Prediction of Low Temperature Crack Spacing in Asphalt Pavements

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ABSTRACT: The recently released AASHTO Design Guide incorporates a number of models that address the different distresses that occur in asphalt pavements. The model used for low temperature cracking (called the Thermal Cracking or TC model) is based on a modified Paris law approach that is more appropriate for thermal fatigue type of cracking. Based on an empirical statistical analysis the model uses the crack propagation evolution to predict the number of cracks and the crack spacing that can develop during the life of a given pavement. A simple model was recently developed at the University of Minnesota based on the asphalt mixture tensile strength and the balance between the temperature shrinkage and the friction at the interface between the asphalt layer and the aggregate base. The model requires both asphalt mixture properties and aggregate properties and, similar to the TC model, predicts the crack spacing for a given pavement configuration. Unlike the TC model, it does not consider any crack evolution and cracks form instantaneously when the thermal stress in the asphalt layer exceeds the asphalt mixture strength. In this paper the two models are tested against field data from Mn/ROAD cells for which crack spacing information was available and recommendations for an improved crack spacing prediction model are made.

KEY WORDS: Low temperature cracking, crack spacing, AASHTO design guide, frictional constraint model, asphalt pavement

1 INTRODUCTION

Low temperature cracking results from the contraction of asphalt pavements under extreme temperature conditions. A single or a few temperature drop events of large magnitudes can result in the initiation and propagation of thermal cracks. This distress is manifested in the form of parallel surface-initiated transverse cracks of various lengths and widths, which are predominantly perpendicular to the center line of the roadway. Both the crack width and length are recorded as part of the distress survey and both affect the calculation of the pavement condition (Miller and Belinger 2003). For a hypothetical uniform pavement system the crack spacing should be constant. Field observations show that indeed low temperature cracks are approximately equally-spaced, with small deviation that result from the inherent variability of the material used and of construction practice.

Different mechanistic-based models can be used to predict the spacing of low temperature cracks. The recently released AASHTO Design Guide calculates the crack spacing using the Thermal Cracking (TC) model (Hiltunen and Roque 1994). A frictional constraint model was developed at the University of Minnesota (Timm 2001). Similar to the work by Zubeck and Vinson (1996), this frictional constraint model estimates the crack spacing based on the balance between the temperature shrinkage and the friction at the interface between the asphalt layer and the aggregate base. Shen and Kirkner (1999) incorporated both the friction at the bottom of the asphalt layer and the nonlinear fracture behavior of asphalt mixtures and developed a model to predict the crack.

In this paper, the TC model and the frictional constraint model are used to calculate the crack spacing for some of the test cells from MnROAD facility. The predicted values are compared with the crack spacing measured at MnROAD and the results are used to make recommendations.

2 MECHANISTIC-BASED MODELS

2.1 Thermal Cracking (TC) Model

The TC model was originally developed as part of the SHRP A-005 contract by Hiltunen and Roque (1994). It was later modified and refined in NCHRP 9-19 (05/99-01/05) [*Guide* 2003] as part of the development of the Design Guide research effort. The TC model is composed of three parts: (1) Calculation of thermal stress; (2) Calculation of crack propagation; (3) Calculation of crack amount. The TC model assumes the existence of initial cracks in pavements due to the flaws in asphalt materials. The crack propagates through the asphalt layer due to thermal loading as temperature in the asphalt layer drops. The crack propagation was modeled using Paris law (Paris and Erdogan 1963) as shown below:

$$\frac{da}{dN} = A(\Delta K)^n \tag{1}$$

where a = the crack length, N = the number of cycles, ΔK = the change of the stress intensity factor, A, n = regression parameters. By defining the temperature change within one day as one loading cycle, the time to grow a crack through the entire depth of asphalt layer can be estimated. To facilitate the prediction of crack spacing, only cracks with the length of the depth of asphalt layer are considered as a "crack", and the distance between these fully propagated "cracks" are used to determine the crack spacing. With this approach the TC model can estimate both the crack spacing and the time required to produce that spacing.

