Study of Open Graded Asphalt Concrete Overlay on Mitigation of Reflection Cracking

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ABSTRACT

Hot-mix asphalt (HMA) overlay is regarded as an efficient method to rehabilitate moderately deteriorated pavements. Despite the application of an adequately designed overlay, when HMA overlays are built on jointed concrete pavement (JCP) or a cracked surface, reflective cracking can develop shortly after the overlay application due to traffic loads and environmental changes. Several remedial techniques, including interlayer systems, have been incorporated into HMA overlays to control reflective cracking. This study examined the behaviour of traffic-induced reflective cracking using a finite element (FE) model for an HMA overlay with and without interlayer systems, and evaluated the performance of interlayer systems in controlling reflective cracking. To achieve these objectives, a three-dimensional FE model was built for a typical HMA overlay constructed over JCP. A linear viscoelastic model and a bilinear cohesive zone model (CZM) were incorporated into the FE model to characterize continuum and fracture behaviour of the HMA. Using the bilinear CZM, reflective cracking initiation and propagation were simulated. Transient moving vehicular loading was applied across a joint to develop reflective cracking. In order to force reflective cracking development by one pass of load application, various levels of overload were applied. Two distinct interlayer systems, sand mix and steel netting with slurry seal, were examined for their effectiveness in controlling reflective cracking. The sand mix was modelled with the LVE model and bilinear CZM. The steel netting interlayer system was modelled with beam elements for steel wires and membrane elements for slurry seal To quantify the status of reflective cracking development, a representative fractured area (RFA_{OL}), that is equivalent stiffness degradation in the entire HMA overlay, was used. A limit state load approach was used to determine the resistance of the HMA overlay to reflective cracking in terms of normalized axle load of an overload equivalent to an 80-kN single-axle load. The service life of the HMA overlay regarding reflective cracking was specified by the number of load repetitions based on the Paris law. A reflective cracking control factor was defined as the ratio of the service life to the HMA overlay without an interlayer system; the factor was used to evaluate the performance effectiveness of these interlayer systems in controlling reflective cracking.

It was found that the bearing capacity of existing JCP played an important role in developing reflective cracking. Reflective cracking potential increased inversely with the modulus of base and sub grade layers. Interface bonding conditions, especially bonding strength, affected the development of reflective cracking. Lower interface bonding strength resulted in greater potential for developing reflective cracking. The study concluded that the sand mix interlayer system extended the service life of the HMA overlay regarding reflective cracking due to its relatively high fracture energy. A macro-crack level of reflective cracking was initiated in the wearing course in the HMA, so-called crack jumping. The softer the sand mix, the tougher it may be, but it may cause shear rutting in HMA overlay. Hence, sand mix fracture energy and thickness thresholds should be identified. The steel netting interlayer system performed better than the sand mix; the performance of the latter *is thickness and fracture energy dependent. When the steel netting interlayer system was installed properly, the reflective cracking service life of the HMA overlay was found to be six times longer than that of the HMA. The performance was still better than sand mix when localized deboning induced. However, severe de-bonding of steel netting can be detrimental to its performance*

Keywords: Hot-Mix Asphalt (HMA), Jointed Concrete Pavement (JCP), cohesive zone model (CZM). representative fractured area (RFA$_{OL}$

