STUDY OF A SUITABLE STRUCTURE OF CEMENT CONCRETE PAVEMENT FOR GUANGDONG PROVINCE

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ABSTRACT

Based on the analysis of the deterioration of cement concrete pavement, this paper studies the main problems in cement pavement structure; analyses the technical requirements for the base course and the impact on load stress of the slab and intensity influenced by the materials and thickness of the base course. Furthermore, an economic comparison of different types of base course and cement pavement is made. Based on the above, a suitable pavement structure of cement concrete pavement for Guangdong Province is proposed, which has important implications for preventing early deterioration of cement concrete pavement.

1. INTRODUCTION

Cement concrete pavement uses cement concrete as a surface material. This kind of structure has the advantages of good rigidity, high stiffness, durability and a small routine maintenance work load, etc. The Chinese design standard prescribes a 30-year life for cement concrete pavement (Ministry of Communications of the People's Republic of China, 2003) and some foreign countries standards prescribe 50 years. Since the 1970s, a great deal of cement concrete pavement has been built in Guangdong Province, as shown in Table 1: cement concrete pavement makes up more than 70% of the total pavement. These cement concrete pavements are having an important effect on the economy of Guangdong Province.

Table 1. Statistics on cement concrete pavement in Guangdong Province (2004).

	Length (km)	Order in China
Total highway	111 450	3
Cement concrete pavement	47 286	1

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However, many investigations on the usage have found that few cement concrete pavements can achieve a 20 to 30 year life cycle, and even some serious problems occur after being opened to traffic for 3 to 5 years. The main early destruction mechanisms are faulting, slab cracks (corner breaks) and slab spalling. The maintenance costs increase greatly because premature failure of the pavement puts a burden on maintenance and service.

Therefore more attention to the design of cement concrete pavement has been paid in recent years. A lean concrete material base course is built and the pavement life is prolonged by increasing the total stiffness of the structure. Visual surveys of many cement concrete pavement maintenance projects show that, compared with granular base courses, the ratio of cracked slabs with a lean concrete base course does not decrease, while the costs increase dramatically after three years.

Due to rain and high summer temperature conditions, serious rutting and water damage restrict the building of asphalt pavement in Guangdong Province. At the same time, there are abundant calcareousness resources in Guangdong Province, which offer advantages and development possibilities for cement concrete pavement. Since the 1990s, cement concrete pavement has developed very fast, with a paving speed of more than 2 000 km per year. Therefore it is important to reconsider the structural design.

2. ANALYSIS OF THE DETERIORATION OF CEMENT CONCRETE PAVEMENT

The typical cement concrete pavement structure that has been used for many years in Guangdong Province is shown in Figure 1. Investigations into the deterioration show that the main causes are faulting, slab cracking (corner breaking) and slab spalling. Figure 2 shows these distresses. Core investigation and bearing capacity tests have shown that the stiffness of most cement concrete pavement slabs are adequate and the bearing capacity of the top of the base course is within normal parameters, whereas the load transferability at slab joint is poor and the voids under the slab are a serious problem. These facts mean that the main destructive problem in Guangdong Province is caused by uneven support of the base course and poor load transfer. In general, the load transfer can be improved by using dowels. However, improving the support condition of the pavement slab by enhancing the stiffness of the base course (such as using a lean concrete base) does not work well and is not economical. Furthermore, it may have some negative effects, such as increasing the possibility of cracking, etc.

Cement concrete pavement (18~26 cm)
Cement stabilized base course (coarse aggregate <50%, 15~25 cm)
Subbase course (optional)
Subgrade

Figure 1. Typical cement concrete pavement structure in Guangdong Province.

Figure 2a. Faulting destruction in cement concrete pavement.

Figure 2b. Corner break destruction in cement concrete pavement

Figure 2c. Slab crack destruction in cement concrete pavement.

