Finite Element Modeling of Premature Transverse Cracking Due to Paving Adjacent Lanes Separately

Feng Mu[1], Kerri A. Cutright[2] and Julie M. Vandenbossche[3]

Abstract

Concrete pavements are often constructed by first paving the mainline followed by the shoulder some time later. It is important to factor the differences in the structure, material properties, and climatic conditions between the mainline and the shoulder into design and construction; otherwise, premature cracking can develop. This study uses finite element modeling to analyze the causes of the transverse cracking in the newly paved shoulder of U.S. Route 22 near Blairsville, Pennsylvania. The key factor responsible for the cracking is identified as the construction sequence causing thermal incompatibility between the mainline and the shoulder. A parametric study is then carried out to quantify the significance of many factors, such as construction sequence, material properties, pavement features and environmental conditions, on the cracking potential. A guideline is then established to prevent the future occurrence of the cracking.

Introduction

Often during construction, it is not possible to finish paving all of the constituents (lanes, shoulders, etc.) during the same construction season due to time and money constraints or other unforeseen circumstances. Therefore, it is sometimes necessary to construct the adjacent lanes at different times of the year other than when the original lanes were constructed. If lanes are going to be tied on during different seasons, different times of a day, or having a different mixture design, it is important to factor these differences into the design. Otherwise, it is possible for premature cracking to occur in the newly paved lane, the existing lane, or both. Cracking can sometimes develop in concrete pavements even before traffic loads are applied due to thermal loads.

A case of premature cracking was identified on U.S. Route 22 nearby Blairsville, Pennsylvania, USA. The mainline was constructed in October 2008 and a 0.6-m inside shoulder was constructed in July 2009, as shown in Figure 1. Within one week after the 0.6-m shoulder was paved, mid-slab cracks in the shoulder were noticed by the Pennsylvania Department of Transportation (PennDOT) engineers. A typical crack is presented in Figure 2. The majority of the cracks propagated across the full width of the shoulder with a few cracks only traversing partially across the width of the shoulder.

[1]Graduate Student Researcher, Department of Civil and Environmental Engineering, University of Pittsburgh, 1121 Benedum Hall, 3700 O'Hara Street, Pittsburgh, PA 15261. Email: fem15@pitt.edu;
[2]Assistant Geotechnical Engineer, Pennsylvania department of Transportation, 1002 West Hamilton Street, Allentown, PA 18101-1013. Email: kcutright@pa.gov;
[3]Assistant Professor (Corresponding author), Department of Civil and Environmental Engineering, University of Pittsburgh, 934 Benedum Hall, 3700 O'Hara Street, Pittsburgh, PA 15261. Email: jmv7@pitt.edu.

It is hypothesized that the cracking is the result of thermal stresses that developed in the concrete shoulder. The hypothesis was made based on the fact that no traffic had been on the shoulder before the crack occurred and therefore the cracking could only be caused by environmental stresses. The possibility of drying shrinkage cracking was also eliminated, since the cracking was noticed at a very early age, i.e. within 7 days, when the concrete was still saturated. It is also unlikely that the cracking is the result of the occurrence of autogenous shrinkage. Historical research (Neville, 1978; Mindess and Young, 1981) shows that concrete with a low w/c ratio (<0.3) and a reactive pozzolan (e.g., silica fume) are susceptible to autogenous shrinkage. However, the concrete used for paving the shoulder has a w/c ratio of 0.42 and the concrete mixture did not contain a highly reactive pozzolan. Therefore, the shoulder most likely cracked due to the tensile stress which developed as a result of differential thermal deformation between the mainline and the shoulder.

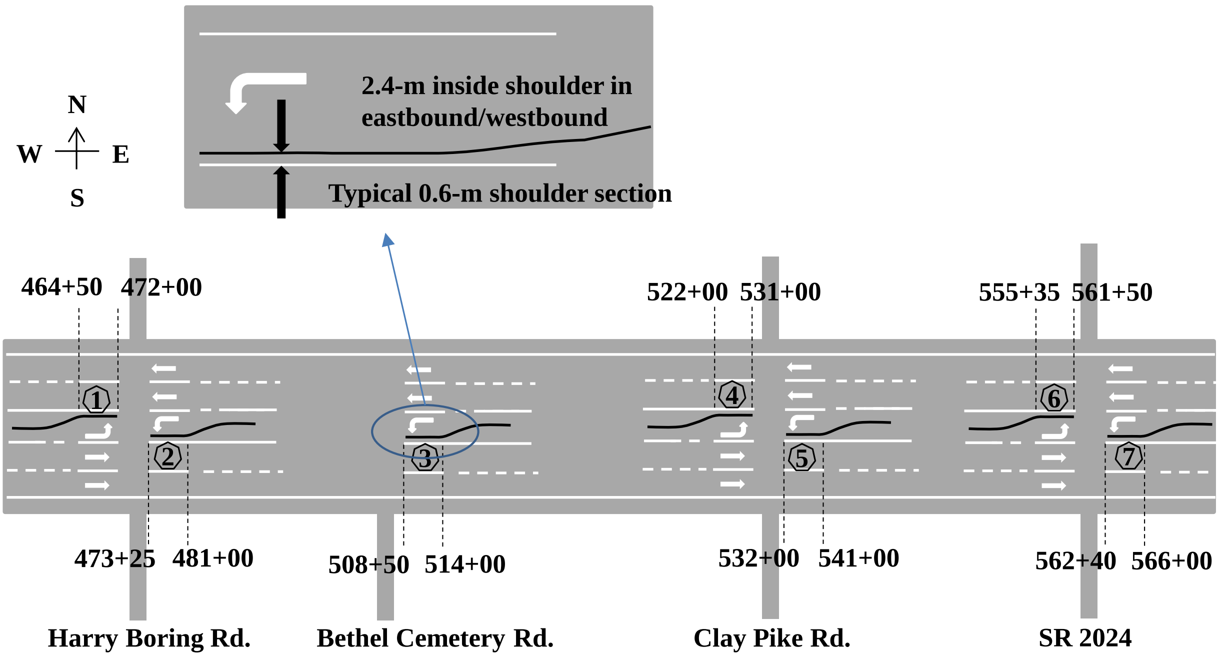

Figure 1. Sections of U.S. 22, Blairsville, PA with premature transverse cracking