1. Introduction

1.1 Reflective Cracking

Pavement rehabilitation is needed to restore the structural and/or functional capacity of deteriorated pavements. Typical pavement rehabilitations include restoration, recycling, resurfacing, and reconstruction. The proper rehabilitation method is determined based on the type and condition of the existing pavement. For a moderately deteriorated Portland cement concrete (PCC) pavement, resurfacing existing pavement with a relatively thin hot-mix asphalt (HMA) layer, known as an HMA overlay, is regarded as an efficient method. HMA overlays are designed to support anticipated traffic volume over a specific period of time. Despite the application of an adequately designed overlay, when HMA overlays are built on a jointed concrete pavement (JCP) or a cracked surface, reflective cracking can develop shortly after the overlay application. Coupled with the presence of discontinuities in existing pavement, reflective cracking in HMA is caused by traffic loads and environmental changes that result in a large amount of movement in the HMA overlay at the discontinuities. Hence, stresses in the HMA overlay are intensified in the vicinity of discontinuities. Since the cracks become an extension of these discontinuities, this process is called reflective (or reflection) cracking. Reflective cracking is classified into four types: transverse, centreline, "D," and widening reflective cracking (Miller and Bellinger, 2003). Transverse reflective cracking occurs directly over a contraction joint of underlying JCP. The location of the reflective cracking coincides approximately with the JCP transverse joint. Centreline and widening reflective cracking are parallel to traffic direction. Several remedial techniques have been incorporated into HMA overlays to control reflective cracking, including placing a thin layer at the interface between an existing pavement

1.2 Problem Statement

Considerable research has been conducted to explain the behaviour of reflective cracking and to examine the performance of interlayer systems using mechanical and empirical methods. These approaches have advantages as well as drawbacks. In field crack surveys, the behaviour of reflective cracking in its early stages of crack initiation and propagation cannot be examined explicitly, since reflective cracking cannot be observed until it reaches the HMA overlay surface. Field tests have other inherent limitations, including high variability. Laboratory tests overcome some field limitations by controlling for material quality, loading characteristics, temperature, and specimen geometry; however, laboratory tests are limited in simulating real-life conditions.

Mechanistic approaches using a layered theory and a finite element (FE) analysis may allow predictions of the pavement response to loading. Compared to layered theory, FE analysis is superior in modelling complicated geometry for interlayer systems and moving traffic loading, allowing it to provide more insights into the development of reflective cracking under various loading conditions. However, conventional FE analysis, which is based on continuum mechanics, has been unable to capture the fracture behaviour of HMA overlays directly. HMA failures have been predicted using transfer functions based on empirical methods.

Fracture mechanics based FE analysis can be used to address the drawbacks of conventional FE analysis. The fracture mechanics approach has been also applied to predict fracture behaviour of HMA using a stress intensity factor (SIF) and the path-independent J-integral in a vicinity of a crack. Recently, a cohesive zone model (CZM) has been adapted to facilitate modelling the entire crack process for HMA pavements (Jeng and Perng, 1991; Soares et al., 2003; Paulino et al., 2004; Song, 2006; Baek and Al-Qadi, 2008; Kim et al., 2009). This adaptation has made it possible to predict the fracture behavior of HMA overlays under stationary traffic loading and temperature variation. To date, the fracture behaviour of HMA overlays under more realistic traffic loading has not been investigated. Also, the performance of interlayer systems depends on the circumstances of HMA overlay design and installation conditions.

1.3 Research Objectives

The principal objectives of this study were to examine the behaviour of traffic-induced reflective cracking using an FE model for an HMA overlay with and without interlayer systems, and to evaluate the performance of interlayer systems in controlling reflective cracking. To achieve these objectives, a typical HMA overlay constructed over a JCP was modelled and a moving traffic loading was applied across a joint. Crack initiation and propagation were modelled in an HMA overlay using a bilinear CZM. Two distinct interlayer systems, sand mix and steel netting, were examined for their effectiveness in resisting reflective cracking.

