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ARTICLE

Concrete pavement rehabilitation procedure using resonant rubblization technology and mechanical–empirical based overlay design

Xin Qiu, Jianming Ling, and Feng Wang

Abstract: Reflective cracking distresses frequently occur on the hot mix asphalt (HMA) overlay due to the movements of the underlying Portland cement concrete (PCC). Rubblization was proven in North America to be an effective approach among slab fracturing technologies for solving the premature reflective cracking problem. This paper presents the procedure of applying the rubblization technology in HMA overlay design in a research effort in China to develop the Chinese standard. In the study, the validity of rubblization was analyzed by a trench survey and sieve tests; the layer moduli of the composite subgrade and rubblized concrete slab were determined using FWD and plate bearing tests and a conversion chart; the thickness design for the HMA overlay over the rubblized PCC pavement was conducted using a Chinese version mechanistic–empirical design process; and finally the in-service monitoring over the pavements built using the developed procedure was conducted to test the validity of the procedure.

Key words: rubblization, reflective cracking, overlay, hot mix of asphalt, Portland cement concrete, mechanistic–empirical design.

Résumé : Des dommages par fissuration réflective surviennent souvent dans le revêtement bitumineux mélangé à chaud en raison de mouvements du béton en ciment Portland sous-jacent. En Amérique du Nord, la fragmentation par résonnance s'est avérée une technique efficace de fracturation des dalles pour résoudre le problème de fissuration réflective précoce. L'article présente la procédure d'utilisation de la technique de fragmentation par résonnance dans la conception des revêtements bitumineux mélangés à chaud dans le cadre d'une recherche en Chine dans le but de développer la norme chinoise. Dans cette étude, la validité de la fragmentation par résonnance a été analysée en effectuant une étude en tranchée et des essais de granulométrie. Les modules de couches de la sous-couche composite et de la dalle de béton fragmentée par résonnance ont été déterminés en utilisant un déflectomètre à masse tombante et des essais de charge avec plaques ainsi qu'une table de conversion. L'épaisseur du revêtement bitumineux mélangé à chaud sur une chaussée sous-jacente, en béton en ciment Portland, fragmentée par résonnance, a été déterminée au moyen d'une version chinoise d'un processus de conception empirique et mécaniste. Finalement, les chaussées construites selon la procédure développée ont été surveillées en service pour valider la procédure. [Traduit par la Rédaction]

Mots-clés : fragmentation par résonnance, fissuration réflective, revêtement, asphalte mélangé à chaud, béton de ciment Portland, conception empirique mécaniste.

1. Introduction

Hot mix asphalt (HMA) overlay is a popular rehabilitation strategy for deteriorated Portland cement concrete (PCC) pavements. However, premature losses of serviceability and structural durability in the overlaid pavement due to reflective cracking distresses are often associated with the HMA overlay rehabilitation over a PCC pavement. Rubblization was proven in the US and elsewhere to be an effective and economical approach among all slab fracturing technologies for solving the premature reflective cracking problem. This paper presents the procedure of applying the rubblization technology in HMA overlay design in a research effort in China. The rubblization technology is relatively new in China and the different characteristics in layer thickness and material property of pavements and structural conditions due to varying design, construction, and operation practices in China have constituted a challenge to this project. The experiences learned from this project could provide valuable information for the construction agencies to further improve the rubblization technology. The major objective of this paper is to show the applicability of using the resonant rubblization technology and related pavement testing and design methods in overlay design and PCC pavement rehabilitation. The main aspects of the study include the analysis of rubblization validity by a trench survey and sieve tests, the determination of layer moduli of composite subgrade and rubblized concrete slabs based upon falling weight deflectometer (FWD) and plate bearing tests, the development of thickness design for the HMA overlay for the rubblized PCC pavement based on the mechanistic–empirical design process, and the in-service monitoring of the trial pavement sections to show long-lasting HMA overlay performance. The main contents of the paper include literature reviews in the background, followed by the implementation of and tests on the rubblization pavement sections, the mechanistic–empirical overlay design process, and finally the conclusions.

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2. Background

In the past decades the mileage of Portland cement concrete (PCC) pavements experienced an enormous growth in China. The PCC pavements are playing a critical role in serving and supporting the local economic developments. Subjected to cumulative traffic loading, material related aging, and environment weathering, however, these PCC pavements eventually deteriorated during their service lives and developed various types of distresses, such as slab cracking, crack spalling, joint deterioration, faulting, and punchouts. When the serviceability drops to an unacceptable level, the PCC pavements must be rehabilitated or reconstructed. Various restoring treatments have been applied to these deteriorated pavements in an effort to extend the service life of the pavements. However, field surveys and observations indicated that even with a costly rehabilitation program such as full depth repairing and undersealing voids with grout, these maintained PCC pavements still could not keep a satisfactory condition and continued to deteriorate noticeably (Chen et al. 2008). A more cost-effective rehabilitation strategy for the deteriorated PCC pavements would be needed.

Although HMA overlay was commonly used as one of the rehabilitation strategies for the existing PCC pavements in China, this repair method has proven less than satisfactory owing to reflective cracking. Reflective cracking is formed when the reflection of an existing crack or joint propagates upward to the new pavement surface. This reflection is primarily induced by both the horizontal and the vertical movements occurring at the joints and cracks in the underlying pavement. The horizontal movements in a bonded HMA overlay due to the concrete slab's contraction and expansion create excessive tensile stresses along the cracks and joints at the overlay interface. The horizontal movements are generally considered to be very crucial for the formation of reflection cracking. The vertical movements along the cracks and joints due to traffic loading will further accelerate the crack propagation process. Reflective cracking is regarded as one of the main distresses in HMA overlays that impose detrimental effects on the serviceability and structure durability of the overlaid pavements. Frequently, initial reflection cracking appears within a year or two in an HMA overlay if proper design and construction techniques are not properly followed (Rajagopal et al. 1996).

