CIVIL ENGINEERING JOURNAL

Article no. 19

THE CIVIL ENGINEERING JOURNAL 2-2022

EQUIVALENT THICKNESS COEFFICIENT OF COLD CENTRAL PLANT RECYCLING PAVEMENT STRUCTURE

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ABSTRACT

In order to promote the development of cold central plant recycling technology and realize the recycling of road solid waste. This research focuses on the equivalent relationship between cold central plant recycling mixture and hot mix asphalt. A large number of on-site investigations were undertaken to collect relevant data. The thickness of the structural layer of the trunk road was obtained by sampling the core. The pavement surface condition index (PCI) was calculated by the road surface conditions investigating, which was used as the evaluation standard. The unreasonable data were removed by SPSS software. The existing decay equation of pavement performance was simplified by MATLAB and optimized by the Marquardt and global optimization methods. The survey data were fitted nonlinearly by 1stOpt software. The multivariate nonlinear regression optimization equation of the equivalent thickness coefficient was established. Ultimately, the equivalent thickness coefficients of cold central plant recycling with emulsified asphalt (CREA) and cold central plant recycling with foamed asphalt (CRFA) were calculated and proposed. The relationship between cold central plant recycling pavement and traditional hot mix asphalt pavement was established.

KEYWORDS

Road engineering, Cold central plant recycling, Pavement surface condition index, Decay equation, Equivalent thickness coefficient

INTRODUCTION

In recent years, with the rapid development of highway construction in China, the roads begin to enter the maintenance phase. A large amount of waste of asphalt mixture was produced. These materials occupied a mass of land and polluted the environment. Generally, cold central plant recycling technology could recycle these old materials [1-2]. Although the technology has been widely used in China, the recycling rate of road pavement materials is less than 30%. However, the utilization in the United States is more than 90%. Obviously, the recycling rate of road pavement materials is far lower than that of developed countries. Now, road milling and reconstruction tasks are becoming more and more prevalent. The cold central plant recycling technology is to break and sift the recycled asphalt pavement. The cold recycling mixture is mainly made up of emulsified asphalt or foamed asphalt, new aggregates, old aggregates, cement, water and so on. The technology is generally applied to binder course and base course of the pavement. The technology could be divided into CREA and CRFA [3]. It has the remarkable advantages of saving resources, low-carbon environmental protection and cost savings. In order to achieve harmonious coexistence of road maintenance and the ecological environment, the national green development concept should be implemented.

Under the combined effect of traffic load and environmental factors, pavement performance during road operation would exhibit different degrees of decay [4-5]. The pavement performance decay model is the theoretical basis for pavement analysis, design, management, construction. Therefore, it is an integral part of pavement research. Additionally, the use of the decay equation is a quantitative description of the process. For example, the service life of pavement is about to end when the performance drops to a certain value. Therefore, it is necessary to describe the decay process of pavement performance accurately. The present service ability index (PSI) pavement performance evaluation model was first proposed by AASHTO [6], which marked the beginning of the research of the pavement performance evaluation technology worldwide. Moreover, the pavement surface condition index (PCI) and international roughness index (IRI) were used by the governments of Alberta and Ontario, Canada in studying the decay performance equation of pavement performance [7-8]. In addition, the maintenance control index (MCI) was proposed as an evaluation model for pavement maintenance quality evaluation index by Japan's Ministry of Construction [9]. Meanwhile, the domestic road performance degradation equation was proposed by Sun Lijun et al [10-11].

According to the method of AASHTO guidelines, different pavement structures have the same service life and performance as long as the number of structures is the same, regardless of the combination of pavement structures. The layer coefficient of pavement structure layer was proposed to measure the performance provided by the unit thickness of the layer material. And the reference equivalent thickness coefficient was 0.6-0.7. Van Wijk et al [12] obtained that the equivalent thickness coefficient of cold recycling mixture with foamed asphalt was between 0.45 and 0.95. And the equivalent thickness coefficient of cold recycling mixture with emulsified asphalt was between 0.39 and 0.93. On the basis of road roughness decay equation established by Sun Lijun, Xu Jun obtained that the equivalent thickness coefficient of the CREA was 0.82.

