Deicing Property of Asphalt Mixture Containing Steel Wool Fiber by Electromagnetic Induction Heating

Cunhong Xu¹, Kejin Wang², Kehong Li³ and Youjie Zong³, *

¹ Qinghai Transportation Construction Engineering Cost Station, Xining 810001, China; xuch20122021@163.com
² Qinghai Transportation Holding Group Co., Ltd., Xining 810001, China; wangkj012021@163.com
³ School of Materials Science and Engineering, Chang’an University, Xi’an 710061, China; likehong1234562021@163.com
* Correspondence: 2020031003@chd.edu.cn

Abstract: Snow and ice is one of the main problems affecting road safety in winter. In order to effectively remove the snow and ice of covering the pavement, the deicing property of asphalt mixture pavement containing steel wool fiber was introduced and investigated by electromagnetic induction heating. Based on the deicing mechanism of Faraday’s law of electromagnetic induction and the Joule’s law, the influences factors affecting deicing efficiency, including length and content of steel wool fiber, ice thickness, output current and ambient temperature were analyzed. Meanwhile, the grey correlation entropy analysis and t-test between the average deicing rate and various influencing factors were explored. BP neural network prediction models of predicting change laws of average deicing rate under different influencing factors were established. The results indicate that the average deicing rate of asphalt mixture adding steel wool fiber increases with the increase of length and content of steel wool fiber. The influence degree of each factor for the average deicing rate is in order as follows: steel wool fiber content, steel wool fiber length, output current, ambient temperature and ice thickness. BP neural network has high accuracy in predicting average deicing rate under various influencing factors and the better simulation results. It is of significance to apply the technology of “electromagnetic induction heating & steel wool fiber” to the efficient deicing of asphalt pavement.

Keywords: road engineering; asphalt mixture; steel wool fiber; deicing property; electromagnetic induction heating; grey entropy method; BP neural network

1. Introduction

Asphalt pavement deicing has always been a key concern of traffic maintenance departments worldwide. In winter, snow and ice of covering the pavement reduce the friction coefficient of road surface and result in insufficient vehicle-mounted braking effect. Traffic accidents frequently occur, and seriously threaten driving safety. In this case, 25%–30% of traffic accidents are caused for icy road conditions in winter [1–3]. At present, the common deicing methods are divided into the passive deicing and positive deicing. Passive deicing methods including mechanical, chemical, artificial and microwave deicing are still dominant [4,5]. Mechanical deicing has higher efficiency, but the maintenance costs are expensive. These kinds of methods may cause damages to the structure of the pavement and ancillary facilities. Even though deicing salt has significant effect, it is easy to cause environmental pollution [6–8]. Deicing salt might erode asphalt pavement and shorten its service life [9–11]. Artificial deicing and microwave deicing have some disadvantages, such as the lower efficiency and environmental pollution [12,13]. Positive deicing includes elastic pavement method, low freezing point method, thermal method. Even though the positive deicing is effective, it still encounters some problems such as ice thickness, limit of environmental temperature, high construction cost and energy consumption [14–23]. Therefore, it is necessary to introduce a new deicing concept and technology to solve the problem of ice and snow covering on asphalt pavement in winter. Phan T M et al. [24]
explored the applicability of microwave heating of asphalt mixtures mixed with steel slag. The research provided ideas for the production of asphalt mixture containing steel wool fiber.

In recent years, researchers have been developing new methods about road deicing. Meanwhile, Norambuena-Contreras, J. et al. [25] investigated steel wool fiber and steel scrap for electricity, heat, microwave crack repair asphalt mixture performance. The void content of asphalt mixture mixed with steel scrap is lower than that of asphalt mixture mixed with steel wool fiber. The long steel wool fiber can form a good conductive channel to increase the conductivity of the asphalt mixture containing steel wool fiber, and it can produce more heat energy. The research of Norambuena-Contreras, J. et al. provides a basis for the deicing research of asphalt mixture containing steel wool fiber. García, A. et al. [26] studied the properties of steel wool fiber asphalt mixture and found that steel wool fiber did not significantly improve the mechanical properties and damage resistance of asphalt mixture containing steel wool fiber. However, steel wool fiber improved the thermal conductivity of asphalt mixture. In order to improve the deicing efficiency of microwave heating asphalt pavement, Guo et al. [27] replaced part of the aggregate with magnetite. Gao et al. [28] studied the deicing property whose microwave heated asphalt mixture containing steel wool fiber and analyzed the optimal content amount of different types of steel wool fiber. Results show that the optimal steel wool fiber contents for microwave heating of asphalt mixture are 0.3% of 006#, 0.6% of 0# and 0.9% of 2#, respectively. Energy of heating deicing by microwave is low and can effectively reduce the adhesion stress between pavement surface and ice layer. However, microwave radiation will produce microwave pollution. In view of the advantages of electromagnetic induction heating with low consumption, no pollution, non-contact, rapid heating rate, and steel wool fiber with excellent electric conductivity and mechanical properties [29–31], the paper introduced electromagnetic induction heating principle. Meanwhile, the economy of steel velvet fiber is investigated qualitatively [32,33]. The relationships of electromagnetic induction heating effect and the deicing of asphalt mixture containing steel wool fiber were investigated. Figure 1 shows the slope of Baldwin Street is as high as 35% in New Zealand.