2. HOT-MIX ASPHALT OVERLAY PAVEMENT MODEL

2.1 Three-Dimensional Hot-Mix Asphalt Overlay Pavement Modeling

2.1.1 Geometry and boundary condition

A three-dimensional FE model was built for a typical HMA overlay placed on a JCP. Figure 4.1 illustrates the HMA overlay pavement model (Baek and Al-Qadi, 2009). This pavement has four layers: an HMA overlay 57 mm thick, two concrete slabs 200 mm thick, a base layer 150 mm thick, and a subgrade layer 10,000 mm thick. The HMA overlay consists of a leveling binder 19 mm thick and a wearing surface layer 28 mm thick. A full-cut construction joint 6.4 mm wide was made in transverse direction to be a vulnerable structure regarding reflective cracking, and joint spacing was 6.0 m. To make it more critical to reflective cracking, no dowel bars or aggregate interlocking are considered in this pavement model, but the effect of joint stiffness is examined. The dimensions of a one-lane concrete slab are 6.0 m in length and 3.6 m in width. Since one concrete slab is geometrically symmetric with respect to the center of the slab, one quarter of the slab was chosen to simplify the pavement model. When moving vehicular loading is applied on the HMA overlay, the symmetric condition is not valid along the longitudinal direction. Because only local behaviors in the HMA overlay in the vicinity of the joint far from the boundary are investigated, the symmetric condition assumes to be held for more efficient computation. Symmetric boundary conditions were applied accordingly to the three faces surrounding the two concrete slabs. Three-dimensional linear infinite elements (CIN3D8) were used at a far-field zone. To set zero-deformation and to minimize reflection of stress wave, called a “quiet” boundary condition for dynamic analysis. Tangential behaviors at pavement interfaces were controlled by the Coulomb friction model, which has been used often in pavement modeling (Yoo and Al-Qadi, 2006). A friction coefficient of 1.0 was assumed for all pavement interfaces except a wearing surface-leveling binder interface, where the bonding condition can be regarded as excellent. A “rough” tangential condition was adapted to the interface by imposing an infinite friction coefficient. No separation in normal direction was allowed in this friction model once two interfaces were contacted. This interface condition is appropriate for conventional pavement modeling in which no debonding is assumed to occur. However, it may not be ideal for the HMA overlay pavement model, because slipping and debonding may occur at an HMA-concrete interface. In future studies, more realistic interface models to simulate slipping and debonding shall be used. To ensure the effect of boundary conditions applied to the quarter-scale pavement model on pavement responses of interest, pavement responses calculated from the quarter-scale pavement model are compared with those from a full-scale pavement model. The geometry and boundary conditions of full-scale and quarter-scale pavement models. The two pavement models consist of the same layers of HMA overlay 57 mm thick, JCP 200 mm thick, base 150 mm thick, and subgrade 10000 mm thick. The size of the full-scale pavement model is 12 m long in the traffic direction, 12 m wide in the transverse direction, and 10 m deep. Each concrete slab is 6 m in length and 3.6 m in width in the full-scale pavement model. Fixed boundary conditions ($u_x = u_y = u_z = 0$, $\theta_x = \theta_y = \theta_z = 0$) are imposed on four outer planes of the subgrade in the full-scale pavement model. The two sides of the HMA overlay, JCP, and base are set to move freely. For the quarter-size pavement model, in contrast, the x-axis symmetric boundary condition ($u_y = 0$, $\theta_x = \theta_z = 0$) is given to the two x-z planes, and the y-axis symmetric boundary condition ($u_x = 0$, $\theta_y = \theta_z = 0$) is given to the y-z plane. Pavement responses of HMA overlay by an 80-kN single-axle dual-tire loading in the full-scale and quarter-scale pavement models are compared. Surface deflections on the HMA overlay directly over the joint along the entire HMA overlay width of 3.6 m. As expected, surface deflections are symmetric to the longitudinal center line of the pavement in the full-scale pavement model. In addition, transverse, longitudinal, and vertical strains are computed at the bottom of the HMA overlay for the full- and quarter-scale. For the half width of the pavement of L of 1.8 m, all strain values of the quarter-size pavement model are fairly identical to those of the full-scale pavement model. Hence, it is valid to apply the axis symmetric boundary condition to the quarter-size pavement model.

2.2 Interlayer System Modeling

Three HMA overlay designs were modeled to evaluate the effectiveness of the interlayer system in controlling reflective cracking. The three HMA overlay alternatives. The HMA overlay model described in the previous section is a control section having no interlayer system.

In addition, it is built on two alternative HMA overlays where sand mix and steel netting interlayer systems are used, while the three HMA overlays have the same structure and materials, with the exception of the following:

Design A (control section): The leveling binder HMA consists of 9.5 mm NMAS of aggregates and PG 64-22 unmodified asphalt binder; Design B (sand mix section): The leveling binder layer is replaced with the sand mix interlayer system whose NMAS is 4.75 mm, and PG 78-28 polymer modified binder is used and Design C (steel netting section): Steel netting interlayer system is placed beneath the leveling binder.

