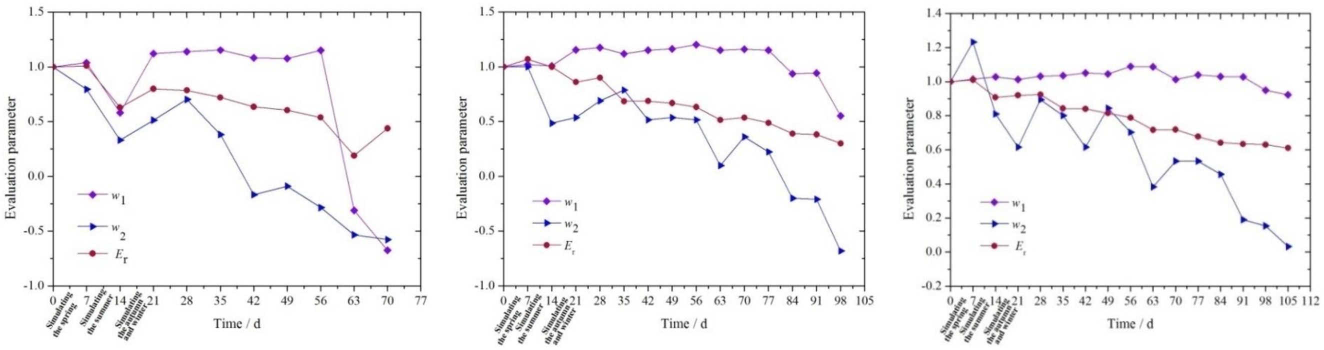
Prior to experiments, all the specimens cured as standards were soaked in prepared solutions for 4 days, in an effort to simulate the effect of spring breeze and high-intensity solar radiation on Xining areas. At the beginning of the experiment, the specimens were taken out and exposed to breeze for 1 hour. According to the meteorological data, the temperature of breeze is 18℃, and the wind velocity is 3.4 m/s; then it was soaked once again in the solutions for 3 hours, followed by exposure to breeze for 1 hour and being soaked again in solutions for 19 hours. During this process, irradiation lights were used for ultraviolet radiation to the specimens for 8 hours. This way 1-day simulation experiment was over. A single-time simulation experiment in spring took a week. A total of 7-time experiments were conducted in this way.

Then the effect of summer high temperature and solar radiation on Xining areas was simulated. The environmental climate simulation test chamber was used for alternate wetting and drying tests. Every day alternation of wetting and drying was conducted twice, with the drying lasting for 2.5 hours each; the temperature was heated to 70℃ ±2℃ with electric heating and then cooled by natural air for 2.5 hours. The 2-time alternation of wetting and drying took 10 hours in all. During this process, the specimens were exposed to ultraviolet radiation for 8 hours. In other words, radiation was conducted in synchrony with the alternation of wetting and drying. Upon completion of the alternation of wetting and drying, the tested pieces were soaked in slat solution for 14 hours. This way 1-day simulation experiment was completed. A single-time simulation experiment in summer took a week. A total of 7-time experiments were conducted in this way.

Finally, the effect of freezing and thawing cycle in autumn and winter on Xining areas was simulated. With the adoption of fast freezing methods, every day the specimens eroded by salt compound underwent freezing and thawing cycle, 6 times, in freezing and thawing experimental device (for each freezing and thawing cycle, the freezing lasted for 2 hours under the temperature of -15℃±2℃ and the thawing lasted for 2 hours under 6℃±2℃ temperature). The slat freezing cycle mentioned here referred to soaking of the whole specimens. A single-time simulation experiment in autumn and winter took a week.

Upon completion of the weekly simulation experiments, the mass (M), ultrasonic velocity (V) and dynamic modulus of elasticity (E_t) of the specimens were measured, respectively. Then we got the relative mass evaluation parameters (ω_1), evaluation parameters of relative dynamic modulus of elasticity (ω_2) and relative dynamic modulus of elasticity (E_r).

Three weeks, namely 21 days, were treated as a major cycle. And the experiment was cycled this way. The specimens were invalided when any one parameter of ω_1 or ω_2 came to zero.



