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Performance Decay Model and Preventive Maintenance of Highway Asphalt Pavement

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Abstract: This work aims to study the law of performance decay of highway asphalt pavement to facilitate preventive highway maintenance. By studying the performance decay law of asphalt pavement, this work proposes to optimize the Back Propagation Neural Network (BPNN) model with the Mind Evolutionary Algorithm, and apply the optimized model to the performance prediction of highway asphalt pavement. Some sections of Xi'an city are selected as sample data to train the neural network. A new type of asphalt material emulsified asphalt is proposed for pavement construction. Finally, the maintenance suggestions of asphalt pavement are given. The results show that the optimized BPNN model has a better fitting effect. The comprehensive evaluation indexes Root Mean Squared Error, Relative Root Mean Squared Error and Mean Absolute Error of the model prediction performance are lower than those of the model before optimization, and the decline rates are 62.46%, 62.46% and 62.71%, respectively. However, the values of Nash-Sutcliffe Efficiency and R^2 increase by different degrees, with the increasing rates of 55.92% and 15.42%, respectively. It reveals that the optimized BPNN has more advantages in predicting road pavement performance, with higher accuracy and lower error rate. It provides a new idea for studying the maintenance of highway asphalt pavement. The performance of new asphalt materials is better than that of ordinary asphalt materials.

Keywords: Asphalt pavement; Road maintenance; Decay law of asphalt performance; Back propagation neural network; Emulsified asphalt

1. Introduction

Asphalt is extracted and processed by modern technology through a long-term and comprehensive process in nature. Its chemical composition and performance characteristics are extremely complex. It is widely used in road engineering. However, asphalt pavement is exposed to the external environment for a long time and is affected by multiple different factors, such as ultraviolet, moisture, and oxidation[1]. The asphalt pavement shall ensure a certain service life without pavement overhaul in a short time. In addition to considering the pavement structure's reasonable design, the pavement mixture's durability shall be ensured. A series of physical and chemical changes, such as evaporation, dehydrogenation, oxidation and condensation, will occur when the asphalt is in contact with air for a long time from production to use[2-4]. At this time, the physical properties of asphalt are gradually hardened and brittle, and it is very easy to crack under the action of external force, so it cannot continue to play its original bonding, sealing and other roles[5-7]. Timely monitoring the anti-sliding performance of asphalt pavement and studying its decay law can help highway maintenance personnel timely maintain the sections with insufficient anti-sliding performance, and help to reduce the probability of traffic accidents caused by uneven roads and reduced anti-sliding performance[8].

Temperature is one of the most crucial factors affecting the function and structural performance of asphalt pavement with a thick asphalt layer (> 30 cm). Accurate pavement temperature prediction at different depths is significant for successful pavement design. The asphalt mixed with water and foreign matters during loading, unloading, transportation and storage will affect the asphalt test results. Therefore, during the asphalt material test, it is necessary to remove the water and foreign matters by heating and sieving and pay attention to temperature control during operation to avoid asphalt aging due to too high temperature. Li *et al.*[9] developed a statistical model to predict the temperature of the asphalt layer. Three test sites were selected and tested with several sensors and data recorders to record the road temperature per hour. Moreover, all test sections could provide meteorological monitoring to collect hourly temperature and hourly total solar radiation. Cho *et al*.[10] used the calculation and analysis program to study the influence of the debonding pavement structure on the fatigue cracking performance and analyzed the pavement response and pavement performance. Then, the stress and strain distribution at the asphalt layer surface and the interface was determined, and the fatigue cracking performance of the debonding pavement structure was evaluated. To evaluate and predict the performance of asphalt pavement more accurately, Wang *et al*.[11] distributed the weights of each measured sub-index based on the hierarchical variable weight method. They evaluated the technical status of asphalt pavement, and established a grey GM (1,1) prediction model for the technical status index of asphalt pavement. Then, the service condition of typical asphalt pavement in humid and hot areas was predicted according to the measured data, and the reliability of the prediction was verified. Finally, maintenance suggestions were given according to the prediction results. The content above reveals that the research on asphalt pavement mostly focuses on the physical level, and the research with established models is less. This work can fill this gap.

This work adopts the method of literature research and model building. By studying the decay law of asphalt pavement, a Back Propagation Neural Network (BPNN) model based on Mind Evolutionary Algorithm (MEA) optimization is creatively established and used to predict the performance index of asphalt pavement. After verification, it is found that the optimized BPNN model has better convergence, smaller error and higher prediction accuracy. For asphalt, a complex special material, the prediction of its performance can help its material to be more durable and not easy to age.

