RESEARCH ON THE STRUCTURAL DESIGN OF ASPHALT PAVEMENTS FOR LOW-COST RURAL ROADS

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ABSTRACT

On the basis of the frequency of application of standard axle loads, the traffic levels of rural roads, as well as their corresponding vehicle types, are classified, and pavement structures, surface course types and thicknesses of rural roads are suggested for the various frequencies of application of standard axle loads. Road base thickness graphs are provided according to the different frequencies of application of standard axle loads, with the different earth foundation moduli and pavement moduli taken into account.

1. INTRODUCTION

The term “rural road” includes county-level roads, town-level roads and public administration-level (village) roads.

In developing countries, rural road construction is most affected by shortages of funds. What concerns road engineers most in rural areas is how to build roads that are not only low-cost, but can also satisfy the traffic demands. In the authors’ opinion, the selection of a pavement structure is the key to reducing the construction cost of rural roads after the route has been determined. Compared with concrete pavement, asphalt pavement is relatively less costly to construct, and is the first choice for rural roads in China. The authors have done some preliminary research on the structural design of low-cost asphalt pavements for rural roads, and their findings are presented here for reference by road construction engineers.

2. TRAFFIC COMPOSITION OF A RURAL ROAD

The traffic on rural roads is usually mixed – on a county-level road it is between 300 and 1 500 vehicles/day, although in a county with a developed economy, the traffic mix on a county-level road may be is relatively high, reaching 1 000 to 2 000vehicles/day. The volume of traffic travelling between countryside and town is 100 to 300 vehicles/day, and the volume between towns is usually less than 100 to 300 vehicles/day . In mixed traffic flow, trucks account for 40% to 70% of the traffic; these are mainly light trucks of less than 2.5 tons (including agricultural vehicles such as electro-tricycles, walking tractors, etc.) and medium-size trucks of 2.5 to 5 tons, but most of these light or medium trucks are overloaded. The proportion of heavy trucks is less than 9%. On some roads to counties, the proportion of overloaded trucks is 5% to 32%, while on some county-level roads connected with national trunk roads or provincial trunk roads, the proportion of overloaded vehicles usually amounts to 20% to 32%.

3. STANDARD AXLE LOAD AND AXLE LOAD CALCULATION

3.1 Standard Axle Loading

The traffic volume on rural roads is not heavy – the flow of traffic is actually light – but considering the practical situation in China, as well as the prevalence of overloaded vehicles, 100 kN, or BZZ-100, was adopted in this research as the standard axle loading.

3.2 Axle Load Conversion

Taking the deflection value of the road surface, or the flexural-tensile stress at the bottom of the asphalt surface, as the design index, the axle load was calculated in accordance with following formula:

$$L_{ef} = \frac{n_s}{n_i} = C_1 C_2 \left(\frac{p_i}{P_s} \right)^{4.35} \quad (1)$$

In this formula:

P_i , n_i is the axle weight of an I-level axle load (kN) and the action frequency

P_s , n_s is the axle weight of a standard axle load (100 kN) and the action frequency

C_1 is the coefficient of the number of axles

C_2 is the coefficient of the wheel set.

A mono wheel set is calculated as 6.4, double wheels as 1, and a four-wheel set as 0.38. If the distance between axles is greater than 3 m, the axles are calculated as separate axle loads, and the coefficient of the number of axles is M. If the distance between axles is less than 3 m, the axles are calculated as double axles or multi-axles, and the coefficient of the number of axles is calculated in accordance with Equation 2 (M is the number of axles):

$$C_1 = 1+1.2\,(M-1) \quad (2)$$

If the flexural-tensile stress at the bottom of a semi-rigid base is taken as the design index, the axle load is calculated in accordance with Equation 3:

$$L_{ef} = \frac{n_s}{n_i} = C_1' C_2' \left(\frac{p_i}{P_s} \right)^{8} \quad (3)$$

Where C_1' is the coefficient of the number of axles and C_2' is the coefficient of the wheel set. A mono wheel set is calculated as 18.5, double wheels as 1.0, and a four-wheel set as 0.09. If the distance between the axles is less than 3 m, the coefficient of double axles or multi-axles is calculated in accordance with: C_1' = 1+2 (M-1) .

