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Ecological Study of Deterioration Performance for Concrete in Saline Soil Environment

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Abstract

According to the principles of terrestrial ecology, the deterioration of concrete used in highway engineering in saline soil environment of Inner Mongolia was studied, and simulated in the laboratory compound salt solution (NaCl, Na_2SO_4, $NaHCO_3$ and Na_2CO_3), single salt solution (Na_2SO_4) and test pieces for mix proportion of three kinds of concrete for datum, mixing 20% fly ash and mixing 20% metakaolin etc. Prediction model of deterioration in concrete was established. It is shown that ecological capacity of anti-wetting-drying cycle in concrete mixing metakaolin is the strongest in compound salt-freeze-thaw cycle test and single salt-freeze-thaw cycle test, freeze-thaw resistance of concrete mixing fly ash is the strongest. Measured values for deterioration prediction model of compressive strength of compound salt-wetting-drying cycle and deterioration prediction model for relative dynamic elastic modulus of compound salt-freeze-thaw cycle were respectively verified in the test, and fitting degrees were respectively 0.880 and 0.929. Resources such as Metakaolin and fly ash in the environment were utilized to improve concrete durability in the environment, which had practical guidance meaning to performance deterioration prediction of concrete material under working condition and environment.

Keywords: terrestrial ecology, saline soil, concrete, compound salt wetting-drying cycle test, single salt wetting-drying cycle test, compound salt freeze-thaw cycle test, single salt freeze-thaw cycle test

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INTRODUCTION

Terrestrial ecology has a wide variety of applications like resources management, and in the long run, be effective for conservation measures. Additionally, soil properties like moisture, pH, nutrient and chemical content, and soil type may be studied. Hetao Area in Inner Mongolia is located in the upstream of the Yellow River, and it belongs to arid and semi-arid climate zone with high temperature and high cold, large difference in temperature between day and night, strong evaporation and serious soil salinization. Harmful irons of saline soil in the area will cause corrosion or damage to concrete materials under coupling for many factors of environment, which causes performance deterioration of concrete structure, and seriously threatens service and durability of concrete structure. In China, ecological researches on deterioration damage of salt on concrete and durability are mainly concentrated on coastal areas, and inland salt lake areas. There are relatively fewer ecological researches aimed at concrete deterioration damage and durability under saline soil environment in the Hetao Area in Inner Mongolia.

Through traffic infrastructure construction for more than ten years, road traffic network in Inner Mongolia Autonomous Region has taken shape, and backbone road network connecting the east and west, the south and the north and radiating the whole area has been formed basically, which provides effective guarantee for economic rapid development in Inner Mongolia Autonomous Region. Seriously affected by soda alkaline soil, salt and alkaline precipitations occur in large area besides road in G6 Expressway and 110 National Highway for sections in Wuyuan County, Linhe City and Dengkou County in Hetao Area, and protective layer falling off and crack damage of concrete structure were formed for road concrete facilities were in high alkaline and saline environment for long time seriously affecting traffic infrastructure. Powers (949) proposing salt freezing ecological damage theory of concrete in the earliest time thought pore structure in concrete would affect durability of concrete, then he proposed hydrostatic pressure theory and osmotic pressure theory. Air-entrained concrete was successfully researched according to those two kinds of theory. Academician Wu and Lian (1999) thought single air-entrained concrete could not solve concrete damaged by salt freezing, and concrete damage was the result subject to coupling of many factors. Concrete

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Table 1. Total mass percentage of soluble salt in different depth (%)

Measurement point	0cm~5cm	5cm~25cm	25cm~50cm	50cm~75cm	75cm~100cm	0cm~100cm
G6 W	0.6745	0.2598	0.2593	0.2576	0.2980	0.3498
110 W	0.4991	0.1747	0.1185	0.1627	0.2792	0.2468
110 D	0.2688	0.1286	0.1031	0.0725	0.0847	0.1316

Table 2. The PH value of soil at a different depth from the surface

Measurement point	0cm~5cm	5cm~25cm	25cm~50cm	50cm~75cm	75cm~100cm	Average PH value
G6W	9.69	9.79	9.75	9.80	9.77	9.76
110W	9.03	9.11	9.00	9.02	8.78	8.99
110D	9.77	9.72	9.53	9.38	9.28	9.54

