Performance-based Whole Life Structural Design Method for Asphalt Pavements

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ABSTRACT: More and more practices demonstrate that asphalt pavement structure based on current design specifications of China can't meet pavement performance and economic needs, and can't avoid premature failures of pavements effectively, either. Therefore it is necessary to develop a new design procedure that is related to pavement performance and life-cycle cost in China. The paper sets up a new performance-based optimization design method for whole life structure of asphalt pavement based on whole life structure behavior equation and life cycle cost analysis model set up previously. The method can provide an optimum design result of asphalt pavement structure based on different economic optimization goal. Several aspects involved in whole life design ideas, whole life pavement structural behavior equations, design criteria, design flows, influence factors and life cycle cost analysis method are expounded. Optimization design software was developed and a design example is presented. The method achieves the unity of pavement structure, material, environmental and economical factors and pavement performance.

KEY WORDS: Asphalt pavement, whole life structural design, pavement performance, life cycle cost analysis.

1 INTRODUCTION

At present, with improvement of road class and traveling speed, growth of traffic volume and axle load, early damage of pavement worsens. Besides self-examining such factors as construction and material, people gradually realize that current pavement design method applied on heavy-duty highway is only a simple extension of low-flow highway, and neglects characteristics of heavy-duty road. Moreover, nearly all structural design methods only give pavement structure thickness that meets traffic requirements mechanically, that is, that ensures that pavement has enough overall strength. However, relevant study indicates that at present much damage to pavement is local damage, and is not much related to overall strength of structure(Lijun et al.2005). Although mechanical characteristics of pavement ensures overall resistance of structure, it is not clearly correlated to pavement performance, and cannot control pavement performance that can be provided by structural combination and mechanical strength designed. Moreover, if selection of pavement structure thickness is only considered from the angle of mechanics, quantitative design of pavement structure combination cannot be guided. Therefore, it is very difficult to optimum-design structural combination of pavement. In addition, pavement design cannot consider primary construction only, and cannot take initial construction cost and service life of this pavement structure into consideration only, either, but shall take various maintenance alternatives that might be adopted in expected analysis period into consideration too. These alternatives include different combination of various initial construction, maintenance and rehabilitation measures（Zukang, 1993）, that is, they reflect the concept of whole life design. Therefore, this study aims to develop a new pavement structure design method – performance- and technical-economical analysis-based whole life asphalt pavement structure design method beginning with performance index and mechanical index. This method considers in terms of “structure, material, load, environment and economy”, selects the most economically-efficient and reasonable structure thickness combination that meets the requirements of design via whole life structure behavior equation and life cycle cost analysis.

This paper will expound in terms of whole life design concept, design standard, design equation and process, factors to be considered, life cycle cost and analysis method and design case.

2 HIGHLIGHTS OF THE DESIGN METHOD

2.1 Whole Life Design Concept

The so-called whole life design means that when pavement structure is selected, not only initial performance and cost of pavement but also performance and cost of pavement after it is overlaid or rebuilt shall be taken into consideration. That’s to say, the best and only pavement structure thickness combination that satisfies performance standard and economical optimization target is sought within the entire life cycle of pavement. Obviously, this is an issue of optimum with minimum total cost (or total expense) as target function and performance index as restraint condition. As shown in Figure 1, several overlay or rehabilitation activities may be included in an analysis period or life cycle. The number of years undergone before each overlay or rehabilitation is a performance period, during which decay mode of performance and duration of the performance period depend on such factors as traffic volume level, pavement structure thickness and modulus, subgrade status, performance standard (such as expected minimum acceptable level) and overlay thickness. Three decay modes (convex type, concave type and reverse S type) are exemplified. By the end of analysis period, if performance of an alternative fails to reach expected acceptable level yet, then it indicates that this alternative still has surplus life. In structural optimization design, different alternatives might have different number and duration of performance period within the same analysis period. Those alternatives that fail to satisfy performance restraint condition will be rejected. Then the alternative with the lowest total cost (or total expense) will be sought among alternatives that satisfy performance conditions. Such design should be reasonable.