At present, because of the characteristics of small traffic volume, low technical standards and good economic conditions, cold central plant recycling technology is being applied to the binder course of the pavement. However, the research on the equivalent thickness of this technology and hot mix asphalt under the same pavement performance is still in a nascent stage. According to the research status at home and abroad, PCI was determined as the evaluation standard. The characteristics of typical road selection were put forward. Then, road age, traffic load and surface thickness were taken as the influencing factors. Additionally, the nonlinear optimization equation of the equivalent thickness coefficient was established. Ultimately, the equivalent thickness coefficient was obtained through the data acquired by investigation of the regenerative and comparison sections of a road. Therefore, it provided the theoretical basis for the development of maintenance and repairing decisions during the life cycle of the road.

MATERIALS AND METHODS

Related Variable Data Acquisition

A large number of on-site investigations were undertaken to collect relevant data in a survey covering 13 cities in Liaoning Province, China. In addition, cold central plant recycling technology was selected as the method in this paper. Meanwhile, 36 typical sections were compared after taking more than 300 core samples. Finally, the physical investigation project distribution map was shown in Figure 1. The investigation areas were marked by stars.

The evaluation criteria should be determined by the level of detail of the basic data and management level when constructing the pavement performance decay equation. In detail, the maintenance quality indicator (MQI) was used as an indicator to evaluate road pavement status. PCI is an important component of pavement maintenance quality index (PQI). It comprises 0.7% of MQI [13]. Additionally, PCI was used as a predictor for pavement performance by Sun Lijun and the government of Alberta, Canada. Meanwhile, the research of the performance decay equation determining the PCI was a priority among these comprehensive indicators. Therefore, comprehensive indicators such as PCI and PSI were used as the object, the road integrity could be better reflected.

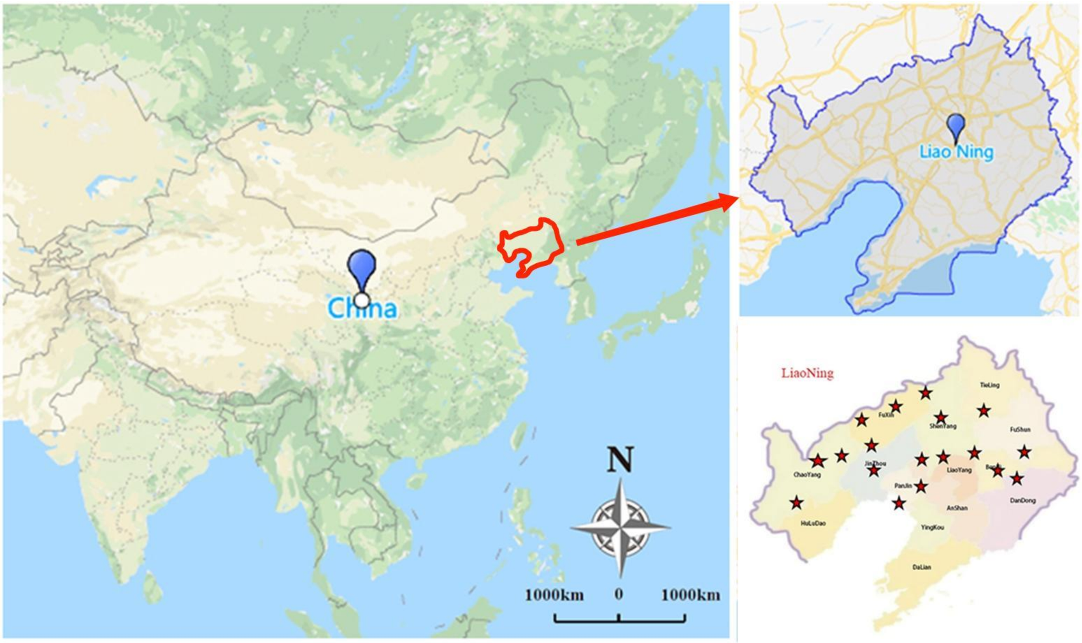

Fig. 1 – Entity survey project distribution (Drawing review No:GS（2019）1685)

Besides, the basic data of PCI could be investigated. Researchers were required to stay within a certain length of road, referring to the relevant guidelines to identify and record the types of road damage [14]. As shown in Figure 2 and Figure 3, the PCI values were obtained based on road surface usage conditions. In order to better reflect the integrity of the road surface and the representativeness of the indicators, the basic data acquisition methods were considered. PCI was used as the evaluation standard for studying the road surface performance decay equation in this research.

