Impact of Salt Freeze-Thaw Cycles on Low Temperature Performance of Asphalt Mixture Based on the Strain Energy Density

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ABSTRACT: With the use of snow-thawing salt in the cold winter, asphalt pavement is damaged easily by salt freeze-thaw cycles. The aim of this research is to study the impact of salt freeze-thaw cycles on low temperature performance of asphalt mixture. Through low temperature bending test, the decay law of strain energy density of asphalt mixture under the conditions of salt freeze-thaw cycles was analyzed, and strain energy density was used for regression by the exponential model, what’s more, the improvement of fiber, anti-stripping agent and slaked lime on the low temperature performance of the mixture were investigated. The results of low temperature bending test showed that the strain energy density of asphalt mixture decreased rapidly after salt freeze-thaw cycles, moreover, the more the times of salt freeze-thaw cycles, the higher the concentration of salt solution and lower the change of freezing temperature, the larger the influence on strain energy density of asphalt mixture. Regression analysis results revealed that the exponential model could well reflect the variation of strain energy density of the mixture with the times change of the salt freeze-thaw cycles. The improvement of basalt fiber on the low temperature performance of the asphalt mixture was very significant under the condition of salt freeze-thaw cycles.

INTRODUCTION

It is well known that ice or snow has significantly bad impact on asphalt concrete pavement. In the winter, asphalt pavement prone to produce snow and ice in Cold Areas, in order to ensure the traffic safety, snow-thawing salt often is used for deicing and melting snow on pavement. Although the method can cause damage to the pavement, compared with the mechanical method and electric heating method, the maneuverability of this method is good, and the price is low, so it is widely used for deicing and melting snow on the road.

With the using of snow-thawing salt and diurnal variation of temperature, asphalt pavement is easy to suffer from salt freeze-thaw cycles. The interaction of temperature, moisture and salt has seriously damage on the pavement, which leads to early disease of pavement, thus the service level and life of pavement sharp declines. So the influence of salt freeze-thaw cycles on low temperature performance of mixture has become the central issue in asphalt concrete pavement.

There have been a great number of studies in the impact of salt freeze-thaw cycles on performance of asphalt mixture. In 2010, FENG Lei studied the influence of chloride salts on freeze-thaw splitting tensile strength of asphalt concrete, the results showed that the freeze-thaw split tensile strength and freeze-thaw corrosion factor of asphalt concrete significantly decreased after chlorine salt erosion and freeze-thaw cycles. In 2012, through the research of the water stability of powder modified asphalt
mixture under salt freezing cycles, Goh S found that the freezing temperature, concentration of snow-thawing salt and the times of freeze-thaw cycles had great influence on void volume, splitting strength and Marshall modulus of rubber modified asphalt mixture. Li Ning reported that freeze-thaw cycles produced bad effect on bending properties of mixture, and the loss model of flexural performance could reflect the effect of freeze-thaw cycles in 2015. Si Wei analyzed the impact of freeze-thaw cycles, asphalt-aggregate ratio, gradation composition on flexural properties of asphalt mixture, the results indicated the asphalt-aggregate ratio and gradation had an obvious effect on the flexural characteristics, and the higher asphalt-aggregate ratio, the smaller the impact of freeze-thaw cycles on flexural characteristics of asphalt mixture.

However, most of the studies are in consideration of effect of the salt freeze-thaw cycles on water stability of the mixture, when relating to the influence of low temperature crack resistance, researchers mainly analyzed the times of freeze-thaw, temperature, asphalt-aggregate ratio and gradation. Little research results have been reported at this point concerning the effect of salt concentration, freeze-thaw temperature and times of salt freeze-thaw cycles on low temperature performance of asphalt mixture and corresponding improvement measures. Consequently, it is essential to study the impact of salt freeze-thaw cycles on low temperature crack resistance of asphalt mixture.

Therefore, the paper simulates the corrosion influence of snow-thawing salt on asphalt mixture in Cold Areas, through freeze-thaw cycles test of asphalt mixture under conditions of snow-thawing salt, the effect of freeze-thaw temperature, concentration of snow-thawing salt and times of freeze-thaw on low temperature performance of asphalt mixture is analyzed, at the same time, strain energy density is used for regression by the exponential model. Finally, the effect of fiber, anti-stripping agent and slaked lime on the strain energy density of the mixture is discussed, which provides reference and basis for the construction of asphalt pavement in Cold Areas.

