CONDITION SURVEY AND ANALYSIS OF FIRST EPOXY ASPHALT CONCRETE PAVEMENT ON ORTHOTROPIC BRIDGES IN CHINA ——A TEN-YEAR REVIEW

By

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Abstract: In China, epoxy asphalt concrete was first used for paving orthotropic bridge decks in 2000, and now is the dominant paving material for long-span orthotropic bridges. Being performing largely well, however, signs of distresses also began to show up on some of these pavements. This paper documents a complete condition survey and analysis of the first epoxy asphalt concrete pavement placed on Chinese long-span orthotropic bridges after being in service for ten years. Results show that about 30 m^2 out of the entire 38,000 m^2 epoxy asphalt pavement exhibited severe distresses, in the forms of potholes and alligator cracks. Some other minor cracks, including regular longitudinal cracks, short hair cracks, bubble cracks, and ring cracks, were also observed. Rutting and shoving, however, were not found on the pavement. Causes of the distresses were analyzed in the paper. Overall it was concluded that epoxy asphalt concrete is appropriate for paving orthotropic steel deck bridges under severe environmental and traffic loading conditions. Some attention, however, needs to be paid during the construction and operation of the deck pavement to prevent distress initiation and development.

Key words: orthotropic bridge, steel deck, pavement distress, epoxy asphalt, on-site survey, pothole, crack

Introduction

Since the beginning of widespread construction of orthotropic steel deck bridges in China in 1990s, most of the bridges had experienced serious premature failure problems in the deck pavements (Gaul 2009; Huang 2006). With frequent overloading and high deck temperatures (up to 70°C) during prolonged summers, cracking, rutting, and shoving were observed on bridges that had used polymer modified asphalt, stone mastic asphalt (SMA), or gussasphalt for deck surfacing, including many critical long-span bridges such as the Humen Cable-stayed Bridge (main span 888 m) (Xu and Zhang 2008) and the Jiangying Suspension Bridge (main span 1385 m) (Chen et al. 2008; Cheng et al. 2005).

To solve the pavement premature failure problem on orthotropic bridges, a new material, epoxy asphalt, was introduced and first applied on Nanjing Second Yangtze River Bridge (NSYRB) in 2000.

As shown in Fig. 1, NSYRB is a 1238 m long cable-stayed bridge, consisting of a 628 m center span, two 246.5 m side spans, and two 58.5 m flanking spans. The center span was the longest among all cable-stayed bridges in China in 2001, when the bridge was opened to traffic. The bridge deck is 37.2 m wide and carries six lanes of traffic, with a 2.8 percent longitudinal slope and a 2 percent transverse slope from the centerline of the bridge. To reduce stresses in the deck pavement, the thickness of deck steel plate was increased to 14 mm from an originally designed value of 12 mm. The total deck area paved with epoxy asphalt concrete is about 38,000 m^2 (Dai et al. 2002).

Epoxy asphalt is a two-phase binder material with a thermosetting epoxy being the continuous phase and asphalt being the discontinuous phase. After curing, epoxy asphalt concrete possesses high strength, good resistance to cracking and permanent deformation. Epoxy asphalt concrete was first used to pave the steel deck of the San Mateo-Hayward Bridge in California in 1967. Since then, it has been used widely for deck paving on U.S. and Canadian orthotropic bridges, including the San Francisco-Oakland Bay Bridge, which carries a heavy traffic of 30,000 cars per lane per day. Epoxy asphalt has been typically performing well on these bridges over a period up to 40 years. However, early failure problems have also been reported on a few bridges where there seemed to be quality control problems during construction.

The recently constructed orthotropic bridges in China, including NSYRB, differ from those North American bridges on which epoxy asphalt concrete was paved in that the new bridges have much longer main spans and mainly use box girders instead of truss girders. Longer main spans lead to higher flexural deformation of the bridge deck, particularly around the span center, under a combination of wind load, traffic load, and temperature change. Box girders trap air inside, which may significantly increase deck temperature in the summer due to lack of ventilation. These changes in bridge structure posed new challenges to the pavement materials and threw doubts upon the performance adequacy of epoxy asphalt concrete on new bridges.

