A THERMAL PAVEMENT RESPONSE MODEL FOR TOP-DOWN REFLECTION CRACKING IN COMPOSITE PAVEMENTS

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Abstract

Reflection cracks in a composite pavement are generally assumed to be caused either by the crack in the hydraulically bound base layer opening and closing as the result of thermal expansion and contraction or by a flexing and shearing action caused by the passage of a wheel load. These processes will induce a stress concentration in the asphalt immediately above the crack, which cause a crack to initiate and propagate towards the surface. However, extensive coring of in-service roads in the UK has shown that reflection cracks often start at the surface of the road and propagate downwards to meet the existing crack in the underlying concrete base rather than travel upwards. Furthermore, field data have shown environmental effects to be the primary cause of reflection cracks in as-laid composite pavements. When the pavement is new, the surface course appears to be ductile enough to withstand the thermally induced stresses but as the asphalt ages it will progressively loose this capability. Modellers generally treat the asphalt surfacing 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 thermal response model, which treats the cement bound and asphalt layers as a complete system and recognises that:

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

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

INTRODUCTION

Models of flexible composite pavements generally regard the asphalt as a passive layer that responds to thermal movements of the crack in the cement bound base. This will result in the prediction that reflection cracks will propagate upwards from the existing crack in the concrete. This view has not been substantiated by field observations carried out by TRL. These clearly show 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 being much higher than that of concrete;
- The larger diurnal temperature changes occurring in the asphalt surfacing;
- Age hardening results in asphalt close to the surface becoming the most brittle region of the asphalt

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 will occur when the tensile stress and related strain induced by traffic and/or temperature changes exceed 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.

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FIELD OBSERVATIONS OF REFLECTION CRACKING

Figure 1 is a typical example of reflection cracking in the UK. In this example, Lane 1 (which carries the majority of heavy commercial vehicles) in on the left and the lightly trafficked overtaking lane (Lane 3), in which heavy commercial traffic is prohibited, is on the right. The motorway has not received maintenance treatment since construction, 18 years earlier. The transverse reflection cracks are relatively evenly spaced and the longitudinal crack in the centre lane is a reflection crack of the longitudinal rip joint in the two concrete base slabs.

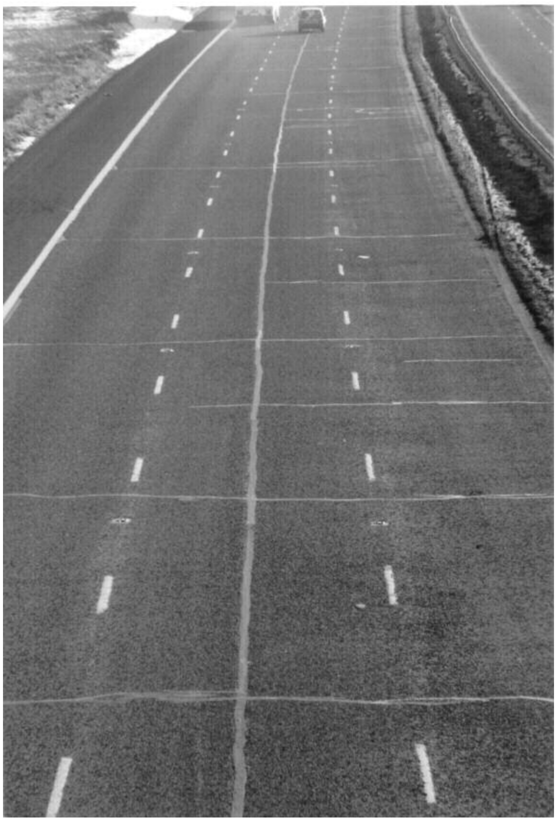


Figure 1. Refection cracks in a typical UK composite motorway

Generally the uniformity of the cracks across all the lanes suggests that traffic stresses are not the primary cause of these cracks. This is further reinforced in this example, where Lane 3 has more cracks than the heavily trafficked Lane 1. Once full-depth cracks have developed, water ingress and traffic will degrade the cracks more rapidly in the most heavily trafficked lanes. The hard shoulder in this example has not cracked but there are other examples in which the hard shoulder and not the traffic lanes have cracked. The reason being that at the time these motorways were built the hard shoulder was constructed with slurry sealed surface rather than the hot rolled asphalt surface course used for the traffic lanes and it is the characteristics of the surfacing that are crucial to the initiation of reflection cracks.