(a) The specimen of ACC1 (b) The specimen of ACC2 (c) The specimen of ACC3

Fig. 1 The rate curves of evaluation parameter of different specimens

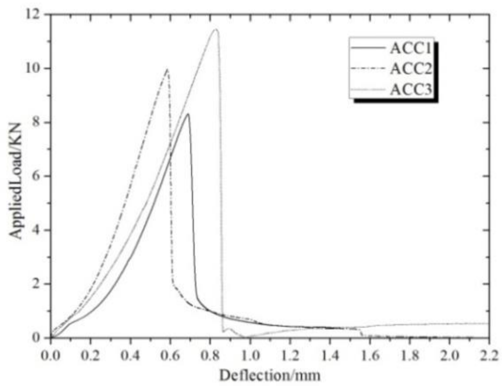


Fig. 2 Load-deflection curves of different specimens

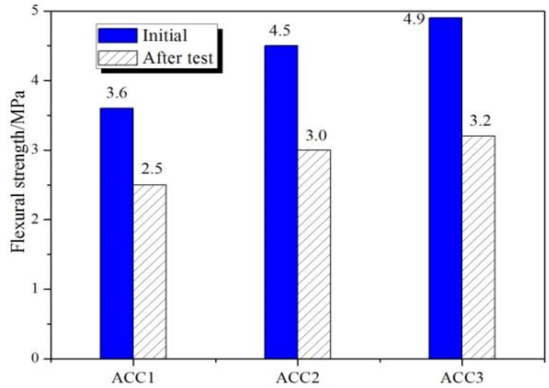


Fig. 3 The flexural strength of different group specimens

3. Results and discussion

Concrete specimens with different mix ratios were tested in simulating natural environment. The rate curves of evaluation parameters of different specimens are presented in Fig. 1.

It can be seen that the first failure time of the specimens (ACC1) was 42d. To be specific, the relative dynamic elastic modulus (ω_2) was less than 0, and the relative dynamic elastic modulus (E_r) was close to the threshold of 0.6, as shown in Fig. 1(a). When the specimens (ACC1) were close to failure, the surface spalling was serious, the mass loss was very large, and the E_r was also decreased sharply; The first failure time of the specimens (ACC2) was 84 d, where ω_2 was less than 0, and E_r was also close to the threshold of 0.6, as shown in Fig. 1(b); The specimens (ACC3) had not yet reached the standard of failure at the censoring time (105 d) , just close to the failure criterion. Particularly ω_2 was close to 0, and E_r was close to the threshold of 0.6, as shown in Fig. 1(c). So far, it can be seen that the deterioration law of ω_2 and E_r was in good agreement. Thus, under the influence of natural environment in Xining area, the durability of fly ash concrete specimens is: ACC3 > ACC2 > ACC1.

In general, when the specimens were failure, ω_2 reached the failure criterion and E_r was close to the threshold of 0.6. However, the relative mass evaluation parameter (ω_1) was not up to the failure criteria. It shows that, in the ALT, ω_2 and E_r can effectively characterize the deterioration process, as the dominant durability degradation index. The reliability of ω_1 is not high, thus it is not suitable to be selected as the main durability degradation index. The dynamic elastic modulus is more sensitive to the environmental factors than the mass loss, so it can reflect the damage degree of concrete. During the test and before the failure, there were a lot of micro cracks in the specimen, and water and salt continued to enter inside the specimen. When measuring the mass, there were a lot of water and salt residue in the specimen, combining with the corrosion products, which made the change of mass not obvious. But he mass changed greatly at the time of failure, which is not conducive to judge the overall deterioration degree within a certain period of time. In case of less surface spalling and before the damage to a certain extent, specimens revealed a rise in mass for each group, the phenomenon of the mass change of the specimen is not obvious, which has also been confirmed by other scholars (Foy *et al*. 1988, Sotiriadis *et al*. 2012, Wang *et al*. 2006, Chen *et al*. 2016).

Basically after the freeze-thaw cycles, E_r decreased greatly compared with the previous two weeks, and it showed a trend of first increasing and then decreasing. Therefore, it can be concluded that the deterioration process of concrete is the outcome of various environmental factors in Xining area. In damage process, the destruction of the salt freezing cycle is the dominant, subordinated by the interaction of the dry-wet cycle and the solar radiation.