2. Methods

2.1 Analysis and modeling of performance decay law of highway asphalt pavement

Asphalt is a dark brown complex mixture composed of hydrocarbons with different molecular weights and their non-metallic derivatives. It is a kind of high viscosity organic liquid. It mostly exists in the form of cypress oil or tar. Its surface is black and it is soluble in carbon disulfide. Asphalt is a kind of waterproof, moisture-proof and anti-corrosion organic cementitious material, which is mainly divided into coal tar asphalt, petroleum asphalt and natural asphalt. It is used in coating, plastic, rubber and other industries as well as pavement. Durability is evaluated by anti-aging performance, fatigue resistance, water stability and skid resistance. The evaluation of anti-aging performance is complex, and many factors affect asphalt aging. The asphalt aging stage includes storage, transportation, mixture preparation and later pavement use. The performance decay of asphalt pavement mainly occurs in the process of contact with the external environment, and the main factors are oxygen and temperature. Asphalt begins to undergo different degrees of thermal oxidative aging reaction from production to putting into use. At present, it is generally believed that thermal oxidative aging can be divided into three stages. The first stage is the transportation and storage after production. At this stage, the contact area between asphalt and air is tiny, and the thermal oxidative aging is not serious. The second stage is the mixing, paving and rolling process of asphalt and aggregate. In this process, the temperature of mixed asphalt will reach about 170°C, the performance index will be sharply reduced and serious thermal oxidative aging reaction will occur. This stage is the main stage of thermal oxidative aging. The third stage is after the asphalt pavement is completed. The aging reaction of pavement under the influence of temperature change, ultraviolet radiation and other factors is also the main aging process.

BPNN has a powerful nonlinear fitting ability. It can regard the unknown system as a black box, train the neural network with the input and output data, take the square of the network error as the objective function in the learning process, and use the gradient descent method to find the minimum value of the objective function. **Figure 1** shows the specific composition:

Figure 1 shows that BPNN is composed of input, hidden, and output layers. Different layers are connected by neurons. Neurons in the same layer are not connected and have forward and back propagation. w_{ij} and w_{jk} represent the connection weight between the hidden layer and the output layer. **Figure 2** is the flow diagram of BPNN training. First, the weights of the hidden layer and the output layer need to be initialized, and then the output of the hidden layer and the output layer is calculated. The calculation method is:

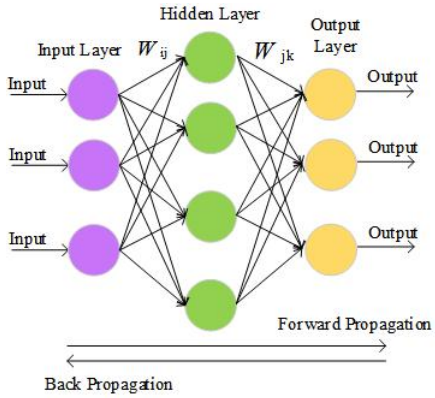

Figure 1. Structure diagram of 3-layer BPNN

$$C_j = f\left(\sum_{i=1}^{n} w_{ij} a_i - x_j\right) \quad (1)$$

$$B_k = \sum_{j=1}^{l} (w_{jk} C_i - y_k) \quad (2)$$

C_j represents the output of the hidden layer, and a_i represents the input. x_j and y_k are the initial threshold value of each neuron in the hidden layer and the output layer. B_k is the actual output of the network. The calculation equation of error e is:

$$e_k = D_k - B_k \quad (3)$$

Where D_k represents the expected output value. Finally, the weight and threshold are adjusted according to the error until the error meets the requirements.

