LONG-TERM PERFORMANCE OF FLEXIBLE PAVEMENTS WITH COLD-RECYCLED ASPHALT BASE LAYER

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ABSTRACT

Cold recycling with emulsified or foamed asphalt has been widely used in China to convert the existing asphalt surface layer to an asphalt base layer. A new asphalt surface layer between 12 and 18 cm is then paved. Since these semi-rigid pavements were originally built with cement treated base, this reconstruction practice has resulted in a special pavement structure: cement treated subbase + cold recycled asphalt base + new asphalt surface. This paper reports the long-term performance of such pavement structure on two expressways located in Jiangxi, China. In-situ distress survey and coring were conducted, as well as data collection of traffic and load spectra. Laboratory testing was then carried out on materials collected from the site. Numerical modelling was also conducted to investigate the possible influence from different materials and design options. Results from this study indicated that the main reason of premature failure of this type of pavement structure was the weakening and fatigue of the cold-recycled asphalt base layer. Poor quality control during construction might be the cause since the air voids of the cold-recycled base layer was found to be much higher than the limit. Structural analysis showed that increasing the new asphalt surface layer from 14 cm to 16 cm on top of a 12 cm cold-recycled asphalt base layer could increase the fatigue life and traffic endurance (in terms of equivalent single axle

load) 1.6-3.2 times. Therefore, it was concluded that increasing the thickness of the new asphalt surface layer could significantly improve the long-term performance of flexible pavements with cold-recycled asphalt base layer.

1 INTRODUCTION

Since the completion of its first major highway in 1989, China has experienced a rapid growth period of highway construction for near 30 years. By the end of 2014, China has built a total of 111,900 km express highways (Ministry of Transport of P.R. China, 2013). Among these roads, 85% are asphalt-surfaced pavements, and 95% use cement treated base (semi-rigid base) (Zhang, 2013). Due to many reasons such as the rapid growth of heavy traffic, overloading, and reflective cracking from the semi-rigid base, most pavements on these highways failed before its design life (15 years) and have undergone one or more major rehabilitations. Cold recycling has been widely used to reuse the existing asphalt surface and convert it to a flexible base, hence reduce the potential of reflective cracking from the semi-rigid base layer (Editorial Department of China Journal of Highway and Transport, 2012). The cold recycling process consists of milling the existing asphalt surface, crushing the recycled asphalt pavement (RAP), mixing them with foamed asphalt or emulsion in-plant or in-place (water and new aggregate are also added in most cases), and then compacting them as a base layer (Ministry of Transport of P.R. China, 2013). New hot-mixed asphalt (HMA) mixtures are then placed on top of the recycled base layer, resulting a unique pavement structure: new HMA + cold recycled asphalt base + semi-rigid subbase.