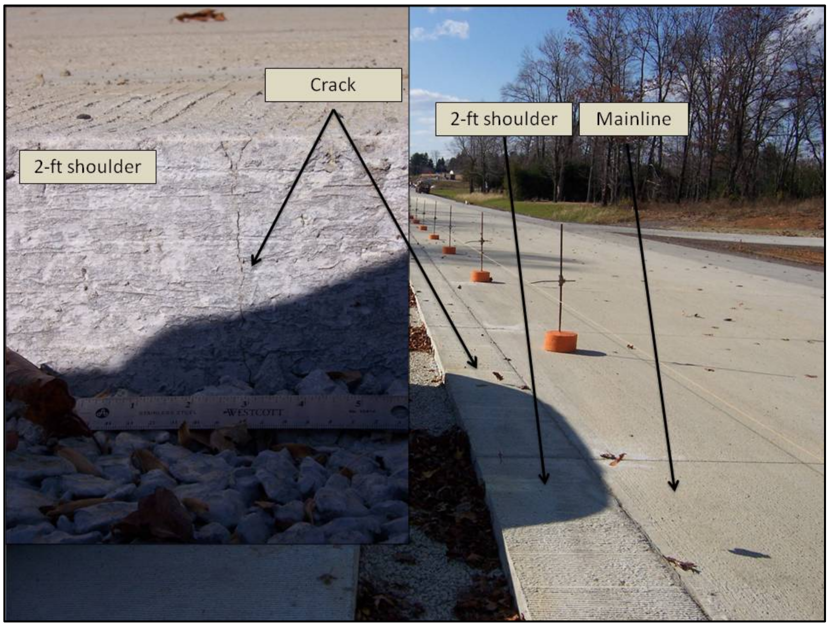

Figure 2. Typical crack in the 0.6-m shoulder of U.S. 22, Blairsville, Pennsylvania.

When concrete sets, a zero-stress temperature is built in. From that point on, concrete slabs tend to contract when the concrete temperature gets lower than the zero-stress temperature and vice versa. The contraction/expansion restrained by the base or the adjacent lane results in the development of stresses. For Route 22, the shoulder and mainline were paved in different seasons, which would likely result in different zero-stress temperatures and thus they would deform differently when subjected to the same ambient temperature. The difference in the thermal deformation between the mainline and the shoulder induces tensile stresses in the shoulder when the zero-stress temperature for the shoulder is higher than the zero-stress temperature for the mainline. Eventually, transverse cracking initiated in the shoulder when the tensile stress exceeded the early-age tensile strength of the concrete.

In this study, the finite element method is used to model the conditions that have resulted in the premature transverse cracking in the shoulder so the factors contributing to the cracking could be identified. A parametric study is then carried out to establish guidelines that will help prevent the future occurrence of premature cracking when paving adjacent lanes separately.

Finite Element Model

A 3-D finite element model was developed using ABAQUS 6.9 (ABAQUS/CAE 2007) to study the mechanism of the premature cracking in the newly paved 0.6-m shoulder. An overview of the model is presented in Figure 3, where it uses 3-D, 20-node, quadratic, reduced integration, brick elements to model all three parts, i.e. the mainline, the shoulder and the base.

Geometry. The size of the shoulder slab is 4.5 m (X) × 0.6 m (Y) × 0.25 m (Z), while the mainline slab is 4.5 m (X) × 3.6 m (Y) × 0.25 m (Z) and the base is 4.5 m (X) × 4.2 m (Y) × 0.1 m (Z). There are tie bars that are 0.75 m long and 16 mm in diameter placed 0.75m on-center between the mainline and the shoulder. Only half of the slab is modeled owing to the symmetry of the problem.

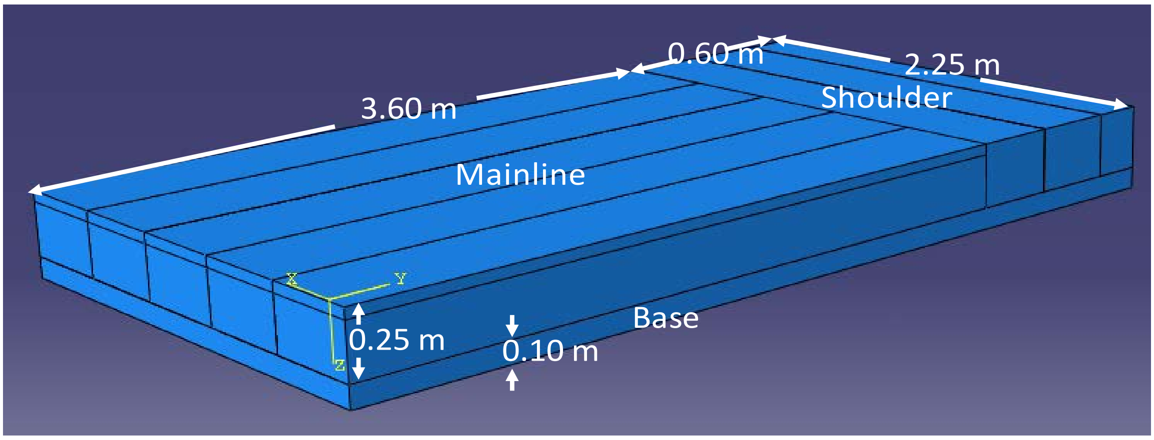

Figure 3. Overview of the three-dimensional finite element model

Meshing. Since the interaction between the shoulder and the mainline is the focus of the study, the mesh used for the shoulder as well as 0.3 m into the mainline was made significantly finer than the rest of the model, as shown in Figure 3. The adequacy of the mesh fineness for the model was determined by reducing the fineness until the nodal stresses at the outside edge converged.