Figure 1. The actual road conditions with large longitudinal slope (pictures from internet). (a) Highway in mountainous area of China; (b) Baldwin Street in New Zealand.

In the paper, under 3 kinds of length and 5 kinds of contents of steel wool fiber, the performances of asphalt mixture containing steel wool fiber were carried indoors, including the adding ways of steel wool fiber, composition design, road performances (high temperature stability, low temperature crack resistance, water stability). With steel wool fiber, low temperature crack resistance of asphalt mixture were improved. The test results show that when the fiber length is 5 mm and the content is 4%, the asphalt mixture has the best pavement performance. Meanwhile, average deicing rate was applied as the evaluation index of asphalt mixture containing steel wool fiber, and the influencing factors on the average deicing rate were explored through grey entropy correlation and t-test.
methods. The BP neural network evaluation models of average deicing rate under various influencing factors were constructed. The research results would provide new references for improving the deicing efficiency of asphalt mixture pavement by electromagnetic induction heating.

2. Materials, Test Equipment and Methods

2.1. Materials

The materials utilized in this study include SK-90# asphalt binder, aggregate, mineral filler. Aggregate and mineral filler is produced in Xianyang, China. The penetration of the SK-90# asphalt binder was controlled between 80 and 100. The ASTM specified properties of the asphalt binder are presented in Table 1.

The coarse and fine aggregates were crushed basalt. Technical indicators of the aggregates are presented in Table 2.

Table 3 presents main properties of limestone mineral filler.

Table 1. Technical properties of SK-90# asphalt binder.

| Material        | Test Items           | Unit   | Value | Specification   |
|-----------------|----------------------|--------|-------|-----------------|
| SK-90# asphalt binder | Penetration at 25 °C | 0.1 mm | 86    | ASTM D5-97      |
|                 | Ductility at 15 °C   | cm     | 182   | ASTM D113-99    |
|                 | Softening point      | °C     | 47.0  | ASTM D36-06     |
|                 | Wax content          | %      | 1.75  | ASTM D3344-90   |
|                 | Flash point          | °C     | 304   | ASTM D92-02     |
|                 | Specific gravity     |        | 1.030 | ASTM D70-76     |
| RTFO binder *   | Mass loss            | %      | 0.15  | ASTM D2872-04   |
|                 | Penetration ratio at 25 °C | % | 60.5 | ASTM D5-97 |
|                 | Ductility at 10 °C   | cm     | 9.8   | ASTM D113-99    |

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

Table 2. Technical properties of aggregate.

| Test Items            | Unit     | Value | Test Method |
|-----------------------|----------|-------|-------------|
| Density               | g/cm³    | 2.830 | T0304       |
| Los Angeles abrasion   | %        | 11.2  | T0316       |
| Polished value        | Non      | 56    | T0321       |
| Adhesivity            |          | 5     | T0317       |
| Fine aggregate angularity | %   | 45    |             |

Table 3. Main properties of limestone mineral filler.

| Test Items                     | Unit    | Technical Requirement | Value | Test Method |
|--------------------------------|---------|------------------------|-------|-------------|
| Apparent density               | t/m³    | ≥2.50                  | 2.705 | T0352       |
| Moisture content               | %       | ≤1                     | 0.42  | T0103       |
| Particle size range<0.6 mm     | %       | 100                    | 100   | T0351       |
| <0.15 mm                       | %       | 90–100                 | 97.8  | T0351       |
| <0.075 mm                      | %       | 75–100                 | 95.1  | T0351       |
| Hydrophilic coefficient        | -       | <1                     | 0.31  | T0353       |

The gradation curve is shown in Figure 2 along with the gradation specification ranges.
The lengths of steel wool fiber are 1, 3, 5 mm, and the diameter is 70 μm. It was produced in Zhangjiagang Xinli Metal Co. LTD, Zhangjiagang, China. The density is 7.220 g/cm³, and tensile strength of single filament is 800 MPa. The macrographs and micrographs of steel wool fiber are shown in Figures 3 and 4 [34].