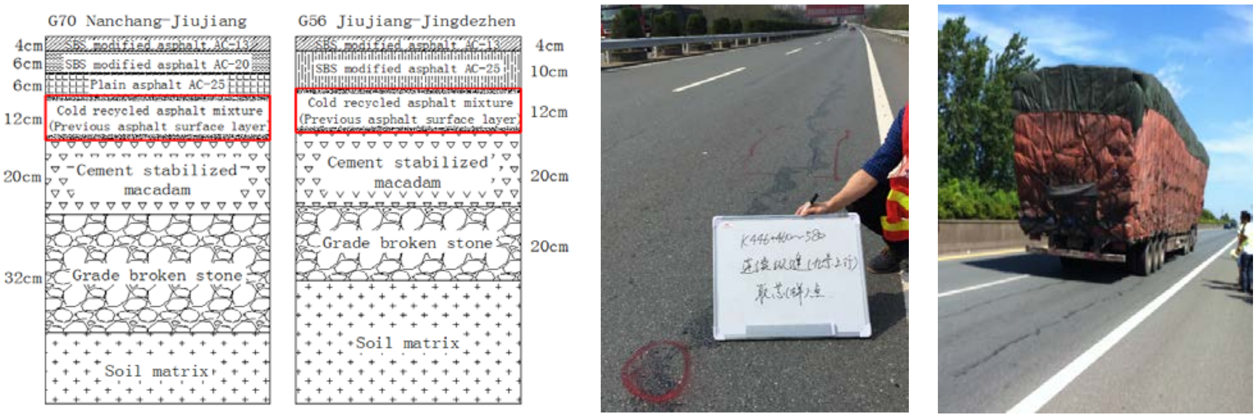
Cold recycling is an economical technique since the material does not need to be heated. Cold recycling with foamed asphalt has been used since the mid-1950s. Foamed asphalt is produced by injecting water into hot bitumen, resulting in spontaneous foaming, while emulsion is asphalt being dispersed in water by an emulsifying agent. Both agents increase the volume of asphalt and help binding aggregate particles together (Wirtgen GmbH, 2010). Because of its limited performance history and the unavailability of a standard mix-design procedure, the use of cold in-place recycling has been limited to low- and medium-volume roads (Peter, 2004). Experience in Ontario, Canada showed that cold recycling is suitable for roadways with moderate to severe distresses where reflection cracking is a concern (Tom, 1999). A study in Louisiana investigated the potential use of foamed asphalt treated RAP as a base course material in lieu of a crushed limestone base underneath a concrete pavement (Louay, 2003). It was concluded that the treated RAP material had a higher in situ stiffness than the limestone base (Chen, 2006). reported a failure investigation of a foamed-asphalt highway project on which severe alligator cracking and deep rutting were observed. Based on the study, it was concluded that the reason was associated with failure of the foamed asphalt base. The base stiffness in the distressed area was about three times lower than it in the intact area. The foamed asphalt base was found to be susceptible to moisture and exhibited a severe loss of strength when subjected to moisture.

The first application of cold recycling in China was reported in 1998. The first specification of cold recycling (JTGF41-2008) was published by the Ministry of Transportation in 2008. It is estimated that more than 20,000 km major highways have been rehabilitated using the cold recycling technique. For example, cold recycling has been used on more than 1,060 km expressways in Jiangxi Province since its first trial in 2007 (Dong, 2006) modified the Superpave volumetric method to design cold recycling asphalt mixture using emulsion (Xu, 2010, 2015) compared the property of cold recycled asphalt mixture using foamed asphalt and the mixture using emulsion asphalt. They found the splitting strength and moisture resistance when use foamed asphalt was better than when use emulsion. Case studies of cold in-place recycling using foamed asphalt were reported in Chongqing (Li, 2008) and Anhui Province (Shi, 2009).

Literature shows that most studies were about the properties of cold recycled asphalt mixture with emulsion and the field performance of projects with such mixtures. However, reports of the long term performance are rare. In particular, no literature was found discussing the unique structure in this research: new HMA + cold recycled asphalt base + semi-rigid base.

2 PROJECT INTRODUCTION AND METHODOLOGY

The projects in concern were expressway G56 from Jiujiang to Jindezhen and expressway G70 from Nanchang to Jiujiang in Jiangxi Province, China. Both roadways were subjected to a major rehabilitation in 2007 and 2009 respectively (a total of 117km and 134km) The original structure consisted of 120 mm asphalt surface, 200 mm cement treated crushed stone base, and subgrade. Cold recycling was conducted to mill the old 120 mm asphalt surface, mix with 3.0% emulsion and 1.7% cement in a plant, and then place and compact as a base layer on top of the original semi-rigid base. On top of this new base layer converted from old asphalt surface are new HMA layers: 160 mm for G70 (60 mm AC25 base course + 60 mm SBS modified AC20 intermediate course + 40mm SBS modified AC13 surface course) and 140 mm for G56 (100 mm AC25 base course + 40mm SBS modified AC13 surface course). Figure 1a illustrates the pavement structure of the two projects. Figure 1b and 1c are right-of-way pictures showing the general condition of the roadway. Both are four lane restricted-access highways. G70 is a part of the national arterial network with a large traffic volume and heavy trucks (Figure 1c).