Boundary Conditions. The displacement in the Y direction is restricted along the longitudinal joint between the two mainline lanes. The symmetric boundary condition is used at the middle of the slab so that only half of the slab needs to be studied. The 10-cm lean concrete base is modeled as an elastic layer with material properties as defined in Table 1. A Winkler-spring foundation was used to represent the composite stiffness of all layers beneath the slab and the base, including a 5-cm 2A subbase, a 0.5-m backfill of rock embankment and a geotextile separator layer above the A-4 subgrade. A k-value of 54 kPa/mm was used, which is typical for concrete pavements. Hall (1997) compared the FWD backcalculated k-values for concrete pavements in the LTPP database and it seems that nearly all the k-values lie between 27 kPa/mm and 135 kPa/mm. In this model, a traction force that points outward along the Y direction was applied to the slab to simulate the frictional restraint provided by the granular subbase. The magnitude of the traction force was established by determining the force required to drag the slab and the base across the subbase. Maitra et al. (2009) suggested a friction coefficient of 0.8, based on which the traction force was determined to be 12.4 kPa.

Contact Interactions. The shoulder is tied to the mainline. The contact between the mainline and the shoulder is defined as “Hard” for the normal behavior and frictionless for the tangential behavior. The hard contact prevents the penetration between the contacting surfaces. The use of a frictionless tangential behavior is also reasonable considering the fact that the longitudinal joint is a cold joint. The shear load transfer between the mainline and the shoulder is realized through the tie bars.

Loading. In this model, loading was applied in two steps. In the first step, a gravity load was implemented and different zero-stress temperatures were applied to the mainline and the shoulder. In the second step, the same transient temperature was applied to the entire model. Temperatures can be applied via direct specification when a uniform temperature is needed or through the use of an analytical field where a mathematical function defines the temperature profile across the depth.

Validation. The finite element model was validated using field data that was collected at a similar section of U.S. 22 close to Murrysville, Pennsylvania. Strains were measured at three different depths using vibrating wire strain gages. The zero-stress temperature profile for the section, which was established by Asbahan (2009), was used to establish the initial condition in ABAQUS. Later on in the analysis, a different temperature profile was introduced into the model to represent a point in time after paving. Twenty-two different temperature profiles were chosen to validate the model, for which the equivalent linear temperature gradients ranged from -0.017 °C/mm to 0.041°C/mm. The predicted strain at the top, middle, and bottom of the slab was compared to the measured strain at the same location for each of the temperature profiles. The correlation coefficient (R^2) between the predicted strain and the measured strain is equal to 0.92, 0.99, and 0.89 for the top, middle, and bottom of the slab, respectively. This indicates that the model accurately reflects the response of the pavement measured in the field for 22 different temperature loading conditions.

Analysis of the Premature Cracking

The finite element model was then used to analyze the cause of the premature cracking in the shoulder of U.S. 22 near Blairsville, Pennsylvania. After defining the inputs for the model parameters, the model was run for each of the seven sections in Figure 1 to establish their stress contours. The predicted stresses can then be compared to the observed cracking to investigate the cause of the premature cracking.

Inputs: Material Property. Some of the key material properties for the finite element model are presented in Table 1 and the other material properties established for this project can be found in the work by Cutright (2010). The elastic modulus, Poisson's ratio, tensile strength (f_t'), flexural strength (MOR) and coefficient of thermal expansion (CTE) for the mainline were established by testing concrete cores pulled from this section of the roadway. For the shoulder, the stiffness and strength at 1 day and 7 days were estimated based on the 28-day compressive strength using the correlations in the Mechanistic-Empirical Pavement Design Guide (ARA, 2004). The thermal coefficient of expansion (CTE) for the shoulder was determined by testing cores pulled from the shoulder. Unlike the stiffness and strength that continue to increase over time, the CTE for concrete does not vary significantly over time.

Table 1. Material properties for the finite element model for U.S. 22, Blairsville, Pennsylvania

	Mainline	Shoulder	Base	Tie bar
Elastic modulus, GPa	31	19 (1-day) 28 (7-day)	14	200
Poisson's ratio	0.17	0.17	0.2	0.3
Modulus of rupture (MOR), MPa	4.5	2.8 (1-day) 3.1 (7-day)	n/a	n/a
Indirect tensile strength (f_t'), MPa	4.0	2.5 (1-day) 2.8 (7-day)	n/a	n/a
Coefficient of thermal expansion (CTE), 10^{-6}/°C	10.5	10.5	5.5	n/a
Unit weight, kg/m^3	2300	2300	2300	n/a

Inputs: Zero-Stress Temperature. The zero-stress temperature is the baseline temperature for determining the deformation in the slab due to changes in temperature. The concrete slab expands when the transient temperature in the slab at a point in time after paving is above the zero-stress temperature and it contracts when the transient temperature is below the zero-stress temperature. The magnitude of the zero-stress temperature is primarily a function of both the ambient temperature during paving and the heat of hydration during curing.