Figure 2d. Spalling destruction in cement concrete pavement

Figure 2. Main types of destruction of cement concrete pavement in Guangdong Province

Uneven support is not only related to the fill of the subgrade and base course and uneven compaction, but also to the invasion of water. The uneven distribution of underground water results in uneven settlement of the weak subgrade. The dynamic water pressure by wheel loads results in pumping which leads to voids under the slab. So the key problem of improving the quality and prolonging the life of cement concrete pavement in Guangdong Province has been how to improve the uneven support condition.

3. MAIN FUNCTION OF THE BASE COURSE IN CEMENT CONCRETE PAVEMENT

The theoretical formula of stress in cement concrete pavement slabs was put forward by Westgaard in the 1920s (Mao-hong Yu, 2002). The formula showed that the subgrade stiffness effects on stress produced by wheel loads are minor. However, the traffic volume was small and the vehicles were lighter at that time, so the destructive phenomena were not large. Therefore, it was not considered that a base course should be set under cement pavement at that time. Since the 1940s, many countries have realised that most pavement destruction is caused by the lack of stiffness of the base course or by an erodible base (Yao zhu-kang, 2003). More and more attention has been paid to the base course. The main technical requirements for the base course in cement concrete pavement are:

- Adjusting the loading state between slab and subgrade so that the subgrade will not be subjected to too great a cumulative distortion in its lifetime, then the normal usage life of the pavement can be ensured by an even and stable support.
- Reducing the erosion of water and the influence of temperature change to prevent washing out and blow-up, thus avoiding cracking or destruction of the slab.
- Enhancing the stiffness of the whole structure and improving the working condition of the cement pavement slab.
- Improving construction conditions to ensure the construction quality of cement pavement.

As we can see from the above, though the base course can increase the total stiffness of cement pavement structure, it is not the main design function. The more important role of base course is its functionality and not its structural forms. The thickness required for functionality is not great The AASHTO test section built in the 1950s showed that a base course with a thickness of 8 to 15 cm is enough to prevent pumping of the subgrade. Research done in recent years also shows that the deterioration is the same for cement concrete pavements with 8 to 23 cm thick base courses (AASHTO, 1986).

4. INFLUENCE OF THE BASE COURSE ON LOAD STRESS IN THE SLAB

Undoubtedly, higher stiffness of the base course can decrease the load stress in the slab caused by wheel action to a certain degree. However, only when the degree of the decreased load stress is considerable, can strengthening the base course be considered as an effective way to decrease the thickness of the slab. In order to analyse the influence of the stiffness of the base course on load stress within the slab, equation 1 recommended by the Chinese highway concrete pavement design specification is used to calculate the load stress in the slab under a standard axle load (100 kN). At the same time, the commercial finite element software ANSYS is also used for checking the computed results.

$$\sigma_{ps}=0.077r^{\mathbf{0.6}}\,h^{\mathbf{-2}} \quad (1)$$

where: σ_{ps}= load stress produced by normal axle load near the free slab edge (MPa)
h = thickness of cement concrete pavement (m)
r = relative rigidity radius in pavement structure (m), $r=0.537h(E_c/E_t)^{1/3}$
E_c = modulus of elasticity of cement concrete (MPa)
E_t= equivalent resilient modulus at the top of the base course (MPa)

In the calculating procedure, the elasticity modulus of cement concrete is evaluated as 3×10^4 MPa, and the standard axle load (100 KN) is adopted. The variables are the equivalent resilient modulus at the top of base course or stiffness of the base course, and the thickness of the slab. When the stiffness of the base course and the thickness of the slab are variable, the load stress level in the slab becomes more complex. In order to make the result more general, the values from a large range of equivalent resilient moduli at the top of the base course and the thickness of the slab are considered. The calculated results are shown in Table 2.

Table 2. Calculated stress in the slab with different base course stiffness and slab thickness under the standard axle load (MPa).