2.2 Selection of Design Index and Design Standard

As stated above, design index of whole life asphalt pavement structure design method is performance index – pavement condition index (PCI). It is a comprehensive index that reflects various damages on pavement. Limitation to the size of this paper, computation of PCI(hundred-point system) based on measuring of various damages is not be included in the paper.Please refer to the relevant documents (e.g.Lijun et al.2005).

As a design index of performance-based asphalt pavement structure design method, its control standard refers to the minimum level of pavement condition acceptable to road users in the end of the performance period. Its value shall be determined based on road class, traffic axle load, local economic development level and people's acceptance of road service level. Based on current situation, three typical standards will be adopted:

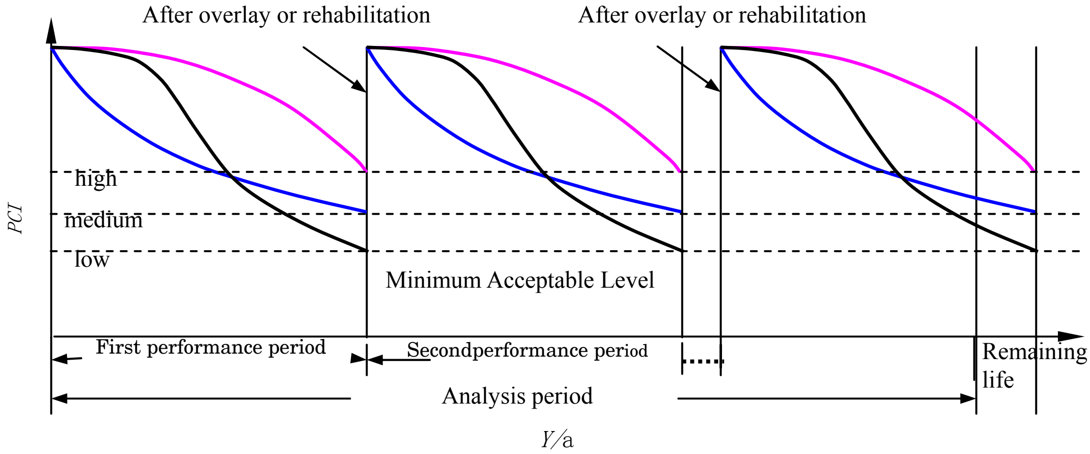


Figure 1: The sketch of whole life design

High standard (PCIt=70): Applicable for structural thickness design of road pavement of high class, high speed and heavy traffic;

Medium standard (PCIt=65): Applicable for structural thickness design of road pavement of secondary high class and heavy traffic.

Low standard (PCIt=60): Applicable for structural thickness design of common road pavement.

However, this method can also realize optimization design of any criteria. In order to inspect mechanical performance of design structure, relevant mechanical checking computation can be conducted on design results.

2.3 Major Factors for Consideration

Analysis period: Analysis period is the duration of life cycle considered in design. Usually it can be selected from 20 ~ 40 years based on class of highway, type of pavement and operating requirement. In principle, it is required that the competitive alternative shall include at least one overlay (rehabilitation) activity, so as to reflect the design concept of whole life.

Design life: Here, it refers to service life that shall be reached at least when performance of all competitive alternatives reaches the minimum acceptable level (specified design standard), i.e., the duration of the first performance period shown in Figure 1.

Environmental factor: The main indices are local annual average humidity and annual average temperature. Influence of environmental factor on structural design result is reflected via influence on performance.

Traffic load factor: Traffic axle load is the most important factor that leads to damage to pavement structure. Here, annual average daily traffic volume (AADT) and equivalent standard axle load (ESAL) are mainly taken into consideration. Consideration on pavement structure combination shall vary with traffic volume.

Material factor: Variety and nature of asphalt has great influence on long-term performance of pavement. This study will consider different influence of modified asphalt and common asphalt on pavement performance in macro aspects. In addition, consideration on material factor is also reflected in selection of type and modulus of various structural layer of pavement.

