Structural Life Analysis of Roller-compacted Concrete Asphalt Pavement

Feng Liu¹,², Chuanhai Wu¹,², Jun Li³,*, Xinquan Xu¹,²

¹ Guangdong Hualu Transport Technology Co., LTD, Guangzhou 510420, Guangdong, China
² Research and Development Center on Road Transport Safety and Emergency Support Technology & Equipment, Ministry of Transport, PRC, Guangzhou 510420, Guangdong, China
³ School of Architectural Engineering of Huanggang Normal University, Huanggang 438000, Hubei, China

* Corresponding author email: lijun@hgnu.edu.cn

Abstract. Based on the long-life test road of Yunluo expressway in Guangdong province, firstly, based on the theory of small disturbance elastic thin plate and the design code of the highway cement concrete pavement, the life analysis of the roller-compacted concrete pavement structure of the Yunluo long-life test road is carried out. The results show that the pavement structure can achieve a 53.2 years long-life. Secondly, in order to verify the reliability of the theoretical analysis results, the strain sensors and the temperature sensors were embedded in different layers of the test road. After years of continuous data collection and based on the constitutive model of the roller-compacted concrete material, the theoretical analysis of the results concluded that the pavement structure can achieve at least 45 years life. The results of theoretical and practical analysis show that the new type asphalt pavement structure on the roller-compacted concrete base can be used as a typical long-life asphalt pavement structure under high temperature, rainy and heavy load conditions in Guangdong province.

Keywords: Road Engineering, Roller-compacted Concrete, Asphalt Pavement, Structural Life.

In the past, the life of the asphalt pavement design is usually between 10 ~ 15 years [1, 2], but with the rise of the long-life asphalt pavement design concept, the asphalt pavement structure layer 40 years without damage has become the goal pursued by all countries [3]. The so-called long-life asphalt pavement [4] refers to an asphalt pavement that has a service life of at least 35 years, and no structural damage occurs within the service life. It only requires periodic maintenance with a maintenance period of no less than 12 years. The long-life asphalt pavements in developed countries in Europe and America are mostly full-thick flexible asphalt pavements, and a large number of high-quality asphalt materials are used in each structural layer [5]. This is quite different from the asphalt pavement structure on the semi-rigid base in our country. The dynamic response law and long-term performance of the long-life asphalt pavement structure on the flexible base can’t be directly used by me. The results of life analysis
of fully flexible asphalt pavement can’t be fully applied to long-life asphalt pavement made of cement-based materials. In order to obtain the life state of the asphalt pavement with cement-based material as the main construction material, this paper carries out life analysis of various types of asphalt pavement structure based on the test section of Yunluo long-lived asphalt pavement in Guangdong province [6].

1. Overview of Yunluo Long-life Test Road
The Yunluo expressway starts in Yunfu city, Guangdong province and ends in Luoding city, Guangdong province, connecting with the Guangwu expressway. The long-life test road is located in the section from Shuangdong to Lubin. As shown in Fig. 1, the test road is paved with four types of pavement structure. Among them, structure 1, structure 2 and structure 3 are all composed of two asphalt layers, and structure 4 is composed of three asphalt layers. Structure 1 base layer and sub-base layer are composed of the semi-rigid material, which are called reinforced semi-rigid base asphalt pavement. This kind of pavement structure is referred to as S1. The structure 2 is the traditional semi-rigid base asphalt pavement, referred to as S2. The structure 3 is an asphalt pavement with RCC as base layer, which is called S3 for short. Structure 4 is an inverted asphalt pavement, referred to as S4. Each pavement structure is paved for approximately 1km. The S1, S3 and S4 are equipped with road mechanics response monitoring sensor system.

![Figure 1. Two types of pavement structure for Yunluo expressway long-life test road](image)

2. Theoretical Prediction of S3 Ultimate Fatigue Life
According to the "Specifications for Design of Highway Cement Concrete Pavement (JTG D40)" [7], the ultimate fatigue life of the RCC roller-compacted concrete asphalt pavement structure is predicted.

