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Freeze-thaw damage model for cement pavements in seasonal frost regions

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Abstract. In order to evaluate the damage of cement concrete pavement after the freeze-thaw cycle in the seasonal frozen area, it is determined that the dynamic elastic modulus and flexural tensile strength by analyzing the influence of the freeze-thaw on the concrete performance. The two indexes are most sensitive to the evaluation of the freeze-thaw damage of the pavement. Based on regression analysis method, two freeze-thaw damage models based on two indexes are established, and the goodness of fit and significance state of the model are tested. The applicable conditions of the two models are determined by response surface test method. The validity of the model is verified by comparing the prediction results of the existing model. The results show that when the water cement ratio is 0.450.48, the gas content is 1 % – 4 %, and the freezing temperature is – 15 °C – 25 °C. The model based on dynamic elastic modulus index has the best evaluation effect. When the water cement ratio is 0.4–0.46, the gas content is 1–3.5, and the freezing temperature is below – 5 °C, the model based on the flexural tensile strength index has the best evaluation effect. The explainable parts of the two models are 99.1 % and 99.2 % respectively, and the fitting degree of the damage evaluation value and the measured damage value is 0.997 and 0.998 respectively. The model has a good fitting degree. The evaluation effect of the model is better than that of the existing model. The determination of the model is of great significance to the future pavement maintenance work.

1. Introduction

Freeze-thaw damage has a significant influence on the mechanical properties of concrete. It is a representative index to evaluate the durability of concrete. After freezing-thawing damage, the surface of cement concrete pavement will produce peeling, pockmarked surface, exposed surface and other phenomena, and internal diseases such as strength decline, frost resistance and permeability reduction will occur, which will seriously affect the driving safety and service life of cement concrete pavement [1]. Therefore, reasonable evaluation of freezing-thawing damage of cement concrete pavement is of great significance to improve traffic safety and extend the service life of pavement [2–4].

The research on freeze-thaw damage of concrete started earlier at home and abroad, and the research results focus on studying the influence of freezing-thawing cycle on different types of concrete or the attenuation law of mechanical properties of concrete under freezing-thawing action. Alsaif [5] designed the rapid freeze-thaw test, compared the damage degree of three kinds of freeze-thaw media to concrete, and established the relative residual compressive strength and flexural strength attenuation equations based on the relative dynamic elastic modulus, which can be used to calculate the compressive strength and flexural strength, but cannot directly calculate the damage degree of concrete. Smith et al [6–8] analyzed the difference of frost resistance between recycled concrete and ordinary concrete, and concluded that the strength grade has a greater impact on recycled concrete, but the strength is only a part of the mechanical properties of concrete, which is not enough to be the only index reflecting the state of

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freeze-thaw failure. Nayak [9] analyzed the characteristics of freeze-thaw damage of concrete, and confirmed that the freeze-thaw damage of concrete is similar to fatigue. The number of freeze-thaw cycles is random under certain damage, but it is only qualitative analysis, and no calculation method of damage is proposed. Grubesa et al [10, 11] used the dynamic triaxial repeated loading method to test the dynamic elastic modulus of subgrade soil, and determined that the dynamic elastic modulus is significantly affected by freeze-thaw, but there is no comparative analysis with other mechanical performance indexes. Fursa et al [12–15] established the concrete freeze-thaw compression failure model based on the improved kupfer-gerstle criterion, which can obtain the compressive strength loss of concrete under different freeze-thaw cycles. However, the freeze-thaw action can damage both the flexural strength and the tensile strength, so the concrete damage model established only based on the compressive strength is not practical. Tianjun et al [16–20] studied the damage mechanism of concrete holes structure under the coupling environment of fatigue load and freeze-thaw cycle, but did not establish the relationship between damage amount, load and freeze-thaw times.

Although the above research deeply analyzes the influence of freeze-thaw damage on various performance indexes of concrete, most of them are based on indoor tests, and do not take into account the actual damage condition of cement concrete road affected by freeze-thaw under the effect of climate in the seasonal freezing area. Moreover, most of them only use one model to evaluate the index, and the damage model established is low accuracy. Therefore, the freeze-thaw damage model of cement concrete pavement suitable for the seasonal freezing area needs to be further improved.

In this study, the freeze-thaw damage index is determined by comparing the influence degree of the concrete performance index affected by the freeze-thaw action. Based on the actual investigation data of the typical roads in the seasonal frost regions, the freeze-thaw damage model is established, and the applicable conditions of the model are determined through the test, to achieve the purpose of establishing the freeze-thaw damage model of the cement concrete pavement suitable for the seasonal frost regions.

2. Methods

2.1. Parameter determination of freeze-thaw damage evaluation model

The indexes for evaluating freezing-thawing damage of cement concrete pavement include dynamic elastic modulus, mass change rate, water absorption rate, flexural strength, compressive strength and crimp-compression ratio [21–25], among them, the mass change rate is the ratio of the mass change value before and after freezing and thawing to the mass before freezing and thawing, from which model parameters for evaluating freezing-thawing damage of cement concrete pavement in seasonal frost regions are selected. According to the test of Sun ming et al [26–29], the binder is CEM I 42.5 N; the coarse aggregate is gravel and pebble with the nominal particle size is 5-20 mm, the apparent density is 2808 kg/m^3; the fine aggregate is natural river sand with the nominal diameter is less than 4.75 mm. Water is a common life in Harbin, Heilongjiang Province, China. The concrete strength grade is C30; the concrete mix ratio is shown in Table 1. Analyze the concrete performance attenuation data obtained through the test, and compare the changes of the above six indexes under the condition of gradually increasing freeze-thaw cycles, as shown in Fig. 1 and Fig. 2.

Table 1. Mix proportion of concrete.