Equivalent resilient modulus on the top of base course (MPa)	Thickness of cement concrete slab (cm)										
	18	19	20	21	22	23	24	25	26	28	30
60	2.03	1.88	1.75	1.63	1.53	1.44	1.36	1.28	1.21	1.09	0.99
100	1.83	1.70	1.58	1.48	1.38	1.30	1.22	1.16	1.09	0.99	0.90
140	1.71	1.59	1.48	1.38	1.29	1.21	1.14	1.08	1.02	0.92	0.84
180	1.63	1.51	1.40	1.31	1.23	1.15	1.09	1.03	0.97	0.88	0.80
220	1.56	1.45	1.35	1.26	1.18	1.11	1.05	0.99	0.93	0.84	0.76
260	1.51	1.40	1.30	1.22	1.14	1.07	1.01	0.95	0.90	0.81	0.74
300	1.47	1.36	1.27	1.18	1.11	1.04	0.98	0.93	0.88	0.79	0.72

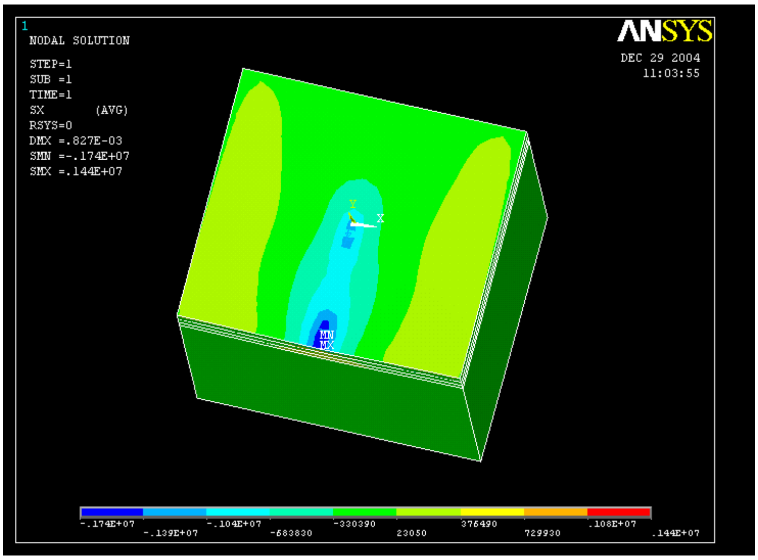

Figure 3. Verification of stress computations by the finite element method.

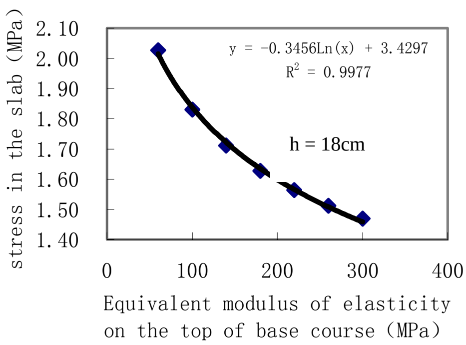

Figure 4a. Load stress in the slab affected by the stiffness of the base course.

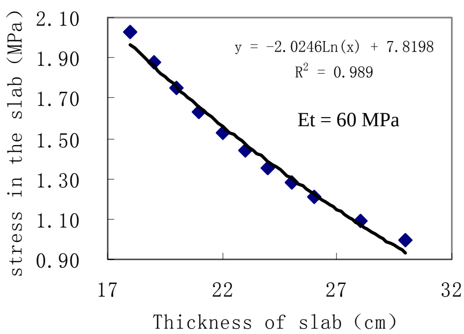

Figure 4b. Load stress in slab affected by the thickness of slab.

Figure 4. Load stress in the slab affected by the stiffness of the base course and thickness of the slab.

As shown in Table 2 and Figure 4, the effect of the load stress in the slab from the stiffness of the base course is far less than the effect of the thickness of the slab. For example, an 18 cm thick slab with 60 MPa equivalent resilient modulus on top of the base course, has a load stress of 2.03 MPa under the standard axle load. If the stress is reduced to 1.5 MPa, the goal can be achieved by increasing the base course or increasing the thickness of the slab. If the thickness of the slab is invariable, the stiffness of the base course has to be increased from 60 MPa to 260 to 300 MPa. If the stiffness of the base course is invariable, the same effect can be obtained by increasing the thickness of slab by 4 cm.

