CONCRETE COEFFICIENT OF THERMAL EXPANSION (CTE) AND ITS SIGNIFICANCE IN MECHANISTIC-EMPIRICAL PAVEMENT DESIGN

David K. Hein, P.Eng
Vice-President, Transportation

Applied Research Associates, Inc.
5401 Eglinton Avenue West, Suite 105
Toronto, Ontario M9C 5K6
(T) 416-621-9555 ext. 1
(E) dhein@ara.com

Sherry Sullivan, MASc, P.Eng, LEED AP
Director, Transportation and Built Environment

Cement Association of Canada
1500 Don Mills Road, Suite 704
Toronto, Ontario M3B 3K4
(T) 416-449-3708 ext. 234
(E) ssullivan@cement.ca

Paper Prepared for Presentation
at the Advances in Pavement Evaluation and Instrumentation
of the 2012 Annual Conference of the
Transportation Association of Canada
Fredericton, New Brunswick

ABSTRACT

The pavement performance models used in the new American Association of State Highway and Transportation Officials (AASHTO) Mechanistic-Empirical Pavement Design Guide (MEPDG) were calibrated to observed field performance from the Strategic Highway Research Program (SHRP) Long Term Pavement Performance (LTPP) test sections and various other test tracks and monitoring sites throughout North America. These are considered to be “global” performance models that are generally applicable across North America. However, agencies using the MEPDG and its associated software application (DARWin-ME) are strongly encouraged to review the global models in the context of pavement performance within their jurisdictions and to undertake local validation and calibration efforts. This local calibration effort would serve to improve the transfer functions that take the MEPDG stress and strain outputs and translate them to pavement performance indicators such as slab faulting, fatigue cracking and pavement roughness. Most major highway agencies across North America are currently completing such local calibration efforts. In Canada, the Transportation Association of Canada sponsored a “roadmap” for MEPDG implementation in Canada.

The coefficient of thermal expansion (CTE) is one of the critical factors considered in the design of concrete pavements. As this factor is rarely specified on Canadian projects, pavement designers typically rely on the MEPDG default values or an average value rather than project specific values. While this tended to produce “reasonable” results when using empirical pavement design procedures, the CTE has a much larger impact on the pavement design when using the much more comprehensive MEPDG procedures. DARWin-ME takes advantage of the advances in material mechanics, axle-load spectra and climate data for predicting pavement performance. Relying on the default values of CTE may lead to flawed assumptions about the pavement’s thermal response and potential distress.

This paper discusses through the importance of project specific values for CTE and provides resources for reliable data. This paper also discusses the FHWA’s standard test method (adopted by AASHTO as TP60-00) for determining the CTE of concrete pavements. FHWA has been using this test method to measure CTE for over 2000 cores from across the US and was collected as part of the Long Term Pavement Performance (LTPP) program.

INTRODUCTION

The pavement performance models used in the new American Association of State Highway and Transportation Officials (AASHTO) Mechanistic-Empirical Pavement Design Guide (MEPDG) [1] were calibrated to observed field performance from the Strategic Highway Research Program (SHRP) Long Term Pavement Performance (LTPP) test sections and various other test tracks and monitoring sites throughout North America. These are considered to be "global" performance models that are generally applicable across North America. However, agencies using the MEPDG and its associated software application (DARWin-ME) are strongly encouraged to review the global models in the context of pavement performance within their jurisdictions and to undertake local validation and calibration efforts [2]. This local calibration effort would serve to improve the transfer functions that take the MEPDG stress and strain outputs and translate them to pavement performance indicators such as slab faulting, fatigue cracking and pavement roughness. Most major highway agencies across North America are currently completing such validation and local calibration efforts [3-7].

In Canada, the Transportation Association of Canada sponsored a "roadmap" for MEPDG implementation in Canada [8]. For the preparation of the roadmap, a survey of 11 major transportation agencies in Canada was completed. This survey asked agencies about their practice with respect to important individual material tests by category. The response for the primary concrete material properties that are used in the MEPDG for concrete is shown in Table 1.