(a) (b) (c)

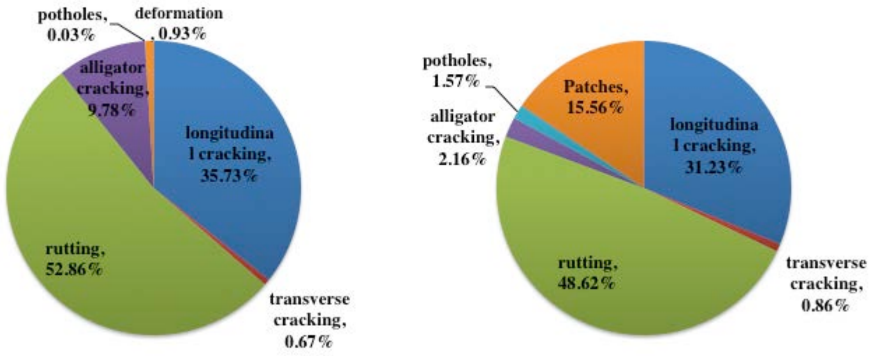
FIGURE 1 (a) Pavement structure, (b) Field investigation on G56, (c) Heavy trucks on G70

The objective of this paper is to (1) report the long-term performance of this unique pavement structure on two expressways located in Jiangxi, China, and (2) investigate possible causes for the distresses observed on the two roadways. In-situ distress survey and traffic data (including load spectra) were conducted. Cores were taken and materials collected for a series of laboratory testing. Numerical modelling was then performed to analyse different structure options with different material properties.

3 RESULTS ANALYSES

3.1 Distress Survey

Manual distress surveys were conducted in May 2014 and April 2015 of the total length (G70-117 km and G56-134km, Cumulative ESALs of G70 and G56 are 6.87E+07 and 1.26E+07, respectively (Table 1)). Results are shown in Figure 2. It was found that rutting, longitudinal cracking, and alligator cracking were the major distresses on both roadways. The three major distresses consists 98.37% and 82.01% for G70 and G56, respectively. Owing to the 15.56% of patches distress in Figure 2b caused by repairing alligator cracking, patches can be included into alligator cracking distress. Therefore, rutting, longitudinal cracking and alligator cracking distresses in G56 totally account for 97.57%。Rutting consists about half of the total area with an average of 12 mm on G70 and 4.5mm on G56. Longitudinal cracks were along the wheelpath (Figure 1b and 1c). Most of the alligator cracking on G56 have been patched. As to the day of distress survey, G70 and G56 have served for 6 years and 5 years after the major rehabilitation, respectively.