2.2 Frictional Constraint Model

This model predicts the crack spacing by studying the frictional constraint given by the aggregate base. Because of the construction joint and/or the flaw of materials, a "free end" is assumed (Timm and Voller 2003). The friction at the interface between the asphalt layer and the aggregate base is balanced by the thermal stress in the asphalt layer that increases with distance from the "free end" until it reaches the tensile strength of the asphalt mixture. The model is based on the Mohr-Coulomb equation and the crack spacing, equal to $1.5X_c$, is computed using the following equation

$$X_c = \frac{E\alpha\Delta T}{\frac{C}{h} + \rho g \tan\phi} \tag{2}$$

where X_c = longitudinal distance from free edge to point at which maximum tensile stress is achieved in the asphalt layer, E = asphalt mixture Young's modulus, α = asphalt mixture linear coefficient of thermal contraction, ΔT = temperature change, C = cohesion, ϕ = friction angle, h = thickness of pavement, ρ = density of asphalt mixture, g = gravity.

3 FIELD DATA COLLECTION

The crack spacing data collected from MnROAD was used to evaluate the prediction from the two models. Since the frictional constraint model uses the cohesion and friction angle of the aggregate base layer, which are not routinely determined in the pavement design process, only the cells for which aggregate base properties were known could be used in the analysis. At the time of this research only data for cells 18 and 22, with class 6 aggregate base, and cell 21, with class 5 aggregate base, was available. The classification of aggregate follows the Minnesota standard specifications for construction (2000).

3.1 Description of Cell 18, 21 and 22

The pavement structures of the three cells are shown in Figure 1. The thickness of all three cells is same, 200 mm (7.9 in). These cells were built before the Superpave specifications were adopted, and traditional binder grades were used: AC 20 binder for cell 18, and pen 120/150 binder for cell 21 and cell 22. The mix design was the same for all three cells.

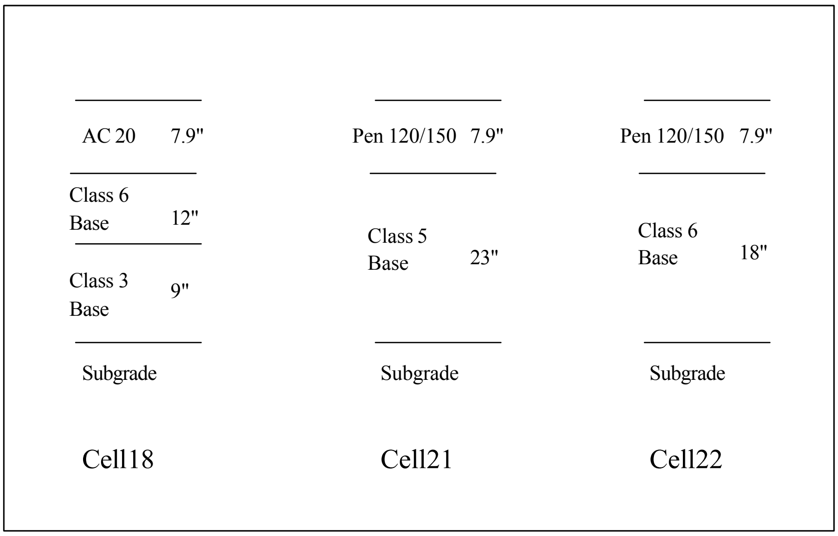

Figure 1: Pavement structure of Cell 18, 21 and 22

The asphalt mixture properties required for both models were determined as part of previous work performed by Stroup-Gardiner and Newcomb (1997). The data is listed in Table 1. The resilient modulus (E) was measured according to ASTM D4123 at a frequency of 1 Hz. and 0.1 second load duration at -18ºC. Two values of tensile strength at two different loading rates were determined for each mixture using the Indirect Tensile (IDT) specimens with dimensions of 100 mm (4 in.) in diameter and 50 mm (2.5 in.) in height.