According to the standard for test method of mechanical properties on ordinary concrete, which is a modified version of Chinese standard (GB/T 50081-2002) (Chinese Standard 2002), concrete specimens were tested at four-point bending after the ALT. The test results are shown in Fig. 2. Because

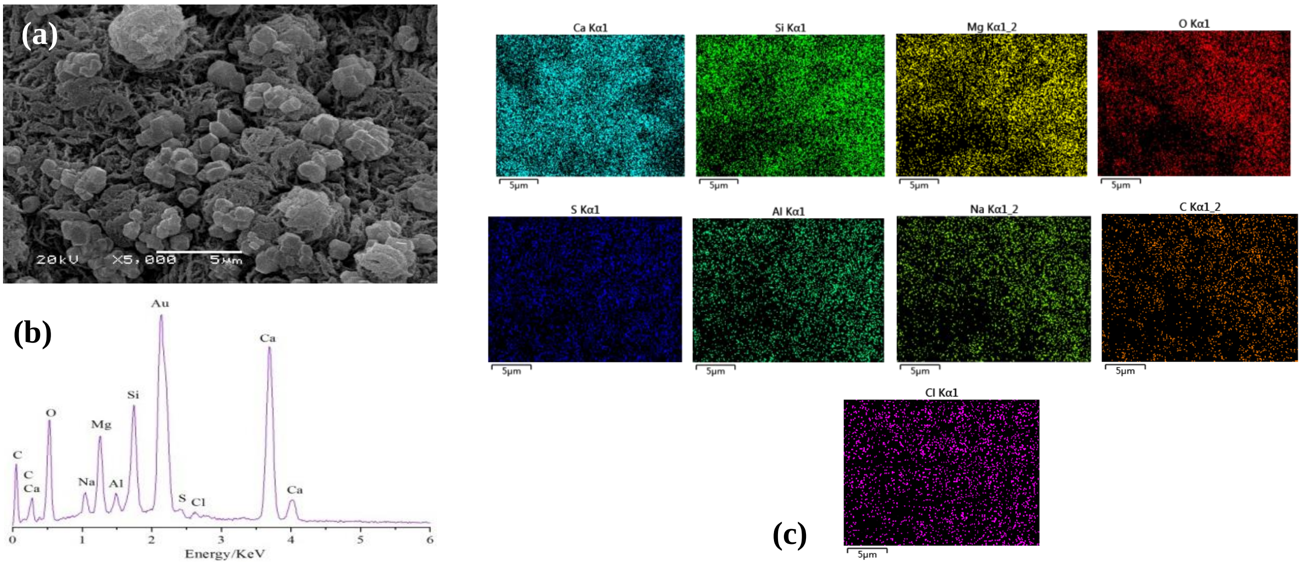


Fig. 4 SEM images of microstructures and plan scanning analysis of sample from ACC2: (a) surface morphology, (b) result of plane scanning, (c) elemental mapping on the sample surface of Ca, Si, Mg, O, S, Al, Na, C, Cl

of non-standard specimens in this paper (100×100×400 mm prisms), the original data needs to be multiplied by the coefficient of 0.85. The average bending strength of each specimen was calculated and compared with that in standard condition. The flexural strength of different group specimens before and after the testing are shown in Fig. 3. It shows that, in the same environment, the flexural strength of each group has a different degree of decline. ACC1 group, ACC2 group and ACC3 group decreased by 30.6%, 33.3% and 32.6%, respectively.

4. Microstructure and chemical properties

The microstructural physical properties of the specimens and chemical element distributions were observed and tested with JSM-5600 LV typed SEM (Scanning Electron Microscope) and the electronic energy equipment. Specimens for SEM analysis were dried using a desiccator and then coated with gold before testing. The scanning speed was 2°/min at a current of 35 mA, and keeping accelerating voltage at 20 kV.