MATERIALS AND TEST METHODS

Materials

In the experiment, SBS modified asphalt was used, the dolerite was selected, and mineral powder was limestone powder. The indexes meet the code requirements. AC-13 type gradation was selected. The optimum asphalt-aggregate ratio was determined as 4.9% by test analysis.

The fibers were Lignin fiber, polyester and basalt fiber, PA-1 type amine anti-stripping agent was selected. The proportion of effective calcium in the slaked lime was more than 60%. Mixing amounts of various additives and asphalt-aggregate ratio of five kinds of modified asphalt mixture are shown in Table 1.
Table 1. Mixing amounts of additives and optimal asphalt-aggregate ratio.

<table>
<thead>
<tr>
<th>Additive agent</th>
<th>Mixing amounts (%)</th>
<th>Optimal asphalt-aggregate ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basalt fiber</td>
<td>0.3</td>
<td>5.2</td>
</tr>
<tr>
<td>Polyester fiber</td>
<td>0.3</td>
<td>5.2</td>
</tr>
<tr>
<td>Lignin fiber</td>
<td>0.3</td>
<td>5.1</td>
</tr>
<tr>
<td>Slaked lime</td>
<td>2.0</td>
<td>5.1</td>
</tr>
<tr>
<td>Anti-stripping agent</td>
<td>0.4</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Test methods

In order to rationally study low temperature performance of asphalt mixture under salt freeze-thaw cycles and to better simulate the actual environment, the three factors of test were selected: freeze-thaw temperature, salt solution concentration and times of freeze-thaw cycles. Different freeze-thaw temperature was determined, that was -10°C~20°C and -20°C~10°C. Considering alternate changes of temperature of the actual area in the winter, and freezing and melting time was selected as 12~13h and 11~12h. In addition, the salt solution concentration was 0, 7%, 13%, 26.5%.

Before the test, the specimens were soaked for 48h in water or salt solution, and then test specimens were put into the plastic bag with the 10mL water or the corresponding salt solution, which kept for 12~13h under the condition of -10°C or -20°C. Then taking out the test specimens, and they were kept for 11~12h under the condition of 20°C or 10°C, that was once of salt freeze-thaw cycles. The salt freeze-thaw cycles of 5, 10, 15 and 25 times were carried out by the steps.

The bending test of asphalt mixture was carried according to JTG-E20-2011 (2011). Finally, the strain energy density was calculated according to damage criterion.

RESULTS AND DISCUSSION

Strain energy density

Based on test methods above-mentioned, salt freeze-thaw cycles test was done in the different conditions. Strain energy density of specimens was 19.62kPa without salt freeze-thaw cycles. Test results of strain energy density at -10°C~20°C are shown in Fig.1, Fig.2 shows test results at -20°C~10°C.
From the Fig.1 and Fig.2, it can be seen that the strain energy density after salt freeze-thaw cycles was lower than the result (19.62kPa) without salt freeze-thaw cycles. When the freeze-thaw temperature was -10°C~20°C, the strain energy density of the specimens was decreased by 28.63%, 39.77%, 41.9%, 43.77% after suffering from 10 cycles in the water and salt solution of 7%, 13%, 26.5%, but at -20°C~10°C, the decline rate was 39.57%, 51.58%, 56.52%, 59.13%. This indicated that strain energy density of mixture decreased gradually with the increasing of salt concentration, and the low temperature performance of mixture was worse and worse, and the decreasing trend was more obvious at -20°C~10°C. At two kinds of freeze-thaw temperature, strain energy density was the largest after the water cycles, and it was the smallest after the cycles in salt solution of 26.5%.

Compared with the test results of the two kinds of different freeze-thaw temperature, if other conditions unchanged, when the salt solution concentration increased from 0 to 7%, the strain energy density reduced by about 10%, but when the concentration increased from 7% to 13% and from 13% to 26.5%, the declining rate was about 5%. Its main reason was that internal void of specimens only suffered from the destruction of water after experiencing freeze-thaw cycles, but the interior of mixture would be Na⁺, Cl⁻ after the specimens suffered the cycles in the salt solution of 7%, which produced chemical corrosion on mixture, and the destruction of the mixture was more serious. So when the concentration of the salt solution developing from nothing, the effect on the low temperature performance of mixture was very significant. But the free Na⁺, Cl⁻ in the mixture was gradually saturated with the concentration of salt solution continuing to increase. If concentration kept on increasing, the change of strain energy density would be unobvious.