The thermal coefficient of expansion/contraction of the asphalt mixture was calculated using equation (3) developed by Jones et al. (1968):

$$B_{mix} = \frac{VMA * B_{AC} + V_{agg} * B_{agg}}{3V_{total}} \quad (3)$$

where B_{mix} = linear coefficient of thermal contraction of the asphalt mixture (m/m/ºC), BAC = volumetric coefficient of thermal contraction of the asphalt cement in the solid state (m/m/ºC), B_{agg} = volumetric coefficient of thermal contraction of the aggregate (m/m/ºC), VMA =

percent volume of voids in the mineral aggregate, V_{agg} = percent volume of aggregate in the mixture, $V_{total} = 100$ percent.

Table 1: Asphalt mixtures properties

Cell ID	18	21	22
Thickness (in.)	7.9	7.9	7.9
Binder	AC 20	Pen 120/150	Pen 120/150
Marshall Design	50	50	75
E @ -18°C (GPa)	16.76	16.24	17.59
Tensile strength (σ_t) @-18°C and 0.25 in/min (kPa)	2,250	2,400	2,390
Tensile strength (σ_t) @-18°C and 0.025 in/min (kPa)	2,270	2,230	1,810
Bulk Specific Gravity	2.289	2.303	2.287
Thermal Coef. (α) (1.0E-5m/m/°C)	1.862	1.862	1.800

3.2 Crack Spacing Data

Pavement distresses, including transverse cracking, are surveyed annually at MnROAD and stored in a data base. The mean values of crack spacing for cells 18, 21, and 22 measured in 2003 and shown in Table 2 were used in the analysis.

Table 2: Crack spacing for Mn/ROAD Cells 18, 21 and 22 (February 2003)

Cell	18		21		22	
Lane	Driving	Passing	Driving	Passing	Driving	Passing
Mean	15.8	19.3	19.1	25.3	22.2	27.0
Standard Deviation	7.35	7.89	12.51	15.22	11.49	12.28

4 PREDICTION OF CRACK SPACING

4.1 TC Model

First, the TC model was used to predict the crack spacing for the three MnROAD cells. The software provides three levels of design that require different type of information. Level 3 is used for routine design and requires material properties collected from routine specification tests. Due to the limited amount of information available for the asphalt mixtures used in the three cells previously described, the level 3 design was used in the analysis. The results summarized in Table 3 indicate that the TC model predicts no thermal cracking occurrence in these three cells.

Table 3: Estimated Crack Spacing, TC Model

Cell ID	Crack Spacing
18	∞
21	∞
22	∞

4.2 Frictional Constraint Model

The frictional constraint model assumes that a crack initiates and propagates instantly once the thermal stress becomes equal to the tensile strength of the asphalt mixture. As a consequence, the numerator in equation (2) can be replaced by the tensile strength σ_t to represent the critical state and can be rewritten as

$$X_c = \frac{\sigma_t}{\frac{C}{h} + \rho g \tan\Phi} \qquad \textbf{(4)}$$

In order to apply this equation to predict the crack spacing, parameters C and Φ need to be known. These parameters were calculated from triaxial test data provided by Mn/DOT Office of Materials for class 5 and 6 aggregates. In the triaxial test the first principle stress (σ_1) can be obtained as the summation of the confining pressure (σ_3) and the deviatoric stress ($\Delta\sigma_d$):

$$\sigma_1 = \sigma_3 + \Delta\sigma_d \qquad \textbf{(5)}$$

which can also be computed as:

$$\sigma_1 = \sigma_3 \tan^2(45 + \frac{\phi}{2}) + 2c\tan(45 + \frac{\phi}{2}) \qquad \textbf{(6)}$$

Since the tests were performed at two different confining pressures, two sets of (σ_1, σ_3) could be obtained for the same type of aggregate and used to solve for the cohesion and friction angle with equation (6). The cohesion and friction angles of class 5 and 6 aggregates and the other parameters used in equation (4) are summarized in Table 4.

The estimated crack spacing from the frictional constraint model obtained using the parameters listed in Table 4 are summarized Table 5.

