A MODEL FOR TOP-DOWN REFLECTION CRACKING IN COMPOSITE PAVEMENTS

K. Nesnas[1] and M. Nunn[1]
(1) TRL Limited, Old Wokingham Road, RG45 6AU, Crowthorne, UK

Abstract

Investigations of as-laid composite roads in the UK have demonstrated that reflection cracks generally initiate at the surface and propagate down to the existing crack in the underlying concrete layer rather than travel up from the crack. The asphalt surfacing is normally treated as a passive layer that responds to the thermal movements of the crack in the cement bound base. This approach will predict bottom-up cracking. This paper presents a new response model, which treats the cement bound and asphalt layers as a complete system and recognises that:

- The asphalt thermal expansion coefficient is much higher than that of concrete;
- Larger temperature changes occur in the asphalt surfacing;
- Age hardening results in asphalt close to the surface becoming the most brittle region of the asphalt.

This response model predicts top-down cracking and, furthermore, it predicts that bottom-up cracking from the existing crack will not normally occur. Field data is also presented to supports these predictions.

1. Introduction

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Models of flexible composite pavements generally treat the asphalt layer as a passive material that responds to thermal movements of the crack in the cement bound base. This results in the prediction that reflection cracks will propagate upwards from the existing crack in the concrete. This is contrary to field observations by TRL, which clearly shows that reflection cracks initiate at the surface of the asphalt layer and propagate downwards. The field evidence also indicates that reflection cracks in as-laid composite roads are caused by thermally induced stresses rather than traffic induced stresses. The main factors influencing this behaviour are:

- The thermal expansion coefficient of asphalt is much higher than that of concrete;
- Larger temperature changes occur in the asphalt layers;
- Age hardening results in asphalt close to the surface becoming the most brittle region of the asphalt

Fax: +44 (0) 1344 770356
E-mail: knesnas@trl.co.uk

Asphalt mixtures display visco-elastic behaviour. If an asphalt test specimen is strained to a predetermined point, and held constant, a stress will be induced. Depending on temperature, this stress will dissipate more or less quickly. This process is called relaxation. At high temperatures the viscous component dominates and total stress relaxation may take a few minutes, and at very low temperatures relaxation can take many hours or even days.

Cracking occurs when the tensile stress and related strain induced by traffic and/or temperature changes exceeds the breaking strength of the mixture. At elevated temperatures stress relaxation will prevent these stresses reaching a level that can cause cracking. On the other hand, at low temperatures, the tensile condition will persist and, therefore pavement cracking will be more probable. It is also recognized that bitumen in a mix ages during its service life. This ageing, which is more severe at the exposed surface of the road, results in a progressive increase in the stiffness modulus of the asphalt together with a reduction in its stress relaxation capability, which further increases the likelihood of cracking.

Thermal gradients and cyclic temperature changes result in a complex situation existing in the vicinity of the crack in the cement bound base. The two main thermal cycles are the diurnal and the annual temperature changes. The annual cycle will cause the crack in the cement bound layer to widen as the temperature falls with the onset of winter and then to close as the weather warms. Superimposed on this slow annual cycle will be larger diurnal swings in temperature. These diurnal swings will be greater close to the surface of the pavement. Deeper down the cement bound layer will be insulated by the thick asphalt surfacing and the temperature will be much more constant throughout the day.

Thermal monitoring in winter of test pavements at TRL has shown the daily swing in surface temperature can be in excess of 14°C compared to a 2°C swing in the cement bound base. These large changes in temperature close to the surface suggest that the largest thermal stresses are generated by the contraction of the asphalt layer and not solely as a result of the movements in the crack of the cement bound layer pulling the asphalt apart. This highlights the need to ensure that the asphalt is considered to be an active layer and not a passive layer responding to the movements in the concrete.

2. Field observations of reflection cracking

Nunn (1989) reported that field investigations of over 50 cracks that had recently initiated in 9 as-laid composite pavements, with 90 to 175 mm of asphalt surfacing, had provided overwhelming evidence that reflection cracks initiate at the surface and propagate downwards. Of the cracks cored, 85% petered out before they reached the crack in the lean concrete. This investigation suggested that it was the properties of the wearing course rather than the lower asphalt layers that determine the onset of reflection cracking. An example of this phenomenon is shown in Figure 1.