Several methods were developed to potentially minimize reflective cracking in HMA overlay over PCC pavements. These methods include sawing and sealing at the joint, increasing the thickness of the HMA overlay, installing stress relieving membrane built at the overlay–PCC pavement interface and using modified asphalt materials, etc. (Julie et al. 2010). The practical experiences demonstrated that these methods exhibited only partial benefits of delaying the propagation of a reflective crack in the HMA overlay, whereas the problem of reflective cracking still reemerged in a few years (Lee et al. 2007).

During the past 20 years, the slab fracturing techniques, which essentially seek to solve the typical poor cracking performance of overlays on PCC concrete by destroying the concrete slab and (or) reducing the slab into smaller fragment sizes, have gained an increasing acceptance (Freeman 2002). The typical slab fracturing techniques include crack and seat, break and seat, and rubblization (NAPA 2006). According to the Illinois Department of Transportation's monitoring study (Thompson 1999), the break–seat and crack–seat techniques could delay the reflective cracks but did not eliminate the reflective cracking in the HMA overlay. The crack–seat and break–seat methods involve breaking of the underlying rigid pavement into relatively small pieces by repeatedly dropping a large weight with the help of pile drivers, guillotine hammers, etc. These pieces are then seated using large rubber tired rollers. Generally, the break–seat technique is applicable to joint reinforced concrete pavement (JRCP), the crack–seat technique for jointed plain concrete pavement (JPCP) whereas the rubblization can be utilized for any type of deteriorated PCC pavements (PCS/Law 1991). The major difference between the crack–seat, break–seat and rubblization methods is the degree to which the slabs are reduced in size: crack–seat and break–seat methods typically reduce the slabs to 305–610 mm fractured pieces, whereas rubblization totally destroys the slabs, effectively reducing them to granular or particular materials (Thompson 1999).

Rubblization involves breaking the existing PCC slab into angular pieces and overlay with HMA. The field test indicated that rubblization resulted in a lower variability in the fractured slab modulus than the other two fracturing methods (Witczak and Rada 1992). The rubblized PCC layer has proven to be a high-strength granular base with strength between 1.5 and 3 times stronger than a high quality, dense-graded crushed stone base in load distributing characteristics (Thompson et al. 1997; Timm and Warren 2004). Additionally, a serial of performance surveys demonstrated that rubblization has been the most effective, economical, and successful technique for addressing reflective cracking (Morian et al. 2003; Ksaibati et al. 1999).

Two types for rubblization are primarily in practical use. One is the resonant frequency breaker (RFB) invented by Resonant Machines company, which employs a low amplitude, high frequency breaking shoe to strike the surface of the concrete pavement (Resonant Machines 2006). The other is the multi-head breaker (MHB) created by Antigo Construction Incorporation, which uses 12 or 16 drop hammers by dropping a 454 kg–680 kg hammer free-fall to fracture the concrete pavement (Antigo Construction 2010). According to research conducted by Thompson et al. (1997), the rubblized base was most effectively obtained with the MHB technology (Thompson et al. 1997). Meanwhile, resonant rubblization has been used successfully in 37 US states and two Canadian provinces (Fitts 2006). Arkansas has rubblized over 300 miles of interstate highway using RFB with excellent results (Decker et al. 2006). Michigan has more than 60 resonant rubblization projects that indicated perfect pavement conditions in the past ten years (Resonant Machines 2006). As a new technology, the RFB was introduced by the Shanghai Municipal Engineering Bureau (SMER) of China in 2005. So far, over 15 km of concrete pavements were rubblized with the RFB technology. With the valuable experiences using RFB in the past years, SMER actively seeks to develop a guideline procedure of using the RFB technology for PCC pavement rehabilitation and HMA overlay design. This paper documents the research efforts of applying the rubblization technology in PCC rehabilitation and HMA overlay design in China and will help the country develop such a guideline for more future applications.

3. Rubblization

3.1. Trial pavement section

Jinshan road was the longest trial pavement section to be rubblized with a resonant breaker in China and the total length of the project was 5689 m. The cross section consisted of motor lanes, non-motor lanes, barriers, and shoulders. Figure 1 illustrates the geometric dimensions of the cross section of the trial road. The design speed for the motor lane was 100 km/h. By 2005 the maximum daily traffic reached 13 433 vehicles per day. The original pavement structure consisted of 24 cm concrete slabs, 30 cm fly ash treated base, and 15 cm sand gravel subbase, respectively. The field survey identified many severe distresses such as longitudinal and transversal cracks, faults, spalling, and settlements. The pavement condition was found in the low service level and the SMER decided to use a new technology, the resonant rubblization, to rehabilitate the deteriorated PCC pavement.

3.2. Rubblization and trench test

The resonant breaker was imported from the Resonant Machines Incorporation (RMI) in 2006. Figure 2 shows the pictures

Fig. 1. Geometric dimensions of trial road (units in metre).