4. DETERMINATION OF TRAFFIC VOLUME ON RURAL ROADS

4.1 Vehicles Adopted in the Design of Rural Roads

The minibus has been adopted as the standard shape for the design of rural roads. Table 1 shows its external dimensions.

Table 1. External dimensions of the minibus.

Length	Width	Height	Front overhang	Distance between axles	Rear overhang
6 m	1.8 m	2 m	0.8 m	3.8 m	1.4 m

4.2 Conversion Coefficient of Vehicles

Table 2. Representative vehicle types and vehicle conversion coefficient.

Representative Vehicle Type	Vehicle Conversion Coefficient	Description
Minibus	1.0	Buses with fewer than 19 seats; trucks with a loading capacity of less than 2 tons
Motorbike	1.0	Motor cycle or motor tricycle
Medium-sized vehicle	1.5	Buses with more than 19 seats; trucks with a loading capacity of more than 2 tons but less than (or equal to) 7 tons
Heavy vehicle	2.0	Trucks with a loading capacity of more than 7 tons but less than (or equal to) 14 tons

Apart from the representative vehicle types listed in Table 2, non-power-driven vehicles, such as animal-drawn vehicles and bicycles, can be taken into account in the calculation of traffic volume on rural roads, in view of their roadside interference.

4.3 Classification of Traffic Volume on Rural Roads

In accordance with their traffic composition and volumes, rural roads can be divided into five grades; the traffic volume required by each grade has also been determined (Table 3).

Table 3. Classification of traffic volumes on rural roads.

Grades	Corresponding road types:	Traffic volume (vehicles/day)	Design service life	Growth rate of traffic volume	Cumulative equivalent degree of axis (N_e) (10 000/lane)
T1	Between villages	≤150	5	4%	≤10
T2	Between villages and towns	150 – 300	5 – 8	5%	10 – 25
T3	Between towns	300 – 800	8	6%	25 – 50
T4	Between counties and towns	800 – 1 500	8 – 10	7%	50 – 100
T5	Between counties	≥1 500	10 – 12	8%	≥100

The traffic volumes specified in Table 3 were obtained by taking the minibus as the standard vehicle type, and converting vehicles of different types according to the vehicle conversion coefficients given in Table 2. In Table 3:

$$Ne = \frac{[(1+\gamma)^t - 1] \times 365}{\gamma} N_s \eta \qquad (4)$$

Where Ns refers to the action frequency of the standard axle loading with the designed traffic lane during the initial operation period of roads.

γ refers to the average annual growth rate of the traffic volume (%) and η is a carriageway coefficient: a single carriageway is 1 and a dual carriageway is 0.6 – 0.7. In view of the overloading of vehicles, the pavement structure must also be supported by a stable, solid roadbed.

5. CLASSIFICATION OF THE STRENGTH OF ROADBEDS

Because China has vast rural areas and very diverse climatic conditions, the modulus of resilience of the roadbed varies greatly. For convenience in designing rural roads, the strength of the roadbed can be divided into four grades, according to its moisture content and its modulus of resilience (Table 4).

Table 4. Classification of the strength of rural roadbeds.

Strength grade	Modulus of resilience of roadbed (MPa)	Wetness of roadbed	Description
S1	25 – 35	Wet – Moderately wet	Newly built roadbed
S2	35 – 45	Moderately wet – Dry	Newly built roadbed
S3	45 – 55	Dry or excavated roadbed	Newly built roadbed
S4	55 – 70	Dry or former roadbed	Pavement of clay-bound (gravel) macadam

6. ANALYSIS OF THE CLASSIFICATION OF TRAFFIC VOLUME AND ROADBED STRENGTH

6.1 Analysis of the Classification of Traffic Volumes

By applying Elastic Multilayer Theory to the pavement structure specified in Figure 1 (hypothesized by combining design principles with practical experience), and by analysing the influence of N_e (the equivalent weight of the action frequency of axle loading for different traffic grades) on the pavement thickness of rural roads, the authors have drawn the following conclusions: if h1, h3 and E0 have been determined, the pavement thickness at adjacent traffic grades will fluctuate between 4 and 5 cm. This conclusion indicates that, with respect to the design and construction of a pavement structure, the classification of traffic volume on rural roads as shown in Table 3 is reasonable and practicable.