Structural type selection: Here, it mainly refers to number of structural layers and type of base course. This method takes common number of structural layers (three, four and five) into consideration. As for type of base course, semi-rigid base course and gravel flexible base course are mainly taken into consideration.

Subgrade status: In this method, subgrade status is reflected by subgrade resilient modulus. And influence of subgrade resilient modulus on structural design result is reflected by influence of deflection.

Economic optimization target: It is total cost of road when it is considered from the angle of administration department, and it is total expenses of road when it is considered from the angle of social benefit(see figure 2). In order to meet demand of different aspects and make it convenient for comparison, this method will provide optimization result under these two economic optimization targets.

Material price: This study strive to seek a balanced structural combination mode based on price status of material for all structural layers on the premise that mechanical requirements and performance requirements are met, so as to minimize total cost or total expense of pavement. When relative price ratio at all layers changes, structural design result reached will change accordingly, instead of keep invariable.

Combination of different maintenance and rehabilitation measures: Pavement might undergo maintenance, overlaying and rehabilitation for many times during analysis period. Different combination of these measures will have different influence on pavement performance, thus have influence on the final design result. At present, combination of different maintenance measures is mainly reflected as combination of different overlay thickness in this method.

Discount rate: Discount rate is an important parameter in economic evaluation of alternative. Its selection has great influence on comparing order of economic excellence of the alternative. In actual application, industry benchmark rate announced by the State Planning Commission and the Ministry of Construction on a regular basis is generally adopted.

3 WHOLE LIFE STRUCTURAL DESIGN EQUATION

Whole life structural behavior equation is the core of performance-based whole life asphalt pavement structure design method, and is a necessary prerequisite for user expense analysis. Through over ten years of accumulation, The subject team led by Mr. Sun Lijun, a professor in Tongji University, sets up the following whole life structural behavior equation including newly-built and overlay asphalt pavement with about 1,000,000 pavement performance survey data(Lijun et al.2005, Liping 2001,Lijun,1995 and 1997, Zhijun 1995 and Fangyan 2001).

$$PCI = PCI_0\left\{1-\exp\left[-\left(\frac{\alpha}{y}\right)^{\beta}\right]\right\} \tag{1}$$

$$\alpha = \lambda\left[1-\exp(-(\frac{\eta}{l_0})^{\xi})\right]K_{r\alpha}K_{m\alpha} \tag{2}$$

$$\lambda = a_1 h^{b_1} N_1^{c_1}$$
$$\xi = a_3 h^{b_3} N_1^{c_3}$$

$$\eta = a_2 h^{b_2} N_1^{c_2}$$

$$\beta = a_4 h^{b_4} N_1^{c_4} l_0^{d} K_{r\beta} K_{m\beta} \quad (3)$$

$$K_{r\alpha} = (0.2868 - 0.0493W)(3.5297 + 0.0393T) \quad (4)$$

$$K_{r\beta} = (0.2992 - 0.0559W)(3.6373 + 0.0126T) \quad (5)$$

Here, PCI is pavement condition index; PCI_0 is initial pavement condition index; y is road age; α is pavement life factor; β is decay mode factor; N_1 is cumulative daily 60-KN ESAL in design lane; l_0 is initial deflection (0.01mm); a, b, c and d are regression coefficient or index. See Table 1; $K_{r\alpha}$ and $K_{r\beta}$ are environmental influence coefficient; T is annual average temperature, ℃; W is humidity coefficient; $K_{m\alpha}$ and $K_{m\beta}$ are asphalt material influence coefficient. Common asphalt is 1.0 and modified asphalt is 1.5 and 1.1 respectively; h is thickness of asphalt course (cm), and thickness of equivalent asphalt course after overlay. $h = h_{zm} + h_e$; Here,

$$h_e = \lambda PCI_t^{\mu} h_o^{V+1} \quad (6)$$

h_e is effective thickness; PCI_t is pavement condition index before overlay; h_{zm} is thickness of overlay course; h_0 is thickness of surface course of original pavement; λ,μ,ν is regression coefficient or index. See Table 2.