Equation 1 in the MEPDG (ARA, 2004) was used in this study to estimate the zero-stress temperature.

$$T_z = [(CC \times 0.59328 \times H \times 0.5 \times 1000 \times 1.8) / (1.1 \times 2400)] + MMT \qquad \text{Equation 1}$$

Where T_z is the zero-stress temperature, °F; CC is the cementitious material content, lbs/yd^3; $H = -0.0787+0.007*MMT-0.00003*MMT^2$ and MMT is the mean monthly temperature for the month of construction, °F.

The cementitious content is 300 kg/m^3 for both the mix used in the mainline and in the shoulder. The construction records for the shoulder and the mainline were reviewed to determine the ambient temperatures during paving. This information is summarized in Table 2. Using the ambient temperatures in Table 2, the range of the zero-stress temperature for the mainline (T_M) and the zero-stress temperature for the shoulder (T_S) was predicted using Equation 1 for all seven sections of the project.

Inputs: Concrete Transient Temperature. The transient concrete temperatures (T_C) during the first week after paving the shoulder were also obtained and presented in Table 2. T_C is the same for the mainline and the shoulder, because the factors that dominate the concrete transient temperature, such as the ambient temperature, slab thickness and concrete absorptivity, emissivity and thermal conductivity, are the same.

Table 2. Available temperature information for U.S. 22, Blairsville, Pennsylvania

Section	Structure	Date paved	Ambient temperature during paving, °C	Zero-stress temperature (T_M or T_S), °C	Concrete transient temperature during the week of shoulder cracking (T_C), °C
1	Mainline	10/20/08	0-16	5-30	13-20
	Shoulder	7/15/09	11-28	22-41	13-20
2	Mainline	Unknown	Unknown	Unknown	Unknown
	Shoulder	7/15/09	11-28	22-41	Unknown
3	Mainline	Unknown	Unknown	Unknown	Unknown
	Shoulder	7/15/09	11-28	22-41	Unknown
4	Mainline	10/17/08	9-13	19-25	17-19
	Shoulder	7/15/09	11-28	22-41	17-19
5	Mainline	Unknown	Unknown	Unknown	Unknown
	Shoulder	10/20/08	11-28	22-41	Unknown
6	Mainline	10/15/08	16-24	28-36	17-19
	Shoulder	10/20/08	11-28	22-41	17-19
7	Mainline	Unknown	Unknown	Unknown	Unknown
	Shoulder	10/20/08	11-28	22-41	Unknown

Inputs: Temperature Difference. The thermal stress and the consequent cracking in the shoulder is a function of two temperature differences. The first temperature difference is between the zero-stress temperature and the transient temperature, i.e. $T_B=T_C-T_M$, °C. When T_B is negative, the shoulder contracts and thus tensile stresses develop in the shoulder provided sufficient restraint is present to retrain this contraction. The second critical temperature difference is the one between T_M and T_S, i.e. $T_D=T_M-T_S$, °C. This is because the mainline provides additional restraint against the contraction of the shoulder and the restraint gets larger as T_D goes negative.

T_D and T_B were calculated for each section and the results are summarized in Table 3. T_D was assumed to be the median of the range given in Table 2. This assumption might be more reliable for the shoulders in Section 4 and Section 6, which have a smaller variation in T_D, i.e. ±3 °C and ±4 °C, respectively. For the shoulder in Section 1, using this assumption might introduce more error due to the large variation of T_D, i.e. ±12 °C. The variation in T_D is also large for all the mainline slabs, i.e. ±10 °C. T_B was calculated considering the lowest T_C, which is the critical pavement temperature for the development of these thermal cracks.

Table 3. Temperature differences for U.S. 22, Blairsville, Pennsylvania

Section	T_M, °C	T_S, °C	$T_D=T_M-T_S$, °C	T_C, °C	$T_B=T_C-T_M$, °C	Percent slabs cracked
1	18	32	-14	13	-5	84
2	n/a	n/a	n/a	n/a	n/a	25
3	n/a	n/a	n/a	n/a	n/a	11
4	22	32	-10	17	-5	57
5	n/a	n/a	n/a	n/a	n/a	0
6	33	32	1	17	-15	0
7	n/a	n/a	n/a	n/a	n/a	0

Results and Discussion: Location of Critical Stress. The stress that developed in the 0.6-m shoulder one week after it was placed was predicted using the finite element model for all seven sections. The contour of the maximum principle stress was obtained for each section. The contour for Section 1 is shown in Figure 4, as an example. In Figure 4, the dark color indicates the stress that develops after 1 day of casting the shoulder is greater than 2.5 MPa (the one-day concrete strength of the shoulder). It is obvious that the stress at the midslab of the shoulder has already exceeded the tensile strength. The development of this stress is mainly due to the restraint from the stabilized base. One can also find a stress concentration around the tie bars from Figure 4. These observations indicate that the cracking could have initiated from the bottom of the slab at the longitudinal joint between the mainline and the shoulder.