Road surface	Asphalt penetration	h = 3 cm E1 = 500 MPa
Road base	Cement (soil-lime-flyash) stable aggregate	h1 = ? E1 = 500 MPa
Subbase	Limey soil (soil-lime-flyash)	h2 = 20cm E3 = 475 MPa
Roadbed		E0 = 25 – 70 MPa

Figure 1. Drawing of pavement structure.

6.2 Analysis of the Classification of Roadbed Strength

Employing Elastic Multilayer Theory, the pavement structure of an ordinary rural road is analysed as shown in Figure 1.

Depending on Ne, the road base (h = 3 cm) and subbase (h2 = 20 cm) remain the same, and the influence of the roadbed strength at neighbouring grades on the subbase is 3 to 5 cm. This conclusion indicates that the strength classification of rural roadbeds is reasonable and applicable to the design and construction of pavement structures.

7. DESIGN OF BITUMINOUS PAVEMENT STRUCTURE

7.1 Sensitivity Analysis of the Design Parameters of Roadbed and Pavement

By means of the sensitivity analysis of the design parameters of roadbed and pavement, it is possible to find the rule by which the structural strength of the pavement changes along with the changes in the design parameters of each structural layer, to find out which layer position is most sensitive in the pavement structure and to determine the recommended values of the structural design parameters.

Road surface	Thickness h	Poisson's ratio ū	Modulus E
Road base	Thickness h1	Poisson's ratio ū1	Modulus E1
Subbase	Thickness h2	Poisson's ratio ū2	Modulus E2
Roadbed		Poisson's ratio ū0	Modulus E0

Figure 2. Pavement structure used in the sensitivity analysis of design parameters.

The bituminous pavement structure of rural roads is generally composed of a road surface, a road base and a subbase (three-level system), as shown in Figure 2. The pavement structure shown in Figure 2 was analysed according to Elastic Multilayer Theory under the double wheel uniform load, assuming that there is continuous contact between the pavement layers. The basic parameters used in the calculation and analysis of pavement structure are:

d/2 = 10.65 cm, p = 0.7 MPa, ū1 = ū2 = ū3 = 0.25, ū0 = 0.35

E1	=	400,	500,	600,	700,	800,	900,	1 000,	1 000	MPa
E2	=	300,	400,	500,	600,	700,	800,	900,	1 000	MPa
E3	=	150,	200,	250,	300,	350,	400,	450,	500	MPa
E0	=	25,	30,	35,	40,	45,	50,	55,	60	MPa
h	=	1.5,	2.0,	2.5,	3.0,	3.5,	4.0,	4.0,	4.0	cm
h1	=	10,	12,	15,	18,	20,	22,	25,	28	cm
h2	=	12,	15,	18,	20,	22,	25,	28,	30	cm

From the analysis of the changes in all the parameters of the pavement structure, and their influences on the distortion of the road surface, road base and roadbed, a number of conclusions have been drawn. First, increasing the thickness of the road surface can effectively decrease the road surface deflection, but will raise the cost. A comparatively economical and effective method is to increase the thickness of the subbase, which is superior to increasing the thickness of the road base, while increasing the thickness of the road surface is the last choice we should make.

As the thickness of the pavement structure increases, the change in road surface deflection will tend to be gentle. When the thickness of the road surface reaches some certain value, the variance in road surface deflection will not be obvious. It is worth mentioning that it is ineffective to try to enhance the bearing capacity of a pavement structure by increasing its thickness. Figure 3 shows the influence of the change in thickness of each pavement layer on surface deflection. It is therefore recommended that the thickness of the road base and subbase should be respectively equivalent to or more than 18 cm and 20 cm when the pavement structures of rural roads are designed.

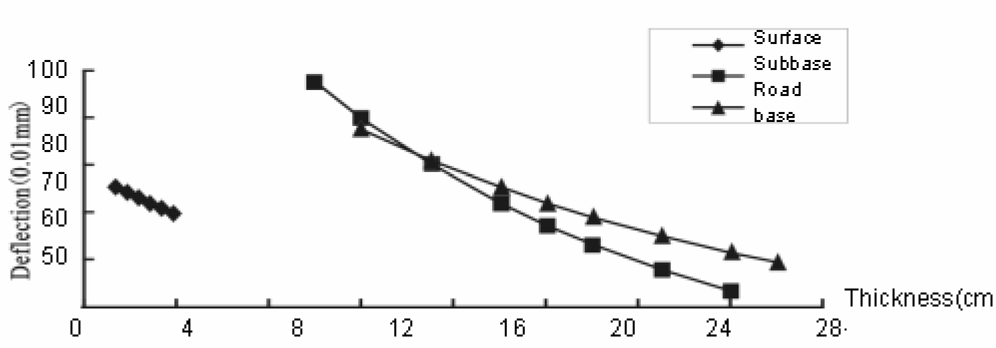

Figure 3. Influence of the change in thickness of each pavement layer on surface deflection.