Code	W/C	Mix proportion of concrete (kg/m^3)			
		Cement	Coarse aggregate	Fine aggregate	Water
NC	0.48	358.34	1096.75	598.42	183

In Fig. 1, with the increasing number of freeze-thaw cycles, the relative dynamic modulus of elasticity and relative compressive strength are reduced, and the loss of relative dynamic modulus of elasticity is more serious, reaching a loss rate of 40 % before 150 cycles. The reason is that the freeze-thaw action makes the pores of concrete larger, the compactness worse and the strength loss increased. After the pores of concrete are damaged, the cracks expand greatly, which makes the dynamic elastic modulus drop sharply. Because the compression failure of concrete belongs to the whole failure and the dynamic elastic the weakest plane controls modulus, the loss of dynamic elastic modulus will be more significant than the loss of compressive strength. The curve of bending tensile strength is observed. During the increase of freeze-thaw cycles, the bending tensile strength decreased sharply until it was completely lost. Compared with the curve of relative dynamic modulus of elasticity, when the decrease of relative dynamic modulus is less than 10 %, the flexural strength is reduced by 23 %, which shows that the flexural strength is very sensitive to freeze-thaw cycle. The compression ratio is basically the same before 100 times of freeze-thaw and increases gradually in the later stage of freeze-thaw, because the reduction of flexural strength of concrete after multiple times of freeze-thaw is greater than the reduction of compressive strength, and the compression ratio will increase.

In Fig. 2, the mass change rate does not change significantly before the number of freeze-thaw cycles reaches 125, and it tends to increase after more than 125 cycles. The reason is that in the early stage of freeze-thaw cycle, although the concrete test block absorbs water, the amount of surface debris peeling is less, and the mass will increase. In the later stage of freeze-thaw, the internal cohesion of concrete will decrease, and the mass of water absorbed is less than that of peeling debris. The rate of change in this mass has increased. The water absorption has no significant change in the freeze-thaw test of concrete, because the water absorption can help to reflect the degree of internal water saturation of concrete structure. After the number of freeze-thaw cycles reaches 100, the concrete does not appear serious peeling and fracture phenomenon, and the water absorption will reach a balance state.

Therefore, in the process of freeze-thaw cycle times increasing from 0 to 200, there is no significant difference between the two node values of mass change rate, water absorption rate and compression fold ratio. In the process of freeze-thaw cycle times increasing, the curve fluctuates up and down, the trend of change is uncertain, and the three indexes do not reflect the clear law affected by freeze-thaw cycle.

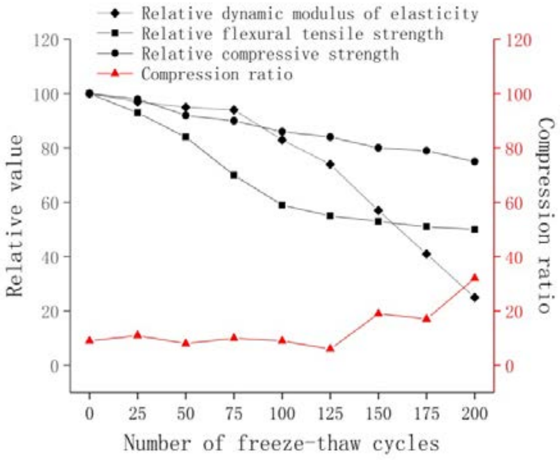

Figure 1. Changes of relative value and compression ratio.

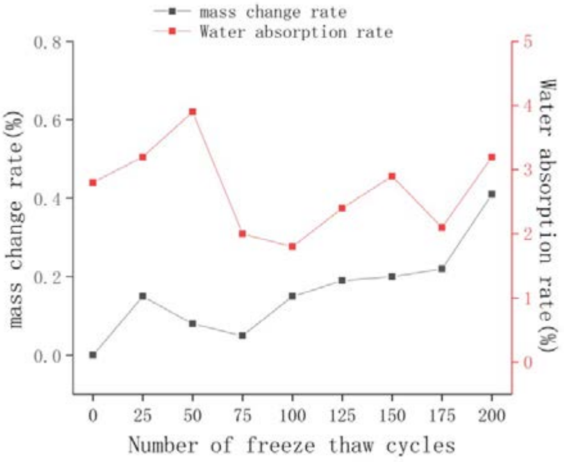

Figure 2. Change of mass change rate and water absorption rate.

Based on the above analysis, among the six indexes of freeze-thaw damage evaluation, the change level of mass change rate, water absorption rate, compression ratio and compressive strength affected by freeze-thaw cycle is relatively low, so the freeze-thaw damage cannot be accurately evaluated, while the dynamic elastic modulus and bending tensile strength are relatively affected by freeze-thaw cycle.

In order to select the most suitable freeze-thaw damage model parameters, the dynamic elastic modulus and flexural tensile strength were further compared. In order to avoid misleading the test results by a single concrete grade, under the freeze-thaw test conditions such as Sunming [26–29], take C40 concrete as an example, the dynamic modulus of elasticity and flexural strength are compared with each other in the case of increasing freeze-thaw cycles, as shown in Fig. 3.

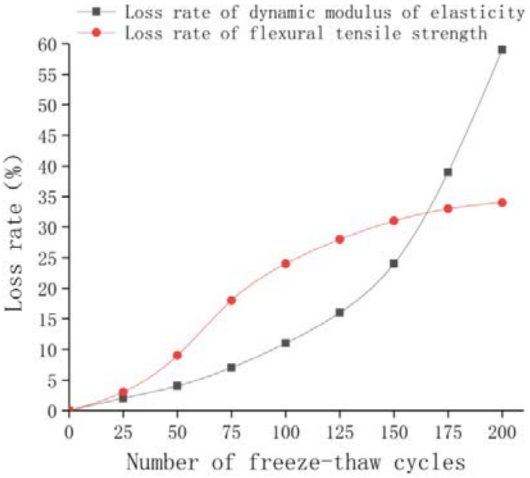

Figure 3. Comparison of dynamic modulus loss rate and flexural strength loss rate.