Fig. 1 Core from recently initiated reflection crack

Fax: +44 (0) 1344 770356
E-mail: knesnas@trl.co.uk

The investigation showed that the onset of reflection cracking was related to the ageing characteristics of the binder in the surface course. It also showed that environmental effects, rather than traffic loading, were responsible for crack initiation in as-laid composite pavements, but the opposite was the case for reflection cracking in asphalt overlays of cracked pavements. The monitoring of measures to inhibit reflection cracking by Nunn and Potter (1993), demonstrated that reflection cracks are far more active in the cold winter months.

The occurrence of reflection cracking in the absence of traffic is shown in Figure 2. This is an untrafficked stub-end of a UK motorway. It had been closed to traffic for over 12 years since its construction by a concrete barrier, which can be seen in the background. The cracking pattern in this section of road was identical to that in the trafficked portion. The growth of grass in the cracks is testament to the lack of traffic.

There were many cases of reflection cracking in the absence of traffic. For example, cracking was often observed in the hard shoulder of motorways accompanied by an absence of cracking in the traffic lanes and vice versa. The reason for this was attributed to the different surfacing material in the traffic lanes and hard shoulder. Also, the occurrence of reflection cracks was monitored in untrafficked experimental composite pavements laid at TRL after several years of environmental loading.

Fig 2. Reflection cracks in an untrafficked section of motorway

This field evidence is consistent with new asphalt surfacing material being ductile enough to withstand thermal loading when it is new. However as it ages, it looses its ability to accommodate the thermally induced stresses and eventually reflection cracks will initiate from the hardened surface layer in the winter months when the thermal stresses are highest and stress relaxation is at its slowest

3. Description of the finite element model for reflection cracking

The finite element modelling of this phenomenon was carried out in three stages. The first involved generating the finite element mesh and defining the load and boundary conditions and material properties. The second involved computing displacements, stresses and strains and in the final stage these results were converted into graphical outputs for ease of understanding.

A schematic representation of a flexible composite pavement is shown in Figure 3. The base consists of strong concrete slabs with regular transverse cracks at 3 m intervals and the sub-base is lean concrete. The finite element mesh of the physical model is illustrated in Figure 4. The overall dimensions of the mesh are 30m long by 4.97m wide. The mesh is built using first order brick elements with infinite elements used for the boundary elements. The top of the concrete base is fully bonded to the asphalt, whereas there is frictional contact between the concrete base and sub-base. The crack in the concrete base was represented by a 1 mm gap.

All layers are assumed to consist of isotropic elastic materials and therefore a stiffness modulus (E) and the Poisson's coefficient (ν) are used to represent their behaviour. A temperature dependent stiffness modulus is used for the asphalt layer. The coefficient of thermal linear expansion (α) is used to model thermal behaviour.