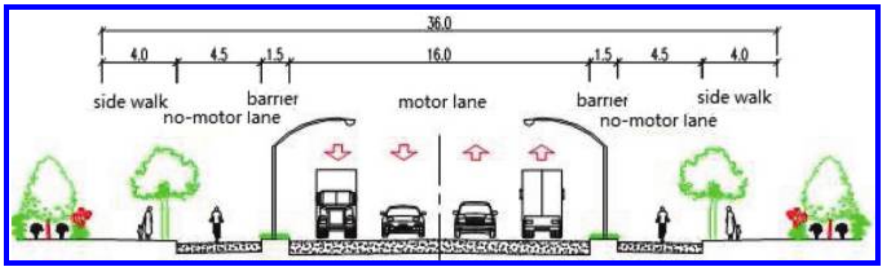


Fig. 2. Resonant frequency breaker used in trial sections.

of the Resonant Frequency Breaker (RFB) machine used in the project. The RFB delivered a low amplitude (<19 mm) and high frequency (42~46 Hz) energy by a shoe to the slab. The work frequency is near to the harmonic frequency of the slab. The vibration energy causes high tensions at the top of the slab that fractures and breaks the slab into pieces.

The particle size and influence depth are the two most important parameters to test the rubblization validity. The two parameters characterize the slab's capability of preventing reflective cracking and providing structural strength. At the trial pavement section, a trench was dug after the rubblization to examine the particle size and influence depth. The results demonstrated that the effects of rubblization were quite evident and the influence depth reached the entire thickness of the slab. Figure 3 shows the pictures taken at the survey trench. When viewed from the trench, smaller size particles of the concrete were located at the upper part of the slab and larger size fractured pieces of the concrete were found in the lower part of the slab, and the size changed gradually along with depth without an obvious boundary. This survey result corresponded with the research conducted by Lee et al. (2007), in which the rubblized PCC pieces were divided into two types of materials that were defined as rubblized concrete and fractured concrete. The particle sizes of the rubblized concrete are finer and can effectively prevent reflective cracking. The presence of the fractured concrete keeps a good integrity in strength and can provide a sufficient bearing capacity for the HMA overlay.

The sieve test samples were divided into two subsets: subset–1 and subset–2. Each subset had 8 samples, which were obtained from the 0 cm to 10 cm and 0 cm to 18 cm in depth respectively of the rubblized slabs. It was difficult to obtain particles below the depth of 18 cm. The gradation curves of the samples are illustrated in Fig. 4. The majority of the particles of subset–1 distribute from 1 cm to 4 cm. The highest percentage (14.6%) was for the 9.5 mm size particles. In contrast, the samples in subset–2 contained many more larger sized particles and the 37.5 mm size particles were found to be the highest in percentage (23.9%). As shown in Fig. 4, the gradation of subset–1 met the specification requirement for the crushed stone base materials, but the gradation of subset–2 exceeded the lower limit of the required gradation. However, the rubblization process satisfied the requirement of the US guideline that restricts the average particle size to 25.5~76.2 mm at the top of the rubblized PCC layer for the rubblized-aggregate gradation (Ksaibati et al. 1999).

3.3. Determination of layer moduli

Rubblization is one of the surface preparation techniques before placing an HMA overlay to minimize reflective cracking, which involves breaking the concrete slab into pieces (Kim et al. 2009). The loss of the bearing capacity of a PCC slab during rubblization must be offset in the design of HMA overlay thickness to satisfy the functional and structural requirements of the pavement structure (Galal et al. 1999). One of the most important aspects of the overlay thickness design is to characterize the layer modulus of the rubblized pavement. Many studies were conducted to predict the modulus of the rubblized PCC slab, however, no consistent modulus model has been developed to depict the rubblized PCC layers, which suggests that the modulus of a rubblized slab is site specific and dependent on the rubblization process itself (Kim et al. 2009; Galal et al. 1999; NCHRP 2004; Thompson 1999). In China, PCC pavement structures are typically paved with thick concrete slabs and cement treated bases (concrete slabs of more than 20 cm thickness and cement treated bases of more than 30 cm thickness over a gravel subbase), which significantly differ from the practices in the US. Therefore, finding a reliable way to estimate the layer modulus of the rubblized PCC pavement could not only provide an accurate parameter for the HMA overlay thickness design, but also benefit the standard use of the rubblization technique in more rehabilitation projects of the PCC pavements. The following steps were developed in the study to estimate the modulus of the rubblized PCC slab.

3.3.1. *Modulus of composite subgrade*

An FWD test was conducted before the rubblization to determine the composite modulus of the subgrade. The composite subgrade refers to the fly ash treated base, gravel subbase, and clay soil roadbed. Deflection data was collected using a PRI 2100 FWD, which applied 50 kN load through a 15 cm high plate at the centre of the PCC slab. The locations of the FWD geophones used in the in situ tests were 0 mm (ω_0), 200 mm (ω_{200}), 300 mm (ω_{300}), 600 mm (ω_{600}), 900 mm (ω_{900}), 1200 mm (ω_{1200}), 1500 mm (ω_{1500}), 1800 mm (ω_{1800}), and 2100 mm (ω_{2100}) from the applied FWD load. The modulus of the composite subgrade can be determined by eqs. (1) and (2) as follows (MOT 2003). As shown in Fig. 5*a*, the modulus of the composite subgrade ranged from 122 to 474 MPa before rubblization, with an average value at 265.5 MPa.

$$E_t = 100\exp\left(3.60 + 24.03\omega_0^{-0.057} - 15.63SI^{0.222}\right) \quad (1)$$

Fig. 3. Rubblization size and depth surveyed by trench.