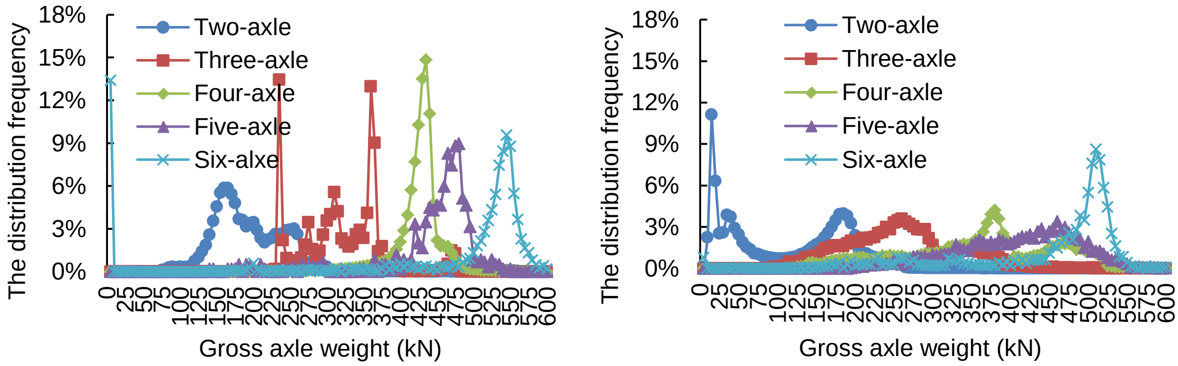


(a) G70 expressway **(b) G56 expressway**

FIGURE 2 Results of distress survey

3.2 Traffic Volume and Load Analysis

Traffic volume and load spectra data were available from the toll stations for the two expressways. Figure 3 shows the load spectra. G70 has many more heavy trucks with gross axle weight over 200 KN（Kilonewton, 1 Pound=4.45 Newton）. This agrees with engineering experience as illustrated in Figure 1c since G70 is a part of the national arterial network.



(a) G70 (2008-2013) **(b) G56 (2010-2014)**

FIGURE 3 Load spectra

To compare the cumulative effect of different trucks, traffic volume and load were converted to equivalent single axle load (ESAL) according to JTG D50 (Specifications for Design of Highway Asphalt Pavement). Using 100 KN single axle as the standard axle (The standard value in Chinese specification：single-axle and dual-wheel group (4 wheels) bears 100KN, each wheel bearing 25 KN), different axle types and axle loads can be calculated by

$$N = \sum_{i=1}^{K} C_1 \cdot C_2 n_i (\frac{P_i}{P})^{4.35} \quad (1)$$

where *N* = equivalent single axle load (passes/day)

n_i = passes/day of the truck in concern

P = standard axle load (100 KN)

P_i = axle load in concern (KN)

C_1 = coefficient for different axle types (single, tandem, tridem, quad)

C_2 = coefficient for different number of tires

Traffic volume and equivalent single axle load are presented in Table 1. It shows that G70 experienced a steady increase of traffic volume from 2008 to 2013. Although the traffic on G56 also increased, the cumulative volume so far for G56 is only 22.93% of that for G70. Furthermore, it is worth noting that G56 has not reached its design ESAL, while G70 has carried almost three times of its design ESAL.

TABLE 1 Traffic volume and equivalent single axle load (ESAL)

Year	**Traffic Volume**		**Ratio (%) (G56/G70)**
	G70	**G56**	
2008	9,763,426	-	—
2009	12,896,486	-	—
2010	15,283,136	4,238,105	27.73%
2011	17,183,510	3,700,704	21.54%
2012	18,483,649	3,948,537	21.36%
2013	20,107,449	4,431,086	22.04%
2014	-	5,170,801	—
Cumulative volume	93,717,656	21,489,233	22.93%
Cumulative ESALs	6.87E+07	1.26E+07	18.34%
Design ESALs	2.357E+07	2.036E+07	-
Cumulative ESALs / Design ESALs	291%	61.9%	

3.3 Laboratory Tests

Based on the previous analysis, pavement distresses in G70 and G56 are considerably serious. However, cumulative ESALs of G70 have reached 291% of projected lifetime, while cumulative ESALs of G56 only reached 61.9% of projected lifetime. Due to similar pavement structures between G70 and G56, this shows that premature failures have occurred in G56. In order to analysis the reason resulting in these premature failures, A series of lab tests were conducted on the materials collected from coring in G56. Table 2 lists the results of thickness, air voids and splitting strength. Three statistics are included, average, standard deviation, and coefficient of variation. The corresponding specification according to Chinese standards are also listed. Average values that did not meet the specification are bolded with red color. The following findings are observed from Table 2.

a. The thickness of each layer are close to the designed thickness. Although the average thickness of the cold recycled base layer 109 mm is less than the intended 120 mm, there are two possible reasons. The one may result from construction quality control issues. The other is possibly caused by the fact that the cold recycled base layer with higher design air voids was compacted leading to a reduction in thickness after nearly 5 years' heavy traffic loading. it is still in the ballpark when the variation is considered.
b. Large air voids were found in the surface course and the cold recycled asphalt base. This is coincident with the bottom-up and top-down cracking observed in the cores. Large air voids is known to reduce the material strength, increase the moisture damage susceptibility, and reduce the service life.
c. The splitting strength of the cold recycled base layer 0.36 MPa is slightly lower than the specification 0.4 MPa minimum.
d. The large standard deviation and coefficient of variation of air voids, which represent the variation of the material, indicate a poor quality control during the construction.