The road surface deflection value is very sensitive to the change of modulus E0 of the roadbed; especially when E0<30 MPa, this value will increase quickly along with the decrease of E0. Next, an increase in the moduli of the road base and subbase is proportionately effective to the decrease in the deflection value of the road surface. Moreover, the deflection value of the road surface decreases the most slowly when the modulus of the surface layer is increased. Figure 4 shows the influence of the modulus of each layer on road surface deflection values.

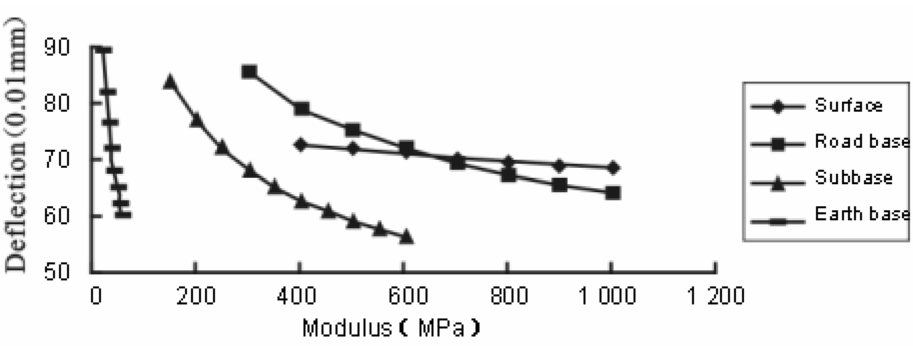

Figure 4. Influence of the change in the modulus of the pavement at each layer on road surface deflection.

The graph in Figure 4 demonstrates the moderately slow rate of change. When the modulus of the pavement structure is increased to reach a certain value, the decrease in road surface deflection will not be apparent. From the above we can conclude that the sensitive layer position for road surface deflection is the subbase, and the next is the road base. To decrease surface distortion, it is recommended that the compaction and stability of the roadbed of low-cost rural roads be enhanced and that materials with a certain thickness and relatively high density be used to pave the subbase at the same time.

7.2 Selection of the Thickness of Each Layer of Low-Cost Rural Roads

7.2.1 Types and Reasonable Thickness of Bituminous Surface Layers

An effort should always be made to decrease the project cost while meeting the traffic and technical requirements. With all the factors integrated, the traffic volume or the accumulated action frequency of standard axle loading within the road's expected design life is used to determine the type and thickness of the bituminous surface (see Table 5).

Table 5. Type and thickness of the bituminous surface of rural roads.

Traffic grade	T1	T2	T3	T4	T5
Road type	Village to village	Village to town	Town to town	Town to county	County to county
Traffic volume	≤150	150 – 300	300 – 800	800 – 1500	≥1 500
Expected design life	5	5 – 8	8	8 – 10	10 – 12
Accumulated axle loading, N_e (10 000 times/lane)	≤10	10 – 25	25 – 50	50 – 100	≥100
Type of road surface	Bituminous surface treatment	Bituminous surface treatment	Bituminous surface treatment	Hot-mix bituminous asphalt	Bituminous concrete surface course
Road surface thickness(cm)	15 – 20	20 – 25	30	30 – 40	60

7.2.2 Establishment of the Thickness of the Flexible Base and Aggregate Subbase

For a low-traffic-volume rural road surface with an accumulated standard axle loading N_e ≤ 500 000, a flexible road base will ensure good functional performance and effectively prevent reflection cracks from propagating from the bituminous surface, provided the materials and grading meet the requirements for high density (degree of compaction ≥ 100%) during construction. To ensure sufficient density and stability of the flexible base, its minimum thickness should be no less than 15 cm.

7.2.3 Establishment of the Thickness of the Semi-Rigid Base

A semi-rigid base usually has good bearing capacity. For rural roads with an accumulated standard axle loading of ≥ 500 000 or roads with low traffic volumes but relatively more overloaded vehicles, the minimum thickness of the semi-rigid base or subbase should be 16 – 18 cm.

