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Durability Prediction of Asphalt Mixture Exposed to Sulfate and Dry-wet Circle Erosion Environment

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Abstract: In order to predict the durability of asphalt mixture exposed to sulfate and dry-wet circle erosion environment, the attenuation laws of the porosity and splitting strength of asphalt mixture were investigated through the accelerated deterioration tests in the condition of 10% Na_2SO_4 solution and dry-wet cycles. Then the sulfate erosion damage mechanism of asphalt mixture was proposed. GM(1, N) model based on grey system theory was established to predict the durability of asphalt mixture. The results indicate that there exist a good correlation between the Volume of air voids (VV) and the splitting strength of asphalt mixture and dry-wet cycle times. The VV increases and the splitting strength decreases with the increase of dry-wet cycle times. Dry-wet cycles accelerate sulfate erosion damage to asphalt mixture. The GM(1, N) grey model can predict the porosity and the splitting strength of asphalt mixture exposed to sulfate and dry-wet circle erosion environment with enough precision, which can reduce the test workload to some extent. Research results can be referred to the life evaluation of asphalt mixture in sulfate enrichment regions.

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***Key words**: Asphalt mixture; Dry-wet circle; Durability; GM(1,N) grey model; Sulfate erosion.*

Introduction

Asphalt pavement is the main paving type of highway because it has many advantages including reduced noise pollution, good skid resistance, improved comfort, convenience of maintenance and recyclability [1]. Asphalt mixture has been widely used in road pavements. However, asphalt pavements are subjected to different levels of durability problems such as high temperature rutting, low temperature cracking, moisture damage and fatigue under the effects of climatic conditions and repeated vehicle loading [2-4]. Among these pavement distresses, moisture damage of asphalt mixture deserves the special attention and a lot of research has been conducted over the years. However, these research results mainly focus on the physical effects of water environment on asphalt mixture [5-8]. Actually, the real work environment for asphalt pavement is more complex especially in the salt lakes and saline soil regions in western China and other similar regions, where the climate environment is relatively severe [9-11]. Asphalt pavement surface exposed to the environment suffer from the erosion of surplus sulfate particles, and dry-wet alternate environment further deteriorate the road performance of asphalt mixture. As a result, asphalt mixture shows severe durability problems. At present, little research has been done on the durability of asphalt mixture exposed to sulfate and dry-wet circle erosion environment and there is few reasonable and applicable forecasting model for the durability of asphalt mixture exposed to sulfate enrichment environment according to the existing literature [12, 13].

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Materials and Methods

Materials

Asphalt

The SBS(I-C) modified asphalt was used for all experiments. The physical properties of asphalt binder were measured following the ASTM standards, presented in Table 1.

Aggregate

The coarse and fine aggregate is crushed basalt, with a density of 2.830 g/cm^3 and maximal size of 16 mm. The gradation of mixed aggregate often applied to asphalt pavement surface course in western China is shown in Table 2. Mineral filler is levigated limestone, with a density of 2.795g/cm^3, and its particle size is in the range of 0–0.3 mm, with 79.7% by mass passing the sieve of 75 μm.

Test Methods

In order to investigate the erosion effects of sulfate and dry-wet cycles on asphalt mixture, a simple and reasonable laboratory experiment procedure was designed as follows. The solution with a concentration of 10% was consist of Na_2SO_4 and purified water. The dry-wet cycle test condition was adopted to speed up the test process. After being prepared through traditional Marshall mix design method and cured for 48 hours, the specimens were stored in purified water and 10% Na_2SO_4 solution for vacuum saturated-water action. Then the specimens were immersed into purified water and Na_2SO_4 solution at 30°C for 12 hours. After that, the specimens were removed to the oven at 30°C for another 12

Table 1. Physical Properties of Asphalt Binder.