Sampling ACC2 group specimens and the SEM images of microstructures and plan scanning analysis of sample from ACC2 are shown in Fig. 4(a), (b) and (c). It can be seen that, after a long-term corrosion, the microstructure becomes porous, the original crystals of C-H and AFt, which were wrapped by C-S-H gel, have been corroded and decomposed or lost in salt solutions, leaving only a small amount of C-S-H skeleton. Some crystals were distributed in the cement gel and embedded in the pores. The attack of magnesium sulfate on concrete is comparatively the most severe and rapid (Aye and Oguchi 2011). Besides in this study, the sulfate ions (SO_4^{2-}) are involved. These crystals contain corrosion products of interior concrete, such as Calcium carbonate, brucite et al, and some others from the solution. The result of plane scanning for scanning position is shown in Fig. 4(b). The element mass fraction (%): C 15.42, O 42.42, Na 2.74, Mg 7.33, Al 1.74, Si 7.72, S 0.60, Cl 0.57, Ca 22.08; Atomic fraction (%): C 24.40, O 50.39, Na 2.26, Mg 5.73, Al 1.22, Si 5.22, S 0.32, Cl 0.30, Ca 10.47. The surface is rich in Ca, Mg, O, Na and C. The distribution of other elements is more uniform, there is no local enrichment phenomenon. In the ALT, the chemical corrosion product contains lots of $CaCO_3$ and Mg $(OH)_2$. Mg and O mainly to form Mg $(OH)_2$, related chemical reaction

$$Ca(OH)_2 + MgSO_4 + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O + Mg(OH)_2 \quad (5)$$

Ca and C mainly to form $CaCO_3$, as follows

$$Ca(OH)_2 + NaHCO_3 \rightarrow CaCO_3 + H_2O + NaOH \quad (6)$$

Or

$$Ca(OH)_2 + H_2O + CO_2 \rightarrow CaCO_3 + 2H_2O \quad (7)$$

$$n\mathrm{CaO}\cdot \mathrm{SiO}_2 \cdot m\mathrm{H}_2\mathrm{O} + n\mathrm{CO}_2 + \mathrm{H}_2\mathrm{O} \rightarrow n\mathrm{CaCO}_3 + n\mathrm{SiO}_2 + (m+1)\mathrm{H}_2\mathrm{O} \quad (8)$$

This reaction leads to the release of Ca^{2+} ions, phenomenon called leaching (decalcification), which accelerate the transfer of the aggressive ions in the material, and corrosion products contribute to a decrease in mechanical properties (Ganjian and Pouya 2005).

Therefore, as the effect of various factors, the damage and deterioration degree of concrete are aggravated. All factors are added together to lead to the destruction of concrete gradually.

5. Modeling based on stochastic approach

Due to the variability of concrete itself and environmental factors, the service life prediction of concrete will be met with a lot of random, fuzzy and incomplete information. Therefore, there is a need, using the method of probability statistics, to make up for the uncertainty of the

Table 4 Data of regression method

	ACC2			ACC1			ACC3		
i	t_i(h)	x_i	y_i	t_i(h)	x_i	y_i	t_i(h)	x_i	y_i
1	1968	7.584773	-3.08631	936	6.841615	-3.08631	2520	7.832014	-3.08631
2	1968	7.584773	-2.36952	936	6.841615	-2.36951	2520	7.832014	-2.36951
3	1977.6	7.589639	-1.93942	940.8	6.846730	-1.93941	2548.8	7.843377	-1.93941
4	1980	7.590852	-1.62602	984	6.891625	-1.62602	2553.6	7.845259	-1.62602
5	1992	7.596894	-1.37598	984	6.891625	-1.37598	2568	7.850882	-1.37598
6	1992	7.596894	-1.16546	988.8	6.896492	-1.16545	2582.4	7.856474	-1.16545
7	2004	7.6029	-0.98165	1003.2	6.910950	-0.98164	2587.2	7.858331	-0.98164
8	2011.2	7.606487	-0.81682	1008	6.915723	-0.81682	2587.2	7.858331	-0.81682
9	2016	7.608871	-0.66591	1012.8	6.920474	-0.66590	2592	7.860185	-0.66590
10	2016	7.608871	-0.52532	1017.6	6.925202	-0.52532	2592	7.860185	-0.52532
11	2016	7.608871	-0.39238	1017.6	6.925202	-0.39237	2592	7.860185	-0.39237
12	2030.4	7.615988	-0.26494	1032	6.939253	-0.26493	2596.8	7.862035	-0.26493
13	2088	7.643962	-0.14116	1080	6.984716	-0.14115	2688	7.896552	-0.14115
14	2088	7.643962	-0.01936	1080	6.984716	-0.01935	2688	7.896552	-0.01935
15	2100	7.649693	0.102178	1094.4	6.997961	0.10217	2697.6	7.900117	0.10217
16	2112	7.655391	0.225351	1104	7.006695	0.22535	2712	7.905441	0.22535
17	2124	7.661056	0.35253	1108.8	7.011033	0.35252	2712	7.905441	0.35252
18	2160	7.677864	0.487018	1149.6	7.047169	0.48701	2731.2	7.912496	0.48701
19	2160	7.677864	0.634079	1152	7.049254	0.63407	2784	7.931644	0.63407
20	2164.8	7.680083	0.803611	1159.2	7.055485	0.80361	2791.2	7.934226	0.80361
21	2184	7.688913	1.019781	1176	7.069874	1.01978	2808	7.940227	1.01978
22	2184	7.688913	1.392612	1176	7.069874	1.39261	2808	7.940227	1.39261