Table 3. The mass percentage of various important ions

Depth (cm)	G6 W		110 W		110 D	
	$\omega(Cl^-)/\omega(SO_4^{2-})$	$\omega(CO_3^{2-}+HCO_3^-)/\omega(Cl^-+SO_4^{2-})$	$\omega(Cl^-)/\omega(SO_4^{2-})$	$\omega(CO_3^{2-}+HCO_3^-)/\omega(Cl^-+SO_4^{2--})$	$\omega(Cl^-)/\omega(SO_4^{2-})$	$\omega(CO_3^{2-}+HCO_3^-)/\omega(Cl^-+SO_4^{2-})$
0~5	0.43	0.30	11.64	0.25	0.47	0.56
5~25	0.47	0.87	3.36	0.74	1.61	1.52
25~50	45.4	1.79	2.17	0.65	0.31	1.63
50~75	0.85	1.00	3.71	0.74	1.54	2.88
75~100	0.89	0.52	2.80	0.65	0.77	2.25

durability researches at home and abroad (Ai et al. 2015, Huang 2013, Lin et al. 2014, Zhang 2014) are mainly focused on damage of chloridion and sulfate ion erosion on concrete structure. Chloridion can corrode rebar in concrete to cause deterioration of the integral strength for the concrete structure. Sulfate ion forms $Na_2SO_4 \cdot 10H_2O$ crystal, and crystal size expands to generate crack, which causes concrete structure deterioration. Practical environment working condition was simulated, and compound solutions for NaCl, Na_2SO_4, $NaHCO_3$ and Na_2CO_3 were prepared in the research. Test piece for normal concrete, fly ash concrete and metakaolin concrete were prepared, and concrete deterioration mechanism and durability under working condition of stimulation environment were explored through brining-wetting-drying cycle test and brining-breeze-thaw cycle test. It has practical guidance meaning to deterioration mechanism and durability service of road concrete structure in Hetao Area in Inner Mongolia.

EXPERIMENTAL

Soil Analysis

According to the researches of Zhang et al. (2015) and Feng (2014), through analyzing soil sample at W in G6 expressway, and W and D in 110 National Highway, contents for chloridion, sulfate ion, carbonate ion/bicarbonate ion were detected. Test pit was conducted on site for sampling, respectively at 0cm-5cm, 5cm-25cm, 25cm-50cm, 50cm-75cm and 75cm-100cm, with each layer subject to quartering for sampling 2000g. Mass fraction for the total amount of soluble salt in different depth, PH values at different depths of soil and mass fraction ratio of important ions are respectively shown in **Table 1**, **Table 2** and **Table 3**. On-site soil sample collection and concrete corrosion are shown in **Fig. 1**.

a. Soil sample taking site b. Concrete corrosion condition

Fig. 1. Site collection of soil samples and situation of concrete corrosion

It can be known from **Table 1** and **Table 2** that soluble salt contents of sampling soil in different depths are different, and soluble salt content in the surface layer of soil is basically the highest. Soluble salt content and PH at W in G6 Expressway are the highest, and average PH value is 9.76.

According to research of ZHANG Hong about engineering classification regulations of saline soil in: the soil is divided into saline-alkali soil bounded by $(CO_3^{2-}+HCO_3^-)/(Cl^-+SO_4^{2-}) > 0.3$. It can be known from analyzing detection data in **Table 3** that soil in the sampling area is saline-alkali soil commonly known as soda alkaline soil.

Table 4. The parameter of reference concrete

Parameter	Group 1	Group 2	Group 3
Water	0.48	0.43	0.53
Cement	1	1	1
Sand	1.85	1.66	2.02
Rubble	3.44	2.97	3.94
Slump	9.50	6.30	17.00
Water-cement ratio	0.48	0.43	0.53
Air content	3.99	2.96	4.22

Notes: material consumptions of mix proportion are both relative proportion of quality

Raw Material

Cement with strengthen of 42.5Mpa is supplied from Mengxi. High performance metakaolin is supplied from Inner Mongolia Chaopai Company with average particle size of 2.5μm, specific surface area of $16m^2/g$, ignition loss of 0.5%, and water demand ratio of 108%. Fly ash with I-level, Fine aggregate with fineness modulus of 2.9 and water content of 3%, and Rubble with particle size of 5~25mm. are supplied from Inner Mongolia.