Based on the above concerns, a research project was initiated and completed to optimize and verify the mixture and structural designs before construction of the deck pavement. The performance of the epoxy asphalt mixture was evaluated extensively in the laboratory, with the optimized mixture design showing a Marshall strength of 56.6 kN, a dynamic stability of 20,137 cycles/mm at 70°C in the wheel tracking test, a -28.4°C fracture temperature in the thermal stress restrained specimen test, and an indirect tensile strength ratio of 91 percent in the Lottman test (Huang et al. 2003; Luo et al. 2010). The final pavement structural design for NSYRB was 50 mm epoxy asphalt concrete, consisting of two 25 mm lifts with an epoxy asphalt bond coat in between (Huang 2006; Huang et al. 2003). This pavement structure was designed for a minimum service life of 15 years, or 12 million 100-kN equivalent single axle loads, and a pavement temperature range of -15°C to 70°C, which were determined based on predicted traffic and weather conditions at the bridge site (Huang 2006). The research project concluded that the epoxy asphalt concrete pavement placed on NSYRB would show good resistance to rutting, moisture, and fatigue damage. To ensure success of this new paving material and design, extreme care was taken during construction to minimize construction related risks, including efforts such as manual picking and screening of aggregate particles to the specified sizes and full coverall on workers to prevent sweat and dust contaminations onto the steel deck. To increase mixture resistance to fatigue damage and to eliminate deck corrosion potential due to moisture infiltration, the epoxy asphalt concrete was compacted to an air-void content level of less than 3 percent, at which the pavement layer is impermeable to both moisture and air.

After being opened to traffic in 2001, the deck pavement did exhibit superior performance compared to other types of asphalt mixtures placed on other bridges. This spurred a wide application of epoxy asphalt for paving orthotropic steel deck bridges constructed thereafter in

China, and currently it is still the case. After being in service for ten years, however, the deck pavement on NSYRB has also been showing a variety of distresses. It is imperative to fully evaluate the conditions of the epoxy asphalt concrete pavement on NSYRB, and to investigate potential causes of distresses. With actual traffic and climate data collected over the past ten years, it is also an appropriate time to re-evaluate the validity of the original steel deck pavement design and to recommend improvements to the design procedure and necessary maintenance activities for keeping the deck pavement in good condition.

Objective

This paper evaluates the condition of epoxy asphalt concrete pavement on NSYRB after being in service for 10 years. The types of pavement distresses are classified, and the causes of each type of distress are discussed. The objective is to provide appropriate maintenance recommendations for extending the service life of epoxy asphalt concrete pavements on long-span orthotropic bridges, particularly those using box girders.

Survey of pavement conditions

Condition survey of the epoxy asphalt pavement on NSYRB was conducted in May 2011. First a windshield survey was used to assess the overall condition of the bridge pavement and to identify distressed areas. After that, lanes were closed around distress locations and a detailed visual survey was conducted to record the severity and extent of each type of distress in the pavement. Every distress was documented and photographed for further analysis.

The windshield survey results are summarized in Fig. 2. As it can been seen, the bridge pavement is in good condition in the two fast lanes, has some longitudinal regular cracks and short hair cracks in the northbound drive lane, and has potholes and irregular cracks including bubble cracks, ring cracks and alligator cracks in the two slow lanes. It is encouraging that no shoving or rutting distress was found on the entire epoxy asphalt pavement. Among all the pavement distresses, about 95 percent of them were observed on the two slow lanes, with 85 percent of the distresses occurring on the northbound slow lane, and 10 percent occurring on the southbound slow lane.

The visual survey provided more details of each type of distress, as described and discussed in the following sections.

Regular cracks

Regular crack is defined as a crack that is mostly caused by structural damage or thermal stress, and propagates longitudinally or transversely. Field investigation of NSYRB pavement shows that regular longitudinal cracks occurred along the positions of deck stiffening ribs or girders, or in the truck wheel paths. One longitudinal crack was found crossing the whole bridge in the northbound drive lane and located on top of the joint of one stiffening rib and the bridge deck, as shown in Fig. 3. In the southbound slow lane, two longitudinal cracks were also observed, one in the center of the lane, and the other in the right wheel path, as shown in Fig. 4.