Table 2 shows that when the slab is thinner, the influence of base stiffness on stress is slightly greater. With increasing thickness of the slab, the influence of the base stiffness on stress decreases. This fact has also been validated by the examination of the test section built at Taizhou, China. When the thickness of the pavement slab exceeds 20 cm, the effect of strengthening the base course is negligible (Wei Chun-hua, 2002). In the last ten years, with the increase of the traffic volume, the level of the vehicle axle load also shows an increasing tendency. Considering this situation, almost all highways have a slab thickness greater than 20 cm. The slab thickness of most expressways exceeds 26 cm. If an overloaded vehicle is taken into account in pavement design, the slab will be thicker. Thus the effect of strengthening the base course will be very little.

Based on the calculation above, the most effective measure to decrease the load stress in the slab is to increase the thickness of the slab, but not to strengthen the base course. In actual pavement design, the equivalent resilient modulus at the top of the base course could hardly exceed the variable range above 60 to 300 MPa. Hence any effect of decreasing the load stress by strengthening the base course can be achieved by increasing the thickness of the pavement slab.

5. INFLUENCE OF THE THICKNESS OF THE BASE AND SUBBASE COURSE ON STRESS IN THE SLAB

It is known from the above calculation and analysis that increasing the thickness of the slab is more effective in decreasing the load stress in the slab. However, both technical and economical aspects should be considered together in pavement design because the unit price of cement concrete is higher than that of base (subbase) materials. According to the above analysis, the resilient modulus at the top of base course is used as a stiffness index of the foundation and this stiffness index relies on the resilient modulus of the subgrade, thickness of the base (and subbase) course as well as the stiffness of the materials. The resilient modulus of the subgrade is related to the characteristics of the soil, the local natural conditions and the hydrological conditions. For a highway, the optional parameters of the stiffness of base (sub base) course are limited. In pavement design, most attention is paid to the determination of the thickness of the base and subbase course and the choice of local materials. For example, a quite often used base and subbase structure is analysed. This is a subgrade with a 43 MPa resilient modulus, base course with a 600 MPa resilient modulus and subbase with a 250 MPa resilient modulus. Taking different thicknesses of the base and subbase course shows a change in the equivalent resilient modulus at the top of the base course. A method recommended by existing specifications is applied to calculate the equivalent resilient modulus at the top of the base course.

Table 3. Influence of the thickness of the base and subbase course on the equivalent resilient modulus at the top of the base course (MPa).

Thickness of subbase (cm)	Thickness of base course (cm)					
	0	5	10	15	20	25
0	43.0	64.5	86.3	108.3	130.4	152.5
5	53.8	77.5	101.6	126.0	150.3	174.8
10	64.8	90.3	116.3	142.4	168.7	195.0
15	75.8	102.8	130.2	157.9	185.6	213.4
20	86.9	115.0	143.6	172.4	201.3	230.3
25	98.0	127.0	156.5	186.2	216.0	245.9

In this case, a value of 600 MPa is used as the resilient modulus of the base course material, which means a semi-rigid material base course. The thickness of the semi-rigid base course will commonly not exceed 25 cm. Thus the results in Table 3 are representative. It can be seen from Table 3 that when the thickness of the base course increases from 0 to 25 cm, the equivalent resilient modulus at the top of the base course will increase from 130 to 150 MPa. Compared with the results in Table 2, this result will decrease the load stress within the slab by 0.4 MPa under the standard axle load, which is similar to the effect of increasing the slab thickness by 3 cm. It is obvious that strengthening the base course is worse than increasing the thickness if economical and construction factors are considered.

6. ECONOMICAL ANALYSES OF STRENGTHENING THE BASE COURSE AND INCREASING SLAB THICKNESS

The unit price of cement concrete is higher than that of base course materials. In order to understand the economical relationship between strengthening the base course and increasing the slab thickness, some relative economical analyses are carried out in this study. The basic price of the main types of base course, taken from *Budget Ration for Highway Engineering* (Ministry of Communications, People's Republic of China, 1992), are listed in Table 4.