![Gradation Curve](image1.png)

**Figure 2.** The Gradation Curve.

![Macrographs of steel wool fiber](image2.png)

**Figure 3.** Macrographs of steel wool fiber. (a) 1 mm; (b) 3 mm; (c) 5 mm.

![Scanning electron microscope images of steel wool fiber](image3.png)

**Figure 4.** Scanning electron microscope images of steel wool fiber.
2.2. Instrument

HD-5KW auto-controlled electromagnetic induction heating equipment produced by Taiguan Power Supply Technology Co., LTD in Jiangmen, China is used for investigations, as shown in Figure 5a. Tix520 infrared imaging device was produced by Fluke Company in Everett, WA, USA, as shown in Figure 5b. Its temperature range is $-20$–$800$ °C.

2.3. Methods

2.3.1. Preparation of Specimen

When mixed with asphalt mixture, steel wool fibers are liable to disperse unevenly. After various mixing processes were attempted, the optimal scheme of solving above question was obtained. After the aggregate and the asphalt were mixed for 90 s, each 10 g steel wool fiber was mixed for 30 s. The asphalt mixture was mixed for 90 s until the steel wool fiber was finally added. The addition of steel wool fiber also increases the connection and interlocking between asphalt, coarse aggregate and fine aggregate [35]. Finally, the Marshall standard specimens containing steel wool fiber were formed, according to Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011).

Standard Marshall test design method was used to determine the optimum proportion of asphalt of AC-13C steel wool fiber asphalt mixture. Five different asphalt proportions of 4.2%, 4.5%, 4.8%, 5.1% and 5.4% were selected, respectively. The relevant Marshall test was carried out according to the requirements of the code. The optimum proportion of asphalt of steel wool fiber asphalt mixture was determined to be 4.8%. Meanwhile, According to Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011), the pavement performance of asphalt mixture met the specification requirements.

2.3.2. Deicing Principle of Electromagnetic Induction Heating

The deicing principle by electromagnetic induction heating is shown in Figure 6. The calculation formula of induced electromotive force is shown in literature [35].

![Figure 5. Test equipment. (a) Electromagnetic induction heater; (b) Tix520 infrared thermal device.](image)

![Figure 6. Flow chart of principle of electromagnetic induction heating deicing.](image)
The induction current generation process is shown in Figure 7. Electrons to move irregularly at high speeds generated induced current. Thermal energy was generated. The calculation formula of the thermal energy is shown in literature [35].

![Figure 7. The generation process diagram of induction current.](image)

The steel wool fiber is the main conductor of heat generation and heat transfer in the asphalt mixture. The heat generated can deice or reduce the adhesion between the ice and the asphalt mixture, thus removing the ice by external force. Figure 8 shows the experimental heating and deicing process.

![Figure 8. The diagram of experimental heating and deicing process.](image)

2.3.3. Electromagnetic Induction Heating Process

Standard Marshall specimens of asphalt mixture containing 2%, 3%, 4%, 5%, 6% steel wool fibers are prepared. There are three different lengths of a certain proportion of steel wool fibers in an asphalt mixture. Specimens were vacuumed under the condition of water retention, and the water layers with a thickness of 3, 6, and 9 mm were injected into specimen surface. Specimens were placed in a constant temperature environment of −5, −10, and −15 °C for 16 h. According to the freeze-thaw cleavage test, the freezing time of the specimens was confirmed. The specimens were frozen at −18 ± 2 °C. The time is 16 ± 1 h. In constant temperature and humidity environment, electromagnetic induction heating equipment was applied to deicing test, and its output current was adjusted to 330, 430, 530 and 630A. The factors affecting the deicing of asphalt mixture containing steel wool fiber were studied. The surface changes and temperature of asphalt mixture specimens were recorded every 15 s. When the ice surface temperature of the specimen is 0 °C, the total deicing time is recorded. The experimental process is shown in Figure 9.
The surface changes and temperature of asphalt mixture specimens were recorded every 15 s. The factors affecting the specimen surface retention, and the water layers with a thickness of 3, 6, and 9 mm were injected into wool fibers in an asphalt mixture.

2.3.4. Grey Relation Entropy Analysis Method

The grey relation entropy analysis method is a new method based on grey relational analysis method. It contains grey correlation coefficient, grey relational entropy and grey entropy correlation degree, analysis of key influencing factors [35–39].