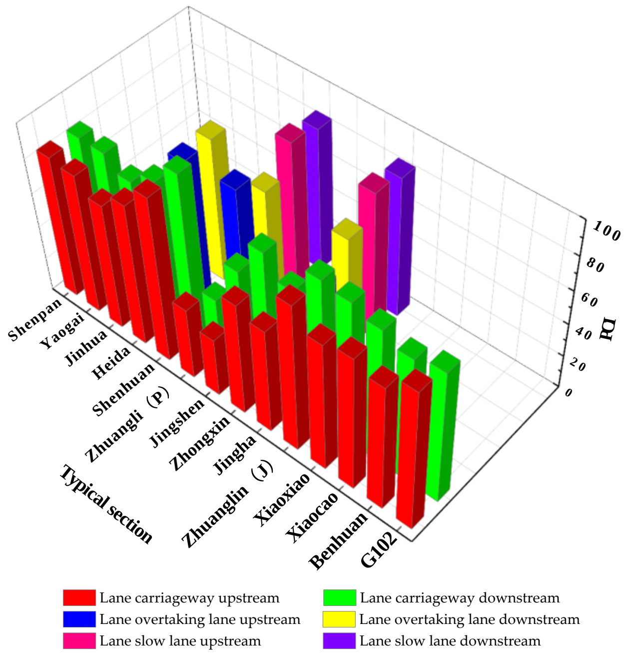

Fig. 2 – PCI of CREA road

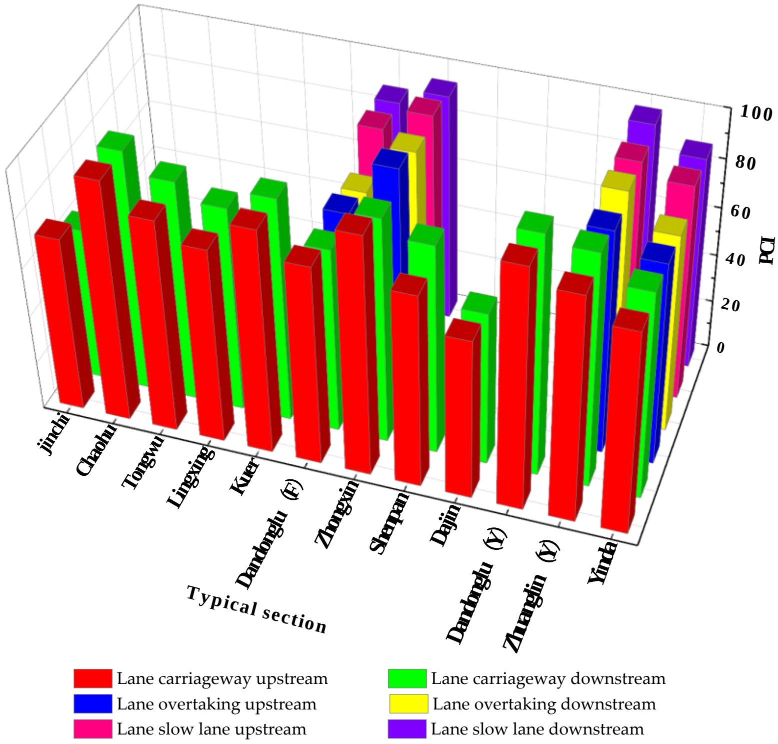

Fig. 3 – PCI of CRFA road

Traffic volume, road age, surface course thickness and other related information were collected to ensure the reliability of the simplified decay equation. On the premise of meeting the requirements of traffic volume data acquisition in relevant norms [15], detailed investigation of traffic volume was carried out for the specific situation of the area where the trunk road was located. As shown in Figure 4 and Figure 5, the traffic volume was obtained by the survey.

