DEEP ANALYSIS ON INTERLAYER RESTRAINING REFLECTIVE CRACKS IN ASPHALT OVERLAY OLD CONCRETE PAVEMENT

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Abstract
It is a common technology in pavement rehabilitation to overlay old concrete slabs with asphalt mixtures. The main problem in this practice is that reflective cracks often show up easily in the asphalt overlay. It is known that the initiation or propagation of the reflective cracks can be delayed or prevented by adding an interlayer between the asphalt overlay and the old concrete pavement. With the three-dimensional finite element model and analysis, the load and thermal stresses in the asphalt overlay on old concrete pavements with cracks were studied. This paper showed a detailed study of the effects of the stress absorbing interlayer and the reinforced layer on restraining reflective cracks. Based on the principles of fracture mechanics, the stress intensity factor around cracks was discussed.

Keywords: Reflective cracks, Asphalt overlay, Interlayer, Three-dimensional finite element method, Stress intensity factor

1. Analysis model and parameters
Static stress analysis was performed in this study using the finite element analysis program SAP91 from ALGOR, Inc. The object model consists of an asphalt concrete (AC) overlay, an interlayer, a cracked Portland cement concrete (PCC) pavement layer and a subgrade. In order to better represent the characteristics of the half space subgrade, its dimensions were extended from those of other layers, as shown in Figure 1. Several assumptions were used in the analysis, as follows.
1) All layers are homogenous, isotropic, continuous and line-elastic materials.
2) The vertical and horizontal displacement at interface is continuous.
3) The deflections at the bottom of the subgrade and the horizontal displacement at side faces of the subgrade are zero; the horizontal displacement of the AC and PCC layers at both ends are zero, but free at two side faces.
4) The weight of the pavement structure is neglected; the joint width is 1 cm; and the load is not transferred through the joint.

It is the vehicle load and temperature change that lead to the reflective cracks in asphalt overlay. From the fracture theory, the reflective cracks in the overlay was caused by tensile stresses at the bottom of the asphalt overlay which creates the opening mode cracks and by the shear stresses which creates the shear cracks. According to other researchers’ results[1], when the load is at the joint, the normal stress and principal stress
at the bottom of the overlay above the joint are compressive, which is due to the rebounding press of the old cement slabs. The shear stress in the asphalt concrete layer along the face over the joint is zero because the structure and load are symmetrical. Therefore, the symmetrical load is not the main cause of the cracking. Unsymmetrical loads are mainly used in the analysis, as shown in Figure 2. The standard axle load configuration BZZ-100 used in pavement design in China is used in the analysis. The wheel loading area is simplified as an 18.9 cm by 18.9 cm square. The distance between two adjacent wheels is 0.32 m.

Without special emphasis, the default material parameters are the following: the asphalt concrete Young’s modulus $E=1200$ MPa, Poisson ratio $\nu=0.25$; the cement concrete $E=30000$ MPa, $\nu=0.15$; the subgrade $E=80$ MPa, $\nu=0.30$.

2. Load stress analysis

2.1 The influence of the thickness of asphalt overlay without interlayer

In this section the stresses at the bottom of the AC layer over the joint were analyzed when the AC layer is overlaid directly upon the cement concrete pavement. It was found that under the unsymmetrical load, the maximum principle stress, $\sigma_{1\text{max}}$, and the maximum shear stress in the x-z plane pointing to the z direction, $\tau_{yz\text{max}}$, are influenced significantly by the thickness of the asphalt overlay. The normal stress in the y direction, $\sigma_y$, is negative at the joint and small positive value near the joint, which has trivial effect on cracking and can be ignored. Therefore, $\sigma_1$ and $\tau_{yz}$ are two main factors leading to the reflective cracks. When the asphalt overlay is thinner, $\sigma_1$ and $\tau_{yz}$ become larger and may exceed the strength limits of cement concrete, which results in the occurrence of reflective cracking. Increasing the overlay thickness can effectively reduce $\sigma_1$ and $\tau_{yz}$. Using 1.0 MPa as the average flexural tensile strength of asphalt concrete, the thickness of the AC overlay should be at least 0.2m in order to inhibit the generation of cracks.

2.2 The interlayer influence analysis

The interlayer is modelled as a linear elastic layer with a 0.01m thickness. The Young’s modulus $E$ is assumed to be in the range of 30-140MPa and 2000-8000MPa for asphalt membrane interlayer and geogrid respectively. Two types of thickness, 0.05 m and 0.10 m, were used for the asphalt overlay. The change of stresses in the overlay at different interlayer moduli is analysed.