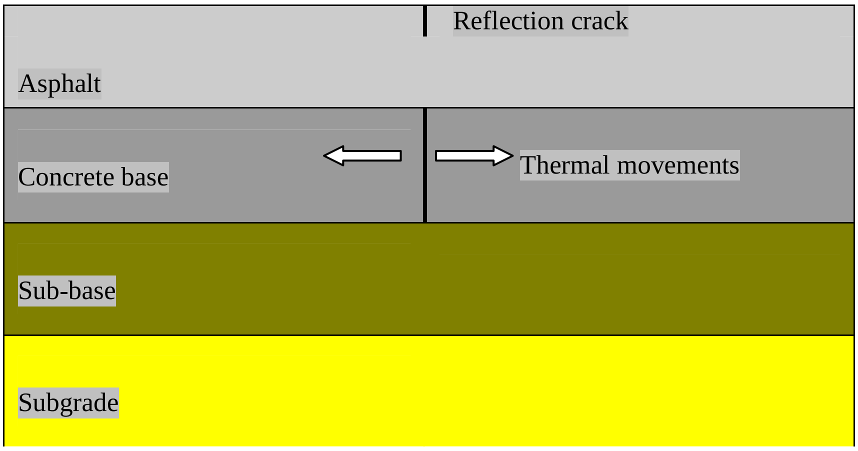

Fig. 3. Schematic representation of a flexible composite pavement

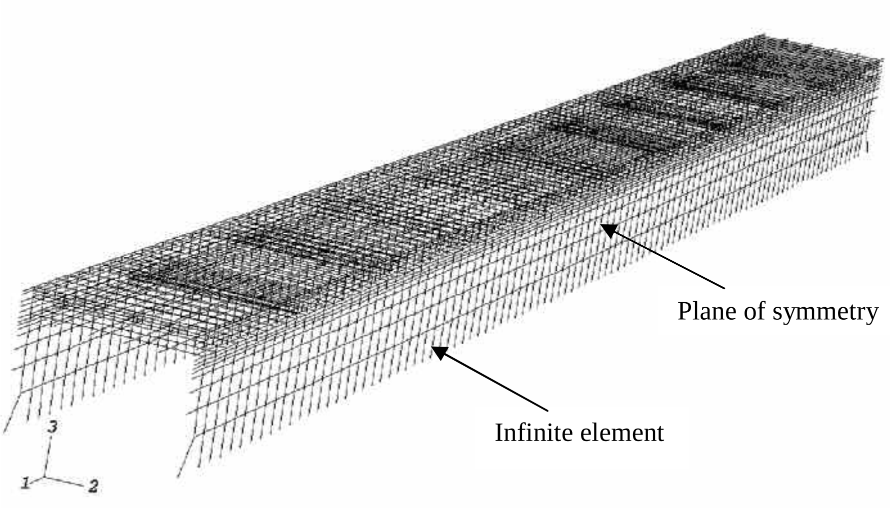

Fig. 4 Finite element mesh of the physical model

Fax: +44 (0) 1344 770356
E-mail: knesnas@trl.co.uk

1.1 Effect of the thermal coefficient of asphalt

The coefficient of thermal linear expansion for the asphalt α_{asp} layer was varied between 2.5E-05 and 1.E-04. The variation of α_{asp} resulted in a linear variation of the thermal stress from 0.65MPa to 3.2MPa at the top of the asphalt layer above the cracked region in the concrete base, and from 0.2MPa to 3.01MPa at the bottom of the asphalt layer.

1.2 Effect of ageing

The effect of ageing was investigated by increasing the stiffness of the top 40mm of the asphalt layer from 3.5 GPa to 12 GPa. The maximum thermal tensile stress at the bottom of the asphalt layer was negligible. On the other hand, the thermal tensile stress, shown in Figure 5 as a function of the stiffness of the surfacing and thickness of asphalt, is high at the top of the asphalt layer, and increases linearly with asphalt stiffness, which is related to ageing. The high thermal tensile stress at the pavement surface will result in the pavement cracking from the top.

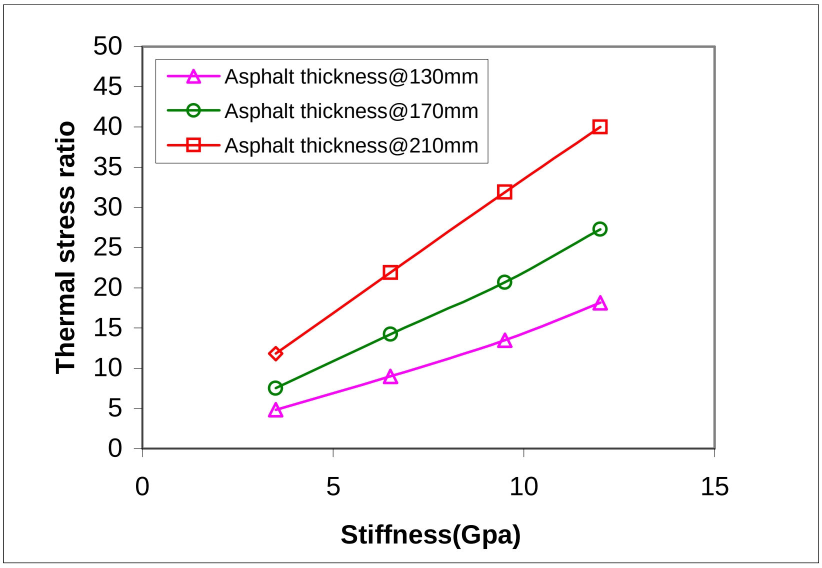

Fig. 5. Ageing effect on thermal stress ratio between top and bottom of asphalt layer

1.3 Effect of asphalt thickness

Analyses using the 3-dimensional finite element mesh (Figure 4), were performed for four thicknesses of the asphalt layer; 90mm, 130mm, 170mm and 210mm. The flexible composite pavements where subjected to thermal cooling, which resulted in curling of the concrete slabs and separation of the sub-base as illustrated in Figure 6. This shows that the maximum thermal tensile stress occurs at the top of the asphalt layer above the crack in the concrete base.