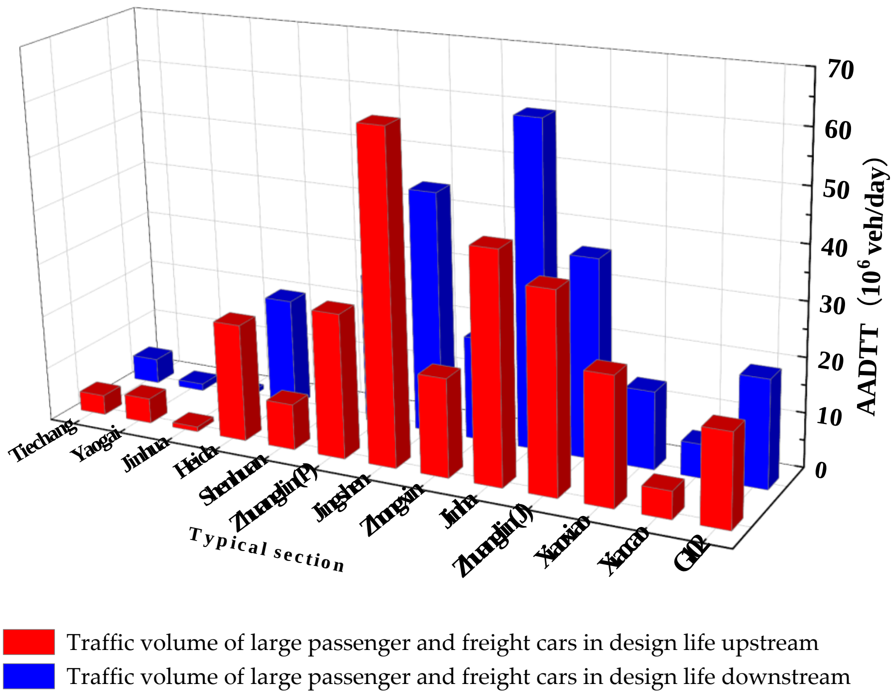

Fig. 4 – Traffic volume of CREA road traffic volume

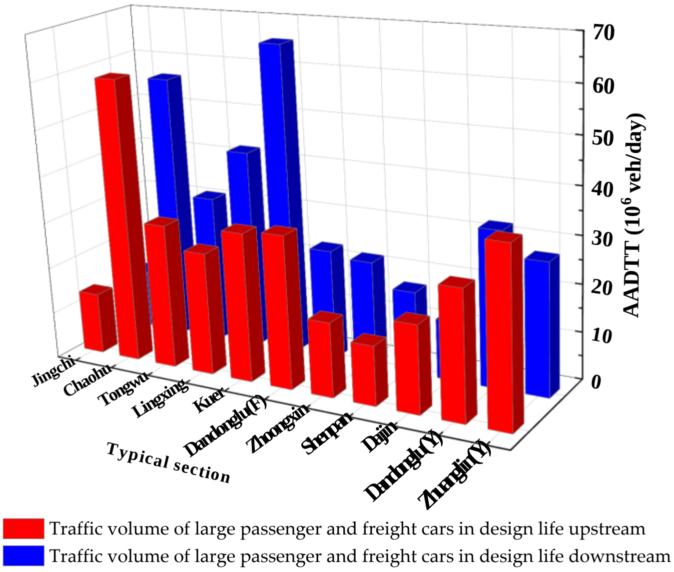

Fig. 5 – Traffic volume of CRFA road traffic volume

Road age, structural layer thickness, road paving materials and maintenance history were obtained by questionnaires and accessing to the construction documents.

In addition, the thickness of the structural layer of the trunk road was obtained by sampling the core to obtain the surface layer thickness under the influence of multiple factors. Considering the extensiveness of the thickness data, the core was sampled according to the following three criteria.

- The core of the decay-free hard shoulder was selected to obtain the thickness of the structural layer close to the initial state of the road surface.
- The core at the wheel track was selected to obtain the thickness of the structural layer under the wheel pressure state.
- Considering the subsequent road performance research, the core at the site of the decay was selected. After the core sample was dried, the thickness of each layer was measured.