5 DISCUSSION

The results indicate that the TC model used in level 3 analysis did not predict any thermal cracking in the three MnROAD cells. This can be partially explained as follows. The TC model does not allow complete crack propagation even under the most severe temperature drop. A crack can propagate only through one sublayer at one time, and therefore it takes at least 4 severe events to form one complete crack that is counted by the model. According to the records, most of the thermal cracks in cells 18, 21 and 22 occurred during one extremely cold winter (1995-1996) when the temperature dropped to -39ºC. This scenario is better represented by the frictional constraint model.

Table 4: Parameters Used in the Frictional Restraint Model

Cell ID	18	21	22
Base Type	CL6	CL5	CL6
Cohesion, psi (kPa)	9.0 (62.1)	11.2 (77.2)	9.0 (62.1)
tanΦ	1.299	0.787	1.299
Bulk Spec. Gravity	2.289	2.303	2.287
Thickness (h), in. (m)	7.9 (0.2)	7.9 (0.2)	7.9 (0.2)
Binder Grade	AC 20	Pen 120/150	Pen 120/150
Tensile Strength at -18ºC (0.25mm/min), (kPa)	2,270	2,400	2,390
X_c, ft. (m)	21.9 (6.7)	19.5 (5.9)	23.1 (7.0)
Crack Spacing (1.5 X_c), ft. (m)	32.9 (10.0)	29.3 (8.9)	34.7 (10.5)

Table 5: Estimated Crack Spacing, Frictional Restraint Model

Cell ID		Measured Crack Spacing [ft]	Predicted Crack Spacing [ft]
18	Driving lane	15.8	32.9
	Passing lane	19.3	
21	Driving lane	19.1	29.3
	Passing lane	25.3	
22	Driving lane	22.2	34.7
	Passing lane	27.0	

The frictional constraint model underestimated the crack spacing observed in the field. The crack spacing predicted using the frictional constraint model and the values from field observations are plotted in Figures 2 and 3. Figure 2 shows that the predicted value is larger than the measured value in the passing lane, which is larger than the measured value in the driving lane for all three cells. The more severe deterioration in the driving lane compared to the passing lane seems to indicate that traffic has a negative effect on the crack spacing. This plot also indicates that the binder type has an effect: cell 18 built with AC20 binder has lower crack spacing than the two cells built with Pen 120/150 binder.

Figure 3 indicates that there is no clear correlation between the predicted values and the measured values. However, this result is based on only three cases and this analysis should be expanded with additional cells as more data becomes available in the future. To further investigate these results a simple statistical analysis was performed. The null hypothesis that the measured value is equal to the predicted value was tested against the alternative hypothesis that the measured value was less than the predicted value for both the passing and the driving lanes. The results are summarized in Table 6 and indicate that in five of the six comparisons the measured values are less than the predicted values (small p-values).

The only exception is cell 21 passing lane for which the predicted value is not statistically different than the measured value.