Material	Test Items	Unit	Value	Specification
SBS Modified Asphalt	Penetration at 25°C	0.1mm	71.0	ASTM D5-97
	Ductility at 5°C	Cm	48	ASTM D113-99
	Softening Point	°C	89.5	ASTM D36-06
	Elastic Recovery at 25°C	%	87.3	ASTM D6084
	Specific Gravity	Non	1.027	ASTM D70-76
RTFO Binder*	Mass Loss	%	-0.02	ASTM D2872-04
	Penetration Ratio at 25°C	%	68.9	ASTM D5-97
	Ductility at 5°C	Cm	24	ASTM D113-99

Note: * Rolling thin film oven (RTFO) aged, according to ASTM D2872-04

Table 2. Aggregate Gradation for AC-13 Mixture Design.

	Percent of Aggregate Passing a Given Sieve Size									
Sieve Size(mm)	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Percent Passing (%)	100	95.5	68	47.1	33.4	23.4	15.2	8.7	7.3	5.2

hours, which was a dry-wet cycle. The splitting tests were conducted with 50mm/min loading rate at 15°C for 15, 30, 45, 60 dry-wet cycles respectively according to ASTM D 4123.

Modeling Method

Grey theory was pioneered by Professor Deng in 1982. The random variables are regarded as grey numbers and the stochastic process is referred to as a grey process for the grey theory. The grey theory can be applied in the research of prediction, decision-making and control, especially in prediction. The primary characteristic of a grey system is the incompleteness of information [14, 15]. The premise of the GM(1, N) model with n-1 relative factors being acted as the associated series besides the predicted seriesis fairly good because the system is whiten by many effectively messages around its forecast origin [16].

Pairs of observations { $x_1^{(0)}$ (1), $x_1^{(0)}$ (2), …, $x_1^{(0)}$ (n)} from a certain dynamic system with n-1 inputs{ $x_2^{(0)}$, $x_3^{(0)}$ …, $x_n^{(0)}$ } and an output $x_1^{(0)}$ are supposed to be available at equispaced interval of time. Consider the original series, it can be obtained that

$$x_1^{(0)}=\{x_1^{(0)}(1),\ x_1^{(0)}(2),\ \ldots,\ x_1^{(0)}(n)\} \tag{1}$$

and

$$x_2^{(0)}=\{x_2^{(0)}(1),\ x_2^{(0)}(2),\ \ldots,\ x_2^{(0)}(n)\} \tag{2}$$

…….

$$x_N^{(0)}=\{x_N^{(0)}(1),\ x_N^{(0)}(2),\ \ldots,\ x_N^{(0)}(n)\} \tag{3}$$

$x_i^{(1)}$ are the 1-AGO series of $x_i^{(0)}$, $i=1,2,...,N$, respectively. In addition, $Z_1^{(1)}$ is the adjacent generated serial of $x_1^{(1)}$,and then

$$x_1^{(0)}(k)+az_1^{(1)}(k)=\sum_{i=2}^{N} b_i x_i^{(1)}(k) \tag{4}$$

is called the grey differential equation of GM(1, N) model, where 1 stands for first-order derivative of 1-AGO series of $x_1^{(0)}$ (called the predicted series) , and n stands for there being n-1 relative series (called the associated series) of the system.

Define $\hat{\alpha}=[a \quad b_2 \quad \cdots \quad b_N]^T$ as the parameter series of grey differential equation of GM(1, N) model and then according to the least square method(LSM), it can be obtained that

$$\hat{\alpha}=(B^T B)^{-1} B^T Y \tag{5}$$

Where

$$B=\begin{bmatrix} -z_1^{(1)}(2) & x_2^{(1)}(2)\ldots x_N^{(1)}(2) \\ -z_1^{(1)}(3) & x_2^{(1)}(3)\ldots x_N^{(1)}(3) \\ |\ \ldots\ \vdots & \ldots \\ -z_1^{(1)}(n) & x_2^{(1)}(n)\ldots x_N^{(1)}(n) \end{bmatrix} \tag{6}$$

and

$$Y=\left[x_1^0(2) \quad x_1^0(3) \quad \ldots \quad x_1^0(n)\right]^T \tag{7}$$

Then

$$\frac{dx_1^{(1)}}{dt}+ax_1^{(1)}=b_2x_2^{(1)}+b_3x_3^{(1)}+\ldots+b_Nx_N^{(1)} \tag{8}$$