When the freeze-thaw temperature was -10°C~20°C, the strain energy density of the specimens was decreased by 20.4%, 41.9%, 50.1%, 62.0% in the salt solution of 13% after the specimens suffered from 5, 10, 15, 25 times salt freeze-thaw cycles. But at -20°C~10°C, the decline rate was 30.5%, 56.5%, 61.3%, 69.7%. It was obvious that the strain energy density of asphalt mixture decreased gradually with the times of salt freeze-thaw cycles increasing under the same experiment conditions. Therefore, the low temperature performance also showed gradual downward trend, and the performance attenuation was more significant at -20°C~10°C. The reason was that
the greater the times of freeze-thaw cycles and the lower the freezing temperature, the bigger icing pressure and salt crystal expansion pressure, and then the impact on low temperature performance of the mixture was also more significant.

**Regression analysis**

Based on the data analysis, the variation of strain energy density of the mixture was nonlinear with the times of salt freeze-thaw cycles, and the change form could be well simulated by the exponential form. Its exponential model is expressed as follows.

\[ y = ae^{bx} + c + \epsilon, \quad \epsilon \sim N(0, \delta^2) \]  \hspace{1cm} (1)

Where "y" is the strain energy density; "a", "b", "c", parameters; "x" is independent variable, representing the times of freeze-thaw cycles; \( \epsilon \) is error term.

The correlation fitting curve is shown in Fig.3 and Fig.4.

![Figure 3. The curves of strain energy density of mixture at -10℃~20℃.](image1)

![Figure 4. The curves of strain energy density of mixture at -20℃~10℃.](image2)

In the model, the mean value of the random variables was 0, which followed the normal distribution, and the parameters were estimated by the least square method. The effectiveness of fitting parameters was evaluated by \( \chi^2 \), and fitting degree of fitting curve was evaluated by \( R^2 \).

Table 2 shows the regression equation of strain energy density.

**Table 2. Regression equation of strain energy density**

<table>
<thead>
<tr>
<th>Freezing thawing temperature (℃)</th>
<th>Salt solution concentration (%)</th>
<th>Regression equation</th>
<th>R²</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10~20</td>
<td>0</td>
<td>( y = 14.016e^{-0.099x} + 5.907 )</td>
<td>0.896</td>
<td>5.02x10^-8</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>( y = 14.067e^{-0.074x} + 5.789 )</td>
<td>0.917</td>
<td>3.64x10^-9</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>( y = 14.367e^{-0.090x} + 5.415 )</td>
<td>0.964</td>
<td>6.98x10^-8</td>
</tr>
<tr>
<td></td>
<td>26.5</td>
<td>( y = 13.928e^{-0.094x} + 5.784 )</td>
<td>0.918</td>
<td>4.56x10^-8</td>
</tr>
<tr>
<td>-20~10</td>
<td>0</td>
<td>( y = 12.956e^{-0.099x} + 6.668 )</td>
<td>0.952</td>
<td>5.49x10^-8</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>( y = 13.272e^{-0.132x} + 6.495 )</td>
<td>0.873</td>
<td>3.71x10^-8</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>( y = 14.582e^{-0.126x} + 5.194 )</td>
<td>0.932</td>
<td>4.92x10^-8</td>
</tr>
<tr>
<td></td>
<td>26.5</td>
<td>( y = 14.879e^{-0.140x} + 4.923 )</td>
<td>0.821</td>
<td>7.65x10^-8</td>
</tr>
</tbody>
</table>
As can we see, the exponential model could well reflect the variation that strain energy density of the mixture was along with the times change of the salt freeze-thaw cycles. The probability value of the ‘F’ was much less than the confidence level (0.05), therefore, the regression curve was very significant statistically. The model was consistent with the test data, what’s more, it had good relativity between strain energy density and cycles. According to the above study, the strain energy density of mixture tended to be stable after 15 times freeze-thaw cycles in different concentrations of salt solution. So the salt solution of 13% and 15 times freeze-thaw cycles was proposed to simulate impact of salt freeze-thaw cycles on low temperature performance of asphalt mixture in Cold Areas.