Short hair cracks

Short hair cracks are defined as cracks with irregular shapes, a length less than 30 cm, a width less than 0.2 cm, and a depth less than 2 cm, as illustrated in Fig. 5. Short hair cracks are mostly observed at the surface of epoxy asphalt pavement on steel bridges. On-site survey on NSYRB revealed that pavement in the northbound slow lane had dozens of short hair cracks, most of which were located in the left wheel path from the southern expansion joint to southern tower.

Bubble and ring cracks

Bubble cracks are characterized with short radial cracks of about 15 cm lengths in at least three directions, as shown in Fig. 6(a). They are caused by moisture trapped underneath the pavement during construction. When deck temperature rises in the summer, the trapped moisture vaporizes and expands its volume, which heaves the impermeable pavement layer to form a pavement bubble. Under traffic loading, the bubble bursts, leaving bubble cracks on the pavement. Under further repeated traffic loading coupled with more ingress of water into the cracked area, ring cracks may appear around the radial cracks, as illustrated in Fig. 6(b). Based on the on-site investigation, both bubble and ring cracks were observed on NSYRB, and most of them were in both the northbound slow lane and the northbound drive lane.

Alligator cracks

A few alligator cracks were found in the pavement on NSYRB. The most serious alligator cracking is in the northbound slow lane at the span center of the bridge, with a cracking area of about 20 m^2, as shown in Fig. 7.

Another serious alligator crack occurred in the southbound slow lane at the span center between southern tower and southern expansion joint. As shown in Fig. 8, this alligator crack is also in the right wheel path.

Potholes and corrosion of steel deck

Potholes are developed from cracks under the coupling action of wheel loading and dynamic water pressure if the cracks are not sealed or patched in time. Long-term observation of epoxy asphalt pavement on NSYRB showed that a pothole first occurred in the pavement in the form as shown in Fig. 9(a). Two potholes were found in the pavement on the northbound slow lane, and had been patched by the maintenance crew of the bridge company. The distressed area is about 0.2 m^2 for one pothole, and about 2 m2 for the other, as shown in Fig. 9(b) and Fig. 9(c), respectively. Moisture was trapped inside the potholes during the patching process, which later caused corrosion of the steel deck, as shown in Fig. 10.

Accident distress (scratching)

Other than the common pavement distresses discussed in the previous sections, accident distress was also found on the NSYRB pavement. A few scratches caused by the striking of objects falling from vehicles were observed in the slow lanes, as shown in Fig. 11.

Discussion of causes of pavement distresses on NSYRB

Effect of traffic condition

With the assistance from NSYRB Co, Ltd., the traffic condition including traffic volume, truck percentage, and truck tire pressure were investigated. The annual traffic volume since the bridge was opened to traffic is listed in Fig. 12. As it can be seen, the annual traffic volume keeps increasing with time, and the daily average traffic volume achieved a value of 59,549 in 2010.

To estimate the truck traffic composition, a 24-hour field traffic survey was conducted in the southbound direction on the bridge, where almost 85 percent pavement distresses occurred. Based on the 15,221 trucks counted in the 24 hours, the truck traffic composition proportion is calculated and shown in Table 1. Survey also shows that all the trucks were driving on either the slow lane or the drive lane, and about 60 percent of the trucks or 90 percent of the trucks with more than two axles were driving on the slow lane. It can be concluded that truck traffic, especially heavy truck traffic, is one main factor contributing to pavement distresses, since the fast lane, which had received little truck traffic, showed little distress, while the slow lane, which had received most heavy truck traffic, showed most serious distresses.