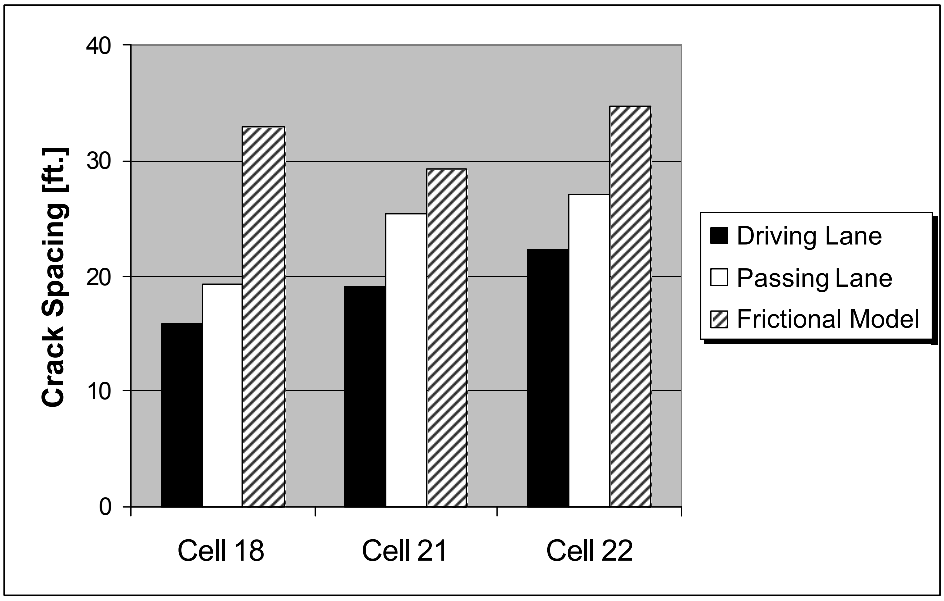

Figure 2: Predicted and measured crack spacing values for cells 18, 21 and 22

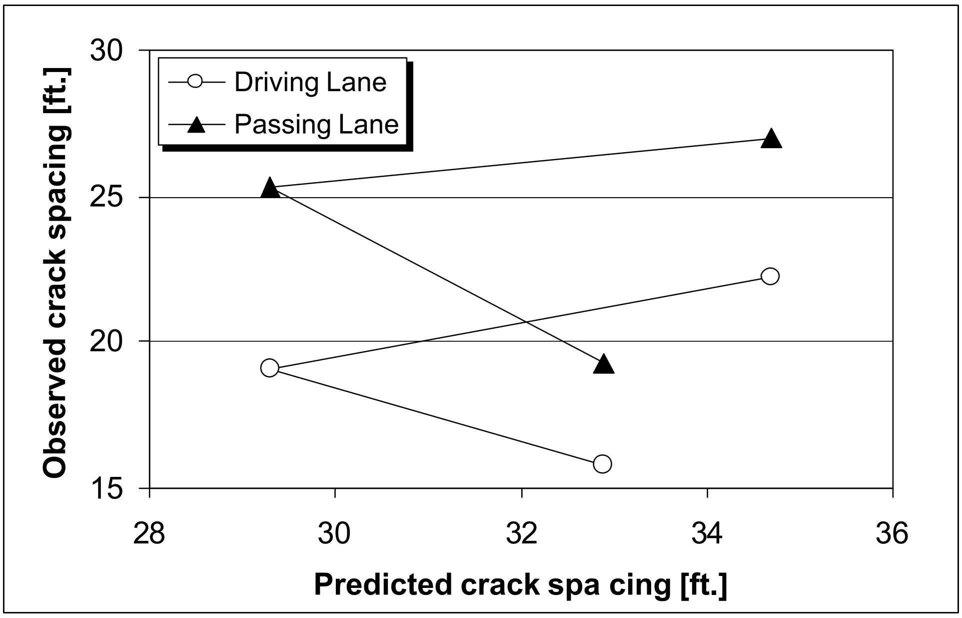

Figure 3: Predicted versus measured crack spacing for cells 18, 21, and 22

The deficiency of the frictional constraint model can be explained by the fact that the values of material parameters used in the model are most likely different than the material parameters in the field. For example the properties of the aggregate materials were measured at room temperature while thermal cracking occurs at very low temperatures at which the aggregate base is in the frozen condition. Research by Sayles (1973) on Ottawa sands in a frozen condition have shown cohesion values of the order of 1 MPa, which are much larger than the cohesion values reported in Table 4. This difference significantly affects the prediction of crack spacing from equation (4). Cohesion values 1.5 to 2 times larger would result in predicted values very close to the measured values. They would not explain the difference between the passing and the driving lanes.

Table 6: Comparison of measured and predicted crack spacing values

			Cell 21	Cell 18	Cell 22
Prediction			29.3	32.9	34.7
Field Measurement	Passing Lane	Mean	25.3	19.3	27
	Driving Lane		19.1	15.8	22.2
	Passing Lane	Standard Deviation	15.22	7.89	12.28
	Driving Lane		12.51	7.35	11.49
	Passing Lane	# of Cracks	10	24	17
	Driving Lane		25	30	21
Hypothesis Test	Passing Lane	t Statistics	-0.83	-8.444	-2.59
	Driving Lane		-4.08	-12.74	-4.99
	Passing Lane	P-Value	0.214	9.19E-09	9.86E-03
	Driving Lane		2.15E-04	1.13E-13	3.56E-05

Further investigation was performed to determine if there is any merit in back-calculating the properties of frozen aggregates by inverting the computation procedure for cohesion and friction angle with triaxial test data. Two pairs of cells were used to back-calculate the cohesion and friction angle of class 3 and class 6 aggregate base. The configurations of the two pairs of cells are shown in Figure 4 and the material properties used in the calculations are given in Table 7.