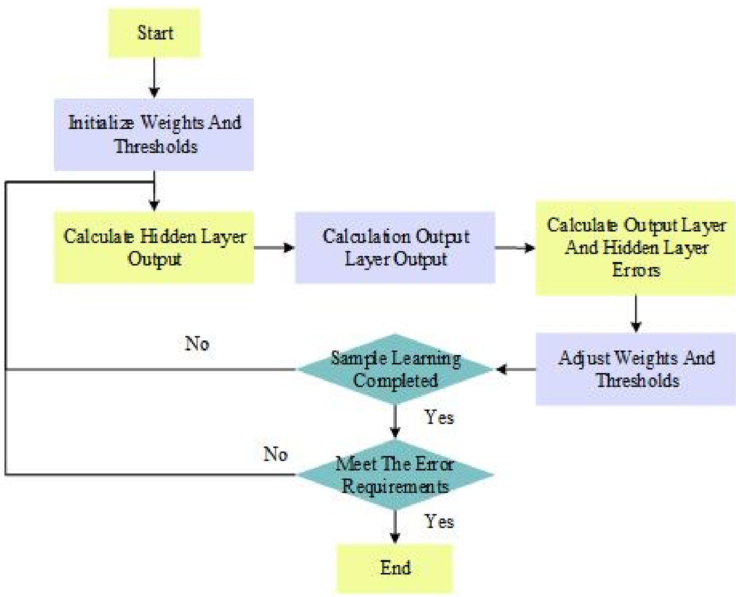

Figure 2. BPNN training process

The MEA derived from the Genetic Algorithm (GA) can be adopted to optimize the initial weight and threshold of BPNN. **Figure 3** shows the specific steps:

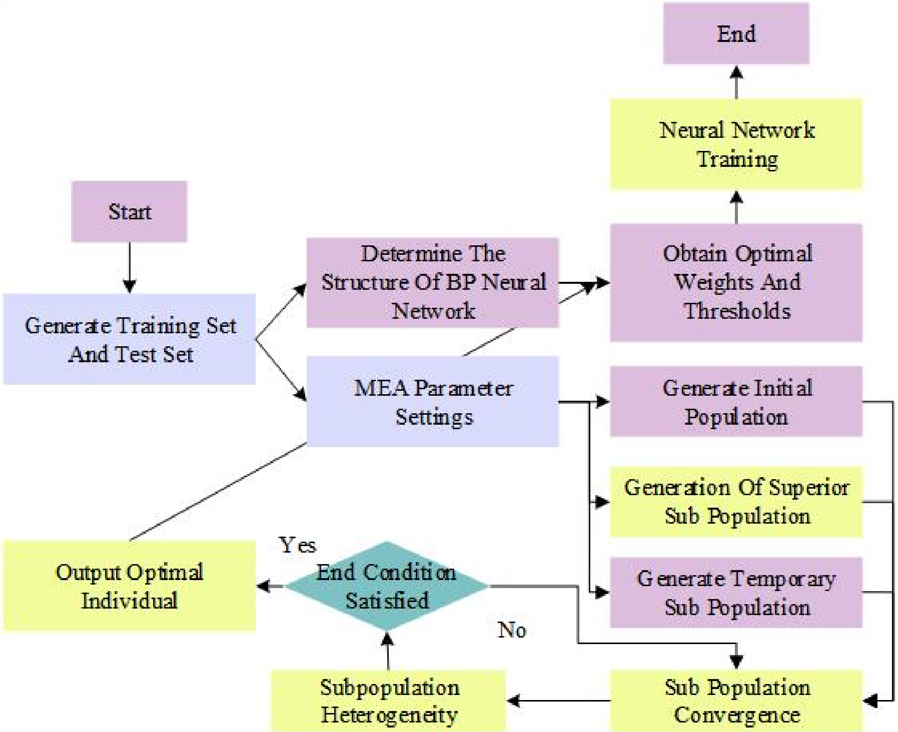

Figure 3. Flow chart of design steps of BPNN optimized by MEA

Figure 3 shows that the initial sample needs to be obtained first, and then the initial population generation function initpop generate is used to generate the initial population. Next, the convergence operation is performed on each sub population until the iteration stops.

The BPNN model optimized by MEA is used to test the performance of asphalt pavement, and a combined model for performance decay of highway asphalt pavement is established. The modeling data are the road maintenance data of Xi'an Highway Administration over the years. Given the influence of multiple factors, 88 sections with a total of 247 km of general roads are finally selected as the dataset for modeling and analysis. The nine factors of highway age, base course compressive modulus, annual average daily traffic volume, annual average temperature and precipitation, surface course compressive modulus, base course thickness, surface course thickness and relative humidity are taken as the influencing factors of pavement performance, as the input of BPNN and input in the form of Pavement Condition Index (PCI).