Example: The expressway in Guangdong province is generally located in highway natural zoning zone IV. It is known that the elastic modulus of the soil foundation \(E_0\) is 40MPa. The elastic modulus of the graded crushed stone \(E_1\) is 300MPa. The elastic modulus of the cement stabilized graded crushed stone \(E_2=E_3\) is 1500MPa. The elastic modulus of the RCC \(E_4\) is 27GPa. The thermal expansion coefficient of the RCC is \(10\times10^{-5}/\text{℃}\). The standard value of bending tensile strength of the RCC is 5MPa. The space between transverse joints of the RCC panel is 5m. The fatigue index of the RCC material is 0.057. The designed axle load \(PS\) is 100kN. The reliability coefficient is 1.25.

The calculation process is as follows.

1) Calculate the elastic modulus of the top surface of the base layer

\[
E_x = \frac{h_1^2 E_1 + h_2^2 E_2 + h_3^2 E_3}{h_1^2 + h_2^2 + h_3^2}
\]

\[
D_x = \frac{h_2^2 E_1 + h_3^2 E_2 + h_3^2 E_3}{12} + \left(\frac{n_1 h_1 + n_2 h_2 + n_3 h_3}{4}\right)^2 \left(\frac{1}{E_1 h_1} + \frac{1}{E_2 h_2} + \frac{1}{E_3 h_3}\right)
\]

\[
h_x = \left(\frac{12D_x}{E_x}\right)^{1/3}
\]

\[
a = 6.22 \times \left[1 - 1.51 \times \left(\frac{E_x}{E_0}\right)^{-0.45}\right]
\]
\[
b = 1 - 1.44 \times \left( \frac{E_p}{E_0} \right)^{-0.55}
\]

(5)

\[
E_t = a h_x^b E_0 \left( \frac{E_x}{E_0} \right)^{1/3}
\]

(6)

In the form:

- \(E_t\) -- Equivalent rebound modulus of the bottom of the RCC plate, MPa;
- \(E_x\) -- Equivalent rebound modulus of the granular layer;
- \(h\) -- Total thickness of the granular layer, m;
- \(D_x\) -- Equivalent bending stiffness, MN•m;
- \(h_x\) -- Thickness of each structural layer, m;
- \(E\) -- Elastic modulus of each structural layer, MPa.

According to the known conditions, from the formulas (1) to (6), the \(E_t\) is 183.62 MPa.

2) Calculation of the load fatigue stress

\[
D_c = \frac{E_c h_c^3}{12(1-\nu_c^2)}
\]

(7)

\[
r = 1.21 \times \left( \frac{D_c}{E_t} \right)^{1/3}
\]

(8)

\[
\sigma_{ps} = 1.47 \times 10^{-3} r^{0.7} h_c^{-2} p_s^{0.94}
\]

(9)

\[
\sigma_{psa} = (1 - \zeta a h_a) \sigma_{ps}
\]

(10)

In the form:

- \(D_c\) -- Section bending stiffness of the concrete surface slab, MN•m;
- \(h_c\), \(E_c\), \(\nu_c\) -- Thickness (m), flexural elastic modulus (MPa) and Poisson's ratio of the concrete surface slab;
- \(r\) -- The relative stiffness radius of the concrete facing slab, m;
- \(P_s\) -- Single axle load for design axle load, kN.

From reference [7], we can know the coefficient \(\zeta\) is 1.65. At the same time, according to the formula (7) ~ (10), \(\sigma_{psa}\) = 1.15 MPa.

3) Calculation of the temperature fatigue stress

It can be seen from literature [7] that the maximum temperature gradient \((T_g)\) in Guangdong province is 86°C/m. It can be seen from the nomograph that the maximum temperature gradient needs to be corrected when there is the influence of the asphalt upper layer, and its correction coefficient \((\xi_t)\) is 0.48.

\[
t = \frac{L}{3r}
\]

(11)

\[
C_L = \frac{1 - \sin t \cos t + \cos t \sin t}{\cos^2 t + \sin^2 t}
\]

(12)

\[
B_L = 1.77 e^{-4.48 h_c T_g / C_L} - 0.131 (1 - C_L)
\]

(13)

\[
\sigma_{t,max} = \alpha \sigma_{t,max} \frac{h_c T_g}{2} B_L
\]

(14)

The regression coefficient of temperature fatigue stress is obtained by looking up the table. \(a_t = 0.841\), \(b_t = 1.323\), \(c_t = 0.058\).