TABLE 2 Results of Laboratory Test of Recovered Asphalt Materials (G56)

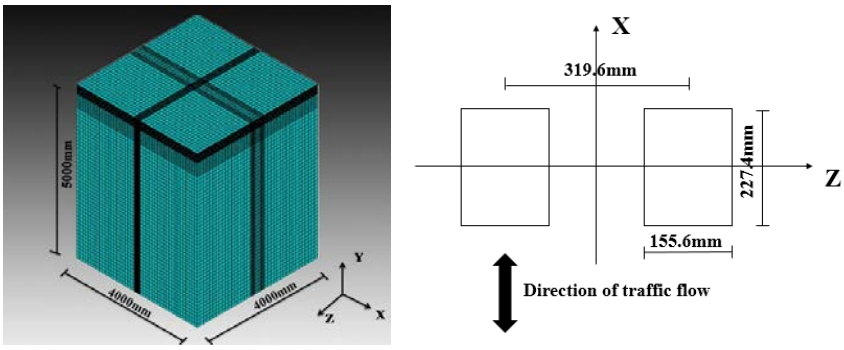
Layer	Property	Average	Std. Dev.	C.V.	Specification
Surface course (AC-13C)	Thickness (mm)	38.9	2.4	6.2	40
	Air voids (%)	**6.59**	2.08	31.6	4~6
	Splitting strength (MPa,25ºC)	1.48	0.22	14.9	1.2~1.6
Intermediate course (AC-20C)	Thickness (mm)	59.1	2.1	3.6	60
	Air voids (%)	4.62	1.93	41.8	3~5
	Splitting strength (MPa,25ºC)	1.21	0.15	12.4	0.8~1.2
Base course (AC-25C)	Thickness (mm)	58.8	3.4	5.8	60
	Air voids (%)	5.26	2.72	51.7	3~6
	Splitting strength (MPa,25ºC)	1.00	0.12	11.8	0.6~1.0
Cold recycled asphalt subbase	Thickness (mm)	109	26	23.9	120
	Air voids (%)	**14.61**	3.2	21.9	9~14
	Splitting strength (MPa, 25ºC)	**0.36**	0.04	11.1	≥ 0.4

Note: Std. Dev. = Standard deviation, C. V. = coefficient of variation

3.4 Fatigue Life Analysis

3.4.1 Numerical Simulation.

To verify the hypothesized mechanism based on field investigation and laboratory testing, numerical simulations were conducted. A 3D model of the pavement structure was built using a finite element software ANSYS (Figure 4a). The model size was 4m×4m×5m (length×width×depth). The bottom of subgrade was restrained in all directions. Layers were assumed to be fully bonded to each other. The element type of 20-node SOLID185 was used. Traffic loading was applied on two rectangular areas to facilitate the rectangular mesh (Huang, 1993). X denotes the direction of traffic flow, Y denotes the direction of pavement depth, and Z denotes the direction of transverse cross-section in this study (Figure 4b).



(a) (b)

FIGURE 4 (a) the 3D finite element model, (b) the loading area.

The material properties used in the finite element analysis are listed in Table 3. These properties are based on typical values used in China.

TABLE 3 Pavement Structure and Material Properties

Layer	Thickness (mm)	*Modulus (MPa)	Poisson's ratio
Asphalt Surface	120/140/160/180/200	10,000	0.35
Cold recycled asphalt base	40/80/120/160/200	8,000	0.35
Cement treated stone base	200	10,000	0.25
Crushed stone subbase	200	250	0.35
Subgrade	-	100	0.40

* modulus values are selected according to median value of recommended range in Chinese pavement design specification.