8. CALCULATION OF THE THICKNESS OF ROAD SURFACE

8.1 Deflection

8.1.1 Road Surface Deflection

Road surface deflection is a type of distortion caused by the vertical load on the road surface. It is a function of each pavement layer and the roadbed, but is also closely related to the service level on the road surface.

8.1.2 Design Deflection

The design deflection of the road surface is the index representing the stiffness of the entire road surface. It is also the deflection value of the road surface established according to the accumulated equivalent axles estimated to pass over a roadway, taking into account the expected design life, road types, road grades and the types of road surface and road base. The design deflection of the road surface is not only the main basis for designing the thickness of the road surface, but also the necessary index for the examination and acceptance of finished roads. Through theoretical analysis and experimental study, the calculation formulas for the design deflection value of the road surface applicable to the pavement structure design of low-cost rural roads are: semi-rigid base: $l_d = 629 N_e^{-0.2} A_s$ or flexible base: $l_d = 1134 N_e^{-0.2} A_s$ (where N_e is the accumulated standard axle loading on a roadway within the design life, and A_S is the modulus of the surface type – the modulus of a concrete surface course is 1.0, that of hot-mix bituminous asphalt and emulsified bituminous asphalt pavements is 1.1, and that of a bituminous surface treatment is 1.2.)

8.1.3 Allowable Deflection

Allowable deflection is the maximum deflection value allowed at the end of the road's service life. Through theoretical analysis and experimental study, the calculation formulas for the allowable deflection value of the road surface applicable to the pavement structure design of low-cost rural roads is: $l_R = 786N_e^{-0.2}$ or $l_R = 1418N_e^{-0.2}$

8.2 Tensile Stress

In view of the less substantial pavement structure of low-cost rural roads and the heavy vehicles passing over them, the maximum tensile stress should be checked by computing the stress of the semi-rigid base and subbase. The tensile stress at the precalculated position at the bottom, σm, should be less than or equivalent to the allowable tensile stress of the materials at this level, namely:

$$\sigma m \leq \sigma_R = \sigma_{sp} / K_s \quad (5)$$

For aggregate stabilised with an inorganic binder: $K_s = 0.35N_e^{0.11} / A_c$ and for fine-grained soil stabilised with an inorganic binder: $K_s = 0.35N_e^{0.11} / A_c$ Ac=1.2.

8.3 Pavement Thickness

To make it simple and convenient for engineers to establish the desired thickness of a rural road pavement, researchers have drawn up graphs for the thickness of the roadbed of low-cost rural roads according to typical pavement structures and the accumulated standard axle loading of rural roads. These are given in Figures 5, 6 and 7.

1. When the accumulated standard axle loading is 0 to 500 000, a 1.5 – 4 cm bituminous surface treatment or bitumen penetration will be adopted for the road surface. For various accumulated standard axle loads and moduli of the soil base course, the equivalent thickness of road base will be as shown in Figure 5.

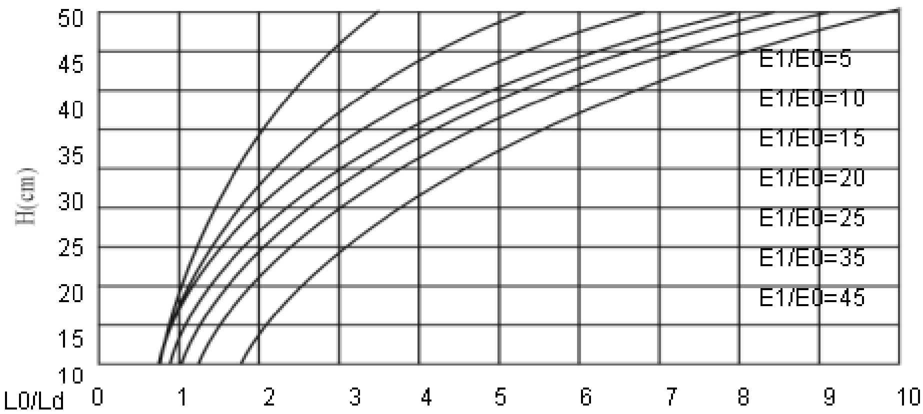

Figure 5. Graph of the design thickness of the soil base with an axle load of 0 – 500 000.