Preparation of Test Piece

According to the researches of Sun et al. (2016) and Su et al. (2014) about the study of long-term performance and durability of concrete, concrete wetting-drying cycle test shall be subject to 100mm×100mm×100mm cubic test piece, and concrete freeze-thaw cycle test shall be subject to 40mm×40mm×160mm cuboid test piece. Compressive strength shall be subject to 150mm×150mm×150mm cubic test piece. Test piece shall be provided with test after 28d of standard maintenance.

Concrete Mix Proportion

In order to reveal performance deterioration mechanism of road concrete structure under saline environment in cold and arid regions, concrete deterioration and durability of three kinds of mix proportions for datum concrete, concrete mixing 20% fly ash and concrete mixing 20% metakaolin etc. were researched in the test. Aggregate is continuous grading (5~10:10~20:20~25=2:3:5), and all parameters of datum concrete are shown in **Table 4**.

Mix proportion of which water-cement ratio is 0.48 shall be selected to be as datum mix proportion. In order to explore influence of admixture on concrete strength in earlier period, compressive strength data of concrete for 3d, 7d and 28 d shall be collected. It is shown in researches of Zhang et al. (2014) and Liu et al. (2015) that mixing amounts of fly ash and metakaolin will affect all performances of concrete, and previous literatures and indoors test data shall be referred to confirm datum mix proportion. On this basis, cement quality internally mixing 20% fly ash and 20% metakaolin concrete are respectively expressed in I0, II20 and III20. Test result of compressive strength is shown in **Table 5**.

Table 5. Concrete compression test results

No.	Compressive strength (Mpa)			Mix proportion
	3d	7d	28d	
I0	24.9	34.4	60.5	Subject to concrete mix proportion in datum group 1.
I20	16.1	30.8	51.1	
III20	17.8	38.9	65.8	

Preparation of Composite Solution

In order to simulate soda alkali soil environment in this area, solution with similar component shall be prepared in laboratory to simulate soil environment, and concrete test piece shall be provided with corrosion damage test. It shall be compared with influence of sodium sulfate solution with relatively mature research result on concrete durability. According to soil detection composition, it is planned to adopt four kinds of anion with environment characteristics for Cl^-, SO_4^{2-}, CO_3^{2-} and HCO_3^-etc., and Na^+ shall be adopted to be positive ion to prepare soluble compound salt solution.

According to detection result, average soluble salt concentration is 0.217%. In order to quicken damage speed of test and test piece, compound solution concentration shall be increased by 10 times, and it is planned to adopt 2.178% compound solution concentration. Two kinds of contrast solution shall be designed in wetting-drying cycle test and freeze-thaw cycle test, and sodium sulfate solution shall also be subject to the same mass fraction of 2.178%.

Design for Wetting-drying Cycle Test and Freeze-thaw Cycle Test

Wetting-drying cycle test is subject to NELD-VS83 testing machine. At present, there are no standards for wetting-drying cycle test of concrete durability of compound salt solution. Compared the effects on concrete corrosion of compound salt solution with sodium sulfate solution, simulated the corrosion of highway concrete in the region affected by soda alkaline soil.

Freeze-thaw cycle test is subject to NELD-FC810 testing machine, and freeze-thaw cycle test is shown in **Fig. 2**. Before freeze-thaw cycle test starts per time, test piece shall be soaked in clean water, compound salt solution and single salt solution for 2d, then freeze-thaw cycle test shall be conducted for 25 times. 1 big cycle is

Fig. 2. Freeze-thaw Cycle Test

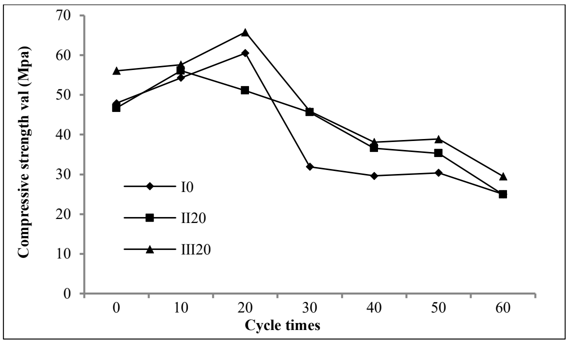


Fig. 3. Concrete compressive strength value after wetting-drying cycle tests of compound salt

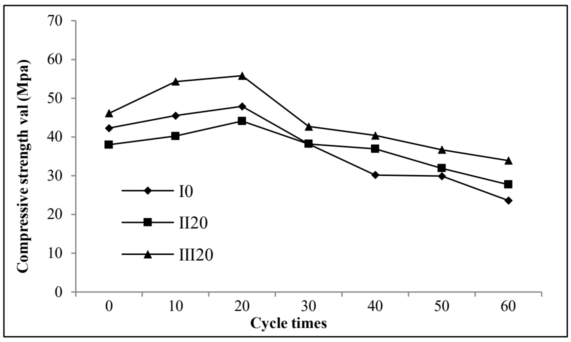


Fig. 4. Concrete compressive strength value after wetting-drying cycle tests of single salt

1 time soaking pulsing freeze-thaw cycle for 25 times. After 1 big cycle, appearance change, mass loss rate and changes in relative dynamic elastic modulus of concrete test piece shall be measured.

