Effect of Portland cement Concrete Mix Properties, Thickness, Joint Layout and Traffic Loading on the PMED Software Predicted Distresses in Jointed Plain Concrete Pavement

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Abstract

Between September 2022 and March 2023, Transportation Association of Canada (TAC) Mechanistic Empirical (ME) Pavement Design Subcommittee completed five sets of design trials using the AASHTOWare Pavement ME Design (PMED) software to assess the effects of portland cement concrete (PCC) mix properties, coefficient of thermal expansion (CTE), slab thickness, dowel diameter, joint spacing and traffic loading on the predicted distresses in jointed plain concrete pavement (JPCP). The trial results using software v2.6 indicated that a better quality concrete results in improved performance in terms of predicted international roughness index (IRI), faulting and cracking. Only a high CTE of >8.0x10^{-6}/ºC seems to affect