In Fig. 3, with the increase of freeze-thaw cycles, the loss rate of dynamic modulus of elasticity and the loss rate of flexural strength increase gradually. Before 150 freeze-thaw cycles, the loss rate of flexural strength is greater than the loss rate of dynamic modulus of elasticity. After 150 freeze-thaw cycles, the loss rate of dynamic modulus begins to lead, and the growth trend of the loss rate of flexural strength slows down gradually. The reason is that the increase of the number of freeze-thaw cycles makes the number of cracks in concrete accumulates and the width of cracks expand gradually. The dynamic modulus loss rate in the later stage of freeze-thaw has the most rapid growth trend, so the dynamic modulus loss rate curve shows a quadratic function trend. However, the internal cohesive force of concrete declines rapidly in the early stage of freeze-thaw, at this time, the loss rate of flexural tensile strength has the most significant growth trend. When the cohesive force drops to a certain extent, the loss rate of flexural tensile strength has a gradual growth trend.

Based on the above analysis, the flexural strength and dynamic modulus of elasticity can reflect the damage state of concrete in the early stage and the later stage respectively. Therefore, in order to evaluate the freeze-thaw damage state reasonably, the dynamic elastic modulus and flexural strength should be taken as parameters to establish the freeze-thaw damage model respectively.

2.2. Establishment of freeze-thaw damage model

According to the above analysis results, the dynamic elastic modulus and flexural strength can reasonably reflect the damage state of concrete structures, and they are easy to detect. Therefore, dynamic elastic modulus index and flexural tensile strength index are taken as damage variables, and regression analysis is carried out through statistical package for Social Sciences (SPSS) software to determine the coefficient of parameters, and freeze-thaw damage models of cement concrete pavement in seasonal frost regions are established respectively. From the typical sections in the seasonal frost regions, 18 sections of three highways, including A, B and C, are selected for core sampling, and the dynamic elastic modulus and flexural strength data of the samples were measured. 120 sets of measurement data of 12 sections were applied to establish the model, and 60 sets of measurement data of the remaining 6 sections were used for model verification.

2.2.1. Dynamic elastic modulus damage model

According to the definition of damage mechanics of concrete [22], the damage variable of concrete is defined as:

$$D=1-\frac{E_N}{E_0}=1-E_r \tag{1}$$

Where: E_N is the dynamic elastic modulus of concrete when the number of freezing-thawing cycles is N, E_0 is the dynamic elastic modulus of concrete when the number of freezing-thawing cycles is 0, and E_r is the relative dynamic elastic modulus.

Due to the cement concrete pavement in the climate environment of the seasonal frost regions is more sensitive to the freeze-thaw effect than the concrete specimens in the laboratory, the accuracy of the model in equation (1) to evaluate the freeze-thaw damage is insufficient. In Fig. 3, the change curve of the loss rate of dynamic modulus of elasticity is in the form of quadratic function. Therefore, the damage model in the form of primary function in equation (1) is improved to the damage model in the form of quadratic function, and the freeze-thaw damage model based on relative dynamic elastic modulus is established as follows:

$$D=aE_r^{\,2}+bE_r+c \tag{2}$$

where: a, b and c are coefficients, and E_r is relative dynamic elastic modulus.

According to the above data, using SPSS (Statistical Product and Service Solutions) analysis method, take E_r as the independent variable and D as the dependent variable to carry out nonlinear regression analysis of the model. The significance test results of the model are shown in Table 2. The regression mean square value is 279 times of the residual mean square value; F value is 404.766, which indicates that the change of dependent variable is caused by the change of independent variable rather than the test error. The explanation of independent variable to dependent variable is high, Sig. value value is 0.002, less than 0.05, which indicates that the secondary regression of model is significant, and regression model can be established between independent variable and dependent variable.

Table 2. Regression model of ANOVA.

	Sum of Squares	df	Mean Square	F	Sig.
Regression	0.558	2	0.279	404.766	0.002
Residual	0.003	5	0.001		
Total	0.561	7			

After the F-test shows that the linear model can be established, it is necessary to determine whether the influence of independent variables on the dependent variables is significant, so the significance test should be carried out on the regression coefficient. The significance test of the regression coefficient is shown in Table 3. The absolute value of the critical value t of the bilateral test is all greater than the significance level, and the Sig. value is less than 0.05, indicating that the independent variable has significant influence on the dependent variable, so both coefficients are retained in the model.

Table 3. Coefficient of regression model.

Parameter	Partial regression coefficient	Partial regression coefficient standard error	Standardized partial regression coefficient	t	Sig.
a	1.023	0.167	1.192	6.116	0.002
b	-2.280	0.207	-2.146	-11.013	0.015
Constant	1.257	0.057		21.994	0.007

The results of goodness of fit test are shown in Table 4. R^2 is the decisive coefficient of dependent variable and independent variable, and R^2 is adjusted to the ratio of mean square deviation to eliminate the influence of the number of independent variables. The closer R^2 and R^2 are to 1, the better the fitting effect of regression equation is. The adjusted R^2 of the model is 0.991, close to 1, and the error of standard estimation is only 0.026, which indicates that the goodness of fit of the model is high, and the dependent variable can be accounted for 99.1 % of the model interpretation.

Table 4. Summary of regression models.

R^2	Adjust R^2	Standard estimated error
0.994	0.991	0.026

The model can be obtained by substituting the coefficient value into equation (2):

$$D = 1.023E_r^{\,2} - 2.28E_r + 1.257 \qquad 3)$$

2.2.2. Bending tensile strength damage model

According to the research results of ShenYin [30] on the loss state of flexural tensile strength under different freeze-thaw cycles, the number of freezing-thawing cycles is in direct proportion to the loss rate of flexural strength. Therefore, if the number of freezing-thawing cycles is N times, the flexural strength is a differentiable function (f_N), and the constant is λ_1, then the expression for the loss rate of flexural strength when the number of freezing-thawing cycles is N to $N + \triangle N$ is:

$$\frac{f\left(N+\Delta N\right)-f\left(N\right)}{f\left(N\right)}=\lambda_1\Delta N \qquad (4)$$

Deformation can be obtained:

$$f\left(N+\Delta N\right)-f\left(N\right)=\lambda_1\Delta N f\left(N\right) \qquad (5)$$

Can become:

$$\frac{df\left(N\right)}{dN}=\lambda_1 f\left(N\right) \qquad (6)$$

By integrating equation (6), we can obtain:

$$\frac{f(N)}{f_0}=e^{\lambda_1 N} \tag{7}$$

Similarly, by repeating the above steps, the loss rate of dynamic elastic modulus can be expressed as:

$$E_r=e^{\lambda_2 N} \tag{8}$$

According to equations (1), (7) and (8), the freeze-thaw damage model based on the loss rate of flexural tensile strength can be obtained as follows:

$$D=d\left(1-\frac{f_N}{f_0}\right)^e \tag{9}$$

where: d and e are the coefficients, and f_0 is the flexural tensile strength when the number of freezing-thawing cycles is 0.