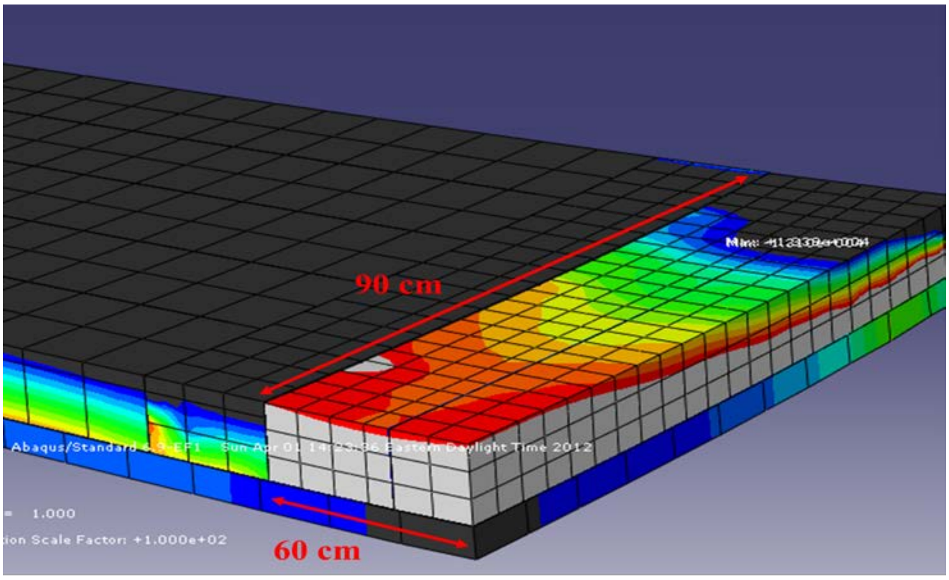

Figure 4. Location of the critical stress: stress concentration at midslab and around the tie bars

Results and Discussions: Cracking Potential. Figure 5 summarizes the average normal stress along the X-direction at midslab one day after paving for various values of T_D and T_B. Assuming that a crack is likely to occur when the average normal stress is larger than 2.8 MPa, it is apparent in Figure 4 that the occurrence of the cracking highly depends on the values of T_D and T_B. A T_D of -14 °C always results in cracking regardless of T_B and a T_D of 1 °C does not result in cracking regardless of the value of T_B. A T_D of -10 °C will result in cracking only when T_B is smaller than -4 or -3 °C.

In Table 3, Sections 1, 4 and 6 have a T_D of -14°C, -10°C and 1°C, respectively. Therefore, it can be concluded that Section 1 showed the highest potential for cracking while Section 6 exhibited the lowest potential for cracking. This prediction of cracking potential agrees very well with the observed degree of cracking for the three sections. The degree of cracking for the three sections is shown in Table 3, in terms of the percentage of slabs cracked within each section, where Section 1 exhibited the most severe cracking and no cracking developed in Section 6.

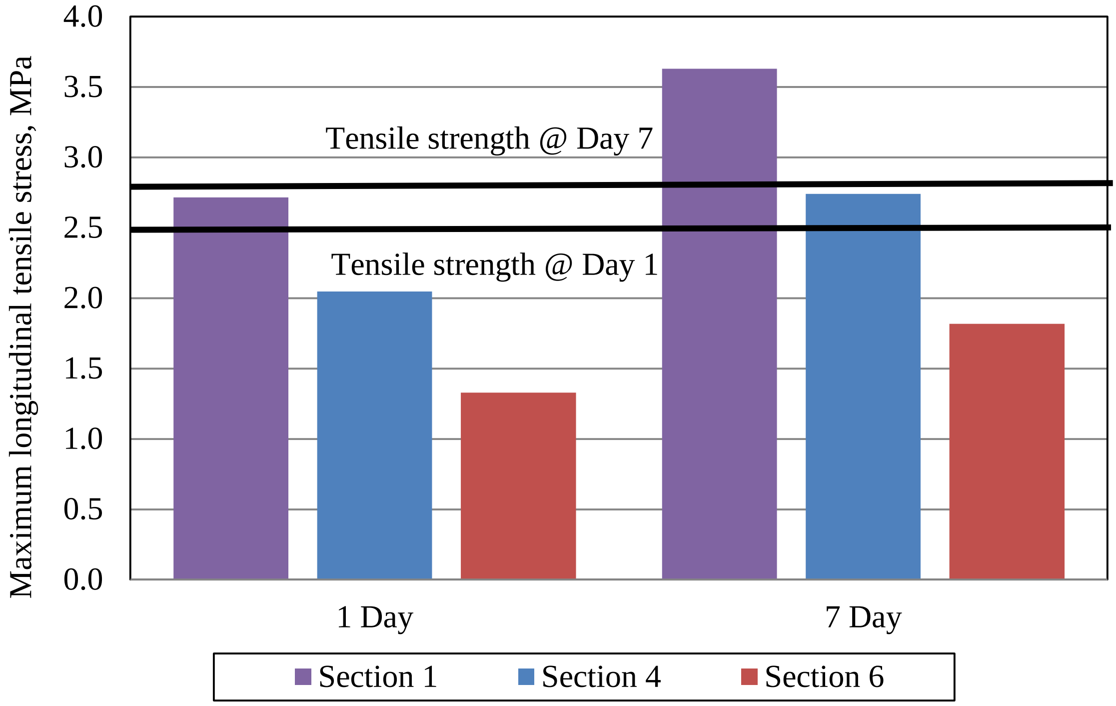

Figure 5. Maximum stress as a function of temperature differences, T_D and T_B

Parametric study

There are many other factors that need to be taken into account when calculating the cracking potential. First, a higher CTE will increase the thermal inconsistency between the mainline and the shoulder. Second, the stiffness and strength of the concrete both develop over time. However, while a larger stiffness results in larger stresses and therefore increases the potential for cracking, a larger strength reduces the cracking potential. Third, the use of a wider shoulder might provide more cracking resistance. Last, temperature gradients curl the slabs and additional tensile stresses are induced when the curling is restrained. In order to investigate the effects of these factors on the cracking potential, a parametric study was conducted and the results are summarized below.

Coefficient of Thermal Expansion. Figure 6 shows the effect of the concrete CTE on the potential of transverse cracking in the shoulder. As expected, a larger CTE results in a higher potential for cracking.