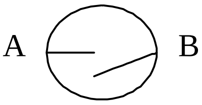
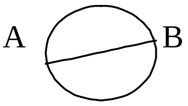
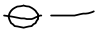
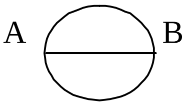
Nunn (*1*) reported that field investigations of over 50 cracks that had recently initiated in 9 as-laid composite pavements, with 90 to 175 mm of asphalt surfacing, have provided overwhelming evidence that reflection cracks initiate at the surface and propagate downwards. Of the newly initiated cracks that were 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. A core illustrating top-down reflection cracking is shown in Figure 2. Many other examples of top-down cracking together with the associated crack in the concrete base were observed in cores that were cut from cracks that had recently initiated or cut at the horizontal tip of a transverse crack. Examples are given in Table 1 for roads with hot rolled asphalt (HRA) surface course and HRA or dense bitumen macadam (DBM) for the other asphalt layers. In all cases the base layer was lean concrete (LC). With many of these cores the asphalt was well bonded with the cement bound base. Top-down reflection cracking was also found in asphalt overlays on jointed pavement quality concrete pavements. The investigations produced no evidence of cracks propagating upwards from cracks in the cement bound base.

Figure 2. Core from a recently initiated reflection crack

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 for asphalt overlays placed to strengthen a pavement damaged by full-depth cracking, traffic stresses are likely to be more dominant. Once the foundation has been weakened by water ingress and *pumping*, traffic induced stresses will dominate. The monitoring of measures to inhibit reflection cracking by Nunn and Potter (*2*), demonstrated that reflection cracks are far more active in the cold winter months when the asphalt is most brittle.

The occurrence of reflection cracking in the absence of traffic is shown in Figure 3. 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.

Table 1. Examples of cores cut through cracks

Transverse reflection crack		Core Surface	Layer	Thickness (mm)	Crack penetration (mm)	
Lane 1	Lane 2				A	B
			HRA	33	16	23
			HRA	65	0	0
			DBM	77	0	0
			LC	170	170	170
			HRA	45	30	35
			HRA	60	0	0
			DBM	80	0	0
			LC	160	160	160
			HRA	39	9	39
			HRA	70	0	0
			LC	150	150	150

There were many cases of reflection cracking in the absence of traffic. As already mentioned, 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.

Figure 3. Reflection cracking 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.

Figure 4 is an example of transverse reflection cracks on the M4 motorway that illustrates a number of features. This road was 17 years old and consisted of 175 mm thick cement bound base covered with 175 mm of asphalt. All layers consisted of the original materials. The cracks have been over-banded and the longitudinal crack was a reflection crack of the rip-joint between the two cement bound base slabs.

Figure 4. Reflection cracks in the centre lane of the M4 motorway

Only the centre lane (Lane 2) had reflection cracks. The heavily trafficked Lane 1 (right-hand side of Figure 3) and the lightly trafficked Lane 3, on which heavy commercial vehicles are not prohibited, were uncracked. The absence of transverse reflection cracks in Lane 1 suggested that traffic loading was not the primary cause of reflection cracking.