Mechanistic analysis for regular cracks

Regular cracks are mostly fatigue cracks caused by repeated traffic loading. To investigate the mechanism of initiation of regular cracks, a three dimensional (3D) finite element model of epoxy asphalt pavement on local orthotropic steel deck was established using the commercial software ADINA. An 8-note 3D solid element was selected to model the asphalt pavement and a shell element was used to model the steel bridge deck. Between the shell and solid elements, rigid links were adopted to make the pavement and steel deck deform together. A sensitivity analysis of stress response was then conducted to determine the FE mesh size. The mesh size was reduced gradually until difference between the stresses calculated with the new and the old mesh sizes was within 5 percent of the stresses calculated with the old mesh sizes (Xu et al. 2009). As a result, areas around the critical stress positions such as ribs were meshed with fine element sizes, while regions located far away from critical stress positions were meshed with coarse element sizes. The final FE model, as shown in Fig. 13(a), included 12756 elements. According to the survey results of tire pressure as shown in Table 1, a standard tire pressure of 0.7 MPa, a 60 percent overloading tire pressure 1.1 MPa, and a maximum tire pressure 1.38 MPa were selected for analysis. The calculated maximum strains in the pavement at various temperatures and tire pressures are shown in Fig. 13. The FEM simulation results show that the maximum pavement strain occurs at the pavement surface on top of a stiffener (rib) of the orthotropic deck, as represented by point A in Fig. 13(b).

Causes of non-regular cracks

Short hair cracks are typically caused by construction defects instead of deficiency in the pavement mixture or structural design. If short hair cracks are not sealed properly, they will develop into alligator cracks due to heavy traffic and environment influences. The relationship between initiation of short hair cracks and construction process needs further investigation to reduce the occurrence of this type of cracks.

Bubble cracks are caused by moisture introduced during the paving process. Sources of moisture include water dripping from bridge towers or cables, residual water on the deck after rain, and sweat from workers during paving. Such moisture contamination may exist on steel bridge decks paved with any type of asphalt mixture. However, it is interesting to observe that bubble cracks only occur in epoxy asphalt pavements, while they have not been observed on steel bridges paved with other asphalt mixtures, such as gussasphalt (with zero air-void content), polymer modified asphalt mixtures and stone mastic asphalt mixtures (with low air-void content). The reason is that epoxy asphalt mixture is mixed and placed at temperatures much lower than other asphalt mixtures so that epoxy resin can cure at a slow rate to ensure sufficient construction time. Typical mixing and compaction temperatures for epoxy asphalt are around 120°C and 110°C, respectively. Such temperatures cannot guarantee complete evaporation of moisture residuals on the steel deck before epoxy asphalt is placed and completely compacted. Therefore, moisture contamination should be strictly forbidden during the constructing process of epoxy asphalt pavement.

Ring cracks always appear around bubble cracks due to repeated traffic loading and/or potential dynamic water pressure. If the non-regular cracks are not timely treated, alligator cracks will be finally formed.

Cause of potholes

If cracks are not sealed in time, water from rain or snow will infiltrate into the pavement. Under the coupling action of heavy truck loading and dynamic water pressure, potholes will eventually develop. To verify the detrimental effect of moisture on epoxy asphalt performance such as resistance to fatigue cracking, a strain-controlled four-point beam fatigue test was conducted on specimens conditioned with moisture. Such a test was designed to simulate the coupling effect of moisture and loading on the deterioration of epoxy asphalt pavement. The preconditioning procedure for moisture treatment was determined as follows: a specimen was first saturated in water at 635mm-Hg vacuum for 30 minutes and then placed in a 60°C water bath for 24 hours; After that, the specimen was cooled to 20°C and wrapped with Parafilm, a moisture-resistant, thermoplastic flexible plastic sheet, to retain its internal moisture. Moisture loss during the fatigue test can be controlled within one gram by Parafilm. Pictures of Parafilm and a beam wrapped with it are shown in Fig. 14.