It can be observed that the presence of interlayer greatly alleviates the stress concentration. For asphalt membrane interlayer, the lower the $E$ is, the more significant the decrease is. For geogrid, it is the opposite. When asphalt membrane is used, the stress at the joint is very low, which is good for reducing the reflective cracks. But two phenomena need to be paid attention to. First, although the bottom $\sigma_y$ is negative at the joint, it is positive at the centre of the loading area, and it increases rapidly with the
decrease of the interlayer modulus. This means that the cracking may happen at locations away from the joint. Second, the pavement surface deflection increases with the decrease of the interlayer modulus, indicating the reduction of the total strength of the pavement structure. All factors must be taken into account for a rational choice of material parameters when the asphalt membrane or other high deformation material as stress absorbing interlayer is used. For geogrid, the stress reduction effect is pretty significant when the overlay thickness is 0.05 m and the interlayer modulus, \( E \), is in the range of 2000-6000MPa. When the \( E \) is larger than 6000MPa, the decrease effect is reduced, and the stress in the geogrid becomes high. When the thickness of overlay is 0.1 m, the reduction of the unfavourable stresses at the overlay bottom, due to the increase of interlayer modulus, becomes trivial; sousing high values of \( E \) is meaningless. Generally, it is not necessary to use a high geogrid modulus. Based on the results in this analysis, 4000-6000MPa should be sufficient. It can also be taken as a conclusion from our study that the stresses when the overlay is 0.05 m thick and the geogrid modulus is 6000MPa or 8000MPa are equivalent to the stresses when the overlay is 0.10 m thick and the geogrid modulus is 2000MPa or 4000MPa. Therefore, increasing the geogrid modulus allows the use of a thinner overlay.

3. Thermal stress analysis

The pavement is an open structure. The temperatures in all layers fluctuate under the influence of many factors, such as solar radiation, environment temperature, wind speed, rain, and snow. At low temperatures contraction deformation will occur in the AC and PCC layers. Low ambient temperatures also lead to the curling deformation in PCC slabs. If these deformations are restrained, high thermal stresses will appear in pavement structure.

To calculate thermal stresses, first we the temperature field in the pavement structure. The variation of the pavement temperature has both daily and yearly cycle patterns. Considering the stress relaxation of asphalt concrete in the long yearly cycle, it is appropriate to concentrate on the effect of daily temperature change. Field measurement and theoretical analysis show that the pavement temperature changes in a pattern similar to a sinusoidal curve. It is assumed that the mean daily temperature at the overlay surface is 0°C, and the temperature variation range covers from -10°C to 10°C. Assume the coefficient of temperature conductivity is 0.0021m²/h and 0.0025m²/h AC and PCC respectively, the coefficient of thermal conductivity is 1.0kcal/m·h·°C and 1.3kcal/m·h·°C for AC and PCC respectively, the temperature fields at the time \( (t_0) \) of lowest average temperature and at the time \( (t_1) \) of maximum negative temperature gradient can be calculated according to the one-dimensional heat-conduction differential equation under the first boundary conditions. It is assumed that the asphalt layer \( E \) is 5000MPa, the membrane \( E \) is 200-800MPa, and that all parameters do not change with temperature. The analysis result under the two temperature fields is shown in Figure 3.

In Figure 3, it shows that \( \sigma_{1\text{max}} \) at the bottom of the asphalt overlay at joint is lager than the stress introduced by load, so as is the \( \tau_{yz\text{max}} \). If the magnitude of temperature drop exceeds 10°C due to situations such as strong wind, rain, etc, these maximum
stresses will become larger. The above analysis suggests that temperature stress is the major cause of reflective cracks in asphalt overlay. Figure 3 also shows that increasing the thickness of asphalt overlay only slightly reduces the maximum stresses in the asphalt overlay at the crack.

Since increasing the thickness of overlay cannot prevent the initiation of cracks caused by thermal stresses, other effective method to reduce cracking should be used. To add interlayer is one approach. The interlayer is much thinner than other pavement layers, so its influence on the pavement structure temperature field can be neglected. Using a 0.05 m thick overlay and the temperature field at the time \( t_{1} \) of maximum negative temperature gradient, the stresses around the joint were calculated for different values of interlayer moduli. The results are shown in Figures 4 and 5.