RESULTS AND DISCUSSION

Result and Analysis of Brining-wetting-drying Cycle Test Concrete Strength

Test piece of compressive strength in the test is subject to datum concrete for reference, and mixing fly ash and metakaolin both strengthen compressive strength of concrete. Compressive strength result of concrete is shown in **Table 6**. Mixing metakaolin obviously strengthens concrete strength in earlier period. Strength III20 of 7d and 28d are respectively improved by 13.1% and 8.7% than I0.

In the research, compressive strength values of concrete test piece after soaking for 10, 20, 30, 40, 50 and 60 days shall be measured. Compressive strengths for brining-wetting-drying cycle test are shown in **Fig. 3** and **Fig. 4**.

Result and Analysis of Compound Salt-wetting-drying Cycle Test and Single Salt-wetting-drying Cycle Test

It can be known from **Fig. 3** and **Fig. 4** that after wetting-drying cycle test starts, strength of datum concrete declines rapidly but loss rate of compressive strength for concrete mixing fly ash is less than datum concrete, which shows that fly ash strengthens concrete strength in the later period. In wetting-drying cycle test, there are solutes such as NaCl, Na_2SO_4, $NaHCO_3$ and Na_2CO_3 etc. in compound solution, and they will enter inner pore of concrete under the function of wetting-drying cycle function to be saturated to form crystal. It is shown in existing research literatures (Liu and Hansen 2016, Su and Wang 2015, Winkler 1975) that NaCl will generate 130% volume expansion at the time of transforming into $NaCl{\cdot}2H_2O$ crystal, and $Na_2SO_4{\cdot}10H_2O$ will generate 311% volume expansion. Na_2CO_3 will generate 148% volume expansion at the time of transforming into $Na_2CO_3{\cdot}10H_2O$, and volume expansion will form internal stress damage at the time of forming crystal to generate new crack and pore. Moving in cycles will generate accumulative damage of concrete.

Analyzing from chemical corrosion damage perspective, $NaHCO_3$ will react with $Ca(OH)_2$ generated by cement hydration, thus generating $CaCO_3$, Na_2CO_3 and $CaCO_3$ to react with calcium silicate C-S-H of hydration to form silicon grey gypsum crystal. Sulfate ion reacts with $Ca(OH)_2$ generated by cement hydration to form gypsum and ettringite etc., but chloridion restrains corrosion of sulfate ion in certain degree according to previous literatures. In general, no matter it is in compound salt solution or sulphate solution, products formed after harmful ions react with $Ca(OH)_2$ generated by cement hydration reacting with hydrated calcium silicate gel C-S-H again will cause continuous decomposition of set cement, and cause concrete strength loss until damage.

