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Evaluating life cycle costs of perpetual pavements in China using operational pavement management system

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ABSTRACT

Highway transportation is considered as vital factor in China's economic growth; many high grade highways have been constructed in China during the last decades. The research and application of perpetual asphalt pavement (PP) technology have been deployed in China since 2000. The semi-rigid pavement has been normally considered as typical pavement of high class highways in the design according to the Chinese experience. The objective of this research is to evaluate the performance of different Chinese perpetual pavements using operational pavement management system and to examine its suitability for use in the design and construction of more economical and durable pavements. It has been found that the use of thin asphalt layers over semi-rigid pavement foundation in PP structure will create more sustainable, economical, and durable PP structures in comparison with typical thick asphalt layers PP structures.

Introduction

General

The Romans built their empire roads network more than 2000 years ago to last for long time using thick layers of durable rock materials, their remaining road pavement layers can be seen intact till now without maintenance or rehabilitation (Steiger, 1995). The building of road networks is important for the growth and prosperity of any nation and for the evolving of economic and social developments. During the last twenty years, the road pavements have been subjected to increasing number and weight of trucks beyond the capacity of their original design limits due to the growing demand on road transport. The increasing cost of maintenance and rehabilitation of roads is a heavy burden on governments, road agencies and road users. This problem has focused the light on the need for building road pavements that survive for long time under heavy and increasing traffic loads with minimum maintenance and rehabilitation costs taking into consideration the recent developments in improving the durability and performance of asphalt concrete materials.

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Perpetual pavement

The perpetual pavement (PP) is defined by Asphalt Pavement Alliance (APA) (2002) as "An asphalt pavement designed and built to last longer than 50 years without requiring major structural rehabilitation or reconstruction, and needing only periodic surface renewal in response to distresses confined to the top of the pavement". This longevity in PP is attributed to the use of special formulated asphalt concrete mixes for the construction of asphalt concrete layers. The upper surface layer is designed to resist wear and top-down cracking, the intermediate asphalt binder layer is designed to resist the rutting and fatigue, and the lower asphalt base layer is designed to resist bottom-up cracking. In PP, the possibility of traditional fatigue cracking is reduced, and pavement distress is limited to the upper layer of the structure. Thus, when surface distress reaches unacceptable level, the economical solution is to mill and replace the top layer. The PP concept can be used for any pavement structure where it is required to minimize rehabilitation and reconstruction costs as well as reducing closures to traffic. These factors are especially necessary on high traffic volume freeways where user delay costs may be very high. The conventional asphalt pavements are usually designed for a 20-year service life, while PP is expected to be in use for 50 years or more. The main problem with the current PP design method is the absence of optimum design of pavement structure and/or layers because of the interaction of many variables as will be highlighted in Section 'Pavement management system' later. The thickness of asphalt layers in PP is usually thick (from 20 to 50 cm). The thickness of PP is determined by limiting the tensile strain at the bottom of asphalt layer (fatigue criterion), while the total thickness of PP structure is determined by limiting the compressive strain on the surface of sub grade (rutting criterion). Increasing the thickness of asphalt layers increases the total stiffness of the pavement structure and decreases the stresses transmitted to the sub grade layer (Asphalt Pavement Alliance (APA), 2002). Due to the large thickness of asphalt layers, higher resistance to bottom-up fatigue cracking, structural rutting, and thinner granular base/sub base layers are expected in comparison with the conventional pavement designs. Since the evolving AASHO pavement design method in the late 1950s, many examples of conventional road pavements which last for more than its design period are reported around the world with only suitable maintenance and rehabilitation of surface layers (Tarefder and Bateman, 2009). The full depth asphalt pavements are well known everywhere since early 1970s (Yoder and Witczak, 1975). The only difference which characterized PP is the design for long time period more than 50 years and for high number of equivalent single axle wheel loads (ESAL) up to 100 millions, which requires thorough analysis of life cycle performance.