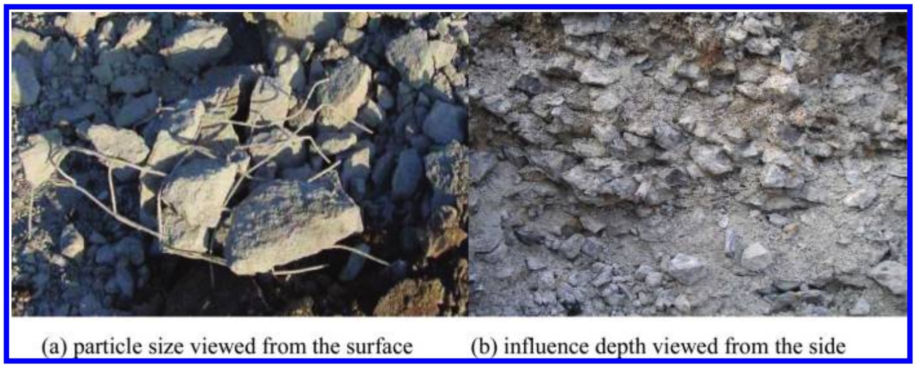
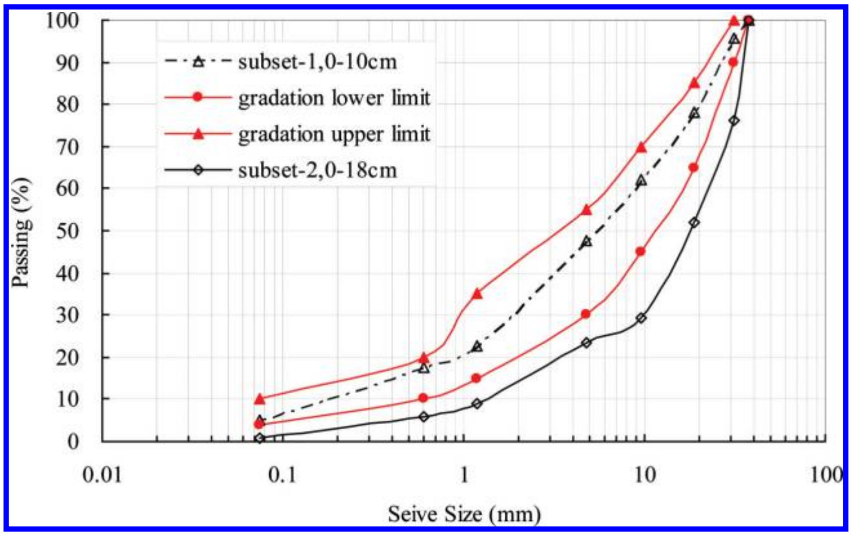


Fig. 4. Comparison of sample gradations.



(2) $$SI = (\omega_0 + \omega_{300} + \omega_{600} + \omega_{900})/\omega_0$$

where E_t is the modulus of the composite subgrade; SI is the coefficient of load diffusion; and ω_0, ω_{300}, ω_{600}, and ω_{900} are the deflection values at 0 mm, 300 mm, 600 mm, and 900 mm geophone locations, respectively.

The modulus of the composite subgrade was also examined by plate bearing tests before and after the rubblization. Before rubblization, the plate bearing test condition was satisfied by removing the concrete slabs at the testing points of the selected test section without disturbing the underlying structural layers. Rubblization was conducted at a neighboring slab of the same test section. After rubblization, the plate bearing test was performed for the rubblized location after removing the fractured PCC pieces. The testing results are presented in Fig. 5*b*. Before the rubblization, the average modulus was 255 MPa, which was quite close to the result determined by the FWD tests. After rubblization, the average modulus was 165 MPa, which was 35% lower than the modulus before the rubblization as expressed in eq. (3). The decrease in average modulus was attributed to the rubblization that disturbed the subbase and subgrade soil layers. It should be noted that the coefficient of variation for the composite modulus from the plate bearing test was 0.12, which was less than the 0.26 calculated by the FWD test data. It suggested that the plate bearing test exhibited more repeatability than the FWD, but the plate bearing test had lower work efficiency than the FWD when the practices of field tests were considered. The above analysis results demonstrated that the modulus of the composite subgrade after rubblization can be determined by the FWD test and calculated by eqs. (1), (2), and (3).

(3) $$E_{\text{after×rubblization}} \approx 0.65E_{\text{before×rubblization}}$$

3.3.2. Modulus of rubblized slab

The modulus of rubblized slab is one of the most important parameters for the HMA overlay thickness design in a mechanistic–empirical (M–E) design approach. The modulus of the rubblized concrete slab could be determined based on the assumption that the deflection (l_1) produced by a load in the original pavement structure should be equal to the deflection (l_2) produced by the same load in the equivalent pavement structure. This assumption is equivalent structure transfer scheme, which is presented in Fig. 6. To the right of Fig. 6, the equivalent subgrade is an elastic half space model including the composite subgrade and rubblized layer. The calculation formulas for l_1 and l_2 are shown in eqs. (4) and (5).