Table 1. Current Practice for Portland Cement Concrete Testing

Property	Number of Agencies Collecting Material Properties (out of 11)		
	Regularly	Sometimes	Never
Modulus of Elasticity	1	1	9
Flexural Strength	3	2	6
Coefficient of Thermal Expansion	2	1	8
Shrinkage	1	2	8
Thermal Conductivity	1	0	10
Heat Capacity	0	0	11

What is significant about the results shown in Table 1 is the fact that virtually none of the major Canadian highway agencies are measuring concrete pavement materials for thermal conductivity and heat capacity. The study went on to complete a gap analysis between current agency practices and those needed for the utilization of the new MEPDG design procedure. The input data for Portland cement concrete pavements outlined in Table 1 was considered to be very important for the MEPDG method, highly relevant for Canadian conditions and a major gap that requires laboratory testing of materials and correlation with other test methods to be able to accurately use the MEPDG for concrete pavement design.

Significance of Coefficient of Thermal Expansion

The hydration of concrete (curing) generates heat. The amount of heat that is generated is a function of a number of things including the temperature at the time of placement, type and fineness of the cement, quantity of supplementary cementitious materials, water content and type and quantity of coarse and fine aggregates. Once set, the thermal expansion and contraction of concrete is a function of cement content, aggregate type, temperature range and relative humidity. Of these, the aggregate type has the greatest influence on the amount of thermal expansion and contraction.

The coefficient of thermal expansion (CTE) in concrete is the measure of how concrete changes in volume in response to changes in temperature. CTE is defined as the change in unit length per degree of temperature change and is dependent on the type of aggregate in the concrete mix and the degree of saturation. Typical ranges for CTE by aggregate type are provided in Table 2.

Table 2. Coefficient of Thermal Expansion (CTE) of Concrete by Aggregate Type [10]

Primary Aggregate Class	Average CTE (/°F x 10^{-6})	Standard Deviation (s) (/°F x 10^{-6})	Average CTE (/°C x 10^{-6})	Standard Deviation (s) (/°C x 10^{-6})	Sample Count[1]
Andesite	4.32	0.42	7.78	0.75	52
Basalt	4.33	0.43	7.80	0.77	141
Chert	6.01	0.42	10.83	0.75	106
Diabase	4.64	0.52	8.35	0.94	91
Dolomite	4.95	0.40	8.92	0.73	433
Gabbro	4.44	0.42	8.00	0.75	8
Gneiss	4.87	0.08	8.77	0.15	3
Granite	4.72	0.40	8.50	0.71	331
Limestone	4.34	0.52	7.80	0.94	813
Quartzite	5.19	0.50	9.34	0.90	131
Rhyolite	3.84	0.82	6.91	1.47	7
Sandstone	5.32	0.52	9.58	0.94	84
Schist	4.43	0.39	7.98	0.70	30
Siltstone	5.02	0.31	9.03	0.56	21
				Total Sample Count	2,251

1. A total of 2,991 CTE values are available in LTPP Standard Data Release 25.0 (January 2011); 628 CTE values were not used due to aggregate class not defined or only one sample available for the primary aggregate type, and 112 CTE outlier values were also not included in the table.

Use of the CTE in the MEPDG

The MEPDG has established three levels of design. Level 3 is the lowest level of sophistication and should be used for facilities of relatively low importance and traffic levels. The input of CTE for a Level 3 design is an estimate based on historical data. This is considered to have a poor level of accuracy as PCC materials can be quite variable and Level 3 estimates have the greatest potential for error. Level 2 inputs for CTE are based on a weighted average of the aggregate quantities and values outlined in Table 2 above. Level 1 values for CTE are considered the most accurate as they are based on actual test results (outlined below).

The thermal expansion and contraction of a concrete pavement can have a significant effect on its performance. Thermal expansion can cause joint lock-up and blowups. Thermal contraction can result in transverse cracking of slabs depending on the joint spacing. Thermal effects also impact slab bending and curling and when joints/edges are curled upwards, there do not have full contact with the base and are subject to cracking under traffic loading. This could be particularly significant for long, thin slabs under heavy, frequent loading.