Perpetual pavements in China

Semi-rigid base asphalt pavement is the main pavement structure in China since 1997 and it comprises about 90% of total pavement structures. China started to design, construct, and test PP expressway sections such as Yan Jiang expressway in Jiangsu province in 2004, Xu Wei expressway in Henan province in 2005, and Binzhou test road in Shandong province in 2005 as reported by Wang (2013). Three PP test sections with fatigue strain of 70 and 125 micro strains as shown in Fig. 1, along with two control sections as shown in Fig. 2, were built during the summer of 2005 as part of a perpetual

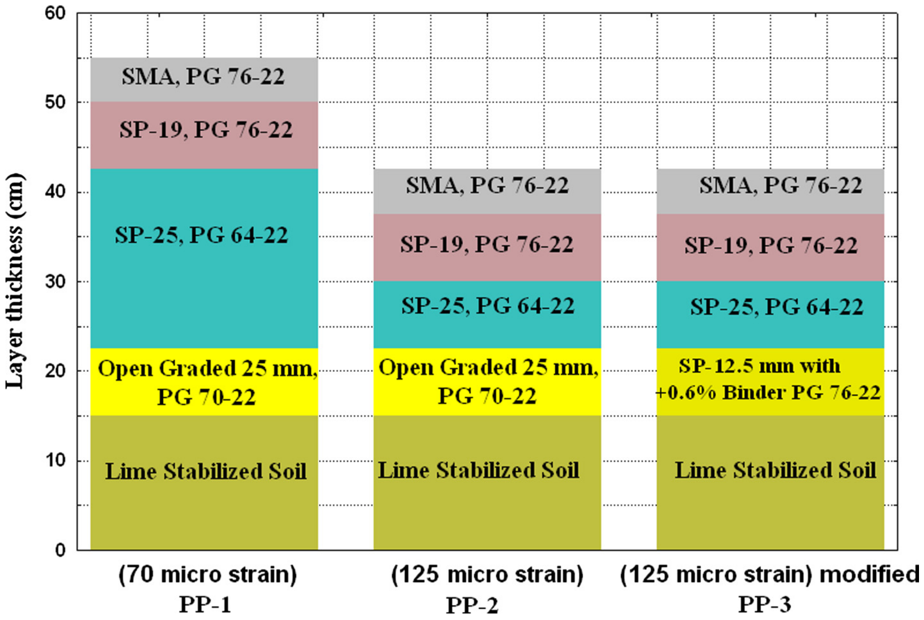

Fig. 1. Perpetual pavement test sections on Shanghai to Tianjin motorway near Binzhou, Shandong Province (Yang and et al., 2006).