(4) $$l_2 = \frac{2p\delta(1 - \mu_2^2)}{E_{t2}}$$

(5) $$l_1 = \frac{2p\delta(1 - \mu_1^2)}{E_{t1}}\overline{\omega}$$

where E_x, h_x, and u_x are the modulus, thickness and Poisson's ratio of the rubblized layer; E_{t1} and u_1 are the modulus and Poisson's ratio of the composite subgrade; E_{t2} and u_2 are the modulus and Poisson's ratio of the equivalent subgrade; p is tire contact pressure, 0.7 MPa; δ is tire contact radius, 15 cm; and $\overline{\omega}$ is the deflection

Fig. 5. Moduli of composite subgrade by falling weight deflectometer (FWD) and plate bearing tests.

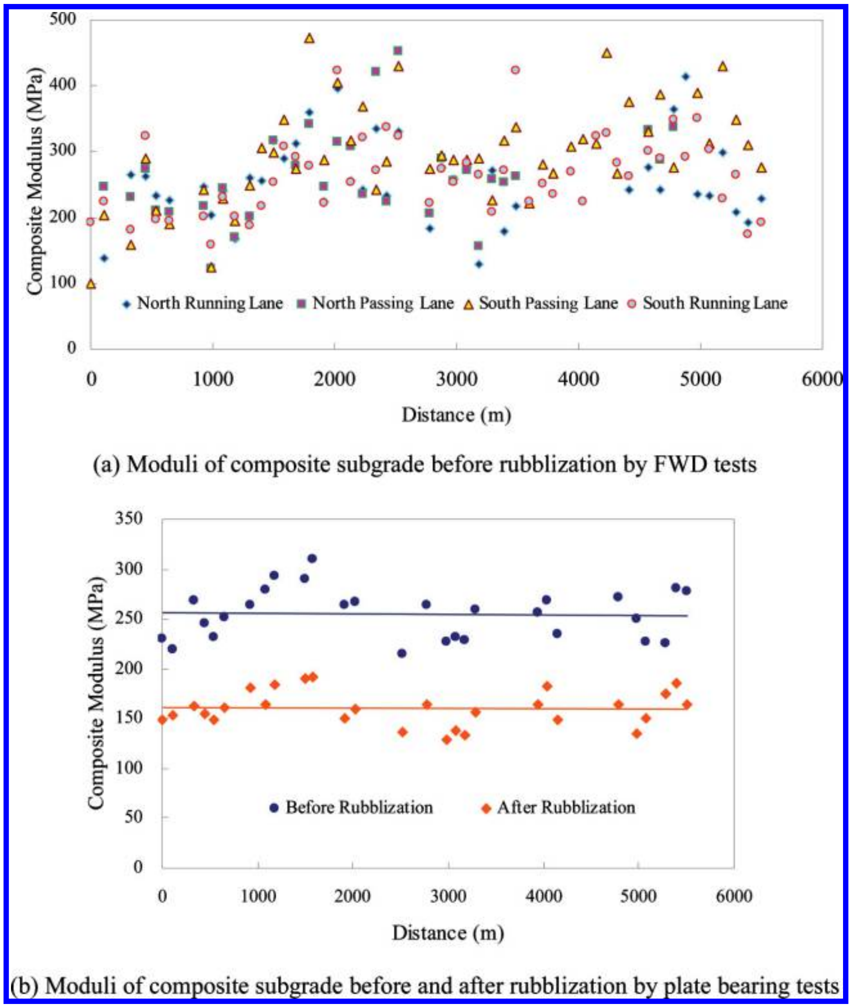
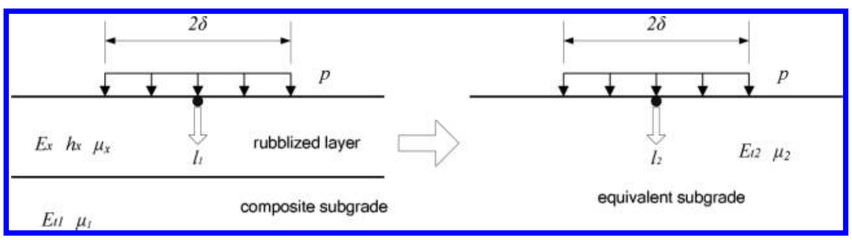


Fig. 6. Equivalent structure transfer scheme.



parameter and has a close connection with the layer modulus, thickness and Poisson's ratio.

The modulus E_{t2} could be measured by the FWD test on the surface of the rubblized concrete pavement; E_{t1} could be obtained by the measurement of the modulus of the composite subgrade using the FWD test before the rubblization and calculated by eqs. (1), (2), and (3). Then the modulus of the rubblized slab E_x could be calculated by using the equivalent structure transfer scheme. A conversion chart was developed and drawn from a comprehensive database to calculate the modulus of the rubblized slab. The database was generated by computing the surface deflection for a wide range of layer thicknesses and moduli. The moduli E_x varied from 300 to 1500 MPa in 100 MPa increment; h_x varied from 20 to 30 cm in 2 cm increment; E_{t1} ranged from 80 to 360 MPa in 20 MPa increment, while u_x, u_1, and u_2 were assumed to be 0.35, 0.3, and 0.3, respectively. The chart is illustrated in Fig. 7.

The following case is provided to explain the calculation process. If E_{t1} and E_{t2} are measured with the values of 120 MPa and 360 MPa, respectively, then E_{t2}/E_{t1} can be calculated to be 3. If h_x is 24 cm, then the quantity E_x/E_{t1} is determined at 9.1 by using the conversion chart in Fig. 7, and then the modulus of the rubblized slab can be calculated as 120×9.1 = 1092 MPa. The moduli of the rubbblized slabs of the trial pavement sections are illustrated in Fig. 8. The results show that the equivalent subgrade modulus ranged from 250 to 520 MPa with the average value being 348 MPa. The modulus of the rubblized slab varied from 470 to 890 MPa and the average value was found at 674 MPa.

