Study on Deicing Mechanism of High-elastic/salt-storage Functional Pavement

Ke Zhong, Mingzhi Sun*, Xue Wang
Research Institute of Highway Ministry of Transport, Beijing 100088, China
*Corresponding author’s e-mail: mz.sun@rioh.cn

Abstract: Snow and ice on pavement surface will reduce anti-skid performance between tire and pavement which will cause traffic safety problem. High-elastic/salt-storage asphalt mixture is a recently widely used functional pavement for snow removal and ice melting. In this paper, a three-dimensional finite element model of pavement structure under five different working conditions is established. Then, the pavement structure under the most unfavorable conditions can be determined through calculating and analysing for the maximum compressive strain index in the ice layer. And the sensitivity of the ice melting effect parameters including ice thickness, temperature, thickness and modulus of high elastic pavement with salt storage were respectively discussed under the most unfavorable conditions.

1. Introduction
Snow and ice on road surface will reduce anti-skid performance between tire and pavement which will cause traffic safety problem. Every year, a large amount of manpower and financial resources are invested by the road administration department to remove snow and ice. Most countries in low latitudes suffer from this problem in winter. According to statistics, nearly half of road traffic accidents in China are related to adverse climatic conditions, in which caused by snow and ice on the road surface accounts for more than 35% of the total traffic accidents in winter. Meanwhile the annual economic losses caused by snow and ice on the road surface amount to hundreds of millions[1-2].

At present, the active road snow-melting and deicing technology can be mainly divided into three types according to the principle: 1) Adding salt-storage materials into pavement mixture to reduce freezing point of ice and snow in the contact surface; 2) Embed a highly elastic material such as rubber particle to the road surface in order to achieve self-stress deicing performance for the pavement surface; 3) The thermal system is embedded in the pavement structure to achieve thermal melting of ice and snow. Although the electrothermal method has a good effect of removing snow and melting ice, its energy consumption is large, the cost is high, and maintenance and repair are difficult. All these factors limit the application of this method. For this reason, the addition of salt storage materials and the incorporation of high-elastic materials in active snow-melting ice technology have become the focus of attention for many road industry researchers[3-5]. However, due to the limitation of test methods, the research on the self-stress deicing mechanism of high-elastic/salt-storage materials has not been thoroughly studied.

With the rapid development of finite element technology, it is possible to solve the above problems. In this paper, the self-stress deicing simulation model of high-elastic/salt-storage asphalt pavement is established by using finite element software Abaqus. The pavement structure under the most
unfavorable conditions can be determined through calculating. And the sensitivity of the ice melting effect parameters including ice thickness, temperature, thickness and modulus of high elastic pavement with salt storage were respectively discussed under the most unfavorable conditions.

2. Model establishment

2.1. Geometric model
The pavement structure is regarded as an elastic layered system, and the objects of study are ice layer, asphalt upper layer, asphalt lower layer, base course, bottom base and soil foundation, and all of them adopt 8-node solid element to establish three-dimensional finite element model. The model is shown in figure 1.

2.2. Constitutive model and material parameters
According to the finite element submodel analysis method, the size of the pavement structure model is set to 600cm×300cm×250cm with considering the calculation precision and calculation speed. According to the typical road structure, the composition and parameters of each structure are as shown in Table 1.

| Structure sheaf       | Thicknesses (cm) | Modulus of elasticity (MPa) | Poisson ratio |
|-----------------------|------------------|-----------------------------|---------------|
| ice layer             | 0.4 (0.4~2.0)    | 1800                        | 0.33          |
| asphalt upper layer   | 4                | 3160                        | 0.25          |
| ordinary asphalt      | 8                | 2600                        | 0.30          |
| salt-storage /high    | 8 (4~20)         | 1000 (500~2500)             | 0.38          |
| elastic asphalt       |                  |                              |               |
| semi-rigid base       | 20               | 1700                        | 0.25          |
| flexible base         | 20               | 1100                        | 0.30          |
| bottom base           | 20               | 800                         | 0.30          |
| soil foundation       | -                | 80                          | 0.30          |

2.3. Loading applied
Standard axial load BZZ-100 is adopted as calculation load. Tire grounding pressure is 0.7MPa. The single wheel compression range is rectangular as 25cm×14cm, and ground area is 350cm². The distance between two wheels is 35cm. The load position where the maximum mechanical response generated in the ice layer is at the center of the two-wheel center located at the center of the road surface, which is the most unfavorable position.
2.4. Evaluation criteria

At present, there is no uniform reference value for the mechanical parameters of ice damage. Based on the relevant research results of the compressive strength standard of ice and the flexural strength of Yanghe ice in the current national bridge design code, and referring to the parameters given by Prof. Li[6] in the paper, the characteristic parameters of ice damage at 0℃ was determined as shown in Table 2.