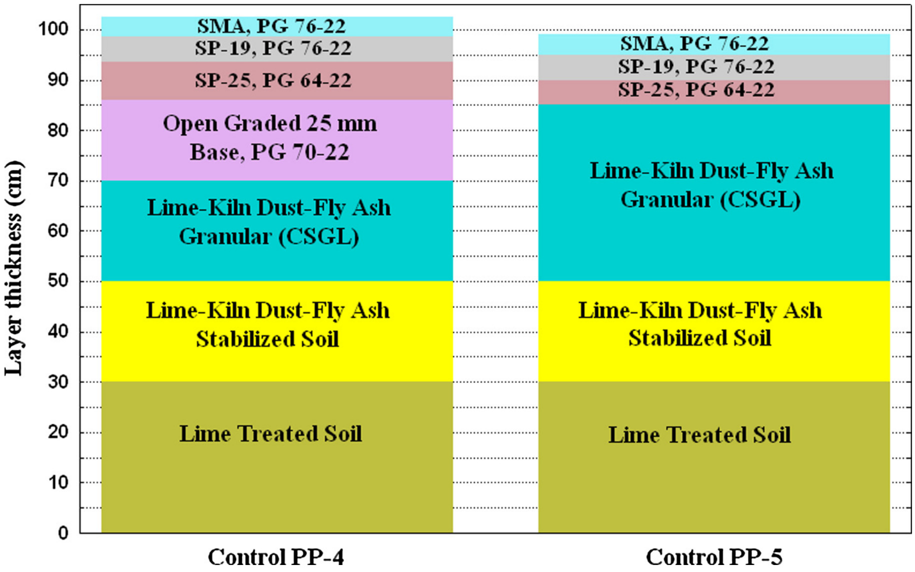

Fig. 2. Two perpetual pavement control experiment sections on Shanghai to Tianjin motorway near Binzhou, Shandong Province (Yang and et al., 2006).

pavement experiment on a newly constructed expressway in Shandong province. A unique feature of the experiment is the heavy traffic loads of China (e.g., average single axle weights exceeding 20 kip (100 kN)) in addition to weigh-in-motion facility and embedded pavement response gauges to document the type and weight of vehicles and corresponding pavement responses (Yang and et al., 2006). Chinese pavement designers try to build their own PP experience by employing their long time experience with long life semi rigid pavement structures as shown in Fig. 3. Wang et al. (2012) reported that the pavement which had been designed as semi-rigid structure and later was replaced by new long-life flexible pavement structure can be considered as a cost-effective alternative to current semi-rigid or rigid pavement technology in China. Different PP designs have been implemented in the construction of new expressways, but the long time performance of these pavements and their comparison with long life semi rigid pavements need further studies as highlighted by Guy et al. (2015), Tran et al. (2015).

Pavement management system

The pavement design process has as its objective the design and management of the pavement throughout its lifetime in order to minimize the total cost. The performance of pavement systems involves the interaction of numerous variables such

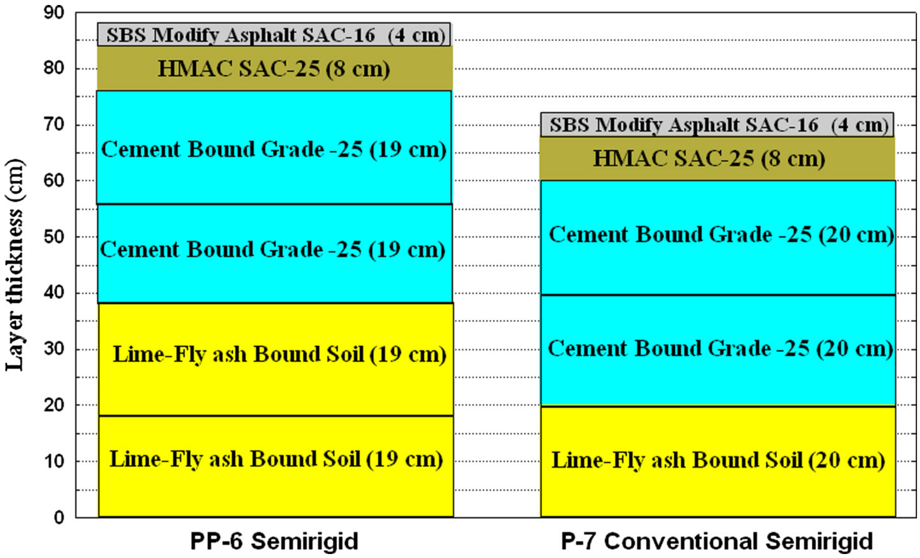

Fig. 3. Semi rigid perpetual of Qing Huang dao freeway and conventional semi rigid pavements (Wang, 2013).

as material properties, environment, traffic loading, construction practices, maintenance activities and management constraints. In order to select an optimum pavement strategy, methods are needed that consider the interaction of these variables and constraints. The development of an operational pavement system model, called SAMP5, a computer program developed by NCHRP project (1–10), Hudson and McCullough, 1973; Nair and Chang, 1973; Lytton and et al., 1975.