4. HMA overlay design

The typical flexible pavement analysis and design is based upon the Burmister multi-layer theory, therefore, after the PCC slabs are broken into pieces and used as a base layer, the Burmister approach

Fig. 7. Chart for calculating modulus of rubblized slab.

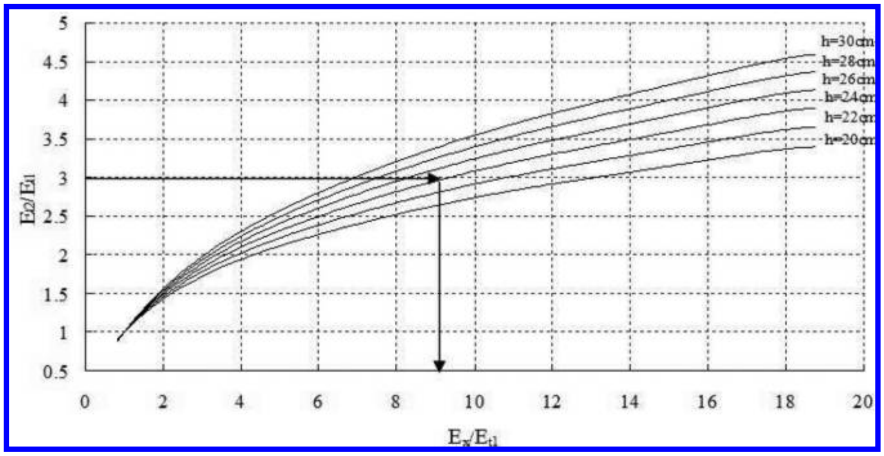


Fig. 8. Results of layer moduli of rubblized slabs.

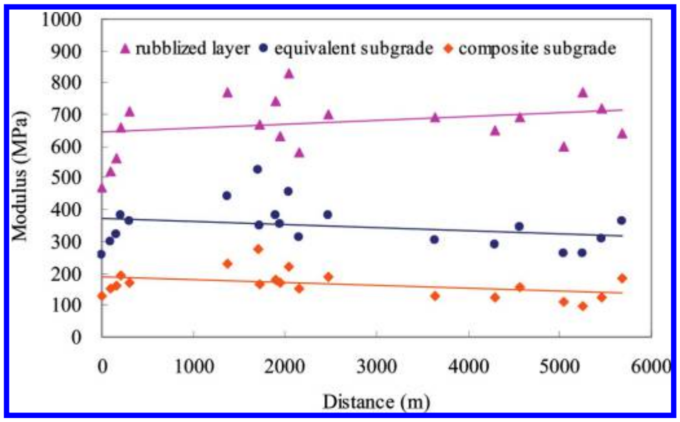
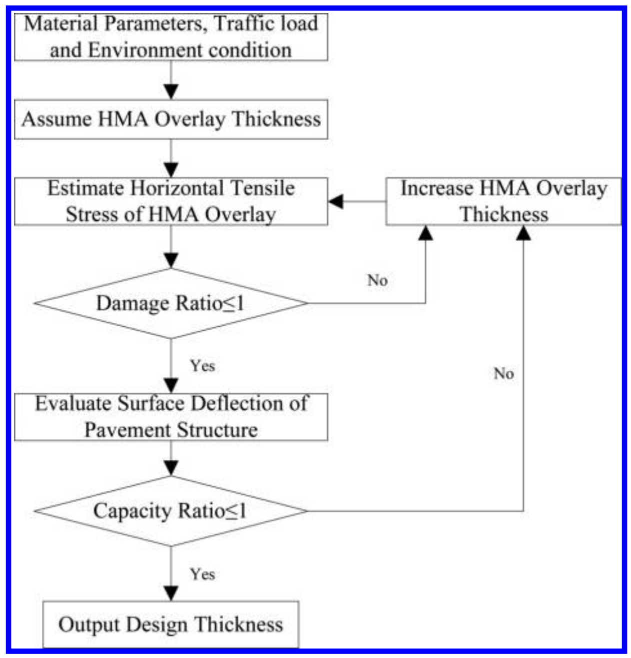


Fig. 9. Design flow chart for hot mix asphalt (HMA) overlay thickness.



may be used to perform the thickness design of HMA overlay of the rubblized pavements (Ceylan et al. 2006). In China, the mechanistic–empirical (M–E) design method has been widely used to conduct new flexible pavement designs. However, there is no specific guide to address HMA overlay thickness design with a rubblized concrete layer. It should be noted that the M–E method used in this study is the Chinese version but not the M–E Pavement Design Guide by AASHTO. In the United States, the M–E approach for the design of HMA overlays on fractured PCC slabs is similar to the design of a new flexible pavement structure (Rodezno et al. 2006). In accordance with the existing M–E design procedure for new flexible pavements in China, this study developed a feasible thickness design and validation method for an appropriate HMA overlay layer to be determined for the rubblized concrete pavement.