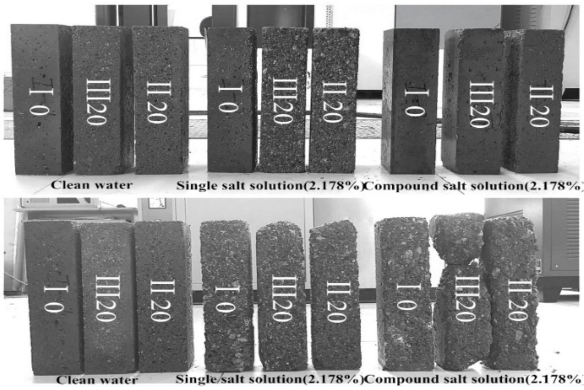
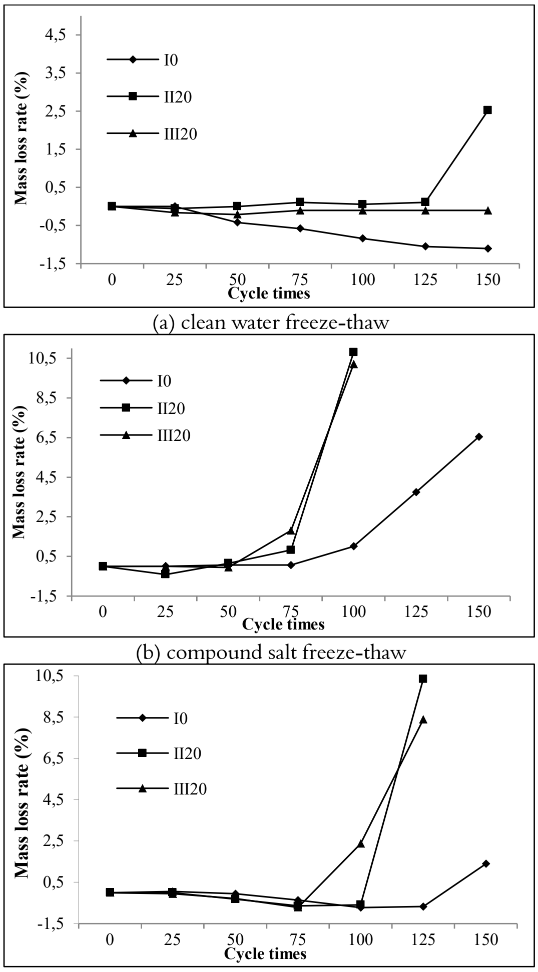


Fig. 5. Mass loss of concrete specimens after different cycle times freeze-thaw cycle test

Result and Analysis for Brining-freeze-thaw Cycle Test

Concrete test piece after freeze-thaw test is shown in **Fig. 5**. It can be known from **Fig. 4** and experiment result of 75 freeze-thaw cycle tests and 150 freeze-thaw cycle tests that cement protection layer on the surface of concrete test piece falls off and aggregate gradually exposes accompanying aggregate falling off with different corrosion degrees due to different soaking solutions with the increasing of freeze-thaw cycle times. In freezing-thaw cycle test of clean water soaking, damage degree of test piece is the smallest, and falling off of protective layer occurs. In freeze-thaw cycle test of compound salt soaking, damage degree of test piece is the largest, and crack occurs in concrete test piece mixing metakaolin. In freeze-thaw cycle test of sodium sulfate solution soaking, damage of test piece is in the middle place accompanying falling off of protective layer and aggregate. There are white saline material precipitating and crystallizing at the time of taking out test piece once, which reflects solubility of single solute Na_2SO_4 declines to precipitate crystal due to low temperature.

Test result for mass loss rate and relative dynamic elastic modulus of concrete test piece after freeze-thaw test are shown in **Fig. 6** and **Fig. 7**. It can be known from **Fig. 5** that in freeze-thaw cycle of clean water soaking, concrete test piece does not reach damaging and stopping test condition. Comparing freeze-thaw cycle test of compound salt and sulfate soaking, obvious damage occurs in concrete test piece, and test stop is all because that mass loss of test piece is > 5%. It can be seen from this that coupling freeze-thaw cycle function under saline soil environment will quicken concrete corrosion, and falling off of protective layer and exposure and falling off of aggregate will occur. Concrete strength includes chemical adhesion and