Table 1: Regression coefficients of a, b, c and d

Parameter	Semi-rigid base course				Granular base course			
	a	b	c	d	a	b	c	d
α	15.7238	0.5861	-0.2064		15.3278	0.5752	-0.2292	
β	119.66	-0.1124	-0.1053		154.8279	-0.1205	-0.1162	
γ	1.5247	-0.1016	-0.0986		1.3573	-0.1123	-0.0884	
B	0.6536	0.3349	-0.0255	-0.0981	0.6681	0.3167	-0.0324	-0.1238

Table 2: Regression coefficient or index

Type of base course	λ	μ	ν	R
Semi-rigid base course	0.000034	2.3564	-0.4207	0.9799
Granular base course	0.000002	2.8764	-0.2528	0.9898

With above whole life structural behavior equation, performance in any year during analysis period or service time when required performance is reached can be forecasted based on region where the project is located, structural composition of pavement, type of base course, ground base modulus, traffic axle load and expected acceptable standard for performance, so as to lay a feasible and good foundation for optimization of pavement structure thickness throughout the life cycle.

4 LIFE CYCLE COST AND ANALYSIS METHOD

See Figure 2 for make-up of cost to be considered in this study (those with * are costs directly related to performance). Here, construction cost and rehabilitation cost are estimated per local material price. Other costs shall be calculated per relevant model(Lijun et al.2005).

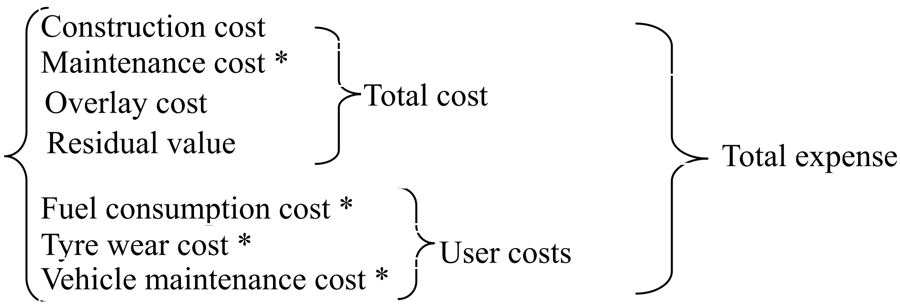


Figure 2 : Costs composition in this research

There are many methods for cost analysis, such as present value method, annual cost method, rate of return method and benefit-cost comparison method, etc. (Zukang,1993). Cost present value method is adopted herein based on analysis purpose and characteristics of pavement engineering, that is, the cost that take place at different time during analysis period is converted to current cost per a preset discount rate, so as to compare on the same basis. In order to meet the demand of different user levels, tow different economic optimization indices are considered, i.e., total cost (excluding user cost) and total expense (including user cost).

5 STRUCTURAL DESIGN PROCESS

Figure 3 is the flow chart of optimum design for the whole life structural thickness of newly-built asphalt pavement. It can be seen from the figure that this method is to seek the best thickness combination under the two economical optimization targets on the basis of considering performance and cost from the angle of whole life.

6 DESIGN CASE

In order to describe the application of this method, this paper takes optimization design for thickness of asphalt pavement with 4-layer structure and semi-rigid base course as an example. In order for comparison, the optimization results of low, medium and high design standards and two economical optimization targets are given on the basis of limitation to other conditions.

6.1 Design Data

See Table 3.