4.1. Design flow chart

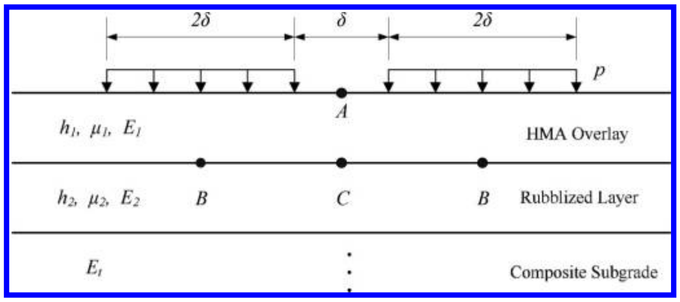
As illustrated in Fig. 9, a design flow chart was developed to determine the HMA overlay thickness of the rubblized pavement. In the overlay design and analysis, the pavement was regarded as a three-layer elastic system including HMA overlay, rubblized PCC slab, and composite subgrade. The design inputs included traffic load information, material properties, and layer thicknesses. The material in each of these layers was characterized by a set of elastic modulus and Poisson's ratio. The material properties of the HMA overlay were provided by engineering judgment and experience on material selection, and the material properties of the rubblized slab and the composite subgrade layers could be obtained as mentioned earlier in the paper. The Poisson's ratios were assumed with reasonable accuracy.

Figure 9 shows a mechanistic–empirical overlay design and analysis process. The thickness of the HMA overlay was initially assumed along with the selection of the overlay material properties. Then, critical immediate pavement responses due to axle loading were calculated using the linear elastic analysis program BASAR. The immediate critical pavement responses were related to the pavement performance by plugging the immediate responses into the Chinese pavement performance equations. The long-term pavement performance in terms of pavement damages at the end of the design life was predicted by valuing the damage ratio and capacity ratio. The ratios should be numerically less than or equal to one for the overlay design to be feasible. The determination of the overlay thickness was an iterative process in which the initially selected thickness was increased for the minimum terminal failure criteria to be simultaneously satisfied.

4.2. Critical pavement responses

The critical pavement responses considered in the M–E design and analysis process included the horizontal tensile stress at the bottom of the HMA layer (σ_m) and the deflection on the surface of the HMA overlay (l_s), which were regarded as closely related to the HMA layer's

Fig. 10. Three-layer pavement subjected to dual tire loading.



long-term performance in terms of fatigue cracking and cumulative rutting respectively. The linear elastic analysis program BASAR was applied to compute for the critical structure responses with the needed design parameters input to the program. The design parameters included the HMA thickness and modulus, rubblized concrete layer thickness and modulus, and modulus of the composite subgrade after rubblization in addition to the data for tire loading. Figure 10 illustrates the calculation points for the critical pavement responses. Point A reflects the location for the critical surface deflection, which is located at the midpoint between the two dual tires' circular loads. Points B and C are the possible locations for the critical tensile stress at the bottom of the HMA overlay, which are located under either of the centres of the two circular tire loads and the midpoint between the two tire loads.

4.3. Structural analysis

A rapid structural analysis approach was developed to facilitate the design and analysis process. Since the critical responses were functions of tire loading (which was fixed), thickness geometry, and elastic modulus of each layer, it would be possible and handy to establish a prediction relationship of the critical pavement responses to the relevant parameters using regression models based on comprehensive computation results (David et al. 1998).

A comprehensive database was generated by computing σ_m and l_s for a wide range of layer thickness and modulus values. The HMA layer thickness varied from 12 to 28 cm and the rubblized layer thickness ranged from 18 to 38 cm. The modulus values ranged from 1200 to 4000 MPa for the HMA overlay, 300 to 1500 MPa for the rubblized concrete, and 80 to 360 MPa for the composite subgrade. The Possion's ratios of the HMA overlay, rubblized PCC, and composite subgrade were assumed to be 0.35, 0.35, and 0.3, respectively. The analysis model was a three-layer elastic system subjected to a dual tire loading with two circular uniformly distributed vertical tire loads as illustrated in Fig. 10. The load contact radius (δ) was at 10.65 cm. The tire-pavement contact pressure (p) was fixed at 0.7 MPa. Prediction models were derived by relating the critical pavement responses (σ_m and l_s) to the layer thicknesses and moduli using the database. The linear prediction functions of σ_m and l_s were regressed and listed in eqs. (6) and (7). The R^2 values of the two prediction functions were above 0.7 indicating strong correlations between the critical responses and the modulus and thickness variables (David et al. 1998).

$$\text{(6)}\quad \mathrm{Ln}(l_s) = -0.374\mathrm{Ln}(E_1) - 0.243\mathrm{Ln}(E_2) - 0.2\mathrm{Ln}(E_3) - 0.251\mathrm{Ln}(h_1) - 0.596\mathrm{Ln}(h_2) + 11.24 (R^2 = 0.989)$$

$$\text{(7)}\quad \mathrm{Ln}(\sigma_m) = -1.492\mathrm{Ln}(E_1) - 0.667\mathrm{Ln}(E_2) + 2.057\mathrm{Ln}(E_3) - 1.352\mathrm{Ln}(h_1) - 0.004\mathrm{Ln}(h_2) - 2.332 \quad (R^2 = 0.767)$$

where E_1, E_2, and E_3 refer to moduli of HMA overlay, rubblized PCC, and composite subgrade, respectively; h_1, and h_2 refer to thicknesses of HMA overlay and rubblized PCC, respectively.