The predictions in Figure 7 show that the maximum tensile stress at the top of the asphalt layer is much larger than that at the bottom with the stress ratio between the two increasing from 1.4 for 90 mm of asphalt to 7.5 for 200 mm of asphalt. Similarly the maximum tensile strain occurs at the top of the asphalt layer above the crack, and the minimum value occurs at the bottom of the asphalt layer.

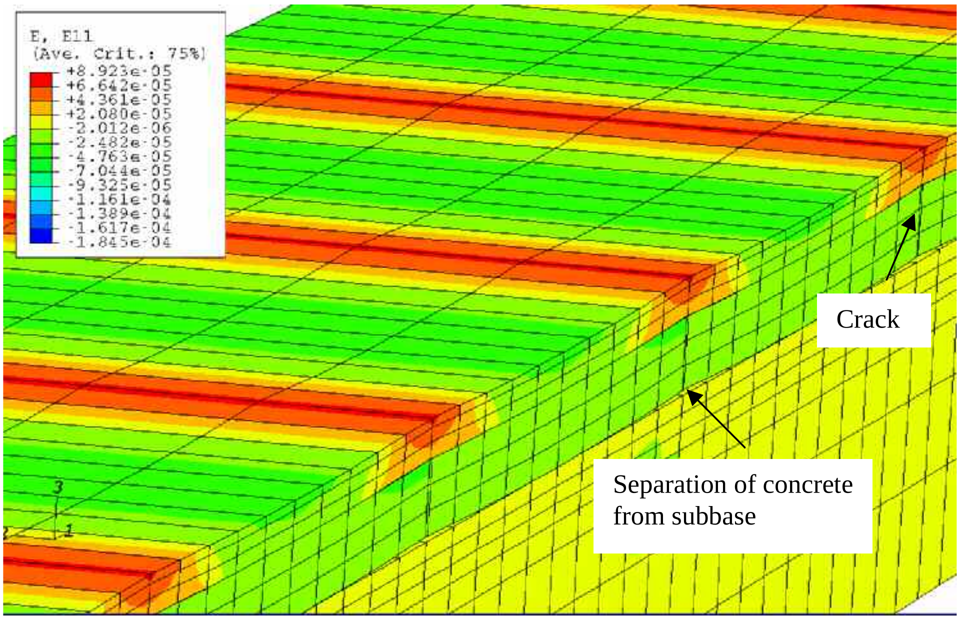

Fig. 6 Detail of pavement curling

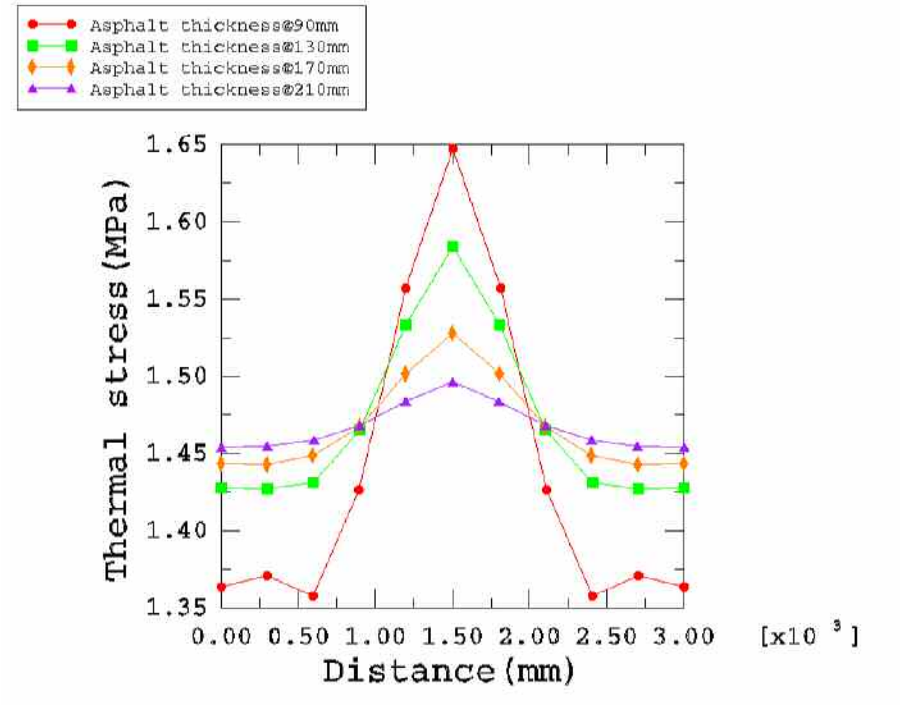

Fig. 7 Thermal stress behaviour at the surface as a function of asphalt thickness