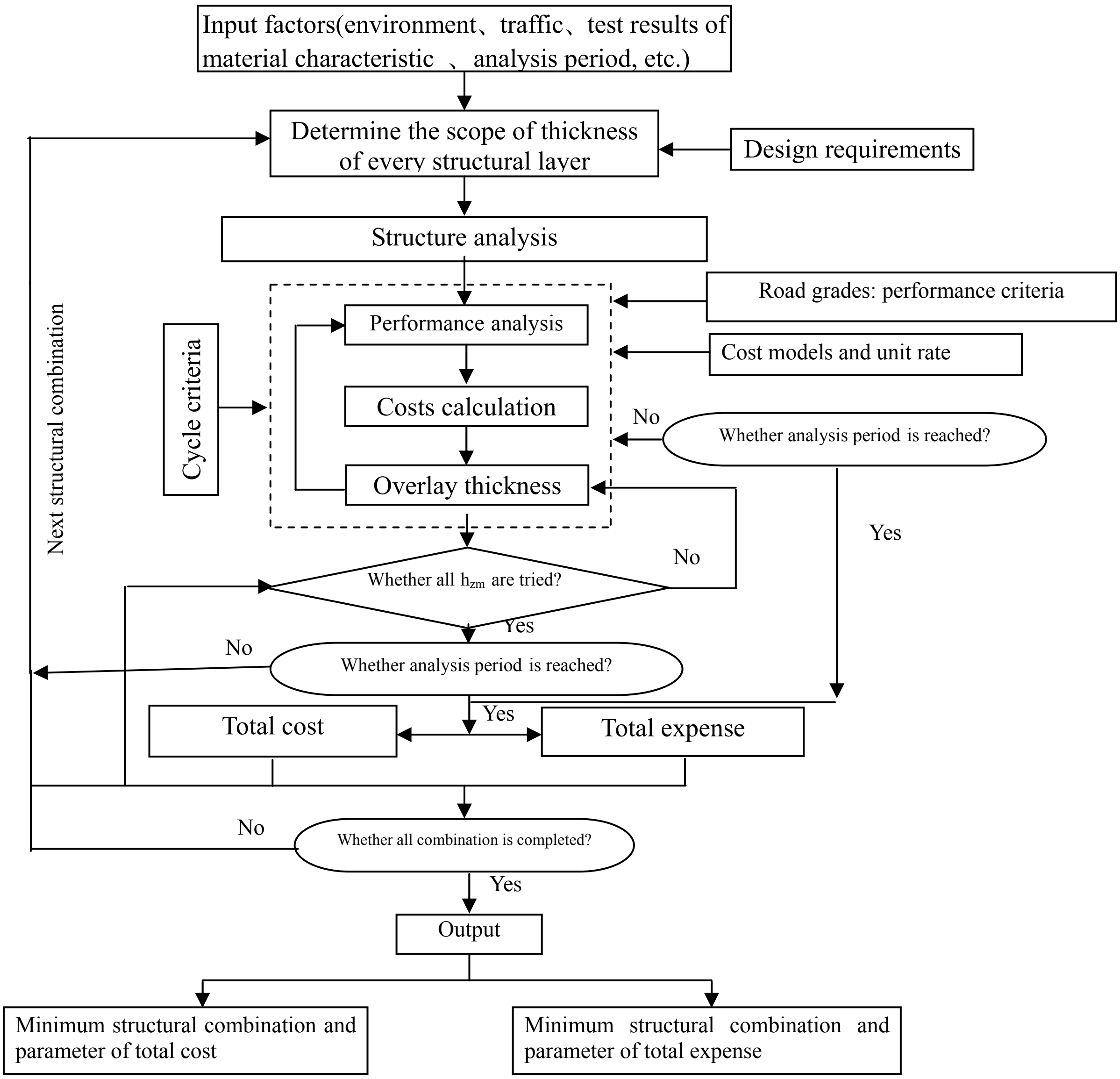


Figure 3: Flow Chart of Optimum Design for Whole Life Structure Thickness of Asphalt Pavement

Table 3: Basic design data for optimization of asphalt pavement structure thickness

Road class	Pavement width	Surface course material	Base course material	Subbase course material	Surface course modulus	Base course modulus	Subbase modulus	subgrade modulus
Class 1	20m	Asphalt concrete	Lime-fly-ash stabilized aggregate	Lime-fly-ash stabilized soil	1200MPa	1500 MPa	800 MPa	45MPa
AADT	N_1	Traffic growth rate	Annual average temperature	Average humidity	PCIt	Analysis period	Discount rate	Limitation of design period
10000	1200	0.05	16.2℃	2.027	60,65, 70	25y	10%	≮10 y

The selection range of surface course thickness is : 8～30cm; selection range of base course thickness is : 15～45cm; the selection range of cushion thickness is 15～30cm; the selection range of overlay thickness is: 2.0～10.0cm.