System analysis model for pavement (SAMP) is an extension of the algorithms in the particular version (SAMP5). There are seven classes of input variables as follows: (1) material properties, (2) environment and serviceability, (3) load and traffic, (4) constraints, (5) traffic delay, (6) maintenance and (7) program control and miscellaneous.

SAMP5 computer program adopts the view that routine maintenance and future rehabilitation (overlay) are part of the total pavement management process. Future costs are discounted to the present and the total cost per unit area is used as the criterion for determining which pavement design is the optimum. The total cost includes also the users cost (a term for the expense to the traveling public of being delayed while detouring on overlay activity). These costs are weighted equally with actual construction cost. It is also generally agreed that pavement materials would have a salvage value which depends mainly upon their expected future use. Pavement design is normally a repeated process, in which the designer assumes a certain combination of thickness of layered materials and subsequently checks the layered system for adequacy form the point of view of traffic and environmental deterioration, construction, and rehabilitation costs, as well as cost of future seal coats, overlays and routine maintenance. The program analyzes the input and gives the output in a way that the designer of the pavement can choose the best design for the pavement needed depending on construction, and maintenance costs. Therefore, the need for pavement with long service life with minimum maintenance cost seems to be an available objective. SAMP5 computer program has been modified (Sultan, 1995) to take into consideration AASHTO 1993 pavement design, (American Association of State Highway and Transportation Officials, 1993). More details about algorithm and the operation as well as modifications of the computer program SAMP5 are available in the literature (Hudson and McCullough, 1973; Nair and Chang, 1973; Lytton and et al., 1975; American Association of State Highway and Transportation Officials, 1993; Sultan, 1995; Sultan and Tong, 2000). This program will be used in this research to evaluate the performance and life cycle costs of PP in China.

Research objectives

1. To determine life cycle costs of selected PP structures in China as previously shown in Figs. 1–3 respectively for different equivalent single axle loads (ESAL) capacity.
2. To find the maximum capacity of these selected PP structures in terms of equivalent single axle loads (ESAL) capacity depending on limiting PP fatigue and rutting criteria.
3. To determine the most suitable PP design depending on the results of life cycle costs analysis and capacity.

Methodology

In order to achieve the objectives of this research the following steps have been carried out:

Data collection

Detailed data collection procedure has been carried out on constructed PP projects in China to find the required values of the input variables for this research analysis purposes. The results of field tests on existing PP projects have been considered, calibrated and compared with different design values in order to determine the most reasonable ones as reported by different researchers in the introduction above.

Life cycle costs analysis

In order to carry out the life cycle costs analysis using SAMP5 computer program (which has been modified (Sultan, 1995) to use AASHTO 1993 design method (American Association of State Highway and Transportation Officials, 1993)), it is necessary to determine the magnitude of its input variables. The magnitude of SAMP5 input variables has been kept constant for each of the studied pavement for comparison purposes except the thickness of pavement layers, properties of materials, design life, and number of equivalent single axle loads (ESAL) in order to find life cycle costs of the selected PP structures. The magnitude of some SAMP5 input variables has been obtained from PP test sections as reported by different researchers as shown in Tables 1 and 2 respectively. The magnitudes of the rest of SAMP5 variables which are related to program constraints, operation, movement of vehicles in the overlay construction zone, etc. are as reported by Sultan (1995), Sultan and Tong (2000) respectively.

Mechanical empirical analysis

The selected PP structures will be subjected to mechanical empirical analysis to find their fatigue and rutting strains in terms of tensile strain at the bottom of asphalt layer and compressive strain on the surface of sub grade using the computer

Table 1
Sample of some SAMP5 input variables.

SAMP5 input variables	Value
Analysis period (years)	Variable
Reliability (%)	90
Over all standard deviation	0.45
Drainage coefficients	1.0
Interest rate (%)	7
Initial serviceability index	4.5
Initial one direction average daily traffic	4500
Final one direction average daily traffic	8000
18 kips equivalent single axle load (millions)	Variable
Percent of trucks in average daily traffic	30
Minimum allowed time to first overlay (years)	7
Minimum allowed time between overlays (years)	7
The relative traffic handling model	3
The relative material cost	1

Table 2
Pavement material properties as input to SAMP5.