Since equation (9) is a nonlinear equation, in order to simplify the method and steps of nonlinear equation in regression analysis, logarithmic function method is used to transform the equation linearly.

To find the natural logarithm of both sides of the equation at the same time, we can get:

$$\ln D=\ln d+e\ln(1-\frac{f_N}{f_0}) \tag{10}$$

Let $\ln D=y$, $\ln d=\lambda_3$, $\ln(1-\frac{f_N}{f_0})=x$, equation (10) can be converted into:

$$y=\lambda_3+ex \tag{11}$$

Thus, the original nonlinear equation can be transformed into a linear equation for solution. Therefore, according to the above data, the SPSS method is extended to analyze the bending strength damage model with X as the independent variable and y as the dependent variable. Table 5 shows the significance test of the model. The regression square sum of the dependent variable is 76.839, and the ratio (mean square) of the regression square sum to the degree of freedom is 32.279, which is much higher than the mean square of the residual error by 0.054. The ratio (F) of the mean regression square sum to the mean residual square sum is 253.56, which is relatively large, and the Sig. value is 0.008, which is less than 0.05, indicating that the linear regression of the model is significant, and the ratio between the dependent variable and the independent variable can be establish a linear model.

Table 5. Regression model of ANOVA.

	Sum of Squares	df	Mean Square	F	Sig.
Regression	76.839	2	32.279	253.56	0.008
Residual	0.114	10	0.054		
Total	0.561	12			

Table 6 shows the significance test of the coefficient. The sig. values of the parameters are 0.009 and 0.012, respectively, which are less than 0.05. The absolute value of the critical value t of the bilateral test is all greater than the significance level, indicating that the dependent variable is greatly affected by the independent variable, and the independent variable and constant should be retained in the model.

Table 6. Coefficient of regression model.

Parameter	Partial regression coefficient	Partial regression coefficient standard error	Standardized partial regression coefficient	t	Sig.
x	4.720	0.144	5.167	16.575	0.009
Constant	-0.968	0.078		-8.301	0.012

Table 7 shows the goodness of fit test of the model. The adjusted R^2 of the model is 0.992, close to 1, and the standard estimation error is only 0.078, indicating that the goodness of fit of the modified model is high, and the explanatory part of the dependent variable can be accounted for 99.2 %.

Table 7. Summary of regression models.

R^2	Adjust R^2	Standard estimated error
0.995	0.992	0.078

The model can be obtained by substituting the coefficient values in Table 6 into equation (11):

$$y = -0.968 + 4.72x \tag{12}$$

The nonlinear equation is transformed into:

$$D = 0.38\left(1 - \frac{f_N}{f_0}\right)^{4.72} \tag{13}$$

2.3. Analysis of applicable conditions of the model

In the climate environment of seasonal frost regions, the dynamic elastic modulus and flexural strength of cement concrete pavement are affected by water cement ratio, gas content and freezing temperature. Therefore, in order to make the model have higher evaluation accuracy, it is necessary to determine the respective applicable conditions of the dynamic elastic modulus damage model and flexural strength damage model constructed.

The range of water cement ratio is 0.4~0.48, and the range of gas content is 1 %~5 %. The range of freezing temperature is from – 5 °C to ~25 °C in the climate of seasonal frost regions. Under the condition of 200 freeze-thaw cycles, the response surface test was designed to observe the change of dynamic elastic modulus and relative bending tensile strength under different water cement ratio, gas content and freezing temperature, so as to determine the applicable conditions of the model. In the test, the water cement ratio, gas content and freezing temperature are used as abscissa, expressed as WCR, GC and FT in sequence; the relative dynamic elastic modulus and relative bending tensile strength are used as ordinate, expressed as ER and FR in sequence. According to the number and range of parameters, the response surface test with 3 factors and 3 levels is selected. The coding level and value are shown in Table 8.

Table 8. 3 factors coding level and value.

Coding level	A(WCR)	B(GC)	C(FT/℃)
-1	0.4	1 %	-5
0	0.44	3 %	-15
1	0.48	5 %	-25

2.3.1 Determine the applicable conditions of the dynamic elastic modulus damage model

When the encoding level of FT is 0, the response surfaces of WCR and GC to ER are designed as shown in Fig. 4. When the WCR value is between 0.45 and 0.48, the GC value is within 1 to 4, the color of the corresponding region is blue, indicating that within this range, ER is significantly affected by WCR and GC, and ER value is in a low horizontal state. The reason is that the larger the water cement ratio of concrete is the more water molecules in the capillary pores are. In the process of freezing-thawing cycle, the volume of water molecules increases when it is frozen, and decreases when it is melted. GC has a great influence on ER. Properly raising the GC value can reduce freeze-thaw damage, and the density of concrete will be reduced if the GC value exceeds 4 %.When the coding level of WCR is 0, the response surface of the designed FT to ER is shown in Figure 5. It can be observed that the corresponding area is blue when the FT value is in the range of -15 °C to -25 °C. The reason is that the lower the FT value is, the faster the freezing speed is, accelerating the concrete damage process. Moreover, the blue color is lighter in this range, indicating that the effect of FT on ER is normal.

Therefore, for the freeze-thaw damage model based on dynamic modulus of elasticity, when the response surface color is close to blue, the corresponding range of water cement ratio, gas content and freezing temperature are the most suitable conditions for the model. When the water cement ratio is 0.45–0.48, the gas content is 1 % – 4 %, and the freezing temperature is – 15 °C – 25 °C, the evaluation effect of the model is the best.