6.2 Optimization Design Results & Analysis

See Table 4 and Table 5.

Table 4: Example of optimization design results

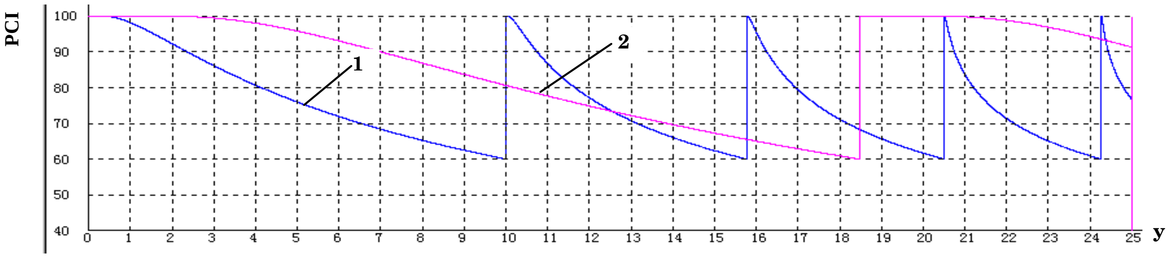
Economical optimum aims	Performance criteria	Each layer thickness（cm）			Overlay thickness（cm）			
		Surface	Base	Subbase	h_{11}	h_{12}	h_{13}	h_{14}
Total cost	PCIt=60	10	15	25	2	2	2	2
	PCIt=65	14	15	27	2	2	2	2
	PCIt=70	18	17	29	2	2	2	2
Total expense	PCIt=60	29	15	29	10	0	0	0
	PCIt=65	30	17	29	10	0	0	0
	PCIt=70	22	17	29	4	10	0	0

Table 5: Life cycle cost under different design results (Unit: RMB 10,000.00 Yuan/Km)

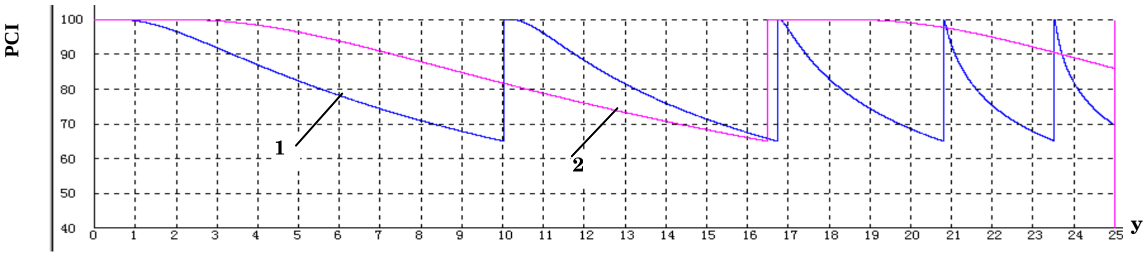
Economical optimum aims	Design criteria	Construction cost	Overlay cost	Total mainten-ance costs	Total user cost	Salvage	Total cost	Total expense
Total cost	PCIt=60	244.56	26.72	31.77	6,769.60	0.22	302.83	7,072.43
	PCIt=65	311.90	26.18	25.68	6,136.98	0.10	363.67	6,500.64
	PCIt=70	384.73	25.33	20.83	5,744.36	0.12	430.77	6,175.13
Total expense	PCIt=60	555.51	27.45	18.81	5,751.62	1.63	600.13	6,351.75
	PCIt=65	577.02	33.20	16.55	5,548.14	1.46	625.32	6,173.45
	PCIt=70	448.83	43.00	16.88	5,454.20	1.29	507.43	5,961.63