2.3.5. BP Neural Network Prediction Model about Average Deicing Rate

BP (Back Propagation) neural network is a multi-layer feedforward network trained in error inverse propagation algorithm. It consists of two processes: the forward propagation of information and the back propagation of error. According to the test data, BP neural network was used to construct the prediction model about influence factors. The calculation steps are as follows.

Sample data selection and normalization processing.

The input layer of the model is influence factors. The output layer is the average deicing rate. 36 sets of test data were selected randomly as the input/output sample data, including 30 sets of training sample data and 6 sets of confirmation sample data. Sample data need normally processing according to the Equation (1). Input and output vectors are within the scope of the interval \([0, 1]\), and conform to the numerical value range that is required by S-shaped logarithmic or tangent function.

\[
y = \frac{x - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}} \quad (1)
\]

Design and train neural network structure.

The model selected a three-layer structure, including the input layer, the hidden layer and the output layer. The hidden layer adopted single-hidden layer. Through a large number of repeated tests, the optimal number of neuron nodes in the hidden layer were determined to be 12. BP neural network structure is shown in Figure 10.

![Diagram of BP neural network structure.](image-url)
For the input and output data both within the range of $[-1, 1]$, the transfer function of the hidden layer was designed as S-type Tansig tangent function, and the transfer function of the output layer was designed as Purelin. The Traingdm function improved additional momentum method was used for training. The learning rate of network training was set as 0.1, and the number of iterations was 1000. The target of training error was 0.00001. The design and training codes of BP neural network are as follows.

```matlab
net = newff (inputn,outputn,hiddennum, {'tansig','purelin'});
net.trainParam.epochs = 100;
net.trainParam.lr = 0.1;
net.trainParam.goal = 0.00001;
net.trainParam.show = 1000;
net.trainParam.showWindow = 0;
net = train (net,inputn,outputn);
inputn_test = mapminmax ('apply',input_test,inputps);
an = sim (net,inputn_test);
BPoutput = mapminmax ('reverse',an,outputps).
```

3. Results and Discussion

3.1. Evaluation Index—Average Deicing Rate

$V_T$ is the average deicing rate. With value increasing, deicing efficiency of asphalt mixture containing steel wool fiber gradually improves.

$$V_T = \frac{\Delta T}{t} \quad (2)$$

where $V_T$ is the average deicing rate ($^\circ C \cdot s^{-1}$); $\Delta T$ is the value of ice layer surface temperature before and after electromagnetic induction heating ($^\circ C$); $t$ is the induction heating time (s).

3.2. Infrared Thermal Images and Temperature Variation of Specimen Surface

The temperatures change of asphalt mixture containing steel wool fiber during heating were recorded, as shown in Figure 11. In the asphalt mixture sample shown in the figure, the content of steel wool fiber is 3% and the length is 5 mm.

![Figure 11](image-url). (a) Ambient temperature of ice layer surface; (b) Temperature of heating for 30 s; (c) Temperature of heating for 54 s; (d) 0 $^\circ C$ on the surface of specimen.

3.3. The Effects of Various Factors on Average Deicing Rate

3.3.1. The Variation Laws of Content and Length of Steel Wool Fiber and Average Deicing Rate

The variation laws of the ice layer temperature and average deicing rate with different content and length of steel wool fiber are shown in Figures 12 and 13.
The influence of content and length of steel wool fiber on ice layer temperature. (a) 1 mm; (b) 3 mm; (c) 5 mm.

As shown in Figures 12 and 13, with the increase of content of steel wool fiber, the average deicing rate increases. These indicate that the content of steel wool fiber has a significant influence on deicing efficiency. The reason is that the increase of content of steel wool fiber led to the increase of conductor in the asphalt mixture. Eventually the heat generated by induction heating per unit time and the average deicing rate on the ice layer surface also increase. In the blank group, the average deicing rate was 0.11 °C·s⁻¹. However, the average deicing rate of the specimens whose steel wool fiber length were 5 mm and content were 6% was 0.47 °C·s⁻¹. The temperature-rising range of the specimens whose steel wool fiber content were 2% and lengths were 1, 3 and 5 mm were smaller. The reason was that the content of steel wool fiber in asphalt mixture was too little, and the heat generated by a small number of conductors through induction current was not enough to improve the average deicing efficiency of the specimens.