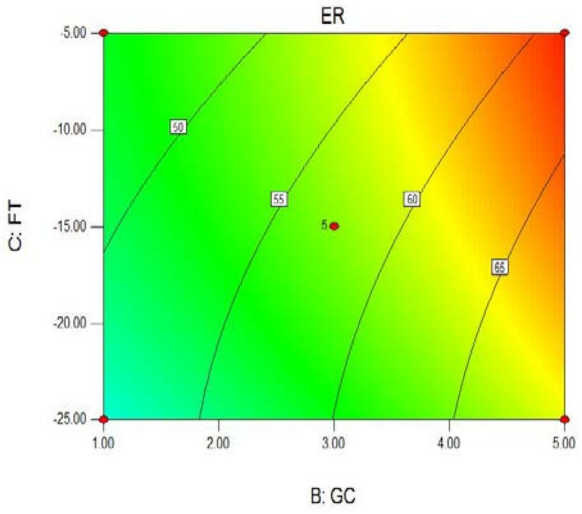

Figure 4. WCR and GC response surface to ER.

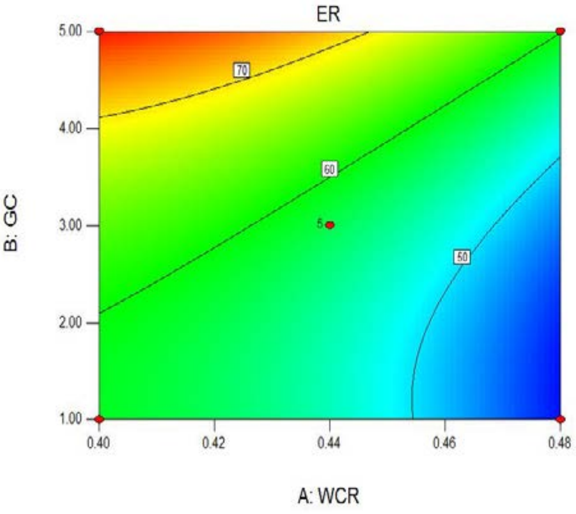

Figure 5. GC and FT response surface to ER.

2.3.2. Determine the applicable conditions of the damage model for flexural tensile strength

When the encoding level of FT is 0, the response surfaces of WCR and GC to ER are designed as shown in Fig. 6. When WCR value is between 0.4 and 0.46, GC value is within 1 to 3.5, the color of corresponding region is blue, indicating that within this range, FR is significantly affected by WCR and GC, while ER value is in a low state. The reason is that when the WCR value is small, there is less moisture in the concrete, which increases the brittleness of the concrete to some extent. The flexural tensile strength is more sensitive to freezing-thawing than the dynamic elastic modulus, and the relative flexural tensile strength does not change significantly when the gas content is more than 3.5 %.When the coding level of WCR is 0, the response surface of the designed FT to ER is shown in Fig. 7. The corresponding areas within the range of -5 °C to -25 °C are all blue, indicating that the change of FT value has no significant effect on FR. If the FT value is less than -5 ℃, the flexural tensile strength will be damaged. At the same time, the width of the blue region corresponding to -5 °C is less than that of the blue region corresponding to -25 °C, indicating that at a lower freezing temperature, the flexural tensile strength loss is relatively large.

Therefore, when the water cement ratio is between 0.4 and 0.46, the gas content is between 1 and 3.5, and the freezing temperature is below -5 °C, the above range is the most suitable condition for the model of freezing-thawing damage of cement concrete pavement in seasonal frost regions. It established based on flexural tensile strength index, and the model has the best evaluation effect.

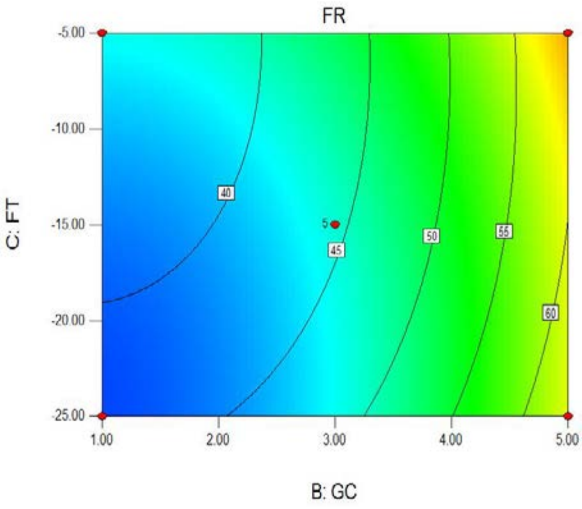

Figure 6. WCR and GC response surface to FR.

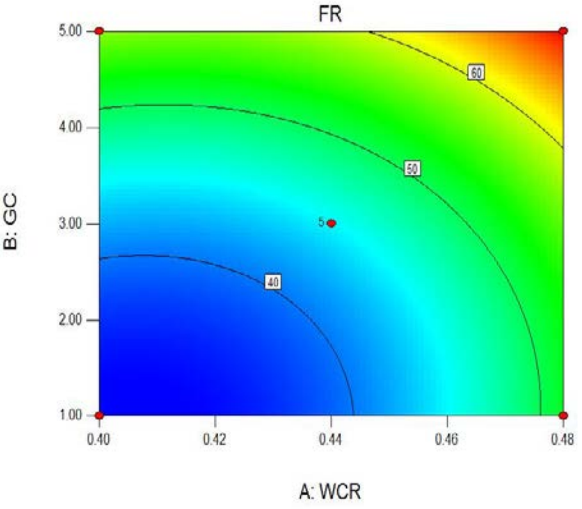

Figure 7. GC and FT response surface to FR.

3. Results and Discussion

3.1. Verification of the same section in different periods

In order to verify the practicability and superiority of the freeze-thaw damage model based on dynamic modulus of elasticity and flexural tensile strength of the cement concrete pavement in the seasonal frost regions, the measured damage value of a road section in the past 8 years and the evaluation value of each model are selected for fitting. The model includes damage mechanics model, dynamic elastic modulus damage model, bending strength damage model, dynamic elastic modulus attenuation model established by Sun Ming [26] and bending strength attenuation model established by Shen Yin [30].