**Improvement measures**

Under the conditions of 15 times freeze-thaw cycles, the salt solution of 13% and the freeze-thaw temperature of -20°C ~10°C, the impact of different additives on low temperature performance of asphalt mixture was simulated. The strain energy density was used for evaluating the low temperature performance, and the test results were shown in Fig.5, and Table 3 show the results of variance analysis.

![Figure 5. The test results of strain energy density.](image)

**Table 3. LSD multiple comparison of strain energy density of different mixture.**

<table>
<thead>
<tr>
<th>Group</th>
<th>Group</th>
<th>Mean deviation</th>
<th>Standard error</th>
<th>Significance</th>
<th>95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without additive</td>
<td>Basalt fiber</td>
<td>-1.88250*</td>
<td>0.20416</td>
<td>0.000</td>
<td>-2.3071 -1.4579</td>
</tr>
<tr>
<td></td>
<td>Polyester fiber</td>
<td>-1.13000*</td>
<td>0.20416</td>
<td>0.000</td>
<td>-1.5546 -0.7054</td>
</tr>
<tr>
<td></td>
<td>Lignin fiber</td>
<td>-0.61500*</td>
<td>0.20416</td>
<td>0.007</td>
<td>-1.0396 -0.1904</td>
</tr>
<tr>
<td></td>
<td>Slaked lime</td>
<td>-1.05500*</td>
<td>0.20416</td>
<td>0.005</td>
<td>-1.4796 -0.6304</td>
</tr>
<tr>
<td></td>
<td>Anti-stripping agent</td>
<td>-0.53500*</td>
<td>0.20416</td>
<td>0.016</td>
<td>-0.9596 -0.1104</td>
</tr>
</tbody>
</table>

From Table 3, it can be known that the differential coefficient is less than 0.05 between mixtures of adding fiber, slaked lime, anti-stripping agent and without additive. It was indicated that those additives improved significantly the low temperature performance of asphalt mixture under the condition of salt freeze-thaw...
cycles. However, the significant difference of different additives also had a greater distinction, and the differential coefficient was 0 between mixtures of basalt fiber, polyester fiber and without additive, which shows that mineral fiber had remarkable effect on low temperature anti-cracking performance of asphalt mixture under the condition of salt freeze-thaw cycles. The improvement of anti-stripping agent was worst, and compared with no additive mixture, the differential coefficient was 0.016. Although it was less than 0.05, the effect was unremarkable compared to other additives. Therefore, it is suggested that the basalt fiber or polyester fiber can be used to improve the low temperature performance of asphalt pavement which is subjected to the salt freeze-thaw cycles in the Cold Areas.

CONCLUSIONS

The impact of salt freeze-thaw cycles on low temperature anti-cracking performance of asphalt mixture was studied by bending test, which was evaluated through strain energy density. The exponential model was used for regression of strain energy density of the mixture with the times of the salt freeze-thaw cycles. In addition, the influence of fiber, slaked lime and anti-stripping agent on strain energy density was analyzed. The following considerations can be drawn from this study:

If the freeze-thaw temperature and the times of freeze-thaw cycles were the same, the strain energy density of mixture gradually decreased with the increasing of salt solution concentration. The higher the concentration of salt solution, the lower the reduced degree of strain energy density.

When the freeze-thaw temperature and salt solution concentration were unchanged, the strain energy density of the asphalt mixture gradually decreased with the increasing of the times of salt freeze-thaw cycles. The more the times of freeze-thaw cycles, smaller the reduced degree of strain energy density. What’s more, the influence of freeze-thaw cycles on the strain energy density of concrete was greater than that of the salt solution concentration. The lower the freezing temperature, the greater the impact on the low temperature performance of asphalt concrete. From the point of view of statistics, the strain energy density could be well reflected by the exponential model.

After asphalt mixture mixed with fiber, anti-stripping agent and slaked lime, the strain energy density had improvement to different extent. The low temperature performance of mixture suffering salt freeze-thaw cycles got significantly amelioration by adding polyester fiber and basalt fiber, and the improvements is that basalt fiber, polyester fiber, slaked lime, lignin fiber, anti-stripping agent by order from large to small. In cold regions, basalt fiber and other mineral fibers are recommended to improve the low temperature performance of asphalt concrete under the condition of salt freeze-thaw cycles.
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REFERENCES