Cores were cut from the full depth of the pavement to obtain more information about the materials and the cracks. Cores that were cut from Lane 1 and Lane 3 in line with the transverse cracks, intersected cracks in the underlying concrete base. Cracks in the asphalt that were in the process of propagating upwards from the cracks in the cement bound base were not detected. Cores cut on cracks that had recently appeared on the surface had cracks similar to those illustrated in the core shown in Figure 2. Sets of cores were also taken along the same transverse line from Lanes 1, 2 and 3 to analyse the properties of the recovered binder from the three lanes. The results showed that the properties of the bitumen recovered from the lower asphalt layers from all three lanes were similar. However, large differences were revealed in the properties of the binder from the Hot Rolled Asphalt (HRA) surface course. The penetration of the binders recovered from lanes 1 and 3 were 41 and 38 respectively and that from Lane 2 was 22. The harder binder in the surface course of lane 2, that was the result of ageing, was considered to be the reason for the reflection cracking in this lane. It is possible that the surface course material for Lane 1 and 3 came from a different mixing plant using a source of binder that had different ageing characteristics to that used in Lane 2. This finding was confirmed by measurements carried out on several other sites. These results (Site A) are given in Table 2 together with those from other sites.

Table 2. Surface course binder properties from cracked and uncracked sites

Site	Road condition	Age of pavement (years)	Thickness of asphalt (mm)	Penetration of recovered binder (dmm)
A1	Cracked	17	175	22
B	Cracked	15	175	23
C1	Cracked	17	175	24
D	Cracked	15	175	24
E1	Cracked	16	150	24
F	Cracked	9	130	31
G	Cracked	13	90	33
A2	Uncracked	17	175	38
A3	Uncracked	17	175	41
C2	Uncracked	17	175	30
E2	Uncracked	16	150	35
H	Uncracked	25	175	37
I	Uncracked	8	150	54

The finite element response model (*3*), described in the next section, was developed to gain some understanding of the mechanism of top-down reflection cracking observed in UK composite pavements.

DESCRIPTION OF THE FINITE ELEMENT MODEL FOR REFLECTION CRACKING

The finite element modelling of reflection cracking 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 and the model concepts are shown in Figure 5. The base consists of concrete slabs with transverse cracks at regular intervals. The finite element (FE) mesh of the physical model had overall dimensions of 30 m long by 4.97 m wide containing several transverse cracks at a predetermined longitudinal spacing in the cement bound base. The FE mesh was built using first order brick elements with infinite elements used for the boundary elements. A finer mesh was used in the vicinity of the cracks. The top of the concrete base was fully bonded to the asphalt, whereas frictional contact between the concrete base and sub-base was included. The crack in the concrete base was represented by a 1 mm gap.

All layers were assumed to consist of isotropic elastic materials and therefore a stiffness modulus (E) and the Poisson’s coefficient (ν) were used to represent their behaviour. A temperature dependent stiffness modulus was used for the asphalt layer. A coefficient of thermal linear expansion (α) was used to model thermal behaviour. At this stage no attempt was made to model the time dependent nature of asphalt. The model developed is a response model that is capable of predicting the thermally induced stresses and strains required to establish whether top-down cracking is plausible.

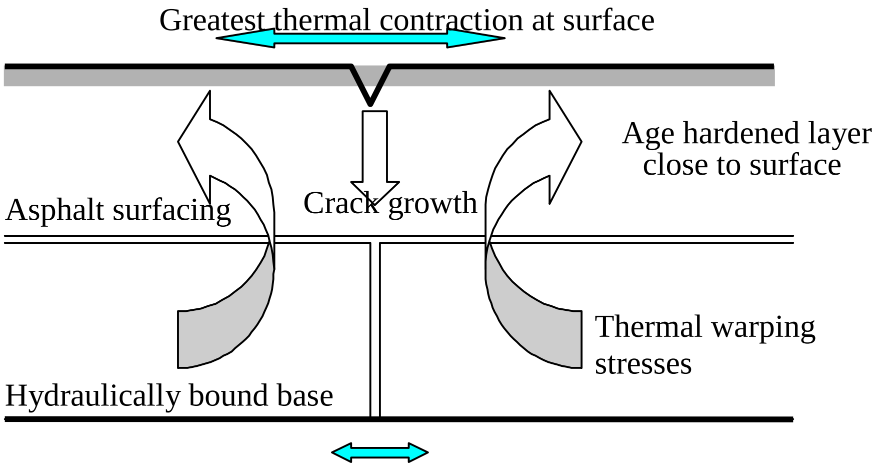


Figure 5. Schematic representation of a flexible composite pavement

A parametric study was carried out to examine the effects of pavement and material variables. This is described briefly in the following sub-headings.