In Fig. 8, the abscissa is the measured value D_m of the damage degree, the ordinate is the evaluation value D_P of the damage degree. The decisive coefficient R^2 of the fitting between the evaluation value of the damage mechanics model and the measured value is 0.980. The decisive coefficient R^2 of the fitting between the evaluation value of the dynamic modulus of elasticity attenuation model established by Sun Ming and the measured value is 0.983, and the decisive coefficient of the fitting between the evaluation value of the dynamic modulus of elasticity damage model and the measured value is 0.983; R^2 is 0.997. This proves that the fitting degree of freeze-thaw damage model with dynamic modulus of elasticity is higher.

In Fig. 9, the decisive coefficient R^2 of the fitting between the evaluation value of the damage mechanics model and the measured value is 0.950, the decisive coefficient R^2 of the fitting between the evaluation value of the bending strength attenuation model established by Shen Yin and the measured value is 0.994. The decisive coefficient R^2 of the fitting between the evaluation value of the bending strength damage model and the measured value is 0.998, indicating that the fitting effect of the freeze-thaw damage model with the bending strength as the parameter is better.

The results show that the dynamic elastic modulus damage model and bending tensile strength damage model are more suitable to evaluate the freeze-thaw damage of cement concrete pavement in the seasonal frost regions.

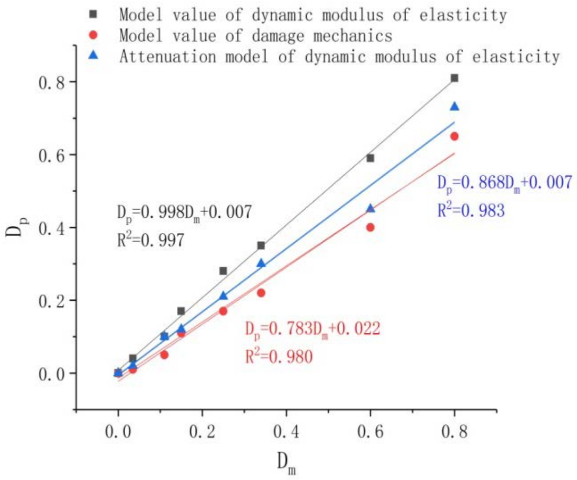

Figure 8. Fitting of ER value.

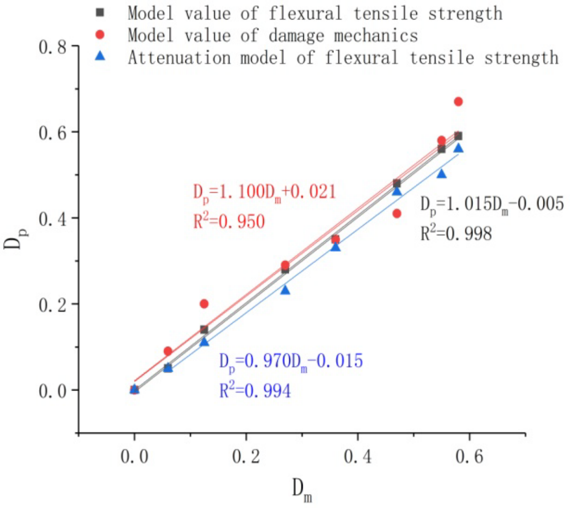

Figure 9. Fitting of FR value.

3.2. Verification of different road sections in the same period

Using only samples from the same section for model verification will make the test lack randomness, and the test results may have large errors. Therefore, the measured damage degree of 6 sections of highways A, B and C in the same year is again selected for verification. In Fig. 10, the abscissa is the numerical number of six road sections in turn, and the ordinate is the damage value. The damage value histogram of different road sections is drawn. Each road section corresponds to eight columnar graphs, four columnar graphs with striation correspond to the dynamic elastic modulus damage value, and the other four columnar graphs correspond to the bending tensile strength damage value.

As shown in Fig. 10, the difference between the damage evaluation value of the damage mechanics model and the damage measured value is the largest. The difference between the evaluation value of the attenuation model established by Sun Ming [26] and Shen Yin [30] and the difference between the measured value and the evaluation value of the dynamic elastic modulus damage model and the bending tensile strength damage model is the closest. The reason is that the damage mechanics model is based on the concrete freeze-thaw test. In the test, one freeze-thaw cycle in the laboratory is equivalent to 14 freeze-thaw cycles in the outdoor, which can only simulate the approximate damage state. However, there are many factors that can damage the field pavement, such as rain, snow, load, other natural and human factors, which damage the cement concrete pavement together with the freeze-thaw effect. The attenuation model established by Sun Ming and Shen Yin also does not take into account the influence of climate factors in the seasonal frost regions on the performance of the cement concrete pavement. Therefore, the damage value calculated by the damage mechanics model and the attenuation model is smaller than the damage degree of the model established based on the field measured data, which proves that the evaluation level of the dynamic modulus damage model and the bending tensile strength damage model is high and has good practicability.

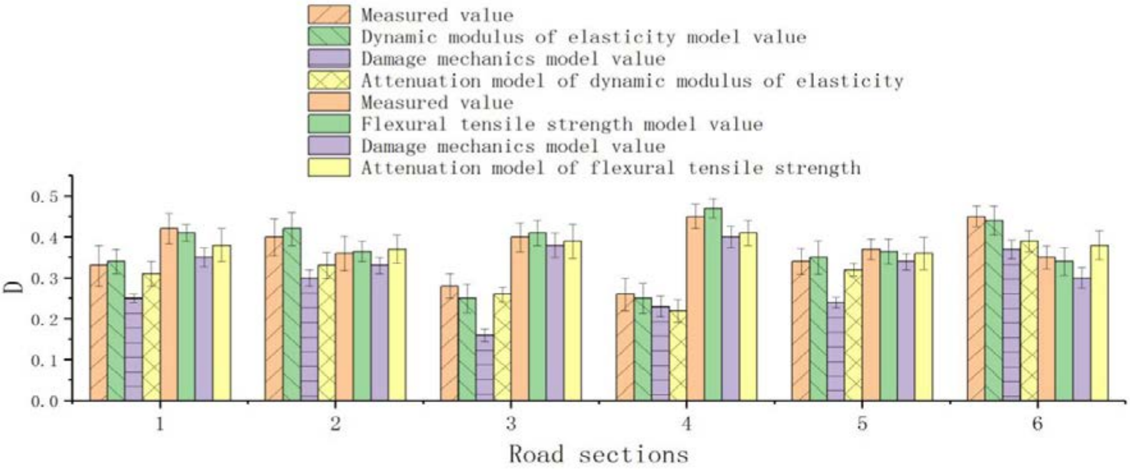

Figure 10. Histogram of ER and FR damage values.