prediction results caused by the randomness of the parameters and the incompleteness of the information. This can make the results of lifetime prediction more realistic and reliable.

Assuming the life distribution of concrete specimens under accelerated conditions obeys two-parameter Weibull distribution and lognormal distribution respectively, the least squares (LS) method and maximum likelihood (ML) method are used to estimate the parameters of the two class of distribution. Then, the method of correlation coefficient and other indicators were applied to analyze the estimation results, so as to determine the distribution law of accelerated life distribution functions for each group specimens, and further obtained the accelerated life reliability function of concrete.

5.1 Model description

The experimental results are utilized as statistical input parameters in a probabilistic deterioration model below.

5.1.1 Weibull distribution

Weibull distribution is a kind of probability distribution function for reliability analysis and life testing, which was first proposed by Swedish Engineer Weibull Waloddi in 1939. It can adapt to a variety of occasions, with greater flexibility. In particular, the failure analysis and failure prediction can be obtained by a small sample, which is a common failure distribution in reliability engineering and life data analysis.

Assuming the service life of concrete (T) obeys Weibull distribution, the cumulative distribution function $F(t)$, Probability density function (PDF) $f(t)$, the failure rate function $h(t)$ and the reliability function $R(t)$ are given by

$$F(t) = P(T \le t) = 1 - \exp[-(\frac{t-\gamma}{\eta})^m], \quad t > \gamma \tag{9}$$

$$f(t) = \lim_{\Delta t \to 0} \frac{P(t < T \le t + \Delta t | T > t)}{\Delta t} = (\frac{m}{\eta})(\frac{t-\lambda}{\eta})^{m-1} \cdot \exp[-(\frac{t-\gamma}{\eta})^m] \tag{10}$$

$$h(t) = \frac{f(t)}{1-F(t)} = \frac{m}{\eta}(\frac{t-\gamma}{\eta})^{m-1} \tag{11}$$

$$R(t)=P(T>t)=1-P(T\le t)=1-F(t) \tag{12}$$

Where γ is the life limit value or position parameter of the minimum value, $\gamma \ge 0$. Considering that the complexity of the distribution model, in this paper, we use the simplified two-parameter Weibull distribution; m is the shape parameter, m>0, which determines the shape of the density function curve; η is the scale parameter, η > 0; t is