Pavement Performance Decay Equation

At present, the pavement structural number (SN) method provided by AASHTO is the most common method for cold regenerative equivalent thickness research [16]. Therefore, the pavement performance of the unit thickness of the structural layer material could be measured by the stratification coefficient in the PSI model proposed by the SN method. Meanwhile, extensive use of performance survey data was simplified. Finally, the decay equation [17-19] was established by Sun Lijun and others. The simplification and equivalent thickness coefficient of the performance decay equation of cold central plant recycling pavement would be studied below based on the performance and experience.

The decay process of PCI is determined by the pavement life factor α and the curve shape factor β uniquely. So, the research of the two parameters is a prerequisite for simplification. In addition, road age, traffic load, type of base layer, type of materials, surface layer thickness and environmental conditions are involved by the two parameters α and β. However, type of base layer, environmental conditions and type of materials could be ignored for the following reasons.

- The structure of the surveyed road section is basically same. For example, the structure of the CREA pavement is basically 3 cm of modified asphalt mixture + 6 cm of cold recycling mixture with emulsified asphalt + the semi-rigid base layer. Therefore, the influence of the base type was ignored.

DOI 10.14311/CEJ.2022.02.0019

- The reclaimed section selected in the survey and the corresponding comparison section are located in the same climate conditions of Liaoning Province. Therefore, the impact of environmental conditions was neglected.
- Materials for paving the investigation section are all from the local area of Liaoning Province. The performance of the paving materials at each level is similar. Therefore, the influence of the material type was neglected.

Therefore, only the factors of traffic load, road age and surface layer thickness were considered. Because of the complexity of the original equation, only the pavement life factor *α* was researched in this paper. Meanwhile, the curve shape factor *β* was used as the regression coefficient in the simplified equation. According to the PCI data of several trunk highways in Liaoning Province, the road age, the surface layer thickness and traffic load were taken as the influencing factors. Formula (1) is obtained by MATLAB and taking related experience into account:

$$\mathrm{PCI} = \mathrm{PCI}_0 \left\{ 1 - \exp\left[-\left(\frac{a \times h^b \times \mathrm{AADTT}^c}{y} \right)^d \right] \right\} \qquad (1)$$

Where PCI_0 is the initial pavement surface condition index, PCI is the pavement surface condition index, *y* is the road age, H is the surface layer thickness, AADTT is the total number of large passenger trucks and *a*, *b*, *c* and d are the regression coefficients of road life.

In formula (1), the value of PCI_0 was 100. The two parts of the hard shoulder and the lane were organized to use the original data properly. As shown in Table 1, the lane data were processed. Firstly, the SPSS software was used to screen and remove the irrational data obtained from small and medium scale conservation in recent years. Then, 1stOpt fitting software was used for secondary development [20] and for multivariate nonlinear regression. Besides, the Marquardt and global optimization methods [21] was used for optimization. Finally, the results of fitting parameters were shown in Table 2 and the fitting regression coefficients were shown in Table 3. As shown in Table 3, the regression coefficient b corresponding to the thickness was greater than 0. In contrast, the regression coefficient c corresponding to the traffic level was less than 0. Obviously, PCI increased gradually with the increase of the thickness, the traffic level decreases. Therefore, according to experience and understanding, the rationality of the regression results was explained from this level. Meanwhile, PCI value could be predicted by 1stOpt. As shown in Figure 6, the correlation curve between the predicted value and measured value could be obtained by simplifying the equation. It could be seen from Figure 6 that the correlation between the PCI prediction value and measured value was good. Meanwhile, the basic extension y=x curve presents a symmetrical discrete distribution. According to the fitting results of R=0.916, R^2=0.839 and Figure 6, formula (1) was ideal. It could reflect the quantitative relationship among PCI, PCI_0, road age, traffic load and surface layer thickness to a certain extent. In addition, it also could provide a basis for the research of the equivalent thickness coefficient.