Effect of asphalt thickness

A 3-dimensional finite element analysis was performed using four thicknesses of the asphalt layer; 90mm, 130mm, 170mm and 210mm. The model simulated flexible composite pavements that where subjected to thermal cooling. This resulted in curling of the concrete slabs and separation of the sub-base when the temperature decreases with depth. Figure 6 shows that the maximum thermal tensile stress occurs at the top of the asphalt layer directly above the crack in the concrete base. The stress ratio between the tensile stress at the surface and at the bottom of the asphalt layer varied from 1.4 for 90 mm of asphalt to 7.5 for the thickest asphalt layer.

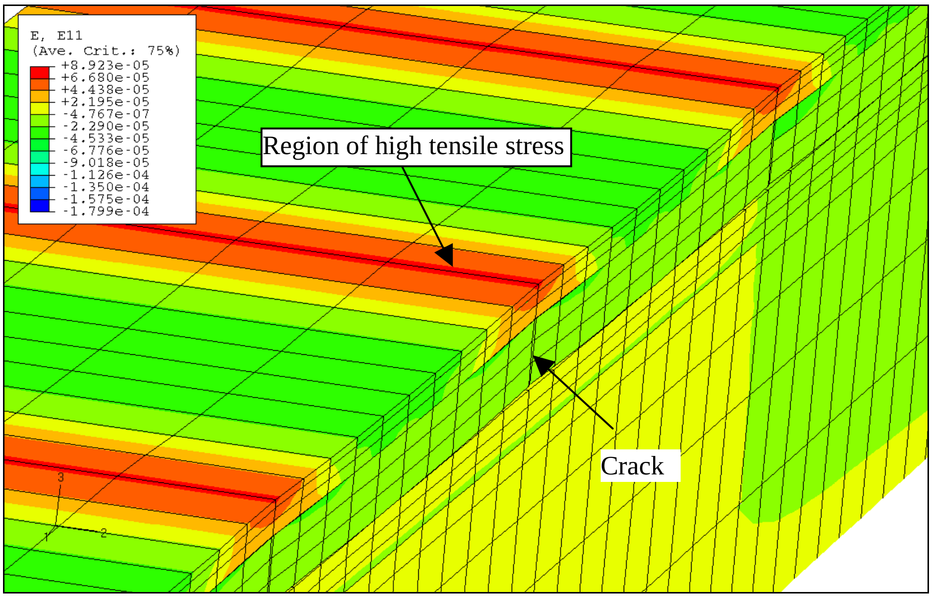


Figure 6. Detail of pavement curling

Figure 7 gives the predicted surface stress for the different thicknesses of asphalt. The peak stress occurs directly above the crack in the cement bound base. The results show that the highest peak stress occurs at the surface with the thinnest asphalt layer and falls off as the thickness of the asphalt increases. This suggests that a thin asphalt covering will crack relatively quickly and the onset of reflection cracking will be delayed with thicker asphalt layers. The magnitude of the tensile stress at the surface will increase as the asphalt age hardens as demonstrated in the next section.