2. When the accumulated standard axle loading is within 500 000 – 1 000 000, a 3 – 5 cm bituminous asphalt pavement and bituminous concrete pavement will be adopted. For various accumulated standard axle loads and moduli of the soil base course, the equivalent thickness of road base will be as shown in Figure 6.

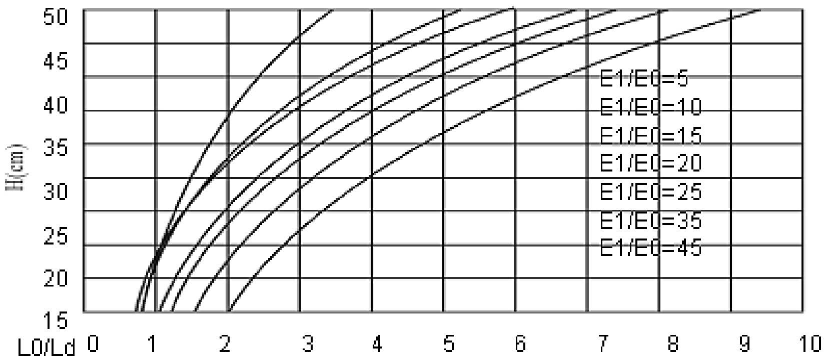

Figure 6. Graph of the design thickness of the soil base with an axle load of 500 – 1 000 000.

3. When the accumulated standard axle loading is within 1 000 000 – 2 000 000, a 5 – 7 cm bituminous concrete pavement will be adopted. For various accumulated standard axle loads and moduli of the soil base course, the equivalent thickness of road base will be as shown in Figure 7.

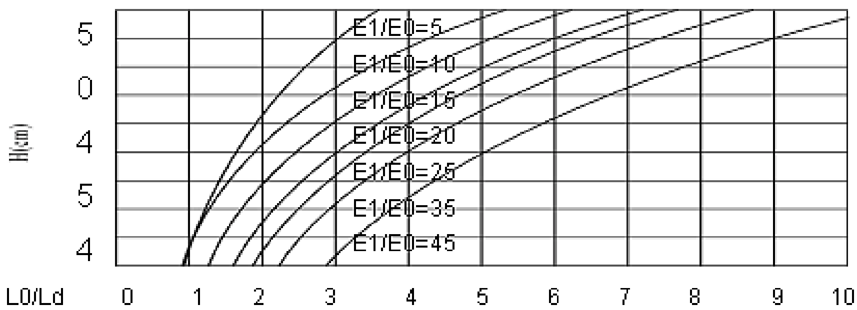

Figure 7. Graph of the design thickness of the soil base with an axle load of 1 000 000 to 2 000 000.

In Figures 5, 6 and 7, Ld is the design deflection value, L0 is the representative deflection value of the soil base, E1 is the modulus of resilience of the road base, E0 is the modulus of resilience of the soil base and H is the equivalent thickness of the base (road base + subbase) obtained through calculation, practical investigation and collection on three-level-pavement roads (including road surface, base and soil base). If the designed roads have four layers, i.e. if a subbase is added, the thickness of the road base, h_1, can be calculated from the formula $h_1 = H - h_2 \cdot \sqrt[2.4]{\frac{E_2}{E_1}}$ according to the regression analysis of the extrapolated results of a number of multi-layer flexible systems and current research findings. In the formula, h_1 is the thickness of the road base (cm), H is the equivalent thickness (cm) found in the graphs with the modulus ratio equal to the modulus ratio of the road base and the modulus of the soil base course, h_2 is the thickness of the subbase (cm), E_1 is the modulus of the road base (MPa) and E_2 is the modulus of the subbase (MPa). (see Figure 2).

9. CONCLUSION

It is well known that China's economy has already entered a period of rapid development, and the road construction industry is also developing extremely quickly. The central government has decided to increase the pace of construction of rural roads in order to boost the rural economy. It has been found from research that compared with concrete pavements, asphalt pavements have a lower construction price, which is adaptable to the relatively underdeveloped economy in the vast rural areas of China. The authors' research has led to the development of a method for the structural design of low-cost asphalt pavements in China. The method suggested in this paper is easy to use and provides an important guideline for the design of asphalt pavement structures in large rural areas.

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