Material type	Cost (US $/m^3)	Modulus (MPa)	Salvage value (%)
STONE-MATRIX ASPHALT SMA, PG 76-22	183.01	4480	30.00
PERFORMANCE MIX SP-19, PG 76-22	163.40	4480	90.00
PERFORMANCE MIX SP-25, PG 64-22	163.40	4480	90.00
RICH BOTTOM LAYER OPEN GRADED 25, PG 70-22	156.86	3450	90.00
PERFORMANCE MIX SP-12.5 WITH +0.6% BINDER, PG 76-22	163.40	4485	90.00
PERFORMANCE MIX SP-12.5 WITH +0.6% BINDER, PG 64-22	163.40	4485	90.00
CEMENT STABILIZED BASE	58.82	830	70.00
LIME-KILN DUST-FLY ASH GRANULAR BASE (CSGL)	54.90	485	70.00
LIME-KILN DUST-FLY ASH STABILIZED SOIL	19.61	240	70.00
LIME STABILIZED SOIL	19.61	110	70.00

program Kenpave (Huang, 2004) and using fatigue and rutting models of (Asphalt Institute, 1986) as shown in Eqs. (1) and (2) respectively.

$$N_f = 0.0796(\varepsilon_t)^{-3.291}(E_1)^{-0.854} \tag{1}$$

where N_f = number of load repetition to fatigue failure (20% cracking), ε_t = tensile strain at the bottom of asphalt layer, E_1 = modulus of asphalt layer, (ksi).

$$N_d = 1.365 \times 10^{-9}(\varepsilon_v)^{-4.477} \tag{2}$$

where N_d = number of load repetition to rut failure (rut depth = 1.2 cm), ε_v = compressive strain on the sub grade surface.

Analysis of PP

Six different PP structures in China have been chosen for the life cycle cost analysis in addition to one conventional semi rigid pavement as shown in Figs. 1–3 above using the modified SAMP5 program. The objective of this analysis is to carry out a comparison between these different pavement structures in terms of present total cost (which includes construction, maintenance, and user cost), maximum service life in years, and maximum capacity in terms of number of 18 kips (8.6 tons) equivalent single axle loads repetitions. It should be noted that trial and error technique has been used to find optimum values of these required variables by different runs of SAMP5 using different input variable combinations. SAMP5 output does not give pavement structure designs (layers thickness and type) exactly similar to the selected six PP structures in China. We have pavement designs and we want to find the value of SAMP5 input variables combination that gives similar designs to our selected PP designs (back calculation); therefore, trial and error technique has been carried out. SAMP5 allows ranges for pavement layers thickness and overlays in addition to many other variables that can be selected as mentioned in this paper previously. More details are mentioned in references Hudson and McCullough (1973), Nair and Chang (1973), Lytton and et al. (1975), Sultan (1995) and Sultan and Tong (2000). The analysis results are as shown in Tables 3 and 4 respectively.

SAMP5 can evaluate the interaction of about 100 input variables which cover a wide range of design, construction, maintenance, performance, economy and management variables. SAMP5 gives the best feasible designs in an increasing order of total cost for the specified magnitudes of input variables. Each run of the program for different combination of pavement layers with different materials gives 30 optimum possible designs in increasing cost order. It is important to notice that user and routine maintenance costs have been excluded from our analysis results because of their small values and they are the same for the selected PP structures due to the absence of structural or rehabilitation overlays during the PP service life. As

Table 3
SAMP5 results for the analyzed PP structures.