is the albinism differential equation or silhouette equation of Eq. (4). From Eq. (8), the modeling value can be derived as

$$\begin{aligned} x_1^{(1)}(t) &= e^{-at}[\sum_{i=2}^{N}\int b_i x_i^{(1)}(t)e^{at}dt + x_1^{(1)}(0) - \sum_{i=2}^{N}\int b_i x_i^{(1)}(0)dt] \\ &= e^{-at}[x_1^{(1)}(0) - t\sum_{t=2}^{N} b_i x_i^{(1)}(0) + \sum_{i=2}^{N}\int b_i x_i^{(1)}(t)e^{at}dt] \end{aligned} \tag{9}$$

When the rangeability of $x_i^{(1)}(i=1,2,...,N)$ is small, the value of $\sum_{i=2}^{N} b_i x_i^{(1)}(k)$ can be deemed as a grey constant. Therefore, the approximate time response equation of Eq.(4) can be derived as

$$\hat{x}_1^{(1)}(k+1) = \left[x_1^{(1)}(0) - \frac{1}{a}\sum_{i=2}^{N} b_i x_i^{(1)}(k+1) \right] e^{-ak} + \frac{1}{a}\sum_{i=2}^{N} b_i x_i^{(1)}(k+1) \quad (10)$$

where $x_1^{(1)}(0)$ is equal to $x_1^{(1)}(1)$. Then

$$\hat{x}_1^{(0)}(k+1) = \hat{x}_1^{(1)}(k+1) - \hat{x}_1^{(1)}(k) \quad (11)$$

Results and Discussion

The volume of air voids (VV) was obtained by Marshall test and the splitting tensile strength was obtained by ASTM D 4123. The results are given in Table 3. From Table 3, it can be seen that there is a good correlation between VV and splitting tensile strength of asphalt mixture and dry-wet cycles. Under the condition of dry-wet circulation and sulfate solution soaking, VV of asphalt mixture increases significantly and splitting tensile strength of asphalt mixture decreases rapidly with the increasement of dry-wet cycles. The main reason is that the specimens have some voids when manufactured and the voids are filled with solution after the action of vacuum saturated-water. Under the synergistic effect of dry-wet circles and sulfate erosion, the internal damage to the asphalt mixture begins to appear and accumulates gradually, resulting in the durable performance degradation and damage of asphalt mixture. The process includes the sulfate erosion damage and the accelerating degradation from dry-wet circles to asphalt mixture.

Damage Mechanism of Asphalt Mixture Exposed to Sulfate and Dry-wet Circle Erosion Environment

Based on the surface tension theory, when water invades into the interface between asphalt and aggregate, the surface tension occures to change, causing asphalt's stripping from the surface of aggregate gradually and eventual water damage. However, the surface tension increases with the increasement of sulfate solution concentration, accelerating the sulfate ion's migration and penetration rate to the interface between asphalt and aggregate. That weakens the interface adhesion between asphalt and aggregate. Three main processes related closely with the damage mechanism are as follows.

Spontaneous Emulsification Effect of Sulfate Solution on Asphalt Film

Asphalt film is thin at the edges of aggregate and is easily broken, causing the micro-cracks to develop and expand under the action of temperature stress and load stress. When asphalt contacts with sulfate solution, the water molecules invade into the asphalt film and probably make the asphalt film emulsified, which is shown in Fig. 1. The substitution effect of water on asphalt provides the possibility for asphalt film strip from aggregate surface gradually.

Stripping of Asphalt Film Immersed in Sulfate Solution

When the fissures or cracks appear, sulfate solution will arrive at the interface between asphalt and aggregate. At this point, the sulfate solution can get a greater proportion of aggregate surface versus asphalt because the surface tension is higher than that of asphalt at normal and high temperature, which accelerating the adhesive strength degradation and stripping of asphalt film. Besides, much sulfate coats on the surface of aggregate with the evaporation of moisture, resulting in further degradation of the adhesive strength between asphalt and aggregate, shown in Fig. 2.