Table 4. Basic price of main types of base course for cement concrete pavement.

	Type of base course			Cement concrete slab
	Cement-stabilising aggregate	Asphalt-stabilising aggregate	Graded aggregate	
The price as the thickness increases 1 cm/1 000 m^2 (RMB: Yuan)	549	2 141	400	1 177

It is known from the above analysis that the effect of increasing the slab thickness by 3 cm is the same as increasing the thickness of the base course by 25 cm. When the slab thickness is increased by 3 cm, the cost increase per 1 000 square meters is 1,177×3 = 3 531 Chinese Yuan. When a cement-stabilised base course with a thickness of 25 cm is used, the cost increase per 1 000 square meters is 549 × 25 = 13 725 Yuan. This means that the cost increase will be almost four times as high. So it is feasible to decrease the stress in the slab by increasing the thickness of the slab from the point of view economy.

7. SUITABLE CONCRETE PAVEMENT STRUCTURES FOR GUANGDONG PROVINCE

The calculated results indicate that the effect of strengthening the base course is limited for the bearing capacity of concrete pavement structure. The design of the base course is still important because pumping of fines and resultant voids below the slab are the main causes of deterioration of cement concrete pavements. Thus, preventing the fine grain part of the base course from being washed out is the basic requirement for the design of base course materials. Reducing the pore water pressure in the base course material should be the main technological measure to prevent washing out and voids under the slab.

Studies in recent years point out that increasing the cement content in base course materials can also prevent the fine grained part in base course from being washed out. The greater the cement content, the better the effect will be. Lean concrete base course material has an excellent effect. However, as seen from the analysis above, the load-bearing capacity of the concrete pavement structure does not rely mainly on the strength and stiffness of the base course materials. Adopting a high-cement-content in the base course appears not to be economical.

Since the pore water pressure is the main cause of pumping and washing out in base course material and results in voids under the slab, reducing the level of the pore water pressure should be the most effective way. It is known from the solution of the 1-dimensional consolidation of the differential equation for saturated soil (equation 2) that increasing the percentage of pores can effectively reduce the pore water pressure. So a base course structure with a higher number of air voids is applied to prevent pumping and washing out. When the air voids percentage in the material exceeds 15%, all of the voids are connected and the pore water pressure is at its lowest level.

$$\frac{K}{\gamma_{\omega}\frac{a}{1+e}} \bullet \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} \quad (2)$$

where: u = pore water pressure
z = coordinate variable along the depth direction of the subgrade
t = time variable
K = permeability coefficient of material
γ_{ω} = density of water
a = compression coefficient of materials
e = voids ratio of materials

Based on the analysis and study above, recommended concrete pavement structure and corresponding functions are as follows:

Cement concrete pavement	Determine the thickness of the slab in accordance with axle load and number of axle load repetitions during pavement life
Base course with porosity	To decrease the pore water pressure, improve the thermal environment of the slab, prevent voids under the slab and reduce thermal stress in the slab
Semi-rigid base course	To improve the uniformity of support of the slab by its stiffness and thickness
Subgrade	Strength, stability and uniformity

8. CONCLUSIONS

Premature deterioration of cement concrete pavements cause serious problems in Guangdong Province. This paper presented a suitable concrete pavement structure for Guangdong Province. The conclusions are as follows:

1) The main reason for premature deterioration of concrete pavement in Guangdong Province is the non-uniformity of the supporting environment of the pavement slab. The non-uniformity is mostly caused by the non-uniformity of fill materials and voids under the slab.
2) The contribution of a base course to the load bearing capacity of concrete pavement structures is limited. It is uneconomical to attempt to increase the strength and thickness of the base course to prolong the life of the pavement structure.
3) In cement concrete pavement structures, the main function of the base and subbase course should be to improve the uniformity and environment.
4) A reasonable structure that suits Guangdong Province is concrete pavement slab + base course with porosity + semi-rigid base course + subgrade.

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