1.4 Effect of crack spacing on thermal stress distribution

The effect of longitudinal crack spacing was examined by modelling the behaviour of pavements with slab lengths of 3, 5 and 15m. Four thicknesses of asphalt surfacing were considered; 90mm, 130mm, 170mm and 210mm. The thermal stress distribution at the surface above the crack is shown in Figure 8 for the pavement with 210mm of asphalt surfacing. This shows that the maximum thermal stress decreases with a smaller crack spacing, and that it is desirable to reduce the crack spacing to delay the onset of reflection cracking.

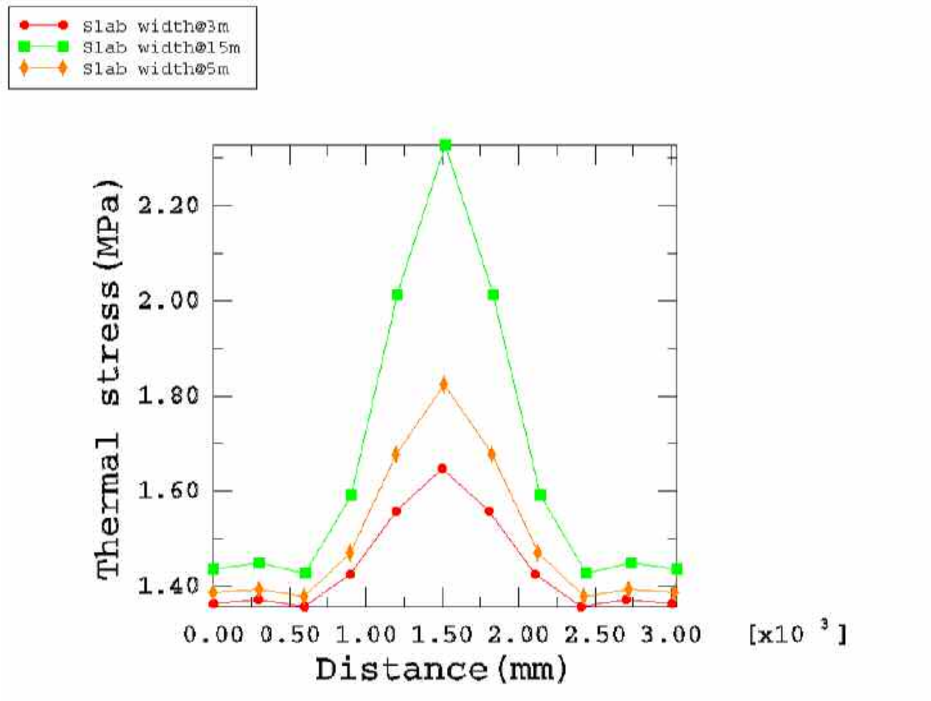

Fig. 8. Thermal stress at the pavement surface as a function of crack spacing

4. Conclusion

This study described the use of a three dimensional model of a flexible composite pavement to examine factors that influence reflection cracking. In the model a more realistic approach was taken by:

- Adopting a 3-D model that removed the constraints of a 2-D model.
- Representing multiple slab elements as individual slabs with a small gap to represent a crack.
- Introducing friction between the slabs and the layer underneath.
- Varying stiffness to mimic ageing and thermal gradients.

A sensitivity analysis was carried out to study the effect of design parameters on the stress distribution at the surface of the pavement. The parameters considered were the thickness of the asphalt layer, the stiffness modulus of the asphalt and the coefficient of thermal linear expansion of the asphalt. The main conclusions were:

- The model was able to give an explanation for the field observation that reflection cracks can initiate at the surface an propagate downwards;
- Reflection cracking in as-laid flexible composite roads can be caused by thermal effects alone.
- For a given construction, the onset of reflection cracking will depend on ageing of the binder and the relationship between temperature and brittleness of the surface course. This suggests that a choice of binder that resists ageing will delay the onset of reflection cracking.
- The model can be used to quantify the effects of inducing cracks in the hydraulically bound base of a flexible composite road and the thickness of the asphalt surfacing.
- The model has potential to be used as a tool to optimise flexible composite design to determine the optimum combination of asphalt surfacing thickness and crack spacing. This will lead to more economic pavement design.

5. References

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Fax: +44 (0) 1344 770356
E-mail: knesnas@trl.co.uk