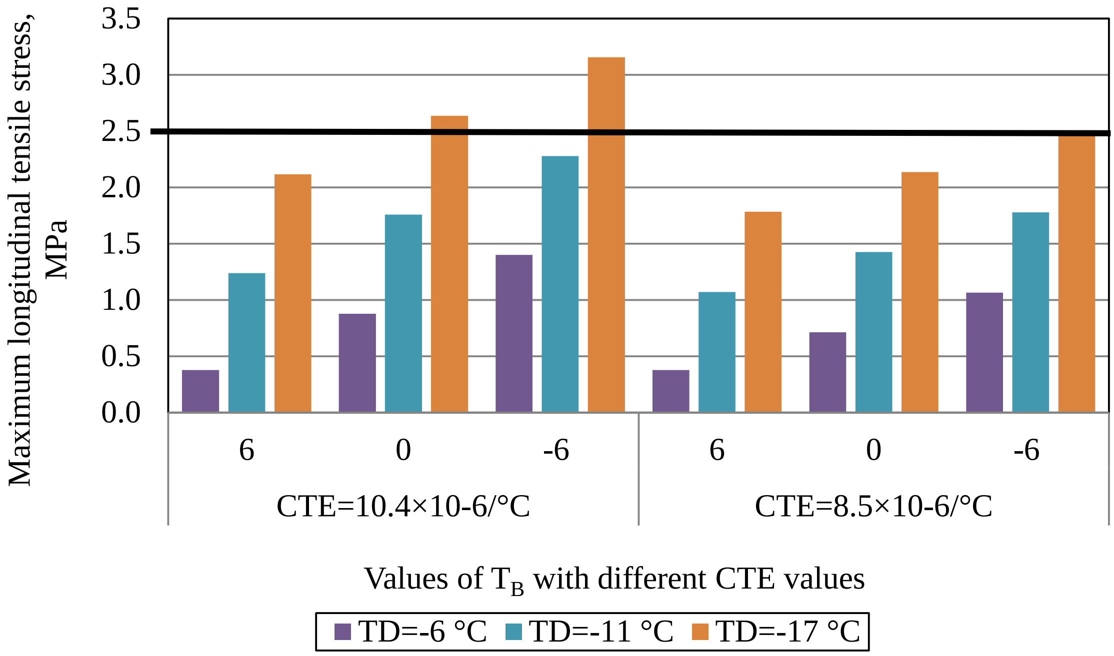

Figure 6. Influence of concrete CTE on the potential of the transverse cracking

Stiffness and Strength. The stiffness of the concrete was only defined using the elastic modulus and Poisson's ratio. By increasing the stiffness, larger stress can be expected. However, the concrete strength also increases with increasing stiffness. Figure 7 shows two different scenarios with different stiffnesses. The stiffness of 19 GPa corresponds to a 1-day indirect tensile strength of 2.5 MPa and the stiffness of 28 GPa corresponds to a 7-day indirect tensile strength of 2.8 MPa. In Figure 7, it seems that the cracking potential is higher after 7 days than after 1 day. Therefore, it can be concluded that the transverse cracks in the shoulder would have more likely occurred at the end of the first week.

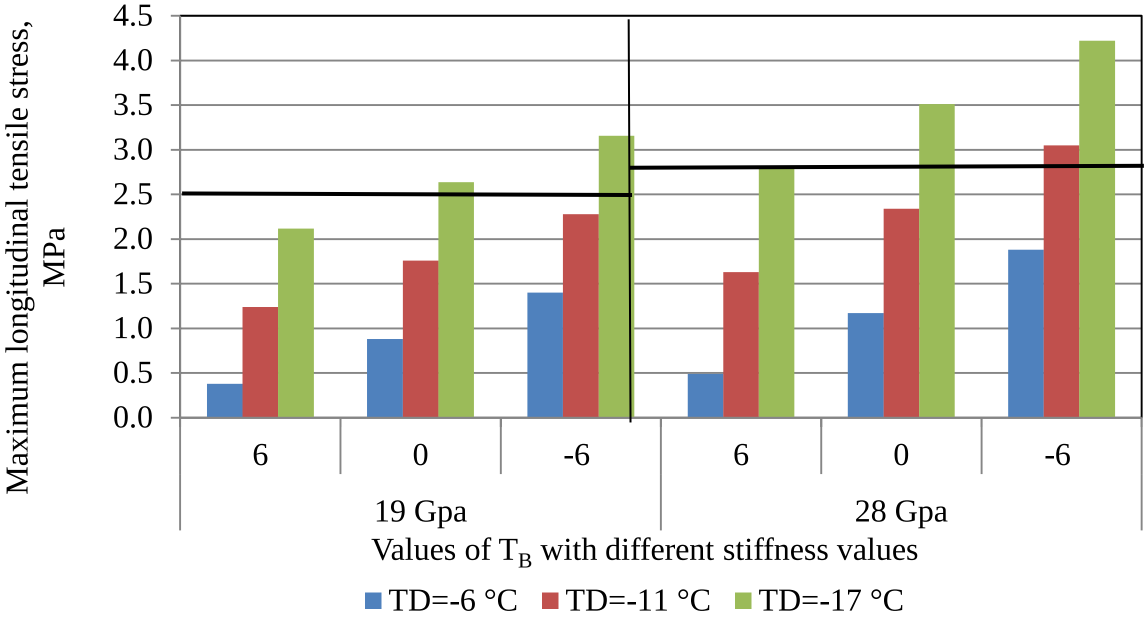

Figure 7. Influence of concrete stiffness and strength on the potential of the transverse cracking

Shoulder Width. The use of a 0.6-m shoulder also increases the potential for cracking, as observed in Figure 8. The critical tensile stress would have been greatly reduced if a wider (3-m) shoulder was used. The stress concentration in the shoulder due to the restraint from the mainline and tie bars has more room to dissipate as the shoulder becomes wider.