FHWA's standard test method (adopted by AASHTO as TP 60-00)

The CTE data used for the original concrete pavement distress models in the MEPDG were found to be incorrect due to an error in the AASHTO TP 60-00 test procedure used [9]. This test method resulted in a higher CTE values being determined. This would in term show a higher sensitivity of the concrete to thermal changes thus resulting in higher levels of slab curling and cracking.

The error was found during the calibration of the CTE test frame. The AASHTO TP 60-00 test method recommends a value of 17.3 x 10^{-6} ºC be used for the 304 stainless steel specimen that is used to calibrate the CTE test frame. However, it was found that the CTE of the 304 stainless steel test frame was actually 15.0 x 10^{-6} ºC using ASTM E 228 test method [10]. Using the ASTM 228 test method in MEPDG models, results in a lower CTE for concrete by the same proportion. This is now being addressed in the new AASHTO T336 test method, which determines the CTE of the stainless steel specimen used to calibrate the CTE frame.

The the current version of DARWin ME, incorporates CTE values that were determined using the original AASHTO TP 60-00 test method.

SCOPE OF SENSITIVITY ANALYSIS

A design sensitivity analysis was completed to illustrate the effect of the CTE on concrete pavement design. The two roadway sections selected for the analysis were classified as minor arterial and major arterial in accordance with the parameters outlined in the Methodology for the Development of Equivalent Pavement Structural Design Matrix for Municipal Roadways [12]. The minor arterial roadway had an annual average daily truck traffic (AADTT) of 1,500 and the major arterial an AADTT of 10,000.

The minor arterial baseline analysis inputs are summarized as follows:
- 200 mm PCC, 200 mm Granular A, 4.5 m slab length, standard3.7 m paving lane, CTE 10.
- 200 mm PCC, 200 mm Granular A, 4.5 m slab length, widened4.2 m paving lane, CTE 10.

The major arterial baseline analysis inputs are summarized as follows:
- 210 mm PCC, 200 mm Granular A, 4.5 m slab length, standard3.7 m paving lane, CTE 10.
- 210 mm PCC, 200 mm Granular A, 4.5 m slab length, widened4.2 m paving lane, CTE 10.

PCC used across Ontario is primarily based on OPSS 350 (MTO 1998), with the following exceptions. All non-structurally reinforced concrete exposed to chlorides and freezing & thawing is 32MPa, Class C-2, with Air Category 1 (varying depending on aggregate size used) with a maximum water to cementing materials ratio (W/CM) of 0.45 (as per CSA A23.1-09). Based on the minimum specifications, the concrete properties in Table 3 were used in the analysis.

Table 3. Portland Cement Concrete Properties

Property	Value
Concrete Strength	32 MPa - 28-day Compressive Strength 5.6 MPa - 28-day Modulus of Rupture 29.6 GPa - 28-day Elastic Modulus
Unit Weight	2,324 kg/m^3
Water to Cement Ratio	0.45

The most commonly available aggregates used in pavement construction in Ontario consist of Granular A base and Granular B subbase. These materials are described in the Ontario Provincial Standard Specifications. The MEPDG input parameters are summarized in Table 4.