Table 2. Ice Failure Strength and Strain at 0℃

| Tensile strength (MPa) | Compressive strength (MPa) | Shear strength (MPa) |
|------------------------|---------------------------|----------------------|
| 0.45                   | 0.60                      | 0.30                 |
| Ultimate tensile strain ($\times10^{-4}$) | Ultimate pressure strain ($\times10^{-4}$) | Ultimate shear strain ($\times10^{-3}$) |
| 2.20                   | 2.30                      | 2.40                 |

3. Results and discussion

3.1. Deicing effect analysis

In order to analyze the influence of salt-storage/high-elastic asphalt layer on the stress and strain of ice layer, the following 5 kinds of pavement structures were proposed to analyze as shown in Table 3 with the temperature by using 0℃.

Table 3. Pavement structure combination under different working conditions

| Working condition 1 | Working condition 2 | Working condition 3 | Working condition 4 | Working condition 5 |
|---------------------|---------------------|---------------------|---------------------|---------------------|
| ice layer 4mm       | ice layer 4mm       | ice layer 4mm       | ice layer 4mm       | ice layer 4mm       |
| ordinary asphalt    | salt-storage /high  | ordinary asphalt    | salt-storage /high  | ordinary asphalt    |
| upper layer 4cm     | elastic asphalt     | upper layer 4cm     | elastic asphalt     | upper layer 4cm     |
|                     | mixture layer 4cm   |                     | mixture layer 4cm   |                     |
| ordinary asphalt    | ordinary asphalt    | salt-storage /high  | ordinary asphalt    | salt-storage /high  |
| lower layer 8cm     | lower layer 8cm     | elastic asphalt     | lower layer 8cm     | elastic asphalt     |
|                     |                     | mixture layer 8cm   |                     | mixture layer 8cm   |
| semi-rigid base 20cm| semi-rigid base 20cm| semi-rigid base 20cm| flexible base 20cm  | flexible base 20cm  |
| bottom base 20cm    | bottom base 20cm    | bottom base 20cm    | bottom base 20cm    | bottom base 20cm    |
| soil foundation     | soil foundation     | soil foundation     | soil foundation     | soil foundation     |

The most unfavorable load position is used to calculate the pressure strain response of ice layer under different working conditions as shown in Fig. 3.
Figure 3. Pressure strain response in ice layer of working condition 5

The maximum compressive strain in the ice layer under different working condition is shown in Table 4.

| Working condition | Working condition 1 | Working condition 2 | Working condition 3 | Working condition 4 | Working condition 5 |
|-------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| Maximum compressive strain ($\times 10^{-4}$) | 1.99 | 2.15 | 2.50 | 2.10 | 2.74 |

The calculated data show that the existence of salt-storage/high-elastic asphalt layer can improve the deicing performance of pavement structure, and the salt-storage/high-elastic asphalt layer located between the lower layer and flexible base can obtain best deicing effect. Therefore, the most unfavorable condition is working condition 5, the pavement structure that is most favorable to deicing, and the following discussion will be carried out under the most disadvantageous condition.

3.2. Parameters Sensitivity analysis of deicing effect

3.2.1. Influence of ice thickness

The thickness of ice layer varies from 4mm to 20mm, and the calculation interval is 4mm. The calculated temperature is 0°C, and the result is shown in Figure 4.

As shown in Figure 4, with the increase of ice thickness, the tensile strain at the bottom of the ice layer decreases gradually. The maximum compressive strain in the ice layer is reduced by 23.7% than that in the 4mm layer when the thickness of the ice layer is thick. When the thickness of the ice layer is 4mm and 8mm, the deicing effect is still obvious, which exceeds the ultimate compressive strain of the ice layer. It shows that the deicing effect of rubber particles on asphalt pavement can only play a role within a certain range of ice thickness.

3.2.2. Analysis of temperature effects

The crystal lattice and strength of ice material vary greatly under different temperature conditions. The lower the temperature is, the stronger the lattice is, the higher the strength of the ice body is, and the greater the ultimate failure stress is. Asphalt mixture is a typical temperature sensitive material whose
modulus is greatly influenced by the temperature, and the overall modulus of the pavement structure changes with the change of temperature. With different environment temperature the high-elastic/salt-storage asphalt pavement will show different deicing and snowmelt performance. According to the related research, the elastic modulus of different layers of pavement structure at different temperatures is shown in Table 5.

Table 5. Elastic Modulus of materials at different layers and different temperatures

| Structure layer                        | Modulus of elasticity (MPa) |
|----------------------------------------|-----------------------------|
|                                        | 0℃  | -5℃  | -10℃ | -15℃ | -20℃ |
| ice layer                              | 1800 | 2300  | 3000  | 3300  | 3800  |
| ordinary asphalt upper layer           | 3160 | 3500  | 4100  | 4850  | 5900  |
| salt-storage/high elastic asphalt mixture layer | 1000 | 1450  | 1950  | 2500  | 3100  |
| flexible base                          | 1100 | 1100  | 1100  | 1100  | 1100  |
| bottom base                            | 800  | 800   | 800   | 800   | 800   |
| soil foundation                        | 80   | 80    | 80    | 80    | 80    |

In order to study the influence of temperature, the force of the ice layer in the range of 0℃ to -20℃ was analyzed and calculated, and the calculation interval was taken as 5℃. The calculated results are shown in Figure 5.