The fatigue test was conducted in accordance to AASHTO T 321. Both dry and moisture conditioned specimens were tested for comparison. The air-void contents of all specimens were controlled under 3 percent, which was the same maximum value specified for the deck pavement on NSYRB. Two test conditions, 600 microstrain at 10°C and 900 microstrain at 20°C, and a 10 Hz sinusoidal loading wave were selected to evaluate the mixture performance. The test results are shown in Fig. 15. As it can be seen, the fatigue life of a moisture conditioned specimen at 10°C is 169,182 cycles, which is about 1/6 of the fatigue life 1,030,091 cycles of a dry specimen. The fatigue life of a moisture conditioned specimen at 20°C is 466,899 cycles, which is around 3/5 of the fatigue life 789,104 cycles of a dry specimen. It clearly shows that moisture conditioning reduced the fatigue life of epoxy asphalt mixture. Therefore, moisture related damage should be noticed and further investigated in a future study.

Conclusions

This paper presents recent condition survey and analysis results of the first epoxy asphalt deck pavement placed in China a decade ago. The following findings are obtained from the study:

- After 10 years in service, most of the pavement on NSYRB is still in good condition, except for a few longitudinal regular cracks, short hair cracks, bubble cracks, ring cracks, alligator cracks and potholes appearing on the slow or drive lanes. The area of the pavement with severe deterioration, such as potholes and alligator cracks, is about 30 m^2, which is a small number compared to the 38,000 m^2 area of the entire epoxy asphalt pavement on NSYRB. No shoving or rutting distress was observed on the bridge pavement.
- Truck traffic is the main factor that contributed to the pavement distresses on NSYRB. The pavement on the two fast lanes showed little distress due to the lack of truck traffic. Contrarily, about 95 percent of observed distresses were on the two slow lanes, which received the most truck traffic, especially heavy truck traffic.
- Regular longitudinal cracks in the pavement generally occurred along U ribs (stiffeners),

where the maximum strain or stress in the pavement is located. Short hair cracks are caused by construction defects. Bubble cracks are caused by moisture contamination from water dripping from towers or cables or from worker sweat during the paving process, and are distresses unique in epoxy asphalt pavement on steel bridge decks. At a later stage, ring cracks may appear around the bubble cracks. If the above cracks are not timely and properly sealed, serious distresses such as potholes and alligator cracks can develop from these cracks under the coupling action of repeated traffic loading and dynamic water pressure.

- Moisture reduces the fatigue life of epoxy asphalt pavements. However, the effect of moisture on the forming mechanism of potholes should be further investigated in the future study.

Based on the above findings, it is concluded that epoxy asphalt concrete is appropriate for paving long-span orthotropic bridges under severe environmental and traffic loading conditions. Attention, however, needs to be paid to restricting significant overloading of truck traffic that may cause cracking in the epoxy asphalt pavement. Care also needs to be taken during construction to prevent operations that may lead to hair cracking in the pavement (e.g., abrupt turning and stopping of a steel roller compactor) or moisture contamination on the steel deck (e.g., dripping of residual water from cables and towers after rain). Timely maintenance (e.g., sealing of minor cracks) of the pavement in service is also important to prevent water infiltration through minor cracks and associated distress development.

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Table 1. Truck Traffic Composition on NSYRB

	Number of axles per truck			
	2	3	4	more than 4
Proportion (%)	42.08	29.93	23.27	4.71
Average Type Pressure (MPa)*	0.95	1.04	1.08	0.97
Maximum Type Pressure (MPa)*	1.21	1.24	1.38	1.10

Note:* indicates that the data is from 130 trucks.

LIST OF FIGURES:

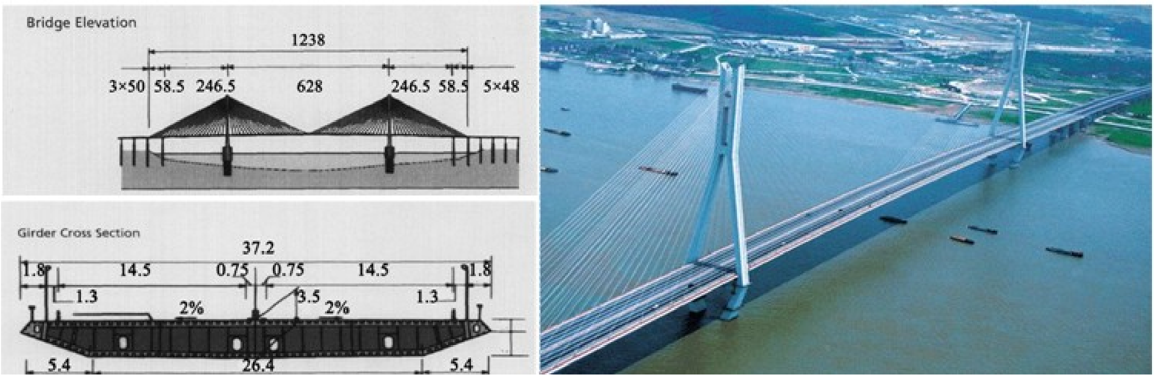


Fig. 1. Sectional drawing and photograph of NSYRB.

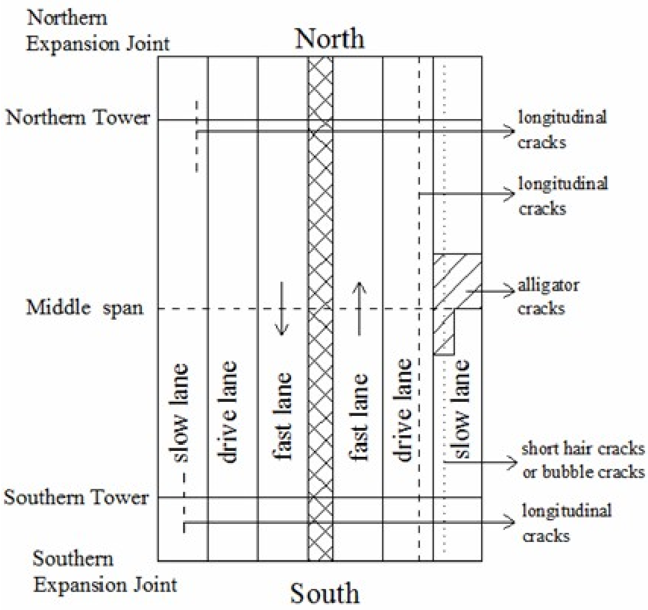


Fig. 2. Types and distribution of pavement distresses on NSYRB.

Fig. 3. Longitudinal regular cracks in the northbound drive lane on NSYRB.

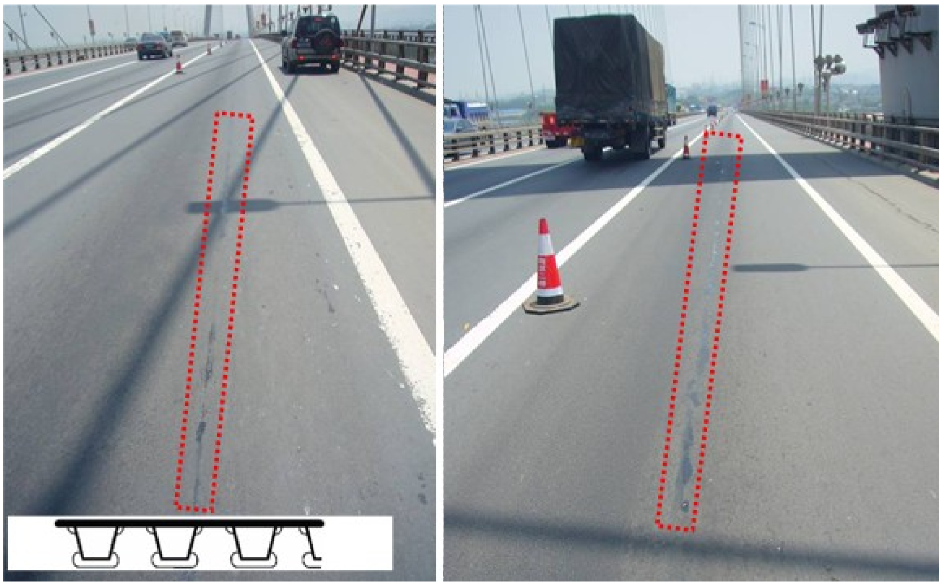


Fig. 4. Longitudinal regular cracks in the southbound slow lane on NSYRB.