Fig. 3. presents the three-phase interface among aggregate, sulfate and asphalt. From Fig. 3, it can be seen that due to the presence of sulfate, the contact surface between asphalt and aggregate becomes smaller and asphalt coating the aggregate shrinks, leading to sharply reduced interface adhesive strength. After that, stripped asphalt film is replaced by sulfate solution membrane.

Table 3. Test Results of VV and Splitting Tensile Strength of Asphalt Mixture with Different Dry-wet Cycles.

Dry-wet Cycles/times	VV/%	Splitting Tensile Strength/MPa
0	3.85	0.759
15	4.23	0.602
30	4.98	0.548
45	5.94	0.492
60	6.97	0.459

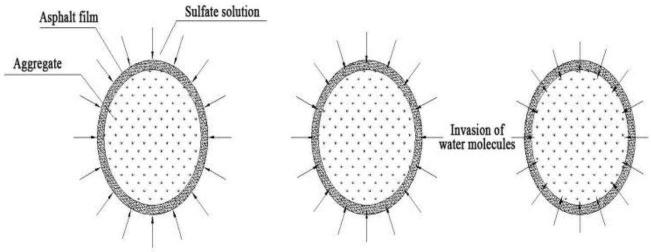

Fig. 1. Permeation of Sulfate Solution to Asphalt Film.

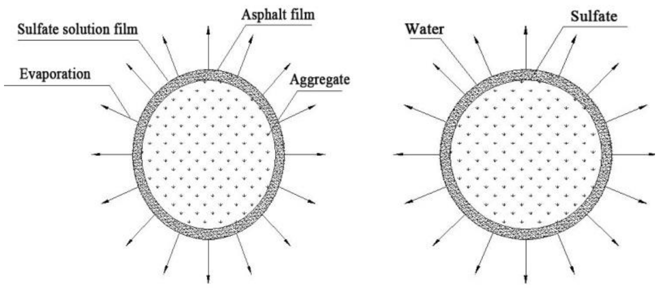

Fig. 2. Action of Sulfate to the Interface Between Asphalt Film and Aggregate.

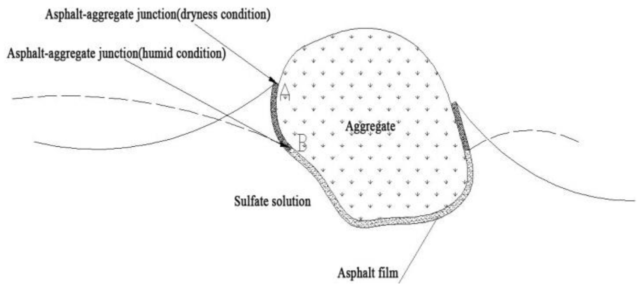

Fig. 3. Interface Adhesion Among Aggregate, Sulfate, and Asphalt.

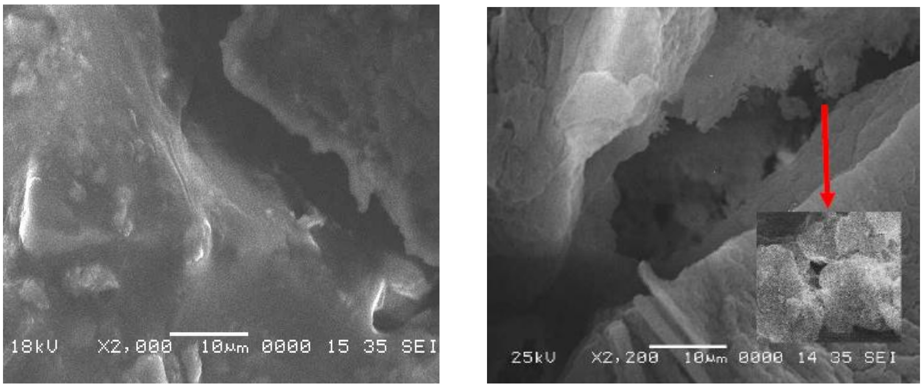

Fig. 4. Void Microstructure Change Inside the Asphalt Mixture Before and After Sulfate Erosion.