Numerical simulations with pavement structure (Figure 1a) were conducted to estimate the tensile stress at the bottom of asphalt layer and base layer. Equation 2 and 3 were then used to estimate the fatigue life for G70 and G56.

3.4.2 Fatigue Life Estimation.

Pavements fail due to fatigue under repetitive loading from both traffic and environmental effects. Both the asphalt surface layer and base layer may experience fatigue failure. This research estimated the fatigue life according to the research results from Chinese Ministry of Transportation (2014). Equation 2 and 3 are for asphalt layer and base layer respectively.

$$N_{f1} = 6.32 \times 10^{(15.6-0.37\beta)} k_{T1}^{-1} \left(\frac{1}{\varepsilon}\right)^{3.97} \left(\frac{1}{E_a}\right)^{1.58} (VFA)^{2.72} \left(\frac{1+0.3E_a^{0.43}(VFA)^{-0.85} e^{(0.024h_a-5.41)}}{1+e^{(0.024h_a-5.41)}}\right)^{3.33} \quad (2)$$

where N_{f1} = fatigue life of the asphalt layer

β = reliability coefficient, in this case, β =1.65

k_{T1} = temperature adjustment coefficient

ε = tensile strain at the bottom of the asphalt layer (10^{-6})

E_a = dynamic modulus of asphalt mixture at 20°C (MPa)

VFA = voids filled with asphalt (%)

h_a = thickness of the asphalt layer (mm)

$$\lg N_{f2} = a - b\left(\frac{k_e \sigma_t}{k_s R_s}\right) - k_D \beta + \lg\left(\frac{k_a}{k_{T2}}\right) \quad (3)$$

where N_{f2} = fatigue life of the base layer

β = reliability coefficient, in this case, β =1.65

R_s = flexural tensile strength of inorganic binding material

k_{T2} = temperature adjustment coefficient, in this case, k_{T2} =0.69

σ_t = tensile stress at the bottom of the base layer (MPa)

k_e = stress modification coefficient due to crack contraction, in this case, k_e =1.25

k_a = fatigue life adjustment due to crack expansion, in this case, k_a =1.89

k_s = adjustment coefficient from field test, in this case, k_s =0.8

k_D = standard deviation, in this case, k_D =1.16

a, b = regression coefficients, in this case, a =13.24, b =12.52

3.4.3 Influence of Layer Thickness and Axle Load on Fatigue Life.

To investigate the influence of heavy load on the two expressways, 120 KN (In order to analyze the influence of the heavy-load on pavement, the 120 KN axle load which is more than standard axle load 100KN is selected to carry on research) was used to simulate heavy loads. As listed in Table 3, five thicknesses of the asphalt surface layer and cold recycled base layer were analyzed. Results are shown in Figure 5a. It is clear that the fatigue life could be increased by increasing the thickness of either the asphalt surface layer or the recycled base layer. Practically, for a project like G70 or G56 which has a defined base layer thickness, it appears that asphalt overlay (increasing the asphalt surface layer) would extend the fatigue life.