4. Conclusions

1. The dynamic modulus of elasticity and flexural strength can be used as the parameters to establish the freeze-thaw damage model of the cement concrete pavement in the seasonal frozen area. Among the indexes that can reflect the damage state of concrete during freeze-thaw, the four indexes of mass change rate, water absorption rate, compressive strength and compression bending ratio do not show the obvious law of being affected by freeze-thaw cycle. In the other hand ,the the relative dynamic modulus of elasticity reaches 40 % loss rate before 150 freeze-thaw cycles, and the rate of flexural strength loss in the initial stage of freeze-thaw is 2.3 times that of dynamic modulus of elasticity.

2. Two models of freeze-thaw damage of cement concrete pavement in two seasonal frozen areas are established. Based on the dynamic modulus of elasticity index, the decisive coefficient R^2 of the model is 0.991, based on the flexural tensile strength index, the decisive coefficient R^2 of the model is 0.992, and the sig. value is less than 0.05, which shows that the two models have high goodness of fit, significant regression effect and statistical applicability.

3. The applicable conditions of the freeze-thaw damage model of the cement concrete pavement in the seasonal frost regions are put forward. Based on the dynamic modulus of elasticity index, the model of the freeze-thaw damage of the cement concrete pavement in the seasonal frost regions is established. When the water cement ratio is 0.45~0.48, the gas content is 1 %~4 %, and the freezing temperature is –15 ℃~25 ℃, the evaluation effect of the model is the best. The freeze-thaw damage model of the cement concrete pavement in the seasonal frost regions based on the bending tensile strength index is established. When the water cement ratio is 0.4~0.46, the gas content is 1 %~3.5 %, and the freezing temperature is below -5℃, the above range is the most suitable condition for the model, and the model has the best evaluation effect.

4. The evaluation effect of the freeze-thaw damage model is better and more practical than the previous model. In different periods of the same road section and the same period of different road sections, the freeze-thaw damage models of dynamic elastic modulus and flexural tensile strength are compared with the damage mechanics model and the existing model respectively. There verified that the decisive coefficient R^2 of the freeze-thaw damage model of dynamic elastic modulus is 0.997, and the decisive coefficient R^2 of the freeze-thaw damage model of flexural tensile strength is 0.998, which is higher than the damage mechanics model and the existing model respectively. Compared with the evaluation value of

damage mechanics model and the evaluation value of existing model, the evaluation value of freeze-thaw damage of dynamic modulus of elasticity and flexural strength model is closer to the measured value of field damage degree.