Fig. 5. Short hair cracks in the northbound slow lane on NSYRB.

(a) Bubble crack (b) Ring cracks

Fig. 6. Bubble and ring cracks in epoxy asphalt pavement on NSYRB.

Fig. 7. Alligator cracks in the northbound slow lane on NSYRB.

Fig. 8. Alligator cracks in the southbound slow lane on NSYRB.

(a) Small pothole (b) Patched pavement for two potholes

Fig. 9. Pothole in epoxy asphalt pavement on NSYRB.

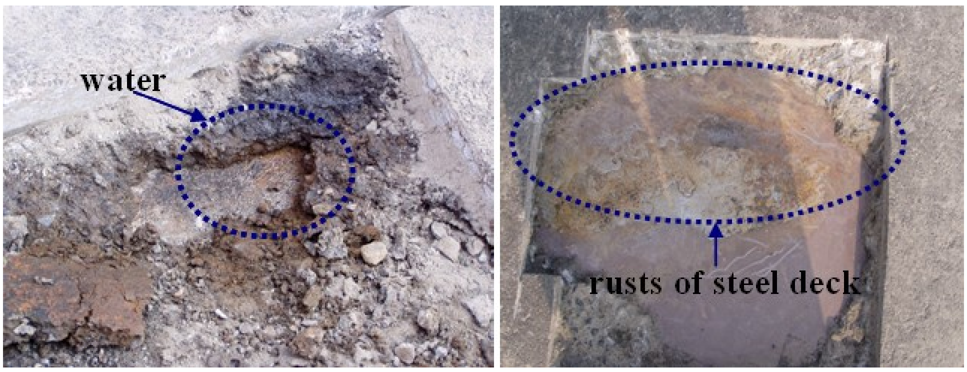


Fig. 10. Water remaining in the pavement and rust of the steel deck on NSYSB.

Fig. 11. Scratching on epoxy asphalt pavement on NSYRB.

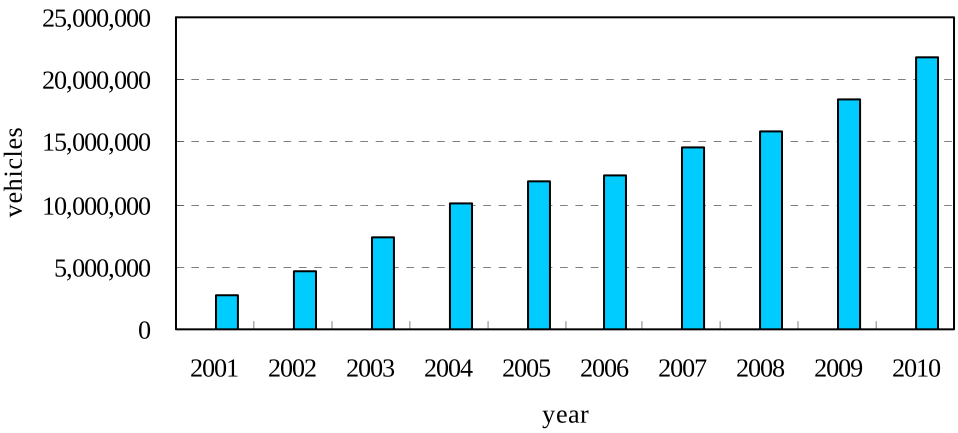
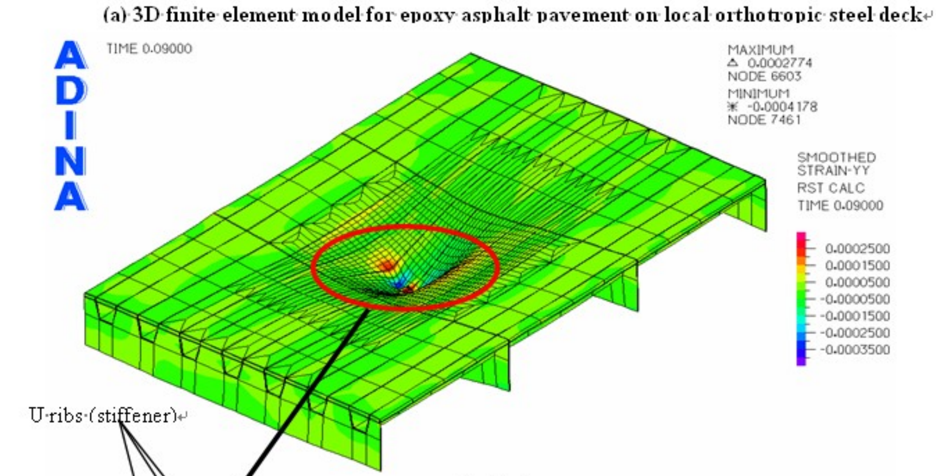
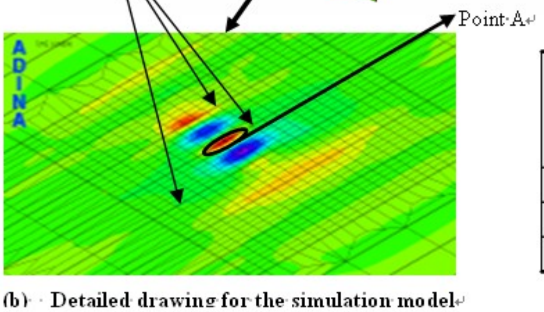