\[
k_t = \frac{f_r}{\sigma_{t,max}} \left[ a_t \left( \frac{\sigma_{t,max}}{f_r} \right)^{b_t} - c_t \right]
\]

(15)

\[
\sigma_{tr} = k_t \sigma_{t,max}
\]

(16)

Check the literature [4] nomogram to get the coefficient \(\zeta\).

\[
\sigma_{tra} = (1 + \zeta h_a) \sigma_{tr}
\]

(17)

In the form:

- \(L\) -- Space between transverse joints of concrete slab, m;
- \(C_L\) -- Temperature warpage stress coefficient of the concrete surface slab;
- \(B_L\) -- Temperature stress coefficient;
- \(\alpha\) -- Concrete linear expansion coefficient;
- \(T_g\) -- Maximum temperature gradient in the area where the highway is located once in 50 years;
- \(f_r\) -- Concrete bending strength;
- \(\sigma_{t,max}\) -- Maximum temperature stress of surface plate under maximum temperature gradient;
- \(\sigma_{tra}\) -- Thermal stress at critical load position of concrete slab with asphalt layer.

According to formulas (11) to (17), the \(\sigma_{tra}\) is 0.113 MPa.

4) Calculate the number of cumulative actions of standard axle load
According to the critical load position in the middle of the longitudinal edge of the RCC plate, the load stress and the temperature stress are not greater than the standard value of RCC flexural tensile strength. The $k_f$ is calculated from formula (18) to (19). Then, the cumulative number of design axle load actions $N_e$ in the design reference period is obtained.

$$\gamma_r(\sigma_{\text{tra}} + \sigma_{\text{pra}}) = 5\text{MPa} \quad (18)$$

$$\sigma_{\text{pra}} = k_r k_f k_c \sigma_{\text{psa}} \quad (19)$$

$$k_f = \frac{N_e}{\lambda} \quad (20)$$

$$N_e = (k_f)^{1/\lambda} = 3.38^{1/0.057} = 1.761 \times 10^9$$

In the form:

- $\gamma_r$ -- Reliability coefficient;
- $k_r$-- Stress reduction factor considering load transfer capacity of joints;
- $k_c$-- Consider the comprehensive coefficient of calculation theory, actual difference, dynamic load and other factors;
- $k_f$-- Fatigue stress coefficient considering the cumulative fatigue action of load stress during the design reference period;
- $\lambda$-- Material fatigue index;
- $N_e$-- Cumulative action times of design axle load in design reference period.

5) Ultimate life prediction

Assuming that the design axle load daily action times ($N_s$) of the design lane is $1.1 \times 39308 = 43239$ axis times. The transverse distribution coefficient of wheel trace (η) is 0.22. The average annual growth rate of the traffic volume is 7%.

$$N_e = \frac{N_s[(1+r)^t-1] \times 365}{r} \quad (21)$$

In the form:

- $\eta$-- Transverse distribution coefficient of the wheel trace;
- $r$-- Average annual growth rate of traffic;
- $t$-- Design base period.

According to formula (21), the service life of this kind of RCC base asphalt pavement structure is 53.2 years. Therefore, it can be seen from the theoretical analysis, by strengthening the base and thinning the asphalt layer, the S3 can realize the long-life of the asphalt pavement under the condition of reliable construction guarantee and timely preventive maintenance.

3. Analysis of Strain at the Bottom of Limit Life Layer

Based on the theory of the elastic thin plate with small deflection and in combination with reference [7], it can be seen that the constitutive relation of the RCC structural layer satisfies equation (22). The stress and strain in the constitutive relation are caused by the combined action of load and temperature.

$$\sigma_{\text{tr}} = E \times \varepsilon \quad (22)$$

In the design of asphalt pavement on RCC base, the RCC structural layer is the main bearing layer. Therefore, in the design reference period, under the combined action of traffic load and temperature gradient, the structural layer does not produce fatigue fracture as the design standard.