(a) clean water freeze-thaw

(b) compound salt freeze-thaw

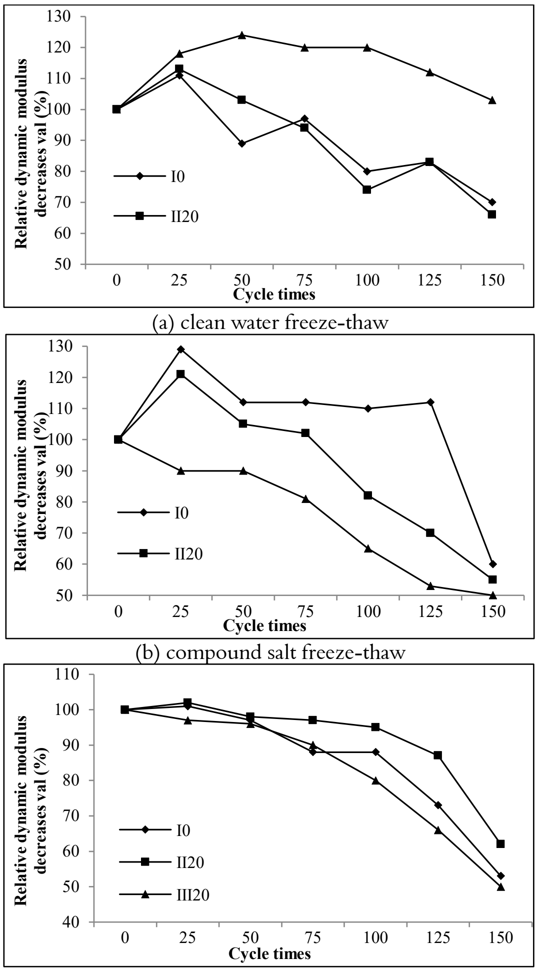
(c) single salt freeze-thaw

Fig. 6. Concrete mass loss rate after freeze-thaw cycle test

mechanical interaction between aggregate and set cement. Falling off of aggregate and decomposition of set cement will cause rapid weakening of concrete strength until test piece is damaged. Admixture can help concrete strengthen strength values in different ages to resist damage of brining freeze-thaw cycle. Performance deterioration rule of clean water-freeze-thaw cycle is the same as single salt -freeze-thaw concrete, and relative dynamic elastic modulus of III20 declines at least. Loss rate for relative dynamic elastic modulus of II20 is slightly smaller than I0, but declining trend of II20 relative dynamic elastic modulus is gentle, which shows that II20 has resistance capability of slowing down damage under these two kinds of working conditions.

Concrete Deterioration Prediction Model

Compressive strength change of concrete in wetting-drying cycle test is obviously divided into 4 stages: linear enhancement stage for strength; rapid descending stage for strength; slow declining stage for



(a) clean water freeze-thaw

(b) compound salt freeze-thaw

(c) single salt freeze-thaw

Fig. 7. Relative dynamic modulus of concrete after freeze-thaw cycle test

strength; relatively rapid declining stage for strength. Compressive strength decaying can be explained by utilizing wetting-drying cycle damage process of concrete. Concrete is composite material composed of cement, coarse and fine aggregate and admixture, and there are micro-void and micro-crack etc. inside concrete in the beginning of forming. Under working condition of wetting-drying cycle for salt solution, firstly, crystal is formed in initial damage, and crystal has compaction function in a certain degree to make concrete strength increase; then crystal generates crystal-expansion function, and soluble ions react with cement hydration products to form harmful matters of gypsum and ettringite etc. to make micro-defects such as micro-crack rapidly run through and make concrete strength rapidly decline; after intersection of micro-defect, speed of strength decaying declines to enter slow decaying period of strength; with increasing of brining wetting-drying cycle times, more cracks and damages occur inside concrete to make concrete enter rapid damage stage for strength in the next round. It shall be subject to fourth-order polynomial simulation, and prediction model for compressive strength deterioration under compound salt-wetting-drying cycle is shown in Equation (1): C is compressive strength value and T_1 is wetting-drying cycle test times. a_1, b_1, c_1, d_1 and e_1 are respectively coefficients related to test condition, and concrete admixture and test cycle times.

$$C(T_1) = a_1 \times {T_1}^4 + b_1 \times T_1^3 + c_1 \times T_1^2 + d_1 \times T_1 + e_1 \quad (1)$$

Freeze-thaw cycle times and relative dynamic elastic modulus of concrete basically conform to approximate damage model of Loland stimulation in freeze-thaw cycle test. Firstly, relative dynamic elastic modulus increases, then it presents nonlinear decline. Therefore, it shall be subject to Loland model to simulate, and deterioration prediction model of relative dynamic elastic modulus under compound salt-freeze-thaw cycle is shown in Equation (2): R is relative dynamic elastic modulus value, and T_2 is cycle times of freeze-thaw cycle test. a_2, b_2, c_2 and d_2 are coefficients related to test conditions, and concrete admixture and test cycle times.

$$R(T_2) = a_2 \times T_2^3 + b_2 \times T_2^2 + c_2 \times T_2 + d_2 \quad (2)$$