In Figures 4 and 5, the bottom stresses of overlay at the joint are greatly relieved, and the top stresses are also slightly relieved. It is interesting to note that the shear stresses are very small for all interlayer moduli. This is because the shear stresses result from the press of the curling concrete slabs on the asphalt overlay, which has a limited influence region. The press is greatly reduced when an interlayer is added between the old concrete pavement and the asphalt overlay. Therefore, the main effect of temperature change on the asphalt overlay with an interlayer is opening mode cracking. Since the tensile stresses in the overlay decreases with the increase of the interlayer modulus for asphalt membrane, and increases for geogrid, a lower modulus asphalt membrane or a higher modulus geogrid is preferred. However, attention should be paid to the selection of high modulus geogrid because the tensile stress in the interlayer also increases with the increase of its modulus. It is found that the thermal stresses are insensitive to the thickness of overlay, and the coefficient of thermal expansion of interlayer has little effect on the stresses at joint.

### 4. Load and thermal stress analysis

In the previous sections, the stresses in the asphalt overlay at the joint under traffic load and temperature change were studied respectively, as well as the effectiveness of interlayer to control reflective cracks. In this section, the stresses under the combination of traffic load and temperature change are studied. The temperature field at the maximum negative temperature gradient \( t_{1} \) was used. Compared to the worst stresses under the effect of temperature change only, when the loads are added, the stress in thinner overlay (0.05m) decreases and the stress in thicker overlay (>0.1m) increases. Generally, when the overlay is thinner, it works well under the combined effects. But no matter how thick the overlay is, the combined shear stress is larger than the shear stress caused by either load or temperature change only. Figure 6 shows that if the overlay is over 0.15 m, the shear stress \( \tau_{y,z} \text{max} \) is larger than that caused by load only in a 0.05 m thick overlay. It shows that the overlay, which works well under load, may not be fit for the situation when the load and temperature works together.

What will the stresses in asphalt overlay be under the combination of load and temperature change, if an interlayer is used? It is assumed the E of interlayer is 200-800MPa or 2000-8000MPa, the thickness of the overlay is 0.05 m. The stresses are calculated at different interlayer moduli.
Compared to the stresses under the effect of temperature change only, $\sigma_{yy}$ reduces slightly, and $\tau_{yz}$ increases significantly. The stress distribution in the overlay changes greatly after the interlayer is introduced. Firstly, the bottom tensile stress at the joint decreases sharply. If a stress absorbing interlayer is used, the lower the modulus is, the sharper the decrease of bottom stress will be. But if a geogrid is used, a sharp fall appears as a consequence of a higher modulus. Secondly, if a stress absorbing interlayer with low modulus and high deformation ability is used, large tensile stress appears at the site marked with "*" (shown in fig.2). As a conclusion from the analysis results, it is found that an appropriate E should be neither too high nor too low. The analysis shows that an interlayer is effective to reduce the shear stress in the overlay, and the stress absorbing interlayer works better than the geogrid. The analysis results also show that when a stress absorbing interlayer is used, the maximum shear stress appears at the middle of the depth of the asphalt overlay. For geogrid, it is at the bottom.

5. The reflective cracks analysis

5.1 Basic concept

It is known from fracture mechanics that whether a crack propagates, and the stress field around the crack determines how fast it does. It has been proved by experiments and theoretical analysis that stress concentration exists at the tip of cracks. Theoretical analysis in fracture mechanics shows that the stress at the crack tip has singularity of $r^{-0.5}$ order ($r$ is the distance between the stress point and the crack tip). When $r$ approaches to zero, the stress will grow to $\infty$, as shown in Figure 7. However, this does not happen in reality, because asphalt concrete is not an ideal elastic material. It consists of asphalt, aggregate, and fillers. When the stress at the crack tip exceeds the material strength limit, cracks appear. The shape of the actual crack is not sharp-angled. Instead, it forms a band of crack section. Because the theoretical tensile stress at the crack tip is singular, it cannot be used directly to judge whether the crack will propagate or not. Figure 7 shows that $\sigma_{yy}$ change in proportion to the constant $K$, which is called stress intensity factor. This factor has simple and clear quantity relationship with boundary stresses and, and the characteristic size of the crack. It not only reflects the singularity of the stress field at the crack tip, but also reflects the average stress level and the effect of crack size. Therefore, it can be used to evaluate whether or not the crack propagates. $K_I$ and $K_{II}$ corresponding to the opening mode cracking and shear mode cracking respectively, can be calculated by the following formula:

$$K_I = \lim_{r \to 0} (\sqrt{2\pi r} \sigma_y)$$

$$K_{II} = \lim_{r \to 0} (\sqrt{2\pi r} \tau_{xy})$$

where $\sigma_y$ and $\tau_{xy}$ are tensile and shear stresses at the tip of a crack respectively.
is the distance between the stress points the tip of the crack.
In this study, the stress state at the crack tip is analysed using the finite element method, then the stress intensity factor obtained according to equation (1) is used to analyse the mechanism of crack propagation.