At the end of the life of the pavement structure, the following two basic conditions must be met. First, the stress value at the end of RCC life is less than or equal to the standard value of flexural tensile strength of RCC material, i.e. 5 MPa. Formula (23) should be satisfied. Secondly, the stress at the end of RCC life is less than or equal to the fatigue stress determined by the combined action of load and temperature. Formula (24) should be satisfied.

$$\sigma_{\text{tr}} \leq 5 \text{MPa} \quad (23)$$

$$\sigma_{\text{tr}} \leq \gamma_r(\sigma_{\text{tra}} + \sigma_{\text{pra}}) \quad (24)$$

Since the elastic modulus ($E_{\text{RCC}}$) of RCC is 27000 MPa, the ultimate strain value of the base layer composed of this kind of material should be less than or equal to $(5/27000) \times 106 = 185 \mu\varepsilon$.

The allowable value of the stress on the right side of formula (24) will change with the change of the pavement design reference period. Here, 85% of the previous 53.2 years is the final life span of S3, which is 45 years. The fatigue strain limit of the RCC layer of the asphalt pavement in different design reference periods is obtained based on 5-year progressive reduction.
For example, if the design reference period of S3 asphalt pavement structure is 45 years, the ultimate strain at the bottom of the RCC structure layer can be obtained according to the theory of small disturbance elastic thin plate.

\[
\sigma_{p,sa} = (1 - \zeta_2 b_2) \sigma_{ps} = [1 - 1.65 \times (0.05 + 0.08)] \times 1.47 = 1.15 \text{MPa}
\]

\[
N_e = \frac{N_1 (1+\eta)^{1-1}}{365} \times 0.07 = \frac{43239 \times (1+0.07)^{45-1}}{365} \times 0.07 = 992147810.4
\]

\[
k_f = N_e^4 = 992147810.4^{0.057} = 3.26
\]

\[
\sigma_{pra} = k_r k_f k_e \sigma_{p,sa} = 0.87 \times 3.26 \times 1.15 \times 1.15 = 3.76 \text{MPa}
\]

\[
E \times \varepsilon \leq \gamma_r (\sigma_{tra} + \sigma_{pra})
\]

\[
27000 \times \varepsilon \leq 1.25 \times (0.113 + 3.76)
\]

\[
\varepsilon \leq 179.39 \mu \varepsilon
\]

Therefore, when the design reference period of the asphalt pavement is 45 years, the tensile strain at the bottom of S3 should not exceed 179.39 \mu \varepsilon before the end of its life. Otherwise, the fatigue cracking will occur and the life will be terminated in advance. The ultimate strain at the bottom of the RCC slab corresponding to different design reference periods is plotted in Fig. 2. With the extension of the pavement design reference period, the ultimate strain of the RCC slab bottom increases linearly, and the relative growth rate is about 4% every five years, and the fitting curve R^2 is 0.9933.

**Figure 2.** Variation of life limit strain of RCC asphalt pavement structure with life cycle

In order to verify the rationality of the theoretical analysis, strain sensors are installed in the long-life test road structure 3 of Yunluo test road in Guangdong province. For space limitation, the plan (Fig. 3a) and elevation (Fig. 3b) of the pavement structure and the distribution of strain sensors in RCC structural layer are shown here. With FWD as the loading tool, 100kN load is applied at the position of line No. 2 and column No. 8 in Fig. 3a. The strain curve is processed by filtering and so on to obtain the strain time history curve of the corresponding measuring point at the bottom of the upper base layer (RCC) layer along the driving direction in Fig. 4. It can be seen from the figure that the peak strain of the RCC layer bottom along the driving direction detected at this time point is 20 \mu \varepsilon. If this value is used as the initial value, considering the variability of the actual project, with a relative growth rate of 20% every 5 years, the bottom tensile strain value of the RCC layer at the end of the S3 life period is 51.4\mu \varepsilon. This value is 3.49 times smaller than the theoretical value of 179.39\mu \varepsilon. It is possible for the S3 of the asphalt pavement structure to achieve a long-life of more than 45 years.
4. Conclusion
In order to verify the rationality of the long-life pavement structure, strain sensors and other pavement mechanical response monitoring systems are set up in the pavement structures of S1, S3 and S4 of four pavement structures of Yunluo expressway. The results of strain response of three RCC structural layers are obtained by FWD loading. At the same time, combined with the constitutive model of RCC material, it is calculated that when the S3 pavement structure reaches 45 years, the strain value of S3 pavement structure layer is far less than the theoretical analysis value. Therefore, the asphalt pavement on roller compacted concrete base can achieve long-life.
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