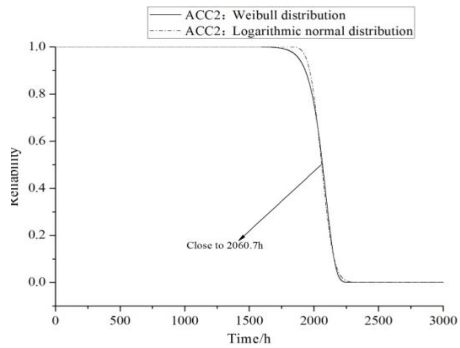


Fig. 5 The reliability curve of different methods

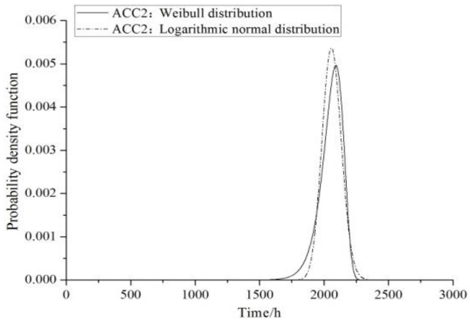


Fig. 6 The PDF curve of different methods

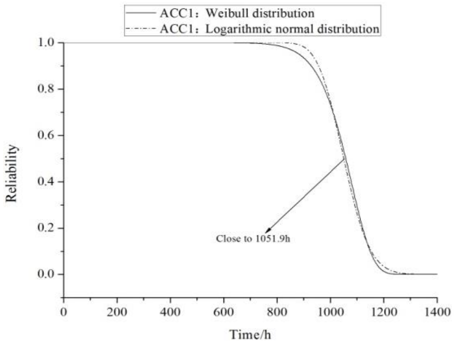


Fig. 7 The reliability curve of different methods

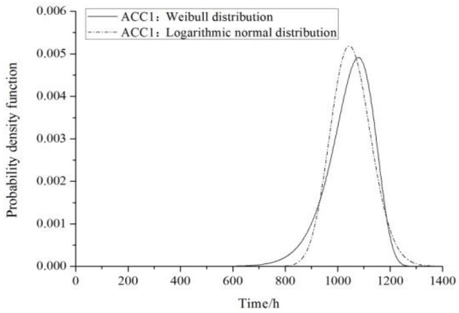


Fig. 8 The PDF curve of different methods

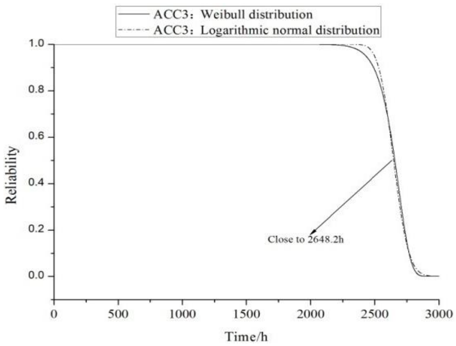


Fig. 9 The reliability curve of different methods

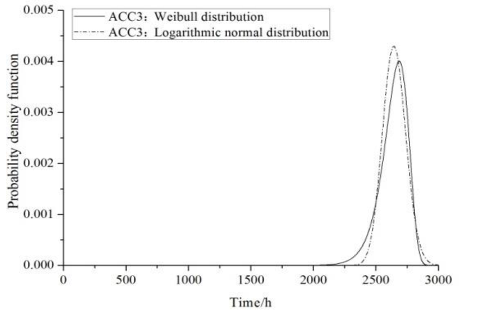


Fig. 10 The PDF curve of different methods

the record value for accelerated life (*T*), $t \geq \gamma$.

5.1.2 Lognormal distribution

If *T* is a random variable, *T*>0 and *Y*=ln*T* meet the normal distribution, $Y = \ln T \sim N(\mu, \sigma^2)$, it's called the *T* satisfies the lognormal distribution. The lognormal distribution is one of distribution function commonly used in reliability domain, and its probability density function *f*(*t*), the cumulative distribution function *F*(*t*) and the reliability function *R*(*t*) are given by

$$f(t) = \frac{1}{\sqrt{2\pi}\sigma t}\exp\left\{-\frac{(\ln t - \mu)^2}{2\sigma^2}\right\} \tag{13}$$

$$F(t) = \int_{-\infty}^{t} f(t)dt = \Phi\left(\frac{\ln t - \mu}{\sigma}\right) \tag{14}$$

$$R(t) = 1 - F(t) \tag{15}$$

Where μ is mean value of logarithm; σ is const logarithmic standard deviation; σ^2 is logarithm variance $\Phi(\cdot)$ is distribution function of standard normal distribution.

5.2 Parameter estimation

In this study, the parameters are estimated based on the ALT of the each group of *N* (*N*=22) specimens.