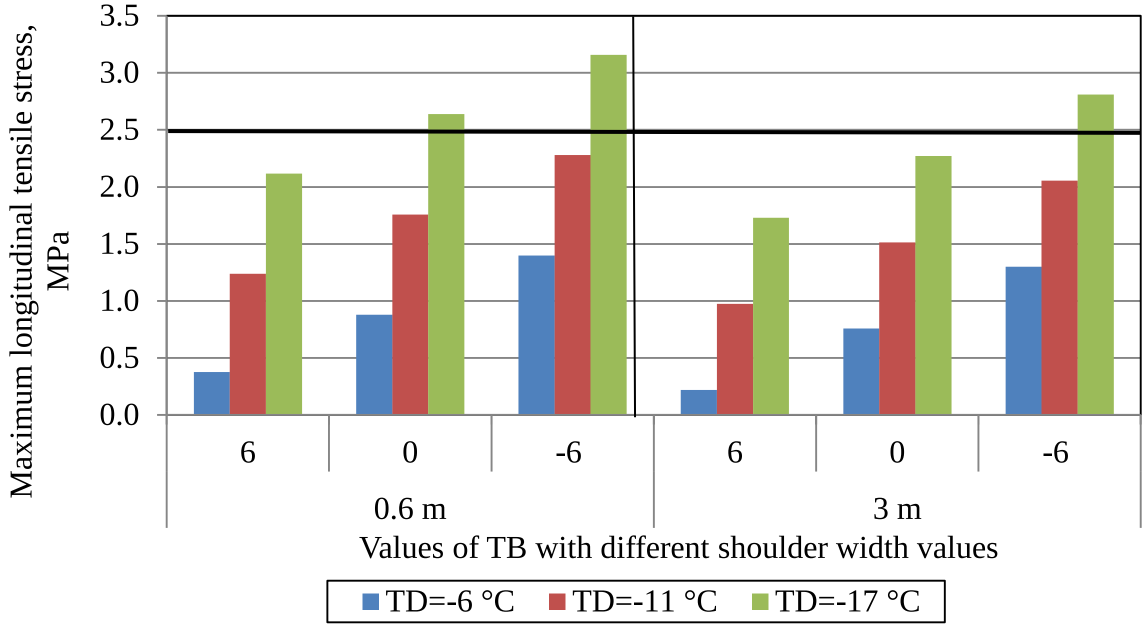

Figure 8. Influence of shoulder width on the potential of the transverse cracking

Temperature Gradient. Curling stresses develop at the top of the slab when the slab is subjected to a negative temperature gradient, i.e. the top of slab being cooler than the bottom, and the flexure of the slab is restrained by its self-weight, the bonded base and the adjacent slabs. By introducing a gradient, the stress due to restraining the curling of a slab is highlighted in addition to the stress due to restraining the uniform temperature change. Two different linear temperature gradients were used, i.e. -0.04 °C/mm and +0.04 °C/mm to compare with the zero gradient condition. Both gradients have the same average temperature as the one for the zero gradient condition.

Figure 9 shows the effect of temperature gradients. In general, the critical curling stress occurs at the bottom of the slab when a positive gradient is present and it occurs at the top of the slab when a negative gradient is present. Therefore, in Figure 9, the stresses with the negative gradients were recorded at the top of the slab and the stresses with the positive gradients were recorded at the bottom of the slab. When there was no gradient present, the critical stress location was at the top of the slab as identified in the previous section.

A positive gradient results in potentially higher cracking than when no gradient is applied, while a negative gradient results in the lowest potential for cracking.

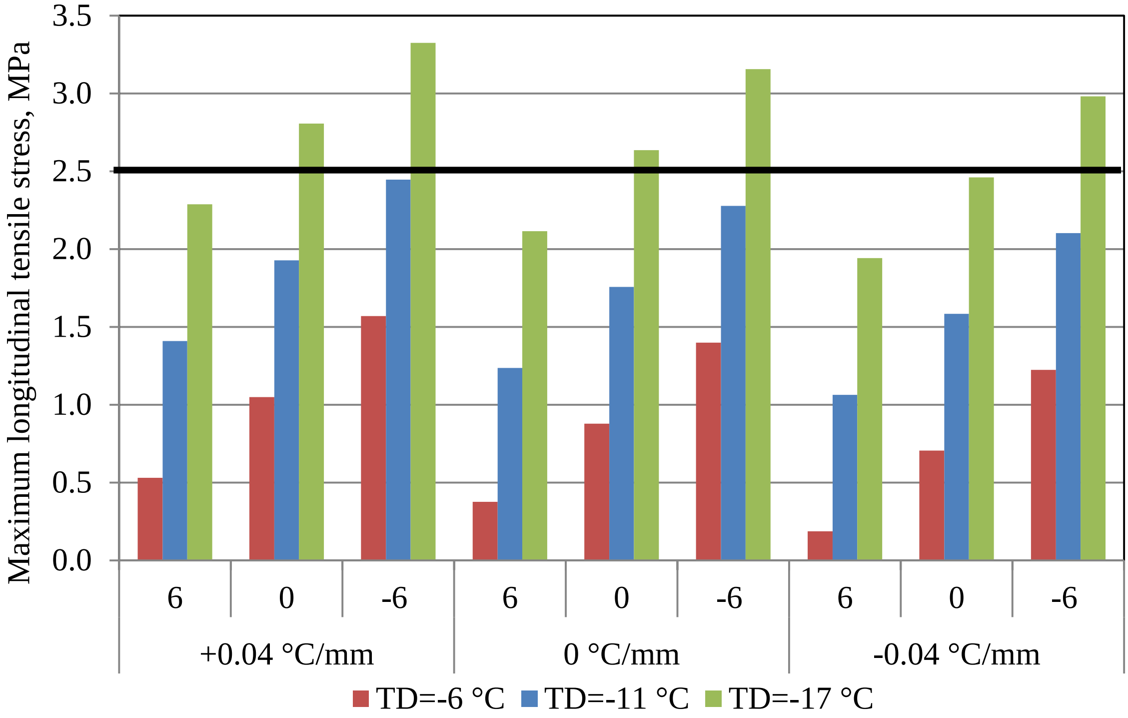

Figure 9. Influence of temperature gradients on the potential of the transverse cracking

Cracking Potential for Paving Adjacent Lanes Separately

The parametric study identified the CTE and temperature gradient, along with T_D and T_B, as the two important factors affecting the potential for premature cracking in the shoulder. Table 4 presents guidelines for determining the potential for a 0.6-m shoulder to develop transverse cracking based on the construction temperature and CTE.