Table 4. Granular Base and Subbase Properties

<table>
<tr><th colspan="2">Property</th><th colspan="2">Granular A</th><th colspan="2">Granular B</th></tr>
<tr><td rowspan="9">Aggregate Gradation (min. and max. percent passing)</td><td>106 mm</td><td>N/A</td><td>N/A</td><td>100</td><td>100</td></tr>
<tr><td>26.5 mm</td><td>100</td><td>100</td><td>50</td><td>100</td></tr>
<tr><td>19.0 mm</td><td>85</td><td>100</td><td>N/A</td><td>N/A</td></tr>
<tr><td>13.2 mm</td><td>65</td><td>90</td><td>N/A</td><td>N/A</td></tr>
<tr><td>9.5 mm</td><td>50</td><td>73</td><td>N/A</td><td>N/A</td></tr>
<tr><td>4.75 mm</td><td>35</td><td>55</td><td>20</td><td>55</td></tr>
<tr><td>1.18 mm</td><td>15</td><td>40</td><td>10</td><td>40</td></tr>
<tr><td>300 µm</td><td>5</td><td>22</td><td>5</td><td>22</td></tr>
<tr><td>75 µm</td><td>2</td><td>8</td><td>0</td><td>10</td></tr>
<tr><td colspan="2">Plasticity Index</td><td colspan="2">0</td><td colspan="2">0</td></tr>
<tr><td colspan="2">Modulus</td><td colspan="2">250 MPa</td><td colspan="2">200 MPa</td></tr>
<tr><td colspan="2">Poisson’s Ratio</td><td colspan="2">0.35</td><td colspan="2">0.35</td></tr>
<tr><td colspan="2">Coefficient of Lateral Pressure (k_0)</td><td colspan="2">0.5</td><td colspan="2">0.5</td></tr>
</table>

The selection of appropriate properties for the subgrade is an important component of any pavement design. For all detailed pavement designs, geotechnical investigations are required to determine specific conditions for the purposes of providing support to the roadway as well as information on the constructability of the pavement. This is an important step for all pavement design projects. The sensitivity analysis was completed using an inorganic silt subgrade with the properties outlined in Table 5.

Table 5. Subgrade Properties

Soil Properties	**Inorganic Silt**
Subgrade Strength	Medium
Resilient Modulus	40 MPa
Equivalent CBR	4
Soil Classification	ML
Liquid Limit	20
Plasticity Index	5

The variable input used in each of the four baseline cases was the coefficient of thermal expansion (CTE). Values of 7, 8, 9, 10, and 11 were used.

RESULTS

The sensitivity analysis for the minor arterial roadway (AADTT = 1,500) is shown in Figures 1 through 3. The analysis for the major arterial roadway (AADTT = 10,000) is shown in Figures 4 though 6. The impact on international roughness index (IRI), slab faulting and transverse slab cracking is shown for each case.