III20 compressive strength prediction model of compound salt-wetting-drying cycle test and prediction model for II20 relative dynamic elastic modulus of compound salt-freeze-thaw cycle test are respectively shown in **Fig. 8** and **Fig. 9**. It can be known from **Fig. 8** and **Fig. 9** that the model reveals performance deterioration rule for road concrete in Hetao Area in Inner Mongolia, taking compressive strength under compound salt-wetting-drying cycle test of III20 and relative dynamic elastic modulus under compound salt-wetting-drying cycle test of II20 as example. According to deterioration theory model of concrete given in the Thesis, it fits well with compressive strength model and relative dynamic elastic modulus, and performance deterioration trends of concrete under these two kinds of working conditions were predicted. Measured values (as shown in **Fig. 8**) for compressive strength under compound salt-wetting-drying cycle were predicted in compressive strength deterioration equation (as shown in **Table 6**) under compound salt-wetting-drying cycle, and fitness value was 0.880. Fitness degree for relative dynamic elastic modulus value (as shown in **Fig. 9**) under compound salt-freeze-thaw cycle was predicted to be 0.929 in deterioration equation (as shown in

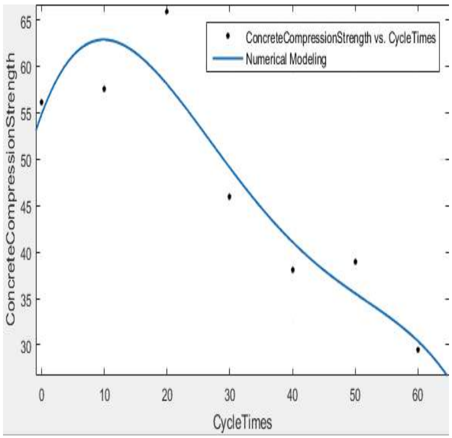


Fig. 8. Prediction modeling of compressive strength of III20 under compound salt-freeze-thaw cycle test

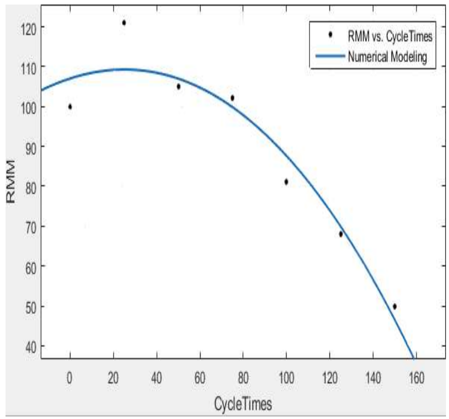


Fig. 9. Prediction modeling of relative dynamic modulus of II20 under compound salt-freeze-thaw cycle test

Table 7) for II20 relative dynamic elastic modulus under compound salt-freeze-thaw cycle as well.

Table 6. Compressive strength degradation equation of concrete under compound salt-freeze-thaw cycle test

Group	Deterioration equation	R-square
III20	$C(T_1) = 3.25 \times T_1^4 + 5.545 \times T_1^3 + 2.927 \times T_1^2$ $-19.5 \times T_1 + 49.08$	0.880

Table 7. The relative dynamic modulus degradation equation of concrete in compound salt-freeze-thaw cycle test

Group	Deterioration equation	R-square
II20	$R(T_2) = -0.5 \times T_2^3 - 12 \times T_2^2 - 20.85 \times T_2$ $+ 99.86$	0.929

CONCLUSION

1. In the test, rapid decay occurs after increasing in test piece strength of compound salt-wetting-drying cycle, and compressive strengths after 60 times when mixing amount is 20% are: metakaolin > fly ash > datum, loss rate of compressive strength: datum > metakaolin > fly ash, metakaolin concrete has the strongest capacity to resist wetting-drying cycle test.
2. In freeze-thaw cycle test of the ecological research, apparent stripping occurs in test piece for freeze-thaw cycle of clean water soaking, and mass-loss rate has not reached 5%. Decrease value of relative dynamic elastic modulus has not reached 60%. There are no damages in freeze-thaw cycle test for compound salt, single salt and sulfate soaking, and apparent stripping and aggregate falling off occur in concrete. Mass loss exceeds 5% after freeze-thaw cycle for 125 times, and decrease values for relative dynamic elastic modulus are both less than 60%. Damage degree of compound salt-freeze-thaw is larger than that of single salt, frost resistance for test piece of fly ash concrete in compound salt-freeze-thaw test is the strongest.
3. Measured values were predicted in deterioration prediction model (1) for compressive strength under compound salt-wetting-drying cycle and deterioration prediction model (2) of relative dynamic elastic modulus under compound salt-freeze-thaw cycle in the test, and fitness degrees were respectively 0.880 and 0.929, which had practical guidance meaning to predict concrete performance deterioration under the working condition in this area.

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