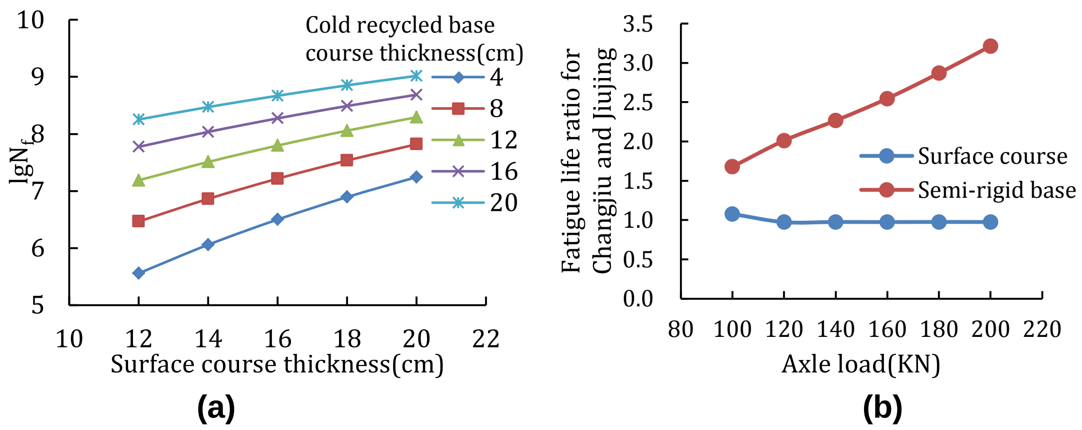


FIGURE 5 Influence on fatigue life due to (a) layer thickness, (b) axle load.

Figure 5b shows the result expressed as a ratio. It shows that the fatigue life of the base layer increases when axle load increases, while the fatigue life of asphalt layer does not change. When the axle load is doubled from 100 KN to 200 KN, the base layer fatigue life of G70 is 1.6~3.2 times that of G56. This indicates the significant contribution to fatigue life from the extra 20 mm asphalt layer that G70 has. In other words, a thicker asphalt layer is favorable to achieve a longer fatigue life.

4 CONCLUSIONS AND RECOMMENDATIONS

Severe premature longitudinal cracking in the wheelpath was observed on two projects with unique pavement structure in Jiangxi, China. The flexible pavements in concern are consisted of hot-mixed asphalt surface layers, cold recycled asphalt base layer, and existing cement treated semi-rigid base. Extensive field investigation, laboratory tests, and numerical simulations were conducted in this study to understand the long-term performance of this special pavement structure. Based on this study, the following conclusions were drawn.

- Rutting, longitudinal cracking, and alligator cracking were the major distresses on both Flexible Pavements with Cold-Recycled Asphalt Base Layer.
- Traffic data show that the cumulative volume for G56 is only 22.93% of that for G70. In addition, G56 has reached 61.9% of its design ESAL, while G70 has carried almost three times of its design ESAL.
- Laboratory tests found that the recycled asphalt base layer had large air voids and low splitting strength. Hence, it is concluded that the primary cause of the observed distress is most likely due to the weakened cold recycled asphalt base layer.
- Numerical analysis shows that the base fatigue life increased when the axle load is increased but the asphalt layer fatigue life kept unchanged. The 20mm extra asphalt layer on G70 led to 1.6~3.2 times of fatigue life comparing to G56. Therefore, a thicker asphalt layer is favorable to achieve a longer fatigue life.

The weakened cold recycled base layer raises a big challenge for repair and rehabilitation. No top treatment would cure the problem which is 160 mm underneath the surface; while any intention to treat the weakened material would have to mill the top intact asphalt layers. Considering the widely application of cold recycling technique in rehabilitating major highways in China since 2000s, a research project to comprehensively investigate the cold recycled base material is warranted. To avoid such problems in the future, cold recycled asphalt mixture has to be carefully designed and well controlled during construction.

ACKNOLEDGEMENTS

This project was sponsored by the Department of Transportation of Jiangxi Province, Jiangxi Ganyue Expressway Co., Ltd. and Chongqing Municipal Science and Technology Commission. The authors would like to thank all engineers and graduate research assistant Luming Ruan for their hard work in field investigation and laboratory testing. In addition, constructive comments from Dr. Danny X. Xiao at University of Wisconsin-Platteville is acknowledged. The opinions expressed in the paper are those of the authors, who are responsible for the accuracy of the facts and data herein, and do not necessarily reflect the official policies of the sponsoring agencies. This paper does not constitute a standard, regulation, or specification.

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