2.3 Steel netting interlayer system modeling

The steel netting interlayer system consists of two major components to be modeled: steel netting and slurry seal. The steel netting has a hexagonal woven grid structure. The dimension of a single aperture of the steel netting is 120 mm traffic direction by 80 mm in transverse direction. In addition, transverse reinforcing bars are placed in a spacing of 240 mm in traffic direction. Each component of the steel netting is modeled with a beam element. Two-node linear beam elements (B31) are assigned for the single wires and three-node quadratic beam elements (B32) are assigned for the double-twisted wires and reinforcing bars. The beam elements have a circular cross section. The diameter is 2.7 mm for single wires, 5.4 mm for double-twisted wires, and 4.9 mm for reinforcing bars (Elseifi and Al-Qadi, 2005a). The linear elastic material property for the beam elements is presented in Table 4.2. The slurry seal is modeled with membrane elements that can carry in-plane force. In the steel netting system, slurry seals have the important roles of providing better bonding to surrounding layers, protecting the steel netting, and absorbing strain energy. From a modeling point of view, the protective function is not necessarily realized. While slurry seals can absorb strain energy, this effect can conservatively be assumed to be insignificant. Slurry seal is used in the steel netting interlayer system to specify bonding conditions at two interfaces at which the steel netting is attached. Two different interface conditions are assumed: the steel netting is attached perfectly to the HMA overlay and normally to the concrete surface. The steel netting is embedded into the slurry seal layer by sharing its nodes with the membrane elements. For the perfect bonding condition, a “tied” constraint is applied to the upper surface of the membrane elements and the bottom of the HMA overlay, so no slip or debonding occurs at the steel netting/HMA interface. Interface conditions between the steel netting interlayer system and concrete surface are controlled by the Coulomb friction model, similar to the other interfaces in this pavement model. The slurry seal was assumed to have a low modulus of 1.0 GPa at -10^{o}C.

3.0 Hot-Mix Asphalt Overlay Behavior at a Joint

Stress analysis was conducted to examine potential problems due to traffic loading in the HMA overlay without interlayer systems (System A). Stress distributions induced at the vicinity of the concrete joint in HMA and concrete slabs as moving loading is applied. To examine critical responses, stress distributions were captured at a middle-cut cross section in a y-z plane under the wheel path. In the Cartesian coordination used in this study, x, y, and z axes indicate transverse direction, longitudinal (or traffic) direction, and depth, respectively. When traffic loading approaches the joint, compressive (negative) vertical stresses ($\square_{zz}$) occur under the loading, and higher tensile (positive) ($\square_{xx}$ and $\square_{yy}$) and shear ($\square_{yz}$) stresses are concentrated at the top of the approaching concrete slab. This results from the flexural behavior of the approaching concrete slab near the joint. As shown in Figure 5.1(a), if the tensile stress at the HMA-concrete interface reaches its bonding and/or shear strength, traffic loading can induce debonding and/or delamination at the interface.

3.1 Limit state load approach

In the limit state load approach, one pass of an overload is applied in order to force reflective cracking in the HMA overlay. A total axle load of the overload is amplified, keeping the same speed, contact area, and normalized vertical contact stress distribution of the 80-kN, single-axle, dual-assembly tire used in the previous analysis (see section 4.21). A limit state load is determined when a macro-crack level of reflective cracking occurs in the entire cross section of the HMA overlay. The limit state load can represent the capacity of the HMA overlay to withstand reflective cracking. The relationship between the overload and the number of load repetitions is established by the standard 80-kN axle load based on the Paris-Erdogan law. The service life of the HMA overlay related to reflective cracking is estimated in terms of the number of load repetitions. Figure 5.4 summarizes the limit state load approach.