Pavement structure number	Max. service life (years)	Max. number of ESAL (millions)	Total cost (US $/m^2)
PP-1	40	80	50.72
PP-2	30	50	42.57
PP-3	30	50	42.83
Control PP-4	40	80	44.66
Control PP-5	20	20	41.06
PP-6	20	20	44.17
P-7 semi rigid	20	20	39.42

Table 4
Mechanistic empirical analysis results for the PP structures.

Pavement structure number	HMA tensile micro strain	Sub grade compressive micro strain	Cracking life (millions)	Rutting life (millions)
PP-1	17.4	128	200	200
PP-2	15.4	190	200	62.62
PP-3	15.4	190	200	62.62
Control PP-4	15.5	184	200	72.30
Control PP-5	19.8	186	200	68.88
PP-6	7.5	15.7	200	147.12
P-7 semi rigid	20.3	17.6	200	88.22

mentioned earlier, PP needs only periodic maintenance to deal with asphalt surface functional distresses which can be solved by milling and replacing of the upper deteriorated asphalt layer in contact with traffic loads without the need for structural rehabilitation (Asphalt Pavement Alliance (APA), 2002). Table 3 has been prepared to show the present total costs, the maximum capacity in terms of 18 kips (8.6 tons) equivalent single axle loads number, and the maximum service life possible without structural overlays of the studied PP structures. The maximum service life (without the need for structural overlays) and maximum capacity in terms of 18 kips (8.6 tons) equivalent single axle loads number (ESAL) have been determined based on the predefined failure criteria of 70 or 125 micro strains for the asphalt fatigue and 200 micro strains for sub grade rutting, (Asphalt Pavement Alliance (APA), 2002). Table 4 has been prepared to show fatigue and rutting strains of the analyzed PP structures and the maximum expected life in terms of millions of 18 kips (8.6 tons) equivalent single axle load repetitions.

Discussion of results and conclusions

The analysis of results can be summarized as follows:

1. The PP-1 structure has the highest construction cost, and maximum capacity (in terms of 18 kips (8.6 tons) equivalent single axle load repetitions). The PP-1 structure has the highest construction cost among all the analyzed PP structures due to its thick asphalt layers. Its performance in terms of (ESAL) is similar to the Control PP-4 structure but with higher construction cost. The expected mode of failure for PP-1 is fatigue while the expected mode of failure for Control PP-4 is rutting due to the thick asphalt layers of PP-1 in comparison with thin asphalt layers of Control PP-4.
2. The PP-2 and PP-3 structures are almost having the same performance from the structural point of view in spite of the difference in their pavement layers.
3. The control PP-5, PP-6, and PP-7 structures are almost having the same performance from the structural point of view in spite of the difference in their pavement layers.
4. Control PP-4 is the most suitable design from the capacity and total cost point of view in comparison with PP-1 for the following reasons:
    I. The thicker asphalt layers of PP-1 (in comparison with PP-4) which has variable modulus value depending on the seasonal degree of temperature may affect its performance under traffic loads. This performance which is difficult to predict during long service life.
    II. Thicker asphalt layer is not preferred because of rapid asphalt aging and stripping due to environment effects.
    III. The asphalt layer of pavement is not an environment friendly material and its disposal or processing at the end of its service life will cause serious problems to the environment unless using recycling techniques.
    IV. The long time Chinese experience in building semi rigid asphalt pavements may prefer Control PP-4 structure in comparison with PP-1 taking into consideration the possibility of converting semi rigid asphalt pavements in China into PP structures by staged construction, (Vavrik et al., 2009).
    V. The analysis results in this research which showed that the semi rigid asphalt pavement (similar to Control PP-4) as the most cost effective PP structure in China are conforming well with the findings of the literature (Wang et al., 2012).

Recommendations for future research

1. It is recommended to carry out further research on the possibility of using recycled asphalt pavement materials in the construction of new PP or to convert old and deteriorated conventional semi rigid asphalt pavements to PP structures.
2. It is preferable to monitor the performance of newly constructed PP for long time periods in order to develop pavement maintenance models using pavement maintenance management system for this type of pavements.

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