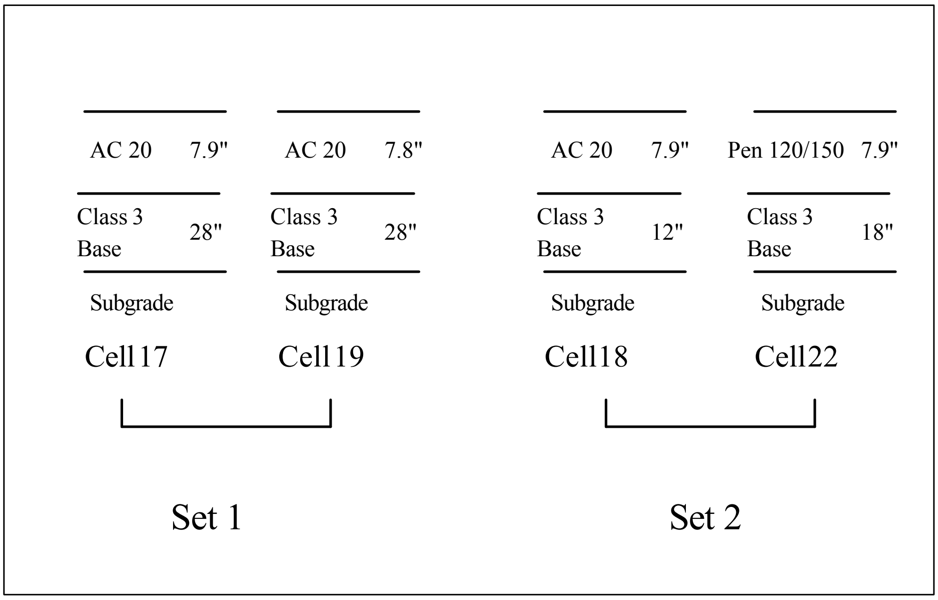

Figure 4: Configuration of cells used in back-calculation

The results of the back-calculation are shown at the bottom of Table 7 and are not reasonable. This clearly indicates the importance of determining material parameters that are representative of the materials behavior at low temperatures in the field.

Table 7: Back-calculation of soil properties

Base Type	Class 3		Class 6	
Cell ID	17	19	18	22
Mixture Density, g/cm^3	2.283	2.289	2.270	2.287
Thickness, in	7.9	7.9	7.8	7.9
Binder Grade	AC20	AC20	AC20	120/150 Pen
Tensile Strength, MPa	2.38	2.8	2.25	2.39
Field Crack Spacing, ft	23.9	15.8	10.9	22.2
Back-calculated C, MPa	**9.96**		**-38.2**	
Back-calculated tanΦ	**-2203.5**		**8546.1**	

6 SUMMARY AND CONCLUSIONS

The thermal cracking (TC) model incorporated in the recently released AASHTO Design Guide, and the frictional constraint model developed at the University of Minnesota were reviewed and used to predict the crack spacing for three MnROAD cells. The comparison between the predicted and observed crack spacing values indicated that

1. The TC model seems to be ineffective in predicting the occurrence of low temperature cracking in asphalt pavements.
2. The frictional constraint model reasonably predicts low temperature cracking. However, due to the lack of material properties for the conditions at which low temperature cracking occurs, it underestimates the crack spacing.
3. Neither of these two models can address the differences between the crack spacing in passing lane and driving lane.

Further research is needed to provide accurate predictions of the crack spacing due to low temperature cracking in asphalt pavements.

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