3.2 Effect of Bearing Capacity on Reflective Cracking Development

Evaluation of existing pavement conditions plays an important role in the design of HMA overlay. Depending on the level of deterioration, an appropriate pre-overlay treatment must be performed prior to construction of the HMA overlay. In addition, structural capacity of the existing pavement is used to determine the thickness of the HMA overlay, taking into consideration its overall structural integrity of the HMA overlay. However, the structural HMA overlay design does not account for reflective cracking localized behavior of the HMA overlay, especially in the vicinity of the joint of existing concrete pavements, although it is relevant to the development of reflective cracking, especially due to traffic loading. Hence, it is necessary to examine the effect of joint condition of existing jointed concrete pavements (JCP) on the behavior of reflective cracking.

4. CONCLUSIONS

In this study, a three-dimensional FE model was built for an HMA overlay on an existing JCP. By integrating a LVE model and bilinear CZM, continuum and fracture behaviors of HMA were characterized. Transient moving vehicular loading was applied to develop reflective cracking. In order to force reflective cracking development by one pass of load application, various levels of overload were applied. The magnitude of the overload was converted to an equivalent number of load repetitions of an 80-kN axle load based on the Paris law. The development of reflective cracking was quantified using representative fractured area (RFA), an equivalent stiffness degradation parameter, and a fracture energy damage parameter that indicates fracture energy dissipation. Two types of interlayer systems were selected: sand mix and steel netting interlayer systems. The sand mix was modeled with the LVE model and bilinear CZM. Compared to the leveling binder, the modulus was relatively lower but fracture energy was higher. The steel netting interlayer system was modeled with beam elements for steel wires and membrane elements for slurry seal. To simulate ideal field installation conditions, steel netting interlayer systems were assumed to bond perfectly to the HMA. The performance effectiveness of the interlayer systems was evaluated in terms of the reflective fracture resistance factor, $\square_r$, defined as a ratio of the number of load repetitions of the HMA with an interlayer system to the HMA without interlayer system.

Using the FE model, this study provided a better understanding of the fracture mechanism in the HMA overlay over JPC due to moving vehicular loading, as well as understanding of the reflective cracking control mechanism of sand mix and steel netting interlayer systems. Under various conditions, the development of reflective cracking was examined and the performance of interlayer systems was evaluated. The main conclusions of this study include the following:

The bearing capacity of existing JCP plays an important role in the development of reflective cracking. The potential for reflective cracking increases inversely with the modulus of base and subgrade layers. Hence, reflective cracking becomes a critical distress when the bearing capacity of an existing JCP is insufficient.

Interface bonding conditions, especially bonding strength, affect the development of reflective cracking. The lower the interface bonding strength, the greater the potential for reflective cracking. On the other hand, interface stiffness insignificantly affects the development of reflective cracking.

The sand mix interlayer system is sufficiently effective in controlling reflective cracking. The sand mix interlayer system extends the service life of the HMA overlay in terms of reflective cracking. The increase in service life depends on fracture energy of the sand mix. The softer the sand mix, the tougher it may be, but it may cause shear rutting in HMA overlay. Hence, sand mix fracture energy and thickness thresholds should be identified**.** Also, as the bearing capacity of existing JCP increases, the performance effectiveness of the sand mix interlayer system gradually decreases, but service life enhancement becomes greater.

Due to higher fracture tolerance of the sand mix, macro-crack level of reflective cracking is initiated in the wearing course in the HMA, so-called crack jumping. In some cases, the crack jump phenomenon can play an important role in the performance of the HMA overlay because it can prevent both penetration of moisture into underlying pavement layers as well as material loss by pumping.

The performance of the steel netting interlayer system is superior to that of the sand mix. When the steel netting interlayer system is installed properly, the reflective cracking service life of the HMA overlay was found to be six times longer than that of the HMA. Local interface debonding at a joint negatively affects controlling reflective cracking initiation, but the steel netting interlayer system is still efficient to retard reflective cracking. Due to improper installation, severe debonding at the interface between the steel netting interlayer system and surrounding layers could significantly reduce control of reflective cracking.

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