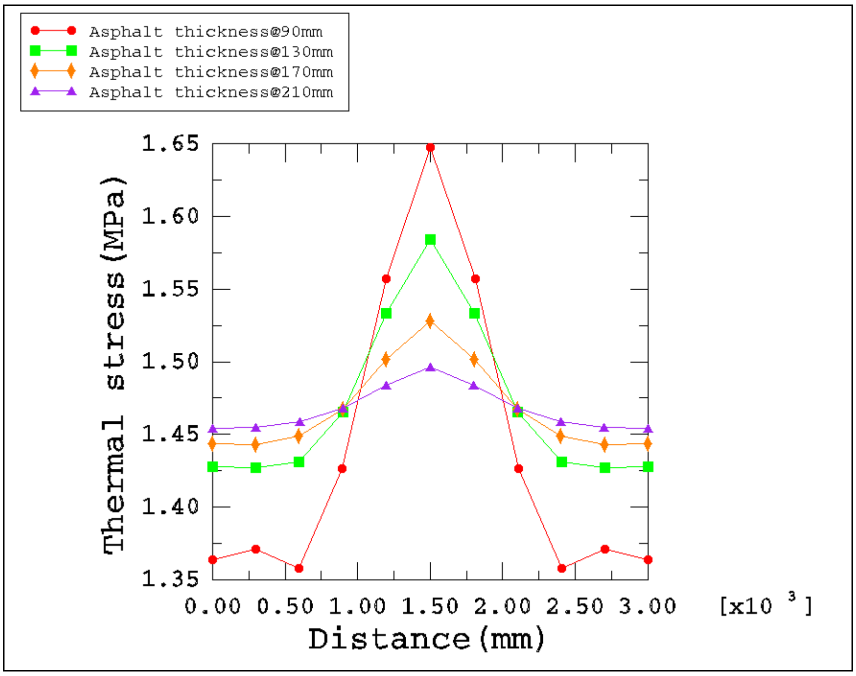


Figure 7. Thermal stress behaviour at the surface above a crack in the concrete base as a function of asphalt thickness

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. This had little effect on the maximum thermal tensile stress at the bottom of the asphalt layer. On the other hand, the ratio of the thermal tensile stress at the top to that at the bottom of the asphalt layer, shown in Figure 8 as a function of the stiffness of the surfacing and thickness of asphalt, indicates that the thermal stress will increase almost linearly as the asphalt becomes stiffer as the result of ageing. Ageing will also reduce the relaxation characteristics of asphalt and its ability to accommodate restrained tensile strain. This suggests that, with age hardening, the tensile stress at the surface will grow with time. At the same time the asphalt will have reduced capacity to withstand this tensile stress and that the onset of reflection cracking will occur when the asphalt ages to an extent that it is no longer ductile enough to withstand the thermally induced tensile condition.

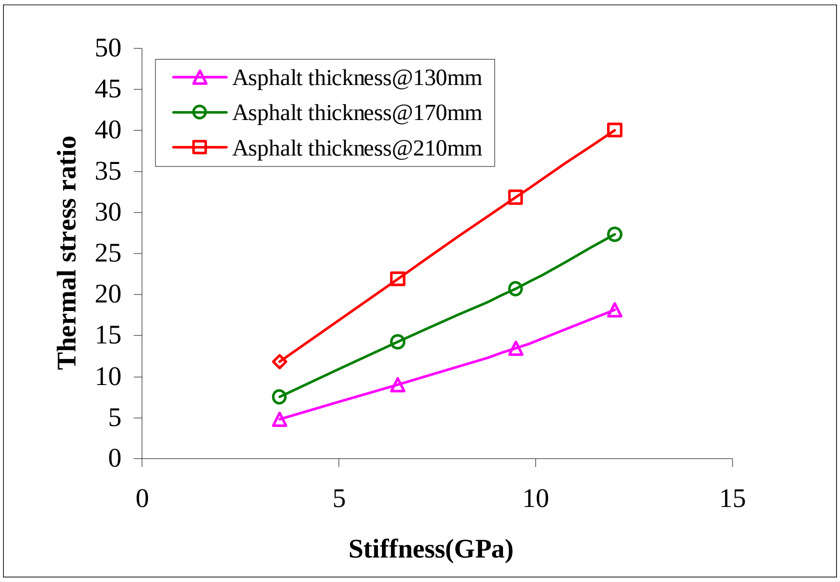


Fig. 8. Effect of increase in the surface course stiffness as the result of ageing on the thermal stress ratio

Effect of slab length on thermal stress distribution

The effect of the longitudinal spacing of cracks 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 9 for the pavement with a 90 mm thick layer of asphalt. This shows that the maximum thermal stress decreases as the slab length or crack spacing decreases, and that it is desirable to reduce the crack spacing to delay the onset of reflection cracking.