The LS method is one kind of point estimation method, which is simple and practical (Mao *et al*. 2008). The method is mainly used to estimate the correlation parameters in the linear function, but for the nonlinear Weibull distribution, there is need to go through a certain transformation, the specific steps are as follows:

For the experiment, assuming $t_1 \leq t_2 \leq \ldots \leq t_r (r=n)$ are a complete sample with the sample size (*r*=*n*=22) from the Weibull distribution. Put the accelerated life data into Eq. (9)

$$F(t_i) = 1 - \exp[-(\frac{t_i}{\eta})^m], i = 1, 2, \cdots, n. \tag{16}$$

Table 5 Assessment result of different methods

	Method	Parameter estimation	r	MTTF/h	CI (95%)
ACC2	$LN(\mu,\sigma^2)$	$\hat{\mu}=7.6301597, \hat{\sigma}^2=0.0013039$	0.9998	2060.722	[2029.617,2091.827]
	$Weib(m,\eta)$	$\hat{m}=28.2347, \hat{\eta}=2093.9908$	0.9208	2053.699	[1875.305,2232.093]
ACC1	$LN(\mu,\sigma^2)$	$\hat{\mu}=6.955604, \hat{\sigma}^2=0.0054033$	0.9993	1051.849	[1019.685,1084.013]
	$Weib(m,\eta)$	$\hat{m}=14.4411, \hat{\eta}=1083.76$	0.9588	1045.278	[871.516,1219.04]
ACC3	$LN(\mu,\sigma^2)$	$\hat{\mu}=7.881009, \hat{\sigma}^2=0.0012335$	0.9998	2648.174	[2609.296,2687.052]
	$Weib(m,\eta)$	$\hat{m}=29.2547, \hat{\eta}=2689.459$	0.9279	2639.409	[2417.95,2860.868]

After transposing Eq. (16) and taking double logarithm, then obtained

$$\ln t_i = \ln\eta + \frac{1}{m}\ln[\ln\frac{1}{1-F(t_i)}] \tag{17}$$

Let $x_i = \ln t_i, a = -m\ln\eta, b = m$ and $y_i = \ln[\ln\frac{1}{1-F(t_i)}]$.

Therefore Eq. (17) can be rewritten as

$$y_i = a + bx_i \tag{18}$$

Eq. (18) is a linear regression model, then, according to know the value of each $E(z_i)$, the LS estimator of a and b can be obtained , and finally the estimate of m and η can be obtained. For this study, the sample size of is known, then the median rank can be used as $F(t_i)$. Define $MR(t_i)$ as the median rank at time t_i, and let $MR(t_i)=\frac{n(t_i)}{n+0.4}, F(t_i)\approx MR(t_i)$. Where $n(t_i)$ is the sequence number after sorting data, and then the value of each y_i can be obtained. Data by using regression methods are shown in Table 4, where t_i(h) is the accelerated life of the ith concrete. $\hat{b}=\frac{\sum_{i=1}^{22}(x_i-\bar{x})(y_i-\bar{y})}{\sum_{i=1}^{22}(x_i-\bar{x})^2}=28.2347$, $\hat{a}=\bar{y}-\hat{b}\bar{x}=-215.9057$.

Furthermore, we can get the estimate of m and η $\hat{m}=\hat{b}=28.2347, \hat{\eta}=e^{-\hat{a}/\hat{m}}=2093.9908$.

The linear correlation degree (r) of x_i and y_i is

$$r=\frac{\sum_{i=1}^{22}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{22}(x_i-\bar{x})^2\sum_{i=1}^{22}(y_i-\bar{y})^2}}=0.9208$$

In this study, the median rank is defined as $MR(t_i)=\frac{n(t_i)}{n+0.4}$, however, the failure distribution function can also use $F(t_i)\approx MR(t_i)=\frac{n(t_i)-0.3}{n+0.4}$, $MR(t_i)=\frac{n(t_i)-0.5}{n}$ and $MR(t_i)=\frac{n(t_i)-3/8}{n+1/4}$. $MR(t_i)=\frac{n(t_i)-0.3}{n+0.4}$ is the most commonly used. But when n is sufficiently large, the values of $F(t_i)$ are very close (Saghafi *et al*. 2009).

Similarly, according to the above method, the linear correlation between the variables x_i and y_i can be obtained, r_1=0.9059, r_2=0.8955 and r_3=0.9161 respectively. Both of them are less than 0.9208. The closer to 1 the correlation coefficient is, the service life (T) obeys the Weibull distribution better. So, in this study, select the median rank ($MR(t_i)=\frac{n(t_i)}{n+0.4}$) is more reasonable for the ALT of concrete with a sample size of 22.