Figure 1. Effect of CTE and Widened Slab on Terminal IRI - 200 mm Slab

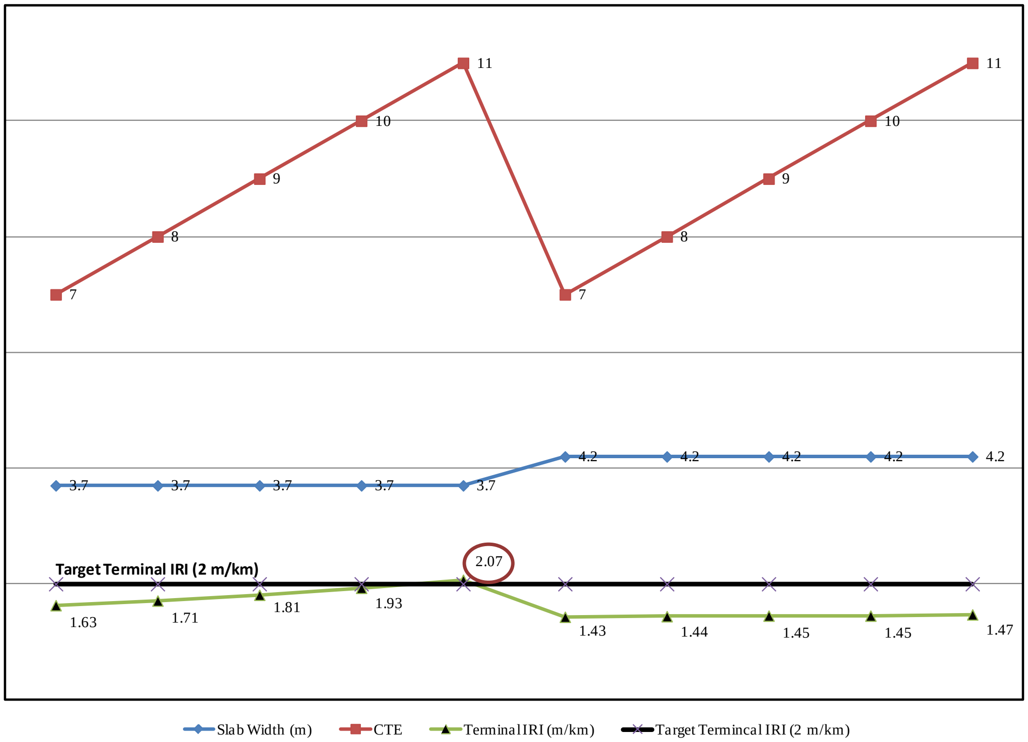

Figure 2. Effect of CTE and Widened Slab on Mean Joint Faulting - 200 mm Slab

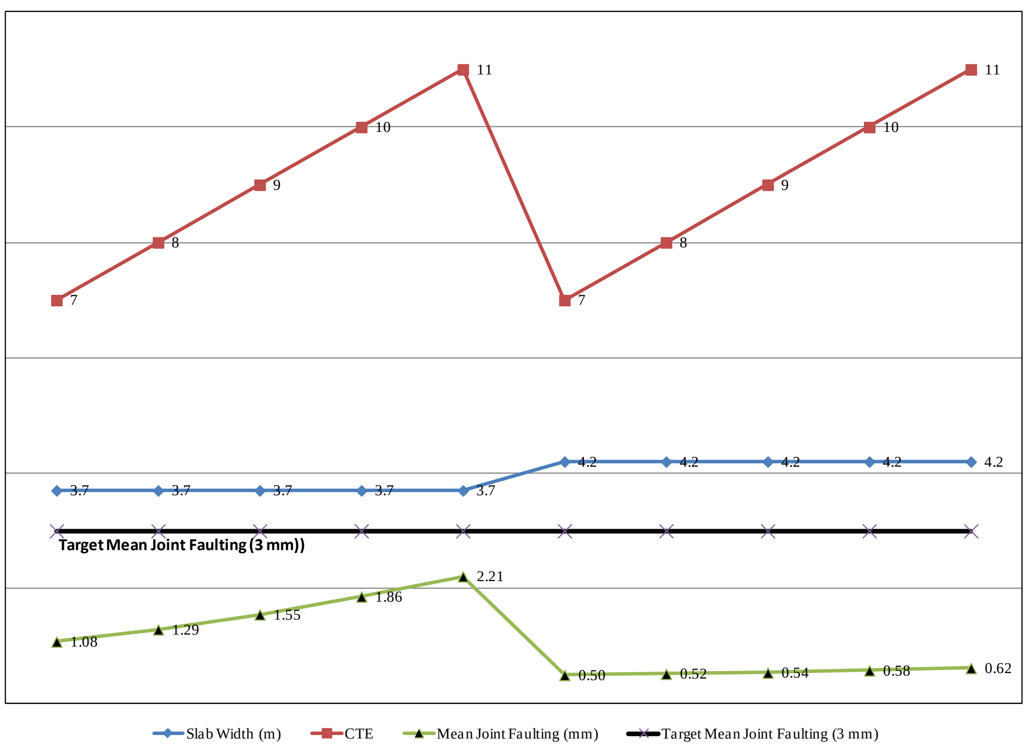

Figure 3. Effect of CTE and Widened Slab on Transverse Cracking - 200 mm Slab

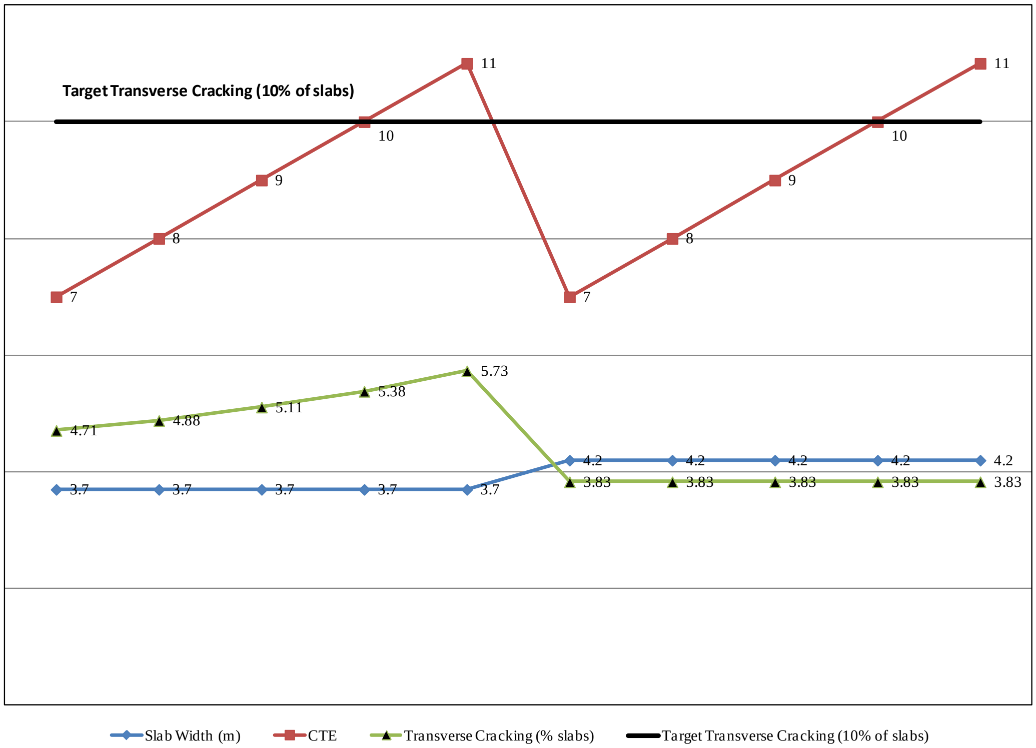

Figure 4. Effect of CTE and Widened Slab on Terminal IRI - 210 mm Slab