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References

1. Chen, S., Ren, J., Song, Y., Li, Q., Sun, J., Che, Y., Chen, J. Salt freeze-thaw damage characteristics of concrete based on computed tomography. Tehnicki Vjesnik. 2019. 26(6). Pp. 1753–1763. DOI: 10.17559/TV-20190819080524
2. Fu, Y., Cai, L., Yonggen, W. Freeze-thaw cycle test and damage mechanics models of alkali-activated slag concrete. Construction and Building Materials. 2011. 25(7). Pp. 3144–3148. DOI: 10.1016/j.conbuildmat.2010.12.006.
3. Li, J., Wang, F., Yi, F., Ma, J., Lin, Z. Fractal analysis of the fracture evolution of freeze-thaw damage to asphalt concrete. Materials. 2019. 12(14). DOI: 10.3390/ma12142288
4. Klyuev, S.V., Klyuev, A.V., Vatin, N.I. Fiber concrete for the construction industry. Magazine of Civil Engineering. 2018. 84(8). Pp. 41–47. DOI: 10.18720/MCE.84.4.
5. Alsaif, A., Bernal, S.A., Guadagnini, M., Pilakoutas, K. Freeze-thaw resistance of steel fibre reinforced rubberised concrete. Construction and Building Materials. 2019. 195. Pp. 450–458. DOI: 10.1016/j.conbuildmat.2018.11.103.
6. Smith, S.H., Qiao, C., Suraneni, P., Kurtis, K.E., Weiss, W.J. Service-life of concrete in freeze-thaw environments: Critical degree of saturation and calcium oxychloride formation. Cement and Concrete Research. 2019. 122. Pp. 93–106. DOI: 10.1016/j.cemconres.2019.04.014.
7. Fediuk, R.S., Lesovik, V.S., Mochalov, A.V., Otsokov, K.A., Lashina, I.V., Timokhin, R.A. Composite binders for concrete of protective structures. Magazine of Civil Engineering. 2018. 82(6). Pp. 208–218. DOI: 10.18720/MCE.82.19
8. Zhao, Q., Cheng, P., Wang, J., Wei, Y. Damage prediction model for concrete pavements in seasonally frozen regions. Magazine of Civil Engineering. 2018. 84(8). Pp. 57–66. DOI: 10.18720/MCE.84.6
9. Nayak, S., Lyngdoh, G.A., Das, S. Influence of microencapsulated phase change materials (PCMs) on the chloride ion diffusivity of concretes exposed to Freeze-thaw cycles: Insights from multiscale numerical simulations. Construction and Building Materials. 2019. 212. Pp. 317–328. DOI: 10.1016/j.conbuildmat.2019.04.003.
10. Grubeša, I.N., Markovic, B., Vracevic, M., Tunkiewicz, M., Szenti, I., Kukovecz, Á. Pore structure as a response to the freeze/thaw resistance of mortars. Materials. 2019. 12(19). Pp. 1–16. DOI: 10.3390/ma12193196
11. Liu, K., Yan, J., Alam, M.S., Zou, C. Seismic fragility analysis of deteriorating recycled aggregate concrete bridge columns subjected to freeze-thaw cycles. Engineering Structures. 2019. 187. Pp. 1–15. DOI: 10.1016/j.engstruct.2019.01.134.
12. Fursa, T.V., Petrov, M., Dann, D.D., Reutov, Y.A. Evaluating damage of reinforced concrete structures subjected to bending using the parameters of electric response to mechanical impact. Composites Part B: Engineering. 2019. 158(June 2018). Pp. 34–45. DOI: 10.1016/j.compositesb.2018.09.042.
13. Xiao, Q.H., Cao, Z.Y., Guan, X., Li, Q., Liu, X.L. Damage to recycled concrete with different aggregate substitution rates from the coupled action of freeze-thaw cycles and sulfate attack. Construction and Building Materials. 2019. 221. Pp. 74–83. DOI: 10.1016/j.conbuildmat.2019.06.060. URL: https://doi.org/10.1016/j.conbuildmat.2019.06.060
14. Hezhev, T.A., Zhurtov, A.V., Tsipinov, A.S., Klyuev, S.V. Fire resistant fibre reinforced vermiculite concrete with volcanic application. Magazine of Civil Engineering. 2018. No. 80(4). Pp. 181–194. DOI: 10.18720/MCE.80.16
15. Song, Z., Lu, Z., Lai, Z. Influence of Hydrophobic Coating on Freeze-Thaw Cycle Resistance of Cement Mortar. Advances in Materials Science and Engineering. 2019. 2019(1). DOI: 10.1155/2019/8979864
16. Tian, J., Wu, X., Zheng, Y., Hu, S., Ren, W., Du, Y., Wang, W., Sun, C., Ma, J., Ye, Y. Investigation of damage behaviors of ECC-to-concrete interface and damage prediction model under salt freeze-thaw cycles. Construction and Building Materials. 2019. 226. Pp. 238–249. DOI: 10.1016/j.conbuildmat.2019.07.237.
17. Fediuk, R.S., Mochalov, A.V., Bituev, A.V., Zayakhanov, M.E. Structuring Behavior of Composite Materials Based on Cement, Limestone, and Acidic Ash. Inorganic Materials. 2019. 55(10). Pp. 1079–1085. DOI: 10.1134/S0020168519100042
18. Ismail, M.K., Hassan, A.A.A. Abrasion and impact resistance of concrete before and after exposure to freezing and thawing cycles. Construction and Building Materials. 2019. 215. Pp. 849–861. DOI: 10.1016/j.conbuildmat.2019.04.206.
19. Kim, J.H., Lee, H.S. Reliability assessment of reinforced concrete rectangular columns subjected to biaxial bending using the load contour method. Engineering Structures. 2017. 150. Pp. 636–645. DOI: 10.1016/j.engstruct.2017.07.061.
20. Tian, W., Han, N. Evaluation of damage in concrete suffered freeze-thaw cycles by CT technique. Journal of Advanced Concrete Technology. 2016. 14(11). Pp. 679–690. DOI: 10.3151/jact.14.679
21. Tsang, C., Shehata, M.H., Lotfy, A. Optimizing a test method to evaluate resistance of pervious concrete to cycles of freezing and thawing in the presence of different deicing salts. Materials. 2016. 9(11). Pp. 1–20. DOI: 10.3390/ma9110878
22. Wang, B., Wang, F., Wang, Q. Damage constitutive models of concrete under the coupling action of freeze–thaw cycles and load based on Lemaitre assumption. Construction and Building Materials. 2018. 173. Pp. 332–341. DOI: 10.1016/j.conbuildmat.2018.04.054.
23. Yu, H., Ma, H., Yan, K. An equation for determining freeze-thaw fatigue damage in concrete and a model for predicting the service life. Construction and Building Materials. 2017. 137. Pp. 104–116. DOI: 10.1016/j.conbuildmat.2017.01.042.
24. Wang, Z.H., Li, L., Zhang, Y.X., Wang, W.T. Bond-slip model considering freeze-thaw damage effect of concrete and its application. Engineering Structures. 2019. 201. Pp. 109831. DOI: 10.1016/j.engstruct.2019.109831.
25. Bharadwaj, K., Glosser, D., Moradllo, M.K., Isgor, O.B., Weiss, W.J. Toward the prediction of pore volumes and freeze-thaw performance of concrete using thermodynamic modelling. Cement and Concrete Research. 2019. 124. Pp. 105820. DOI: 10.1016/j.cemconres.2019.105820.

26. Sun, M., Xin, D., Zou, C. Damage evolution and plasticity development of concrete materials subjected to freeze-thaw during the load process. Mechanics of Materials. 2019. 139. DOI: 10.1016/j.mechmat.2019.103192
27. Mak, K., Fam, A. Freeze-thaw cycling effect on tensile properties of unidirectional flax fiber reinforced polymers. Composites Part B: Engineering. 2019. 174. Pp. 106960. DOI: 10.1016/j.compositesb.2019.106960.
28. Wei, J., Zhang, L., Li, B., Wen, Z. Non-uniformity of coal damage caused by liquid nitrogen freeze-thaw. Journal of Natural Gas Science and Engineering. 2019. 69. DOI: 10.1016/j.jngse.2019.102946
29. Klyuev, S.V., Khezhev, T.A., Pukharenko, Y.V., Klyuev, A.V. Experimental study of fiber-reinforced concrete structures. Materials Science Forum. 2018. 945. Pp. 115–119. DOI: 10.4028/www.scientific.net/MSF.945.115
30. Shen, Y., Liu, J., Zhou, S., Li, G. Experimental investigation on the freeze–thaw durability of concrete under compressive load and with joints. Construction and Building Materials. 2019. 229. Pp. 116893. DOI: 10.1016/j.conbuildmat.2019.116893.

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