3.3.2. The Variation Laws of Ambient Temperature and Average Deicing Rate

The variations of ice layer temperature and average deicing rate with different lengths of steel wool fiber and ambient temperatures were investigated. Take steel wool fiber content of 4%, output current of induction heating equipment of 630 A and ice thickness of 3 mm as an example. Figures 14 and 15 are analysis results.
Figure 14. The influence of lengths of steel wool fiber and ambient temperature on deicing temperature. (a) $-15^\circ$C; (b) $-10^\circ$C; (c) $-5^\circ$C.

Figure 15. The influence of lengths of steel wool fiber and ambient temperature on average deicing rate.

In Figures 14 and 15, the variations of ambient temperature affected the ice layer surface temperature and the average deicing rate. At the same time as the steel wool fibers, the average deicing rate gradually increased with the increase of ambient temperature. The range of rising temperature of the ice layer surface increased, and the total time of reaching to $0^\circ$C of the ice layer surface temperature decreased. The average deicing rate was improved. At the identical ambient temperature, as the length of steel wool fiber increases, ice layer surface temperature increased. When the ambient temperature was $-5^\circ$C, the total time of reaching $0^\circ$C for ice layer surface temperature of the specimens whose length of steel wool fiber was different decreased. Meanwhile, the average deicing rate increased, as the length of fiber increases, because the heat of longer fibers was more. When the ambient temperature was $-5^\circ$C, the average deicing rates of the three types of specimens whose lengths of steel wool fiber were different reached the highest. When the ambient temperature was $-15^\circ$C, the average deicing rates of the three types of specimens were lower. The reason is that the lower ambient temperature led to more heat loss generated by induction heating and less heat transfer. As a result, the time of rising to $0^\circ$C for the ice layer surface temperature was prolonged and the average deicing rate decreased.

The influence degrees on average deicing rate under induction heating were obtained through grey correlation entropy analysis, as shown in Figure 16.
The range of rising temperature of the ice layer surface increased, and the total time of reaching to 0 °C of the ice layer surface temperature decreased. The average deicing rate decreased by induction heating. Meanwhile, the average deicing rate decreased. As a result, the time of rising to 0 °C was prolonged and the average deicing rate decreased by induction heating. As a result, the time of rising to 0 °C was prolonged.

Figure 16. The grey entropy correlation of five influencing factors.

In Figure 16, the content of steel wool fiber has the greatest influence on the average deicing rate, followed by the length of steel wool fiber. The content and length of steel wool fiber are the main factors. The output current, ambient temperature and ice thickness are secondary factors. The ice thickness has little effect. Therefore, in the actual working conditions, in order to improve the deicing efficiency, the optimal content and length of steel wool fiber should be taken as the main control indexes.

3.4. Results of t-Test

Statistical analysis of test data was conducted to analyze the influencing factors. The relationships between average deicing rate and length and content of steel fiber wool, ice thickness, output current and ambient temperature were determined, as shown in Table 4. Through the t-test (Table 5), the length and content of steel wool fiber and output current is positively correlated with the average deicing rate. The ice thickness and ambient temperature is positively correlated with the average deicing rate. They have significant impacts on the average deicing rate.

Table 4. The relationships between average deicing rate and factors.

| Title                              | Average Deicing Rate |
|------------------------------------|----------------------|
| Multiple R                         | 0.901                |
| R square                           | 0.812                |
| Adjusted R square                  | 0.783                |
| Standard Error                     | 0.4770               |
| Intercept                          | 0.112                |
| Slope X1/(Content)                 | 0.056                |
| Slope X2/(Length)                  | 0.040                |
| Slope X3/(Ice thickness)           | −0.033               |
| Slope X4/(Output current)          | 0.035                |
| Slope X5/(Ambient temperature)     | −0.001               |
| Regression equation                | Y = 0.112 + 0.056X1 + 0.040X2 − 0.033X3 + 0.035X4 − 0.001X5 |

Table 5. t-test for slope.

| Evaluation Index | Factor                          | T Statistic | p-Value | Significance | CI Lower Limit | CI Upper Limit |
|------------------|---------------------------------|-------------|---------|--------------|----------------|----------------|
| Average deicing  | The content of steel wool fiber | 7.223       | 0.000   | Significant  | 0.040          | 0.072          |
| Average deicing  | The length of steel wool fiber  | 5.810       | 0.000   | Significant  | 0.026          | 0.054          |
| Average deicing  | Ice thickness                   | −6.858      | 0.000   | Significant  | −0.043         | −0.023         |
| Average deicing  | Output current                  | 2.376       | 0.000   | Significant  | 0.018          | 0.043          |
| Average deicing  | Ambient temperature             | −0.29       | 0.000   | Significant  | −0.008         | 0.006          |
3.5. BP Neural Network Prediction Model

6 sets of data were selected as confirmation samples, as shown in Table 6. The variation laws of average deicing rate on the surface of specimens under 5 influencing factors by BP neural network prediction model are shown in Figure 17.