Fig. 12. Annual traffic volume on NSYRB.





FEM simulation results

Type pressure (MPa)	The maximum strain of pavement at different temperatures and type pressure (microstrain)		
	10° C	20° C	30° C
0.70	198	326	624
1.10	308	507	971
1.38	387	637	1218

Fig. 13. FE model and simulation results for epoxy asphalt pavement on local

Fig. 14. Paraflim M sheet and beam with moisture-conditioning.

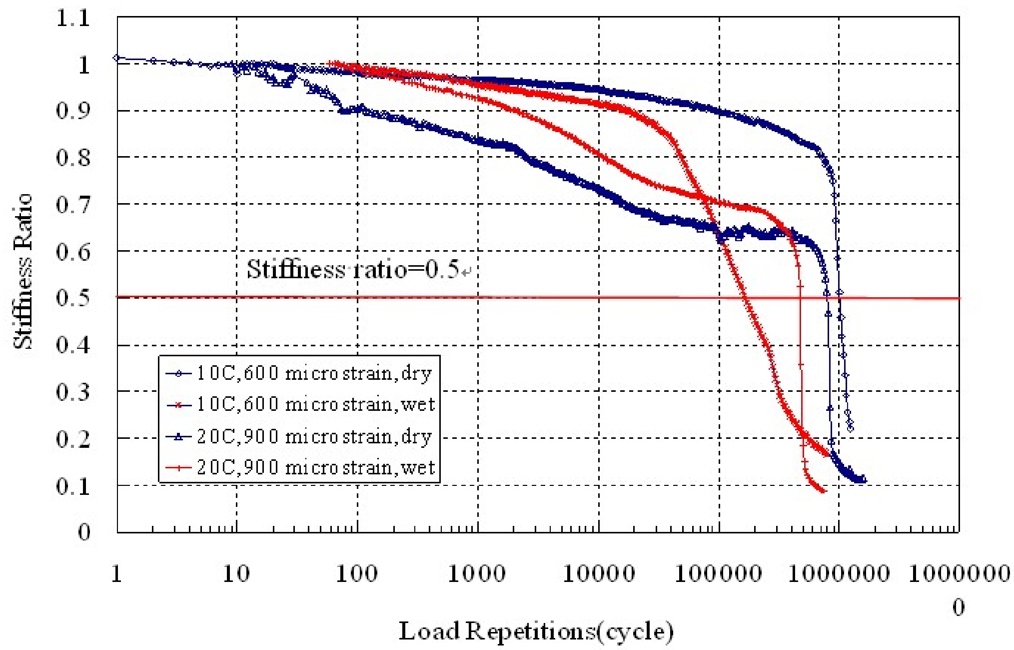


Fig. 15. Fatigue test results for dry and moisture-conditioned epoxy asphalt beams.