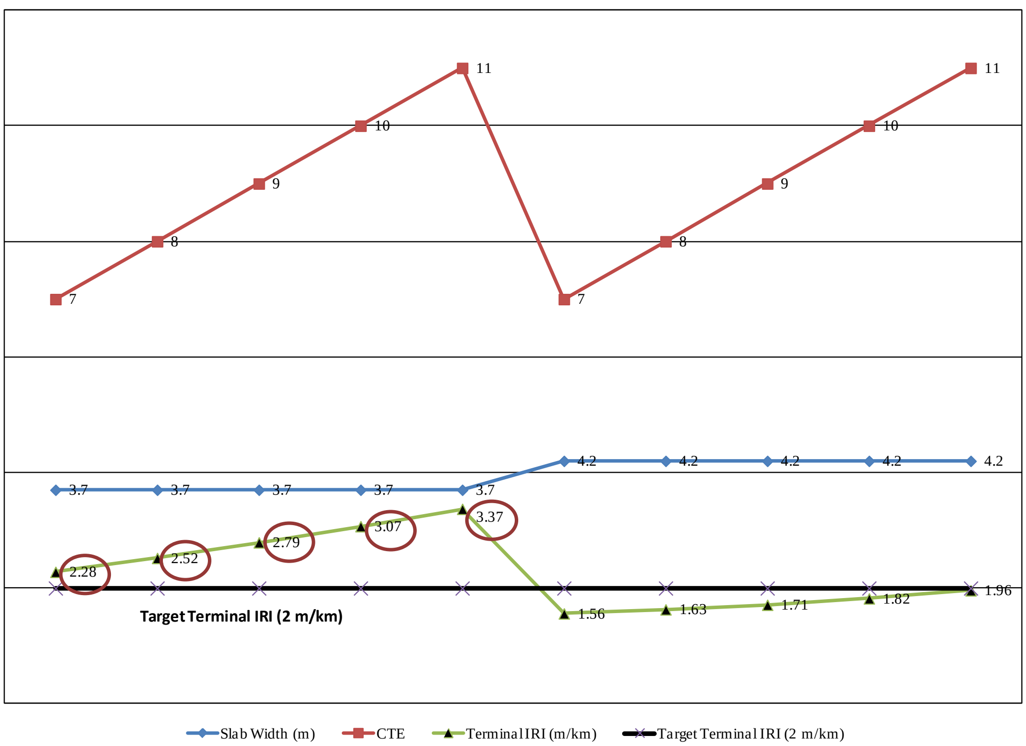

Figure 5. Effect of CTE and Widened Slab on Mean Joint Faulting - 210 mm Slab

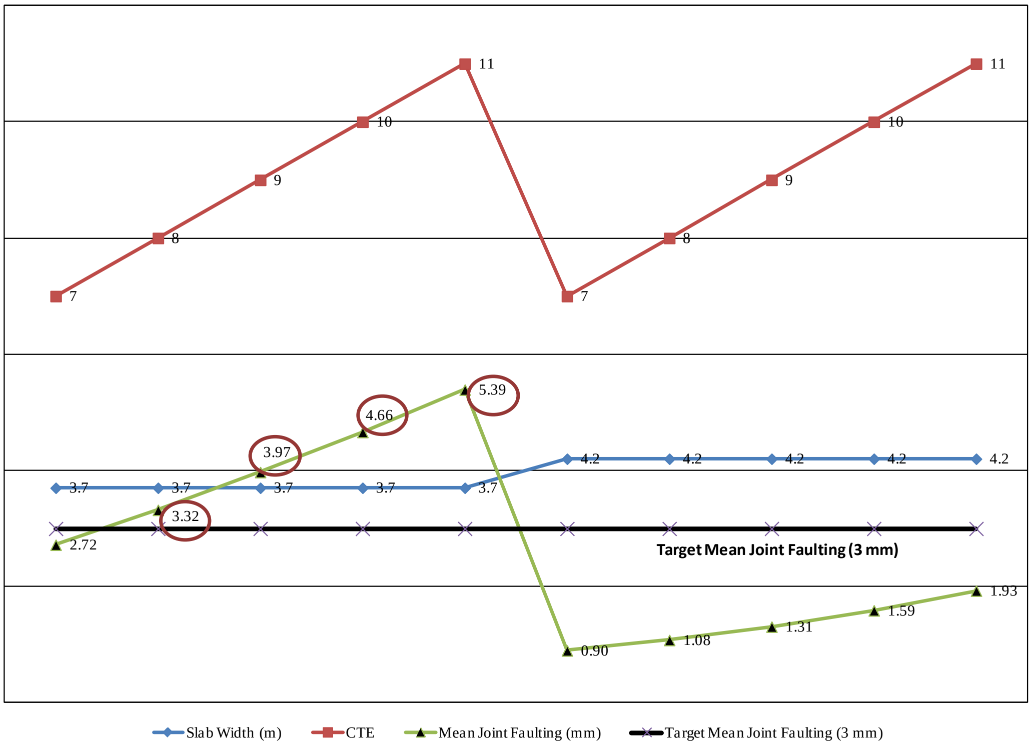

Figure 6. Effect of CTE and Widened Slab on Transverse Cracking - 210 mm Slab

A general summary of the results of the sensitivity analysis in varying the input of the coefficient of thermal expansion from 7 to 11 $10^{-6}/^{o}C$ are as follows:

Minor Arterial Roadway (200 mm PCC)

- For 3.7 m slabs, IRI increased from 1.63 to 2.07 m/km (+27 percent)
- For 4.2 m slabs, IRI increased from 1.43 to 1.47 m/km (+3 percent)
- For 3.7 m slabs, joint faulting increased from 1.08 to 2.21 mm (+105 percent)
- For 4.2 m slabs, joint faulting increased from 0.50 to 0.63 mm (+26 percent)
- For 3.7 m slabs, transverse cracking increased from 4.71 to 5.73 percent (+26 percent)
- For 4.2 m slabs, transverse cracking did not change