The whole life design result of pavement structure is not just thickness combination of different structural layers. It also includes overlay thickness combination during different performance periods. It can be seen from Table 4 and Table 5 that: ① When it is optimized as per total cost, with the improvement of design standards, the thickness of surface course rises significantly, while overlay thickness during future performance periods is generally sustained at an initial value set at optimization; ② with improvement of design standards, the total cost at the same traffic level rises while the total expense drops. This is because an improvement of design standards means an increase of performance level, and a reduction of maintenance cost and user costs, which means the total expense drops. ③ Pavement structure thickness combination optimized as per total expense is significant better than that optimized as per total cost. This is because an option with good performance is preferred when optimization is carried out per minimum total expense. Good performance requires strong structure. ④ In make-up of life cycle cost, the user costs accounts for a large proportion, followed by construction cost. And pavement performance and traffic volume are directly related to user costs. Therefore, the higher the traffic volume is, the higher the proportion users cost accounts for, and the more significant the advantage in optimization as per total expense is. ⑤ Figure 4 gives the comparison of performance curves during analysis period of two economical optimization targets of different design standards. It can be seen that the differences between the two economical optimization targets are significant. ⑥The restriction of duration of the first performance period actually controls decay process of initial performance. The restriction herein is no less than 10 years. Other number of years can be restricted as required, for example, to no less than 8 years, 12 years or 15 years. This value shall be selected based on road class and heaviness of traffic.

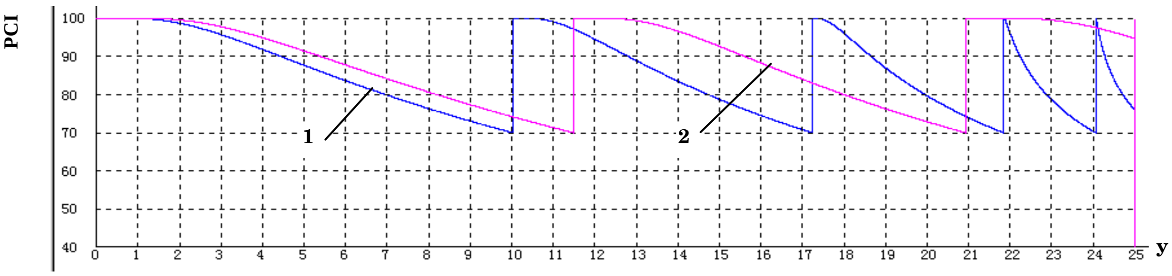
In Figure4, 1 is the optimization result per total cost,2 is the optimization result per total expense.



(a) Low standard (PCI_t=60)



（b）Intermediate standard (PCI_t=65)



(c) High standard (PCI_t=70)

Figure4: Comparison chart of performance curves of different economical optimization targets of semi-rigid base course

7 CONCLUSION

In view of shortcomings of current design methods for asphalt pavement structure at home and abroad, this paper proposes a new optimization design method for whole life asphalt pavement structure thickness based on performance and life cycle cost analysis. On the basis of considering such factors as structure, materials, load, environment and economy, this method reaches an economically efficient and reasonable structure thickness combination that meets performance index with minimum total cost and minimum total expense during life cycle as the economical optimization targets respectively. It can also realize optimization design of asphalt pavement structure thickness that meets different design requirements under given conditions (such as analysis period, discount rate, selection range and step of different structural layer thickness and overlay thickness, traffic volume and traffic composition, etc.).Therefore, this study can provide theoretical guidance for optimization design of structure thickness of newly built asphalt pavement or overlay asphalt pavement of different road grades, and enrich connotation of pavement management system, providing theoretical foundation and technical support for implementation of asphalt pavement management system at project level. This design method can make up for the lack of consideration in performance and economical factors in asphalt pavement structure design method in China for a long time, so as to really realize quantitative design and sole solution of pavement structure thickness combination, and be of high significance in providing theoretical guidance for asphalt pavement structure thickness composition design.

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