The different number of hidden layer nodes in BPNN will affect the final prediction accuracy of the model. The appropriate number of nodes will save training time, and it is not easy to produce over fitting phenomenon. Here, the number of input layer nodes n of BPNN model is 9, the number of output layer nodes m is 1, and the number of hidden layer nodes is 7. **Table 1** shows the parameter settings when using MEA for optimization:

Table 1 Parameter setting of MEA

Parameter	Value
Population size	200
Number of superior sub population	3
Number of temporary sub populations	3
Maximum iterations	10

The evaluation indexes of the model include: Relative Error (RE), Root Mean Squared Error (RMSE), Relative Root Mean Squared Error (RRMSE), Mean Absolute Error (MAE), Nash-Sutcliffe Efficiency (NSE), and R^2 (Correlation Coefficient). The calculation equations are as follows:

$$RE = \frac{|B_i - D_i|}{D_i} * 100\% \quad (4)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(B_i - D_i\right)^2} \quad (5)$$

$$RRMSE = \frac{1}{D}\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(B_i - D_i\right)^2} \quad (6)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n} | B_i - D_i \quad (7)$$

$$NSE = 1.0 - \frac{\sum_{i=1}^{n}\left(B_i - D_i\right)^2}{\sum_{i=1}^{n}\left(D_i - \bar{D}\right)^2} \quad (8)$$

$$R^2 = \frac{\left(\sum_{i=1}^{n}\left(B_i - \bar{B}\right)\left(D_i - \bar{D}\right)\right)^2}{\sum_{i=1}^{n}\left(B_i - \bar{B}\right)^2 \sum_{i=1}^{n}\left(D_i - \bar{D}\right)^2} \quad (9)$$

Among them, the smaller the values of indicators RMSE, RRMSE and MAE are, the smaller the deviation is and the higher the precision of the model is. The closer the indicators NSE and R^2 are to 1, the higher the fitting degree and reliability of the model are, and the better the quality is.

The neural network can effectively predict the decay degree of asphalt pavement. Moreover, it is crucial to study new asphalt materials to delay aging. Emulsified asphalt is a kind of road-building material with low viscosity and good fluidity at room temperature, which is formed by diffusing the road asphalt normally used at high temperature into the water through mechanical mixing and chemical stabilization (emulsification). It is dispersed in an aqueous solution containing an emulsifier in the form of tiny droplets to form an oil in water or oil in water asphalt emulsion. Emulsified asphalt expanded perlite thermal insulation material is made of emulsified asphalt as binder, added with expanded perlite, and stirred and pressurized at room temperature. In multiple road construction applications, emulsified asphalt provides a safer, energy-saving and environmental protection system than hot asphalt, because this process avoids high-temperature operation, heating and harmful emissions. Emulsified asphalt can be used at normal temperature and can be used with cold and wet stones. When it is demulsified and solidified, it will be reduced to continuous asphalt, the moisture will be completely removed, and the final strength of the road material can be formed. This emulsified asphalt is used for road upgrading and maintenance, such as stone chip seal coat, and it has many unique applications that cannot be replaced by other asphalt materials, such as cold mix and slurry seal coat. Emulsified asphalt can also be used for new road construction, such as tack coat oil and prime coat oil.

2.2 Suggestions on asphalt pavement road maintenance

Asphalt pavement maintenance can be divided into daily patrol and inspection, minor repair and maintenance, medium repair, overhaul, reconstruction and special maintenance works. The daily patrol inspection and inspection contents include: whether there are obvious pits, cracks, bumps, subsidence, looseness, rutting, oil flashing, waves, pitted surfaces, frost heave, mud boiling and other diseases on the pavement, and their harm degree and trend and whether there are deposits on the road that may damage the road surface or hinder traffic. The preventive maintenance suggestions for highway asphalt pavement are given according to the characteristics of different seasons:

In spring, the temperature shrinkage cracks of asphalt pavement and other cracks shall be well grouted and repaired, and the potholes, looseness, churning and other diseases shall be promptly and quickly repaired. The temperature is high in summer, which is a favorable season for the construction of asphalt pavement maintenance works. It is necessary to deal with oil spillage in a high-temperature period, remove excessive upheavals and waves, timely repair the damage temporarily repaired in winter and spring rain, and restore the service quality of the pavement. In autumn, the weather gradually cools down from high temperatures. The southeast coastal areas are vulnerable to typhoons and rainstorms. The northeast and northwest regions will be affected by the cold air activities in the north. In the repair of asphalt pavement, people must pay close attention to the weather forecast. It is necessary to complete the annual plan of the maintenance project as soon as possible, and timely do a good job in the preventive maintenance and repair of winter diseases, such as crack filling and sealing repair, prevention and control of frost heave and brittleness, and timely repair of pits and grooves and emulsified asphalt slurry seal. In winter, related personnel should continue to do a good job in the prevention and control of winter diseases, and do a good job in snow prevention, ice prevention, anti-skid, resistance drainage, emergency rescue and road maintenance material procurement and preparation.