Table 4. GM(1, N) Model Prediction Results

Dry-wet Cycles/times	VV/%			Splitting Tensile Strength/MPa		
	Measured Value	Predicted Value	Relative Error	Measured Value	Predicted Value	Relative Error
0	3.85	3.85	0.00%	0.759	0.759	0.00%
15	4.23	4.21	0.45%	0.602	0.602	0.00%
30	4.98	4.99	-0.20%	0.548	0.543	0.91%
45	5.94	5.90	0.67%	0.492	0.495	-0.61%
60	6.97	6.95	0.29%	0.459	0.457	0.44%
75	/	8.18	/	/	0.430	/
90	/	9.62	/	/	0.408	/
105	/	11.30	/	/	0.396	/
120	/	13.27	/	/	0.393	/

Under the influence of dry-wet circles, internal microstructure of asphalt mixture has some changes before and after sulfate erosion, shown in Fig. 4. When specimens are placed in dry environment, moisture in sulfate solution evaporates from voids in asphalt mixture and generated sulfate crystallization volume expands. If there is no enough room to shelter the extra increasing volume in the inner of asphalt mixture, fissures come into being. At the same time, the evaporation makes moisture constantly move from the voids to the external, generating seepage pressure in pore channel of asphalt mixture. Under the joint action of expansion pressure and seepage pressure, voids of asphalt mixture continuously extend and derive some microfracture so as to aggravate the crystallin erosion of Na_2SO_4. With the increase of dry-wet cycles, material damage accumulates, eventually leading to macroscopic diseases in asphalt mixture.

GM(1, N) Model for Durability Prediction of Asphalt Mixture Exposed to Sulfate and Dry-wet Circle Erosion Environment

Set the VV and splitting tensile strength as parameters. GM(1, N) model for durability prediction of asphalt mixture exposed to sulfate and dry-wet circle erosion environment can be built according to Eqs. (1) to (11). Based on the model accuracy verification, values of above two parameters are predicted for the 75, 90, 105 and 120 dry-wet cycles respectively, presented in Table 4.

Table 4 shows GM(1, N) model prediction results of VV and splitting tensile strength of asphalt mixture. It shows that the relative error between model calculation and actual test results is within 5%. The model prediction accuracy meets the precision requirement and need no residual error correction. Therefore, the established GM(1,N) grey model can well predict the VV and splitting tensile strength of asphalt mixture exposed to sulfate and dry-wet circle erosion environment.

The prediction results show that the VV increases gradually and the splitting strength of asphalt mixture first decreases and then levels off with the increase of dry-wet cycle times for AC-13 mixture. The reasion is that under the synergy of dry-wet circulation and sulfate erosion, repeating expansion pressure and seepage pressure make the internal cracks in asphalt mixture continuously produce and extension, leading to the degradation of asphalt mixture durability. When the degradation comes to a certain extent, materials macroscopic failure occurs.

Conclusions

(1) There is a good correlation between the VV and the splitting strength as the durability factors of asphalt mixture and dry-wet cycle times. The VV increases obviously and the splitting strength decreases significantly with the increase of dry-wet cycle times under sulfate erosion condition.

(2) Sulfate solution is easier to invade the interface between asphalt binder and aggregate than purified water to accelerate water damage along with crystal expansion made in dry environment reducing the interface strength, playing the key role in the rapid attenuation of the performance of asphalt mixture. In addition, dry-wet cycles accelerate sulfate erosion damage to asphalt mixture.

(3) The established GM(1, N) grey model can well predict the VV and splitting tensile strength of asphalt mixture exposed to

sulfate and dry-wet circle erosion environment. It is reasonable and can reduce test workload to some extent.

(4) Research results can be referred to the life evaluation of asphalt mixture in sulfate enrichment regions. However, systematic test methods and evaluation system on the durability of asphalt mixture in the sulfate erosion environment are still in lack, and further research on that will need to be conducted.

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