Tab. 1 - Partial data used for fitting

Route name	Regeneration method	Average thickness (cm)	Average daily traffic (vehicle/day)	Road age (year)	−ln(1−PCI/100)
G102	CREA	6.233	3313.289	3	1.801810
Benhuan	CREA	8.127	513.688	3	1.452434
Jinhua	CREA	7.920	205.475	3	1.400393
Yaogai	CREA	10.225	719.163	1	1.774902
Xiaoxiao	CREA	10.722	4215.070	7	1.723167
Jinshen	CREA	10.850	3159.183	4	0.980829
Heida	CREA	10.244	3698.555	2	1.917323
Xiaocao	CREA	7.533	1348.432	3	1.698269
Zhuanglin	CREA	13.633	6392.855	6	1.161066
Zhongxin	CREA	9.033	3319.710	1	3.194183
Tongwu	CRFA	11.250	734.860	1	2.277892
Lingxing	CRFA	8.800	819.047	2	1.760261
Jinchi	CRFA	8.200	3051.451	5	1.139434
Zhongxin	CRFA	14.025	3346.108	1	3.194183
Shenpan	CRFA	8.400	3664.310	2	1.786772
Dajin	CRFA	10.625	3701.409	3	1.049822
Kuer	CRFA	10.425	1164.360	1	2.617296
Dandong	CRFA	9.620	500.539	6	1.683623
Tongwu	CRFA	11.250	734.856	1	2.277892

Tab. 2 - Fitting calculation results

Regeneration method	RMSE (root mean square error)	SSE (sum of squares for error)	R (correlation coefficient)	R^2 (coefficient of determination)
CREA	0.4141	1.8864	0.9160	0.8390
CRFA	0.3089	0.7631	0.8911	0.7941

Tab. 3 - Fitting regression coefficients

Regeneration method	a	b	c	d
CREA	1.699	0.795	−0.072	0.752
CRFA	0.135	2.407	−0.127	0.326

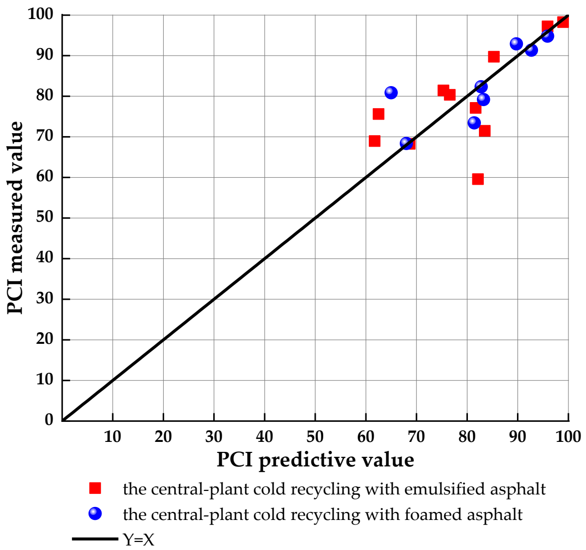

Fig. 6 – Measured and predicted values correlation curve

Equivalent Thickness Coefficient Calculation

The equivalent thickness coefficient of the cold regenerated layer is defined as the ratio between the thickness of the structural layers of the conventional hot mix asphalt and the cold recycling mixture on the same road surface performance. Based on the established PCI prediction equation, formula (1), the nonlinear optimization equation formula (2) of the equivalent thickness coefficient was obtained:

$$\mathrm{PCI} = \mathrm{PCI}_0\left\{1 - \exp\left[-\left(\frac{a\times\left(h_{surfacelayer}+K_{equivalent}h_{lowerlayer}\right)^{b}\times\mathrm{AADTT}^{c}}{y}\right)^{d}\right]\right\} \quad (2)$$

As shown in Table 4, the research data for hot mix asphalt were given. Firstly, the regression coefficient of Table 3 was substituted into formula (2). Then, the PCI data obtained by the survey were fitted by 1stOpt. Moreover, the parameters were optimized by the Marquardt method. Finally, as shown in Table 5, the equivalent thickness coefficient of the CREA was 0.587. In addition, the equivalent thickness coefficient of the CRFA was 0.632.