Based on the criterion, the best way to avoid the development of transverse cracking in the 0.6-m shoulder is to construct the shoulder and the mainline under similar climatic conditions. If it is unavoidable to construct the mainline and shoulder in different seasons, Equation 1 can be used to determine the difference in zero-stress temperatures between the mainline and the shoulder. The potential for cracking can then be determined using Table 4.

Based on typically temperatures in Pennsylvania, the potential for this type of cracking in the 0.6-m shoulder will only exist when paving the mainline in October when the night temperature is quite low and the shoulder in April. In Pennsylvania, the months May through September provide pavement temperatures, especially at night, that are moderate and not too low and therefore this type of cracking will tend not develop. It is also possible to pave in April and October as long as the ambient temperature is relatively high in October or the mainline and shoulder will be paved in the same season. One should also note that the effect of temperature gradients is not considered in Table 4. Therefore, caution should be paid when using Table 4 in areas where large temperature swings exist.

Table 4. Cracking potential based on construction sequence and CTE

	CTE 10.4 x10^{-6} /°C		
	T_B, °C		
T_D, °C	-6	0	6
-17	Crack	Crack	Uncrack
-11	Uncrack	Uncrack	Uncrack
-6	Uncrack	Uncrack	Uncrack
	CTE 8.5 x10^{-6} /°C		
	T_B, °C		
T_D, °C	-6	0	6
-17	Crack	Uncrack	Uncrack
-11	Uncrack	Uncrack	Uncrack
-6	Uncrack	Uncrack	Uncrack

Note: Highlighted Cell Indicates Risk a Crack May Develop

Conclusions

In this study, a finite element analyses was undertaken to investigate the premature transverse cracks in the 0.6-m shoulder of U.S. 22, Blairsville, Pennsylvania. The following conclusions were made based on the analyses.

The cracking initiated due to the thermal incompatibility between the mainline and the shoulder. Paving the mainline and the shoulder in different seasons results in different zero-stress temperatures, from which thermal stresses that exceed the tensile strength of the concrete can develop. Two temperature differences were identified as having a significant impact on the potential for cracking, namely the difference in the zero-stress temperature between the mainline and the shoulder, i.e. T_D and the difference between the pavement transient temperature and the zero-stress temperature, i.e. T_B. The critical combinations of T_D and T_B that result in an increase in the potential for transverse cracking are presented in Table 4. Based on this analysis, the premature cracking in the shoulder could have developed any day within the first week after paving.

A large CTE increases the probability of cracking. The use of a concrete with a lower CTE will then help to reduce the cracking potential if the mainline and shoulder are to be paved during different seasons. The use of a wider shoulder will most likely reduce potential for cracking with respect to the narrower 0.6-m shoulder.

The presence of a positive temperature gradient increases the probability that a crack will develop. The values of T_D and T_B should follow the guidelines proposed in Table 4. When at all possible, both values should be kept to a minimum. If paving in a region where large daily swings in temperature are common, additional considerations should be made regarding the magnitude and type (positive or negative) of gradient that will be expereinenced.

Based on this study, constructing the mainline and shoulder separately in Pennsylvania in the months of May to September will not typically result in the development of transverse cracking in the shoulder. If the mainline is constructed later in the fall (after September), the contractor should tie on the shoulder when the values of T_D and T_B meet the criteria defined in Table 4. It is possible to pave the shoulder in April if the mainline is paved in October as long as the ambient temperature in that October is higher than normal. To estimate the best times for paving in other climatic regions, Equation 1 can be used to determine the difference in zero-stress temperatures for each month.

References

ABAQUS/CAE (2007). *Version 6.7*. Providence, Rhode Island: Dassault Systems.

ARA Inc., ERES Consultants Division. (2004). *Guide for mechanistic-empirical design of new and rehabilitated pavement structures.* Final report NCHRP 1-37A, Transportation Research Board of the National Academy, Washington, D.C.

Asbahan, R. (2009). *Effects of the built-in construction gradient and environmental conditions on jointed plain concrete pavements.* Ph.D. thesis, University of Pittsburgh, Pittsburgh, Pennsylvania.

Cutright, K. A. (2010). *Effects Guidelines for paving adjacent concrete lanes separately.* Master thesis, University of Pittsburgh, Pittsburgh, Pennsylvania.

Hall, K.T., Darter M.I., Hoerner T.E., and Khazanovich, L. (1997). *LTPP data analysis phase I: validation of guidelines for k-value selection and concrete pavementperformance prediction.* Technical report FHWA-RD-96-198. Washington, DC:Federal Highway Administration

Maitra, S. R., Reddy, K. S., and Ramachandra, L. S. (2009). “Experimental Evaluation of Interface Friction and Study of Its Influence on Concrete Pavement Response.” *Journal of Transportation Engineering , 135* (8), 563-571.

Mindess, S. and Young, J. F. (1981). *Concrete*, Prentice-Hall, Inc., 671 pp.

Neville, A.M.(1978). *Properties of Concrete*, 2nd Edition, Pitman Publishing, London, 687 pp.