Table 6. The confirmation samples of original data.

| Test Number | Fiber Content/% | Fiber Length/mm | Ice Thickness/mm | Output Current/A | Ambient Temperature /°C | Average Deicing Rate/°C·s⁻¹ |
|-------------|-----------------|-----------------|-----------------|-------------------|-------------------------|---------------------------|
| 1           | 4               | 5               | 3               | 630               | −15                     | 0.34                      |
| 2           | 5               | 3               | 3               | 530               | −15                     | 0.32                      |
| 3           | 6               | 3               | 3               | 430               | −15                     | 0.34                      |
| 4           | 6               | 3               | 3               | 530               | −15                     | 0.43                      |
| 5           | 3               | 3               | 3               | 430               | −15                     | 0.20                      |
| 6           | 2               | 3               | 3               | 430               | −15                     | 0.14                      |

Figure 17. (a) Prediction results of average deicing rate by BP neural network prediction model; (b) Prediction results of residual by BP neural network prediction model; (c) Prediction results of relative error by BP neural network prediction model.
In Figure 17, there is a good correlation between the data of average deicing rate predicted by BP neural network prediction model and the randomly selected test truth values. The prediction results and test truth values are shown in Table 7. The residuals and relative errors meet the test requirements. The results of BP neural network prediction model are more accurate. Therefore, BP neural network prediction model is feasible to predict the variation laws of average deicing rate under five influencing factors, and the prediction results have some practical reference values.

Table 7. Prediction results and test truth values of average deicing rate.

| Test Number | The Predicted Average Deicing Rate/ °C·s⁻¹ | The Actual Average Deicing Rate/ °C·s⁻¹ | Residual% | Relative Error% |
|-------------|------------------------------------------|---------------------------------------|-----------|-----------------|
| 1           | 0.36                                     | 0.34                                  | -2        | -6.1            |
| 2           | 0.34                                     | 0.32                                  | -2        | -6.1            |
| 3           | 0.33                                     | 0.34                                  | 1         | 3               |
| 4           | 0.43                                     | 0.43                                  | 0         | 0               |
| 5           | 0.21                                     | 0.20                                  | -1        | -5              |
| 6           | 0.14                                     | 0.14                                  | 0         | 0               |

4. Conclusions

The deicing experiments of asphalt mixture containing steel wool fiber were conducted by electromagnetic induction heating. Some conclusions were obtained as follows:

- The electromagnetic induction heating deicing technology opens up a new idea for pavement deicing. The average deicing rate of asphalt mixture increases with the increase of length and content of steel wool fiber.
- According to the grey correlation entropy analysis, the length and content of steel wool fiber, ice thickness, output current and ambient temperature have influences on the average deicing rate of asphalt mixture, among which the content and length of steel wool fiber (internal factors) are the main factors affecting the deicing performance under induction heating.
- Under different influencing factors, BP neural network prediction models about average deicing rate are constructed. These models have high prediction accuracy and its prediction results have certain practical reference value.

Based on the above research conclusions of this paper, the following work needs further improvement:

1. The deicing research of smooth pavement surface has been studied, so the deicing research of steep slope and fast turning pavement in mountainous area are considered. The deicing research under different slopes such as 5%, 10% and 15% are investigated, which can provide security for special pavement section and reduce the economic cost of deicing in winter for road maintenance department.

2. Based on the deicing parameters of steel wool fiber asphalt mixture, the development of deicing machinery suitable for practical engineering is considered.

Author Contributions: Investigation, Data curation, C.X.; Investigation, Formal analysis, K.W.; Methodology, Investigation, K.L.; Methodology, Investigation, Y.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Transportation Department Project of Qinghai Province (No. 2018-02).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data, models, and code generated or used during the study appear in the submitted article.

Conflicts of Interest: The authors declare no conflict of interest.
References

1. Shen, C.P.; Lv, J.L.; Ma, G.Q. Research on maintenance technology of snow and ice removal on expressway in winter. *Highw. Traffic Technol.* 2008, 25, 239–242.

2. Wang, H.; Wang, Z. Evaluation of pavement surface friction subject to various pavement preservation treatments. *Constr. Build. Mater.* 2013, 48, 194–202. [CrossRef]

3. Cheng, G.Z.; Li, H.; Xu, L. Analysis of characteristics of snow covered pavement and its evaluation of driver’s driving tension. *J. Jilin Univ.* 2011, 41, 355–359.