Tab. 4 - Hot mix asphalt survey data

Route name	Lower layer thickness (cm)	Average daily traffic (vehicle /day)	Road age (year)	−ln(1−PCI/100)
G102	5.35	4083.822	3	1.812792
Lingxing	4.45	829.0357	2	1.743096
Tongwu	4.40	1582.445	1	2.249550

Tab. 5 - Fitting calculation results

Regeneration method	RMSE	SSE	R	R^2
CREA	0.4365	0.7623	0.9097	0.8275
CRFA	0.1657	0.1098	0.8919	0.7954

AASHTO conducted research on cold recycling pavement based on the more suitable method of medium and light traffic roads. And the reference equivalent thickness coefficient of 0.6-0.7 based on the horizon coefficient was provided by AASHTO. Meanwhile, the roads targeted by this research were mostly trunk highways with medium and light traffic. And under the conditions of the binder course of the pavement, the equivalent thickness coefficient of the CREA was 0.587 in this research. In addition, the CRFA was 0.632. Obviously, these values were close to the reference value given by AASHTO. Therefore, the rationality of the results was further explained in this research. However, the equivalent thickness coefficient of the CREA pavement obtained by Xu Yan based on physical engineering was 0.82 [22]. Because the project of applying regeneration technology to the base course was investigated by Xu Yan. And the stress and environmental impact of the base course was weaker than that of the surface course. Obviously, the equivalent thickness coefficient obtained by Xu Yan was larger than the equivalent thickness coefficient provided by this research and AASHTO. Therefore, it was concluded that, when the cold central plant recycling technology was applied to the binder course of the pavement, the performance of 10 cm cold central plant recycling pavement was equivalent to that of 6 cm the traditional hot mix asphalt pavement.

As shown in Figure 7, the equivalent thickness coefficient of the measured and predicted values of the CREA and CRFA were obtained by formula (2). Apparently, the correlation between the predicted and measured values was good. Furthermore, the CREA technology is controlled by many indexes. Such as, the construction technology is difficult and the variability of construction is large. Therefore, the road performance of different road sections shows differences. On the contrary, the CRFA construction process is less difficult than the CREA. In addition, its variability is much smaller. So the road performance of CRFA is relatively stable. To sum up, compared with the CRFA, the dispersion of the CREA is more significant.

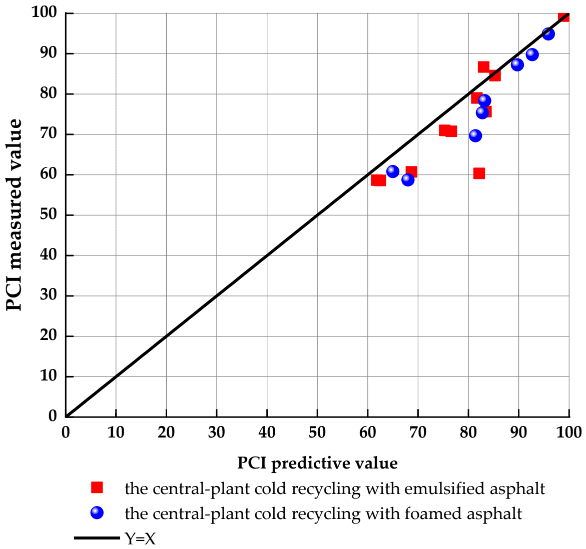

Fig. 7 – Measured and predicted values correlation curve

CONCLUSION

- Under the conditions of the actual situation, the quantitative relationship between road age, surface layer thickness, traffic load and the PCI is obtained as follows:

$$\mathrm{PCI} = \mathrm{PCI}_0 \left\{1 - \exp\left[-\left(\frac{a \times h^b \times \mathrm{AADTT}^c}{y}\right)^d\right]\right\}$$

- According to the simplified decay equation of pavement performance, the equivalent thickness coefficient of the CREA is calculated to be 0.587 (R=0.9097, R^2=0.8275). In addition, the equivalent thickness coefficient of the CRFA is 0.632 (R=0.8919, R^2=0.7954). That is, the performance of 10 cm cold central plant recycling pavement is equivalent to 6 cm the traditional hot mix asphalt.

- The dispersion of CREA is significantly greater than that of CRFA. Because of the construction process, the cold regeneration variability of the CREA is greater than that of the CRFA. Therefore, the road performance of CRFA is relatively stable.

ACKNOWLEDGEMENTS

Thanks are due to the platform support provided by Shenyang Jianzhu University and professors' guidance for this research. This study was supported by Liaoning Distinguished Professor Program [grant numbers tpjs2017003]; the key Program of Basic Scientific Research of Higher Education of Liaoning Province [grant numbers LJZ2017001].

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