3. Results and Discussion

3.1 Comparison of prediction errors of BPNN model for asphalt pavement data

After the model is established, the test samples are input to test the prediction ability of the asphalt pavement performance of the model. **Figure 4** shows that the predicted value of the BPNN model optimized by MEA is closer to the actual value, indicating that the optimized BPNN model has a better fitting effect.

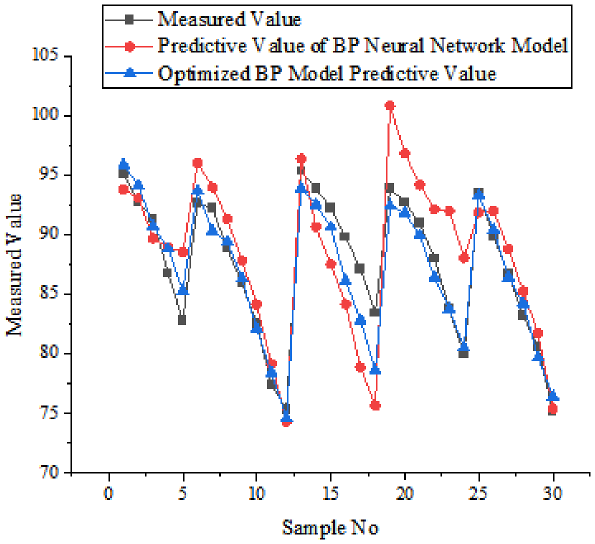

Figure 4. Comparison of prediction effect before and after MEA optimization of BPNN model

3.2 Analysis of overall performance evaluation index

In order to further evaluate the prediction performance of the BPNN model before and after optimization, the evaluation indexes established above are used for evaluation. Figure 5 shows the results. It reveals that the RMSE, RRMSE and MAE of the BPNN model optimized by the MEA are lower than those before optimization, and the decline rates are 62.46%, 62.46% and 62.71%, respectively. However, the values of NSE and R^2 increase in different ranges, with the increasing rates of 55.92% and 15.42%, respectively. It suggests that the optimized BPNN model has greatly improved the prediction accuracy of performance indicators for highway asphalt pavement, because MEA has optimized the initial weight and threshold of BPNN, improved the generalization ability of the network, improved the accuracy and reduced the error.

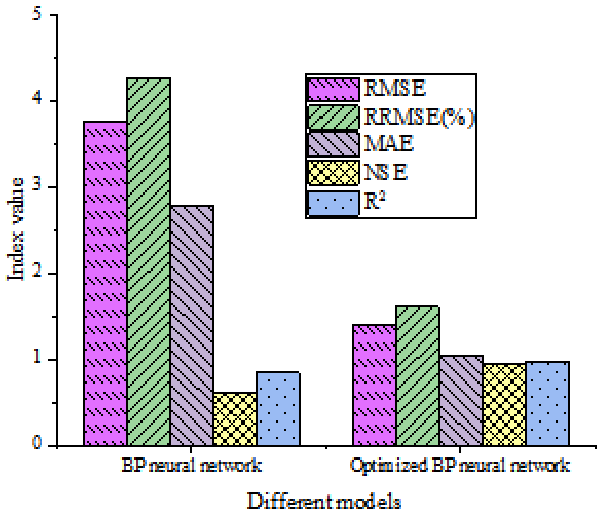

Figure 5. Comparison of evaluation indexes before and after BPNN model optimization

4. Conclusion

Asphalt is a hydrophobic material, and its internal soluble substances will be reduced due to the long-term penetration of water, resulting in an aging reaction. When used on highways, it is easy to cause pavement cracks, looseness and deformation. Accurately predicting the performance of asphalt pavement and taking effective maintenance measures are very effective measures for road maintenance. Moreover, their combination with better materials to delay the aging of asphalt can better increase the service life of the road. By studying the aging law of highway asphalt pavement, this work establishes an MEA-optimized BPNN-based prediction model for asphalt pavement performance decay, and tests some ordinary roads in Xi'an as sample data. The results show that the prediction performance of the BPNN model optimized by MEA is better than that before optimization, with high accuracy and low error. Finally, the concept and usage of an emulsified asphalt material are put forward. Its application in pavement maintenance can better help the highway maintain good performance and reduce traffic accidents to a certain extent. However, there are still some research deficiencies. For example, the established model has only been tested for some pavements in Xi'an, and the volume of sample data is relatively small. In the future, it is planned to expand the sample range, and classify and predict the roads with asphalt pavement according to the performance grade to verify the model's performance. Moreover, the proposed new emulsified asphalt material will be applied to the actual road paving to test the real performance of the improved asphalt material.

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