Major Arterial Roadway (210 mm PCC)

- For 3.7 m slabs, IRI increased from 2.28 to 3.37 m/km (+48 percent)
- For 4.2 m slabs, IRI increased from 1.56 to 1.96 m/km (+26 percent)
- For 3.7 m slabs, joint faulting increased from 2.72 to 5.39 mm (+98 percent)
- For 4.2 m slabs, joint faulting increased from 0.90 to 1.93 mm (+114 percent)
- For 3.7 m slabs, transverse cracking increased from 7.64 to 14.64 percent (+92 percent)
- For 4.2 m slabs, transverse cracking increased from 3.83 to 4.39 percent (+15 percent)

CONCLUSIONS

The results of the sensitivity analysis indicate that the selection of the appropriate value for the coefficient of thermal expansion is important in the consideration of municipal roadway rigid concrete pavements. The following specific conclusions can be drawn from the analysis:

- The CTE significantly impacts the amount of joint faulting.
- The CTE has a lesser impact on the percentage of cracked slabs. However, the percentage of crack slabs increases as the slab width is reduced and the traffic level is increased.
- Variations in the CTE have less impact on the projected roughness of the pavement.
- With the widened slab, the damage increased with the CTE, but the increase in distress is considered to be lower.

Overall, care should be taken in determining the correct CTE to use for design for reduced slab width and higher trafficked pavements.

ACKNOWLEDGEMENTS

The authors would like to thank the Ready Mixed Concrete Association of Ontario for the use of the base pavement designs used for this analysis.

REFERENCES

1. Applied Research Associates, Inc., “Guide for Mechanistic- Empirical Design of New and Rehabilitated Pavement Structures”, Final Report, NCHRP Project 1-37a, Washington, D.C., March 2004.

2. American Association of State Highway and Transportation Officials (AASHTO), “Guide for the Local Calibration of the Mechanistic-Empirical Pavement Design Guide”, Washington, D.C., 2010.

3. Applied Research Associates, Inc., “Development of Design Standards for the City of Winnipeg Streets”, City of Winnipeg, 2011.

4. Applied Research Associates, Inc., “Pavement Structural Design Guidelines”, City of Toronto, Works and Emergency Services, Transportation Division, 2006.

5. Mrawira, D., Welch, W., Schonlau, M., and Haas, R., “Sensitivity Analysis of Computer Models: World Bank H – III Model”. Journal of Transportation Engineering, ASCE, Vol. 125, No. 5, pp. 421-428, Sept. /Oct., 1999.

6. Tighe, S., He, Z, Al Assar, R., and Haas, R., “Calibrating Mechanistic-Empirical Pavement Performance Models with an Expert Matrix”, Proceedings, Transportation Association of Canada Annual Conference, Halifax, 2001.

7. Haas, R., Tighe, S., Doré, G and Hein, D., “Mechanistic-Empirical Pavement Design: Evolution and Future Challenges”, Proceedings, Transportation Association of Canada Annual Conference, Saskatoon, 2007.

8. Doré, G., Tighe, S. and Hein, D., “Roadmap for the Calibration and Implementation of the Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures”, Transportation Association of Canada, November 2005.

9. Crawford, G., J. Gudimettla, and J. Tanesi, “Inter-laboratory Study on Measuring Coefficient of Thermal Expansion of Concrete,” presented at the Annual Meeting of the Transportation Research Board, Washington, DC, January 2010

10. FHWA, "Coefficient of Thermal Expansion in Concrete Pavement Design", ACPT Tech Brief - FHWA-HIF-09-015, U.S. Department of Transportation, Federal Highway Administration, October 2011

11. Applied Research Associates, Inc., "Methodology for the Development of Equivalent Pavement Structural Design Matrix for Municipal Roadways. Including Maintenance and Rehabilitation Schedules and Life Cycle Cost Analysis", Ready Mixed Concrete Association of Ontario, January 2011.