Figure 5. Mechanical response of ice layer at different temperature

The results show that with the decrease of temperature, the maximum compressive strain in the ice layer decreases sharply. When the temperature drops to -20 ℃, the maximum compressive strain decreases by 43.4% compared with that at 0 ℃, and when the temperature is -5 ℃, the maximum compressive strain decreases by 43.4% when the temperature is -5 ℃. The maximum compressive strain in the ice layer is $2.33 \times 10^{-4}$, which is very close to the ultimate compressive strain of the ice layer. When the temperature is lower than -5 ℃, it can be considered that the ice breaking effect of the salt storage high elastic layer is very little. The results show that the ice and snow melting effect of high elastic asphalt pavement with salt storage tends to decrease with the decrease of temperature, and when the temperature drops to a certain extent, it has no ice melting effect.

3.2.3. Influence of thickness of salt-storage/high-elastic layer

In order to analyze the influence of the thickness of salt-storage/high-elastic layer on the deicing effect of pavement structure, comparing and analyzing the stress of ice layer under different thickness of high elastic layer. The thickness of the salt-storage/high-elastic layer varies in the range of 4cm~20cm with the calculation interval is 4cm. The thickness of other structural layers remains constant as working condition 5. The results are shown in figure 6.
With the increase of the thickness of salt-storage/high-elastic layer, the maximum compressive strain of the ice layer decreases. The thickness of the high elastic layer increases from 4cm to 20 cm, and the maximum compressive strain in the ice layer decreases by 22%.

3.2.4. Influence of salt-storage/high-elastic layer Modulus
Comparing and analyzing the stress of ice layer under different modulus of salt-storage/high-elastic layer. The variation range of modulus is 500MPa~2500MPa with the interval is 500MPa. The calculated temperature is 0℃, and the results are shown in figure 7.

When the modulus of salt-storage/high-elastic layer has increased from 500MPa to 1500MPa, the maximum compressive strain in the ice layer decreases by 41%, and the decrease is larger. With the further increase of the modulus of salt-storage/high-elastic layer, the stress in the ice layer tends to be stable. This indicates that the pavement structure with low modulus of salt-storage/high-elastic asphalt will have better deicing performance.

4. Conclusions
In view of the deicing mechanism of salt-storage/high-elastic materials, the ABAQUS finite element analysis software is used to establish the model, and the sensitive factors affecting the deicing effect of salt-storage/high-elastic materials are analyzed. The main conclusions are as follows:

1) The existence of salt-storage/high-elastic layer can improve the deicing performance of pavement structure, and the deicing effect is better when the high elastic layer is located at the lower layer;
2) The thicker the ice layer is, the less the effect of melting ice and snow on pavement structure is;
3) The deicing effect of salt-storage/high-elastic layer in a certain temperature range will be lost at very low temperature;
4) There is a reasonable thickness range of salt-storage/high-elastic layer, which is determined from 4 cm to 8 cm;
5) The modulus of salt-storage/high-elastic layer has a significant effect on the stress inside the ice
layer. The pavement structure with low modulus of salt-storage/high-elastic layer shows better deicing effect.

Acknowledgements
The research work described herein was funded by the Fundamental Research Funds for the Central Research Institute (Grant No. 2017-9066 & 2017-9059) and the Innovation Fund for Research Institute of Highway (Grant No. 2018-A0028). This financial support is gratefully acknowledged.

References
[1] Tan Yiqiu, Sun Rongrong, Guo Meng, et al. (2013) Study on ice and snow removal performance of salt storage asphalt mixture. Chinese Journal of Highway Engineering, 26(1):23-29.
[2] Hassan Y, Halim A O A E, Razaqpur A G, et al. (2002) Effects of Runway Deicers on Pavement Materials and Mixes: Comparison with Road Salt. Journal of Transportation Engineering, 128(4):385-391.
[3] Cui Longxi. (2010) Study on Asphalt Mixture for Salt Storage. Chongqing Jiaotong University.
[4] Zhou Chunxiu. (2006) Research on Application Technology of Rubber Particles Asphalt Mixture in Ice and Snow. Harbin Institute of Technology.
[5] Xu Ruiqin. (2011) Research on ice-breaking performance of rubber granular asphalt mixture. Chang’an University.
[6] Li Zhijun, Wang Yongxue. (2000) Design parameters of sea ice engineering in Bohai Sea. Ocean Engineering, 18(1): 61-64.