4.4. Ratios of damage and capacity

The critical pavement responses were compared with their respective allowable values to decide if the overlay thickness design would be adequate for the repetitive loads during the design life period. The allowable values for the critical pavement responses were based on the long-term pavement performance equations in China. Equation (8) is the terminal criterion of damage ratio for the critical tensile stress of the HMA overlay. Equation (9) shows the terminal criterion of capacity ratio for the critical surface deflection of the pavement.

$$\text{(8)}\quad \frac{\sigma_m}{\sigma_R} \le 1$$

$$\text{(9)}\quad \frac{l_s}{l_d} \le 1$$

where σ_R is the allowable tensile stress at the bottom of the HMA overlay and l_d is the allowable deflection at the surface of the HMA overlay. In accordance with the current M–E design procedure of flexible pavements in China, l_d and σ_R were related to the long-term performance at the end of the design life of the pavement. These relations are interpreted in eqs. (10) and (11), respectively.

$$\text{(10)}\quad l_d = 600N_e^{0.2}A_c\, A_s\, A_b$$

where N_e is the number of repetitions of 100 kN axle load for one lane in the design life; A_c is highway classification parameter, 1.0 for expressways or first class highways, 1.1 for second classes, and 1.2 for other classes; A_s is wearing course type parameter, 1.0 for HMA; A_b is base type parameter, 1.6 for rubblized slab layer. The unit of l_d is 0.01 mm.

$$\text{(11)}\quad \sigma_R = \sigma_s / K_s$$

$$\text{(12)}\quad K_s = 0.09N_e^{0.22} / A_c$$

where σ_s is the maximum indirect tensile strength of HMA at 15 °C; K_s is the structural coefficient of tensile strength. The unit for σ_R is MPa.

The above two ratios should be numerically less than or equal to one for the overlay thickness design to be permissible. If any of the ratios exceeded one, it would mean that the terminal performance of the pavement would not be sufficient for the anticipated traffic load repetitions, and then the HMA overlay thickness should be increased and the analysis process be repeated.

4.5. Validation of overlay thickness

According to the established design procedure for HMA overlay thickness, two different thickness results of HMA overlay designs were delivered to Jinshan road. The 25 cm and 20 cm overlay thicknesses were assigned to the road section from K67 + 293 to K67 + 474 and the section from K67 + 474 to K72 + 145, respectively. The validity of the designed thicknesses of the HMA overlays was examined by conducting Benkelman Beam (BB) deflection tests on the trial sections. To undergo 12.95 million 100 kN axle loads required in the design life of 20 years, the allowable deflection on the pavement surface was 40 (0.01 mm) based on eq. (10). It is shown from the results in Table 1 that all the deflections of the tested lanes were less than the maximum allowable deflection of 40.

In Table 1, NR, NS, SS, and SR denotes north running lane, north passing lane, south passing lane, and south running lane, respectively. Up to now (after 6 years), the field surveys have indicated that the rubblized pavement sections are performing very well without any visible load related distresses, such as cracking and

Table 1. Results of Benkelman Beam deflection test on trial sections.

Pavement section	Number of tests	Lane	Mean (10^{-2} mm)	Standard deviation (10^{-2} mm)	Variation coefficient
Section One	45	NR	30.3	8.4	0.318
(K67+293 to	50	NS	27.8	5.5	0.2
K67+474)	48	SS	29.2	7.1	0.264
	46	SR	27.9	7.8	0.322
Section Two	45	NR	31	7.4	0.276
(K67+474 to	50	NS	29.2	5.7	0.21
K72+145)	48	SS	29.4	5.5	0.201
	46	SR	34.2	6.8	0.214

Note: NR, north running lane; NS, north passing lane; SS, south passing lane; SR, south running lane.

rutting. Therefore, the developed HMA overlay thickness design approach is viable and reasonable for achieving long-lasting performance of HMA overlays on rubblized PCC pavements. In addition, there were no complaints from business owners and residents during the rubblization operations due to the minimum disturbance.

5. Conclusions

This paper presents the research progress in developing a guideline procedure for the utilization of the resonant rubblization technology and the associated overlay design procedure for PCC pavement rehabilitations in China. The main findings are summarized as follows:

(1) The effect of rubblization was evident and the influence depth arrived at the entire thickness of the concrete slab. The rubblization process satisfied the specified aggregate gradation requirement for the particle size to be within the range of 25.5～76.2 mm at the top of the rubblized PCC.
(2) Before rubblization, the modulus of the composite subgrade ranged from 122 MPa to 474 MPa by FWD tests with an average value at 265.5 MPa, which was close to the average result of 255 MPa by plate bearing tests. After rubblization, the average modulus of the composite subgrade was 165 MPa, which was 35% lower than the modulus before rubblization. A conversion chart was developed to calculate the modulus of rubblized slabs based on the deflection equivalence principle. The modulus of the rubblized slab varied from 470 to 890 MPa with an average value at 674 MPa.
(3) The design procedure of overlay thickness for rubblized pavements was developed based on a mechanistic–empirical (M–E) method. The definitions of critical pavement responses, for the horizontal tensile stress at the bottom of the HMA layer and the deflection on the surface of the HMA, were effectively related to the long-term performance of the overlaid pavement. Effective thickness designs of overlays were conducted using the procedure.
(4) The field surface condition surveys indicated that the rubblized pavement sections have performed very well without any visible load related distresses. The developed procedure of using the resonant rubblization technology and the mechanistic–empirical HMA overlay thickness design approach is viable and reasonable for achieving long-lasting performance of HMA overlaid rubblized PCC pavements.

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