4. Wang, H.; Yang, J.; Liao, H.; Chen, X. Electrical and mechanical properties of asphalt concrete containing conductive fibers and fillers. *Constr. Build. Mater.* 2016, 122, 184–190. [CrossRef]

5. Kim, M.S.; Jung, D.U.; Hong, J.S.; Kim, T. Thermal modeling of railroad with installed snow melting system. *Cold Reg. Sci. Technol.* 2015, 109, 18–27. [CrossRef]

6. Wahlin, J.; Leisinger, S.; Klein, P.A. The effect of sodium chloride solution on the hardness of compacted snow. *Cold Reg. Sci. Technol.* 2014, 102, 1–7. [CrossRef]

7. Yan, X.; Li, F.Y.; Liu, T.W.; Zhang, Y.; Ma, X.P.; Wang, X.J. Effects of deicing chemicals on ecological environment. *J. Ecol.* 2008, 27, 2209–2214.

8. Wang, Z.; Zhang, T.; Shao, M.; Ai, T.; Zhao, P. Investigation on snow-melting performance of asphalt mixtures incorporating with salt-storage aggregates. *Constr. Build. Mater.* 2017, 142, 187–198. [CrossRef]

9. Wang, T.; Guo, D.D.; Chen, Y.; Zhou, H.; Sun, D. Study on the effect of snow melting agent on the anti-sliding performance of road under low temperature conditions. *Highway* 2019, 64, 267–271.

10. Tan, Y.Q.; Sun, Z.R.; Guo, M. Study on snow and ice removal performance of salt storage asphalt mixture. *China Highw.* J. 2013, 26, 23–29.

11. Yu, W.S.; Zhang, X.C.; Zhong, K. Deicing characteristics of high elastic storage salt melting ice and snow asphalt mixture. *J. China Univ. Min. Technol.* 2015, 44, 912–916.

12. Wang, J.; Wang, X.; Ding, L.; Fu, L. Microwave sensitive coating materials and equipment for Snow removal. *J. Chang. Univ.* 2018, 38, 49–57.

13. Sun, Y.; Wu, S.; Liu, Q.; Hu, J.; Yuan, Y.; Ye, Q. Snow and ice melting properties of self-healing asphalt mixtures with induction heating and microwave heating. *Appl. Therm. Eng.* 2018, 129, 871–883. [CrossRef]

14. Wang, H.; Zhao, J.; Chen, Z. Experimental investigation of ice and snow melting process on pavement utilizing geothermal tail water. *Energy Convers. Manag.* 2008, 49, 1538–1546. [CrossRef]

15. Mirzanamadi, R.; Hagertoft, C.E.; Johansson, P.; Johansson, J. Anti-icing of road surfaces using hydronic heating pavement with low temperature. *Cold Reg. Sci. Technol.* 2018, 145, 106–118. [CrossRef]

16. Mirzanamadi, R.; Hagentoft, C.E.; Johansson, P. An analysis of hydraulic heating pavement to optimize the required energy for anti-icing. *Appl. Therm. Eng.* 2018, 144, 278–290. [CrossRef]

17. Qin, K.; Ma, Q.Y.; Wu, J.R. Experimental study on properties of asphalt concrete under the coupling of temperature and corrosion. *Silic. Bull.* 2013, 32, 952–956.

18. Liu, K.; Xie, H.; Jin, C.; Huang, S.; Wang, F. The equivalent plasticity strain analysis of snow-melting heated pavement concrete exposed to inner elevated temperatures. *Constr. Build. Mater.* 2017, 137, 66–75. [CrossRef]

19. García, Á.; Schlangen, E.; van de Ven, M.; Liu, Q. A simple model to define induction heating in asphalt mastic. *Constr. Build. Mater.* 2012, 31, 38–46. [CrossRef]

20. Zhou, C.X.; Tan, Y.Q. Influence factors of snow and ice removal performance of rubber granular asphalt mixture. *J. Build. Mater.* 2009, 12, 672–675.

21. Chen, Y.Z.; Li, Z.X. Deicing mechanism of asphalt pavement with rubber particles. *J. Cent. South Univ.* 2013, 44, 2073–2081.

22. Hu, W.J.; Jiang, Y.Q.; Ma, Z.L. Research and analysis of bridge surface thermal snow melting model. *J. Harbin Inst. Technol.* 2007, 39, 1895–1899.