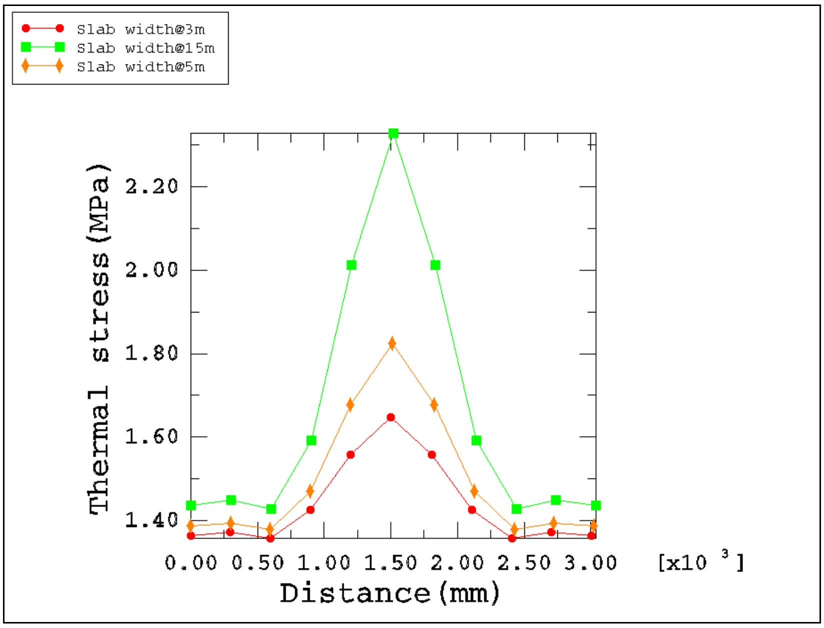


Figure 9. Thermal stress at the pavement surface above the crack in the concrete base as a function of slab length

It is now common practice in the UK to pre-crack the cement bound base at 3 m intervals during the construction phase. This model shows that this practice will reduce the thermally generated stresses considerably and this will help to delay the onset of reflection cracking.

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 crack in the concrete base.

CONCLUSIONS

This paper summarises a field study of reflection cracking in composite pavements in the UK. Extensive coring, of in-service pavements, demonstrated that reflection cracks in as-laid composite pavements generally initiate at the surface, above the crack in the cement bound base, and propagate downwards to meet the crack in the cement bound base. The empirical evidence also showed that thermal effects, rather than traffic-induced stresses, were the primary the reason for the occurrence of reflection cracks. Ageing of the binder in the surface course and thickness of the asphalt cover were also shown to be important contributory variables.

A 3-dimensional finite element model of the thermal behaviour of a flexible composite pavement was developed to examine the factors that influence reflection cracking. In this model a more realistic approach than commonly taken was achieved 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 investigate the effect of the important material and construction 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, the coefficient of thermal linear expansion of the asphalt and the longitudinal spacing between transverse cracks. The main conclusions were:

- The model was able to give an explanation for the field observation that reflection cracks can initiate at the surface and 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 and the longitudinal spacing between the transverse cracks. This suggests that a choice of binder that resists ageing, thicker asphalt layers and pre-cracking the cement bound base will delay the onset of reflection cracking.
- The model has the potential to be used as a tool to optimise flexible composite design to determine the optimum combination of asphalt surfacing thickness and the longitudinal crack spacing. This will lead to more economic and more sustainable pavement design.

The model developed was capable of predicting the main features of top-down reflection cracking in the UK in a qualitative manner. However, to develop a more mechanistic approach the model would need to be enhanced by including ageing, visco-elasticity and relaxation characteristics of asphalt as well as including crack initiation and propagation modules.

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