Lognormal distribution $LN(\mu, \sigma^2)$ belongs to the position-size distribution, Parameter was estimated by using the maximum likelihood (ML) estimation method. In case of complete sample, the ML estimator of μ and σ^2 are

$$\hat{\mu}=\frac{1}{22}\sum_{i=1}^{22}\ln t_i=7.6301597$$

$$\hat{\sigma}^2=\frac{1}{22}\sum_{i=1}^{22}(\ln t_i-\hat{\mu})^2=0.0013039$$

Let $Z_i=\frac{\ln t_i-\mu}{\sigma}$, the linear correlation degree (r) of variable is

$$r=\frac{\sum_{i=1}^{22}[(Z_i-\bar{Z})(\ln t_i-\ln\bar{t})]}{\sqrt{\sum_{i=1}^{22}(Z_i-\bar{Z})^2\sum_{i=1}^{22}(\ln t_i-\ln\bar{t})^2}}=0.9998$$

5.3 Reliability assessment

Based on the total life data-driven of the whole ACC2 group, the parameter estimation of the total sample was obtained. The research should be based on the combination of model derivation and experimental verification. Taking ACC2 group as an example, stochastic approach was used to model the reliability function. During to the limitation in space, this paper only present the reliability assessment results of other groups.

Bring the parameter values obtained above into the Eq. (12) and Eq. (15), the reliability function curve of the specimen can be obtained, as shown in Fig. 5. Furthermore, the probability density function curve of the specimen is shown in Fig. 6. According to the same method, the reliability function curve and the probability density function curve of ACC1 and ACC3 is also shown in Fig. 7, Fig. 8, Fig. 9 and Fig. 10, respectively.

The reliability function curve and probability density function curve of concrete specimens based on lognormal distribution and Weibull distribution function are shown

Fig. 5 and Fig. 6. As shown in figures, the evaluation results obtained by two methods are similar. As time goes on, the accelerated life reliability of the specimen starts to fall from a certain period of time, eventually down to 0. When the reliability level is 0.5, the median lifetime ($t_{0.5}$) of two methods is close to the average accelerated life $\overline{T}$ ($\overline{T}$ =2060.7h).

As shown in Fig. 6, the probability density curve based on lognormal distribution is on the left side of that based on Weibull distribution, and the left curve is narrower, which is closer to $\overline{T}$. It indicates that the evaluation accuracy of accelerated life based on lognormal distribution is improved.

According to the established model, point estimate of Median-Time-To-Fail (MTTF), 95% confidence interval (CI) of accelerated life are calculated by using different methods. Putting them together with the parameter estimates and correlation coefficients of (r), they are all listed in Table 5.

By contrast, the correlation coefficient based on the lognormal distribution is closer to 1, indicating that it is better than the Weibull distribution method; The value of MTTF is also close to $\overline{T}$ =2060.7h; the length of 95% confidence interval is shorter, also shows the evaluation results is more accurate.

In summary, the lognormal distribution function is more suitable to describe the reliability process of concrete specimens under ALT conditions.

6. Conclusions

Based on the results of the investigation, the main conclusions can be drawn:

• For indoor artificial accelerated durability life test, it should fully consider the different climatic conditions in different regions. Especially in the western region of China, the influence factor of the high solar radiation intensity should be considered. It is necessary to design a concrete ALT system to simulate the real natural environment, and the ALT is more close to the service process of the concrete structure under the actual conditions.

• In the process of ALT of concrete, the relative dynamic elastic modulus can be used as the dominant durability evaluation parameter, which is more sensitive to the environmental factors than the relative mass evaluation parameter. In the process of the damage, the destruction of the salt freezing cycle is the dominant, and subordinated by the interaction of the dry wet cycle and the solar radiation.

• The reliability evaluation method based on accelerated life data provides a solution to the reliability evaluation of concrete with long life and small sample. Weibull distribution and lognormal distribution can effectively describe the durability degradation of concrete specimens. Relatively, the lognormal distribution is more effective.

• What needs to be further studied is to establish the relationship between normal stress level in actual environment (temperature stress, humidity stress and salt concentration stress, etc.) and the high stress level in the accelerated environment, that is determine the relational model between the damage degradation rate of concrete and the applied stress. Finally, the reliability assessment and life prediction of concrete specimens under real environment can be made by using accelerated life data.

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