23. Wei, H.; He, Q.; Jiao, Y.; Chen, J.; Hu, M. Evaluation of anti-icing performance for crumb rubber and diatomite compound modified asphalt mixture. *Constr. Build. Mater.* 2016, 107, 109–116. [CrossRef]

24. Phan, T.M.; Park, D.W.; Le, T.H.M. Crack healing performance of hot mix asphalt containing steel slag by microwaves heating. *Constr. Build. Mater.* 2018, 180, 503–511. [CrossRef]

25. Norambuena-Contreras, J.; Gonzalez, A.; Concha, J.L.; Gonzalez-Torre, I.; Schlangen, E. Effect of metallic waste addition on the electrical, thermophysical and microwave-cracking performance of asphalt mixtures. *Constr. Build. Mater.* 2018, 187, 1039–1050. [CrossRef]

26. García, A.; Norambuena-Contreras, J.; Bueno, M.; Partl, M.N. Influence of steel wool fibers on the mechanical, thermal, and healing properties of dense asphalt concrete. *J. Test. Eval.* 2014, 42, 1107–1118. [CrossRef]

27. Guo, D.; Sha, A. Snow melt and deicing technology based on the heating effect of microwave and magnetic coupling. *J. Shandong Univ.* 2012, 42, 92–97.

28. Gao, J.; Guo, H.; Wang, X.; Wang, P.; Wei, Y.; Wang, Z.; Huang, Y.; Yang, B. Microwave deicing for asphalt mixture containing steel wool fibers. *J. Clean. Prod.* 2019, 206, 1110–1122. [CrossRef]

29. Liu, Q.; Wua, S.; Schlangen, E. Induction heating of asphalt mastic for crack control. *Constr. Build. Mater.* 2013, 41, 345–351. [CrossRef]
30. Pamulapati, Y.; Elseifi, M.A.; Cooper, S.B., III; Mohammad, L.N.; Elbagalati, O. Evaluation of self-healing of asphalt concrete through induction heating and metallic fibers. Constr. Build. Mater. 2017, 146, 66–75. [CrossRef]

31. Silva, J.D.A.A.E.; Rodrigues, J.K.G.; de Carvalho, M.W.; Lucena, L.C.D.F.L.; Cavalcante, E.H. Mechanical performance of asphalt mixtures using polymer-micronized PET-modified binder. Road Mater. Pavement Des. 2018, 19, 1001–1009. [CrossRef]

32. Oreto, C.; Veropalumbo, R.; Viscione, N.; Biancardo, S.A.; Russo, F. Investigating the environmental impacts and engineering performance of road asphalt pavement mixtures made up of jet grouting waste and reclaimed asphalt pavement. Environ. Res. 2021, 198, 111277. [CrossRef]

33. Antunes, V.; Freire, A.C.; Quaresma, L.; Micaelo, R. Evaluation of waste materials as alternative sources of filler in asphalt mixtures. Mater. Struct. 2017, 50, 254. [CrossRef]

34. Obaidi, H.; Gomez-Mejide, B.; Garcia, A. A fast pothole repair method using asphalt tiles and induction heating. Constr. Build. Mater. 2017, 121, 592–599. [CrossRef]

35. Yang, F.; Li, K.; Xiong, R.; Guan, B.; Zhao, H. Investigation on deicing property of steel wool fiber reinforced asphalt mixture by induction heating. Adv. Mater. Sci. Eng. 2019, 201, 121–126. [CrossRef]

36. Garcia, A.; Bueno, M.; Norambuena-Contreras, J.; Partl, M.N. Induction healing of dense asphalt concrete. Constr. Build. Mater. 2013, 49, 1–7. [CrossRef]

37. Garcia, A.; Norambuena-Contreras, J.; Partl, M.N.; Schuetz, P. Uniformity and mechanical properties of dense asphalt concrete with steel wool fibers. Constr. Build. Mater. 2013, 43, 107–117. [CrossRef]

38. Xiong, R.; Chu, C.; Qiao, N.; Wang, L.; Yang, F.; Sheng, Y.; Guan, B.; Niu, D.; Geng, J.; Chen, H. Performance evaluation of asphalt mixture exposed to dynamic water and chlorine salt erosion. Constr. Build. Mater. 2019, 201, 121–126. [CrossRef]

39. Polaczyk, P.; Ma, Y.; Xiao, R.; Hu, W.; Jiang, X.; Huang, B. Characterization of aggregate interlocking in hot mix asphalt by mechanistic performance tests. Road Mater. Pavement Des. 2021, 22 (Suppl. 1), S498–S513. [CrossRef]