5.2 Symmetric load effect
It is recalled from previous discussion that the symmetric load is not the main cause of cracking. Calculation using a 0.1 m overlay and symmetric load shows that the shear stress in the overlay at the crack tip is zero, and the tensile stress in the direction of Y is negative. So is the $K_1$ or $K_{II}$. This proves that the crack is closed under symmetric load. This is because the modulus of old concrete pavement is much larger than that of asphalt concrete, so that the neutral axis the pavement is below the interface of the AC and PCC. The stress state in the AC overlay is in compression, which leads to the closure of the crack.

5.3 Unsymmetrical load effect
What is the appropriate thickness of asphalt overlay is always the focus of research. Here the effect of overlay thickness on the propagation of crack is analysed. From the analysis in previous sections, we know that the tensile stress in the AC overlay is negative under the unsymmetrical load, the corresponding stress intensity factor $K_1$ is negative. Figure 8 shows the change of $K_{II}$ in response to the change of overlay thickness.

From Figure 8, $K_{II}$ decreases gradually with the increase of overlay thickness, so it is an effective way to reduce the initiation of shear crack by increasing the overlay thickness.

Asphalt is a temperature sensitive material, whose modulus is affected by temperature greatly. The modulus in winter can be ten times as large as the modulus in summer. Field observation of the performance of overlay indicates that the reflective crack is much easier to appear in winter than in summer. When the temperature decreases sharply and in a large magnitude, the cracks in asphalt overlay propagate quickly. The mechanism is analysed from the stress intensity factor point of view. Figure 9 shows the change of $K_{II}$ corresponding to different overlay moduli.

It can be seen that higher overlay modulus leads to a larger $K_{II}$, which means that the propagation speed in winter is larger than that in summer. This is consistent with the field observation. The tensile stress in the direction of Y around the joint and the $K_1$ are negative under the unsymmetrical load, which do not promote the propagation of cracks. Previous analysis shows that an interlayer between the asphalt overlay and the old cement pavement can relieve the adverse stresses at the joint, which means that it can reduce the probability of the occurrence of cracks. But what if the crack gets across the interlayer? In order to analyse the stress intensity factor under unsymmetrical load, the original model and parameters are used, with the assumption that the interlayer breaks at the crack location. The result shows that the tensile stress intensity factor $K_1$ is still
negative, so that the normal stress does not promote crack propagation. Figure 10 shows the change of shear stress intensity factor $K_{II}$ with respect to the interlayer modulus. It can be seen from Figure 10 that higher interlayer modulus results in higher stress intensity factor $K_{II}$, and, higher crack propagation rate. When the interlayer modulus exceeds 60MPa, the increase rate of $K_{II}$ tends to be slower.

Figure 11 shows the result when the interlayer (geogrid) doesn’t break at the crack. The geogrid is selected because it has high tensile strength. It will not break at crack thoroughly. When fatigue-induced damage appears at the bottom of asphalt overlay, geogrid will still work to reinforce the overlay. Figure 11 shows that $K_{II}$ decrease with the increase of f geogrid interlayer modulus, which means the crack propagation rate is reduced.

6. Conclusions

1) The reflective crack in asphalt overlay is mainly caused by the traffic load and temperature change. The load is the major cause of shear mode crack for it makes the overlay have relative vertical movements at the two side of the joint. Temperature is the major cause of opening mode crack, for it leads to the horizontal movements of the overlay at the joint. Temperature has more significant effect than the load.

2) Increasing the thickness of asphalt overlay can control the initiation of cracks caused by load. But it has no obvious effect on controlling cracks caused by temperature when no interlay is added. In order to control this type of crack by only increasing the thickness of the overlay, the thickness of the asphalt overlay should be at least 0.2 m.

3) It is an effective way to reduce the stress concentration at the joint if a stress-absorbing layer with low modulus and high deformation ability is used as interlayer. The material of low modulus has more obvious effect. But lower modulus leads to higher bottom tensile stress at other site away from the joint, so the modulus of interlayer should not be less than 30MPa. Higher modulus will accelerate the propagation of cracks. From a systematic point of way, 60MPa is appropriate for stress absorbing interlayer. When geogrid is used as the interlayer, the higher the modulus is, the better its effect is, but higher modulus also leads to higher internal stress. According to the analysis result, 4000-6000MPa is proper. It should have a high tensile strength in order to sustain the large internal stress.

4) When traffic load and temperature change work together, the bottom shear stress is larger than that under the load or temperature only. Generally, the two factors will mutually aggravate the cracking. An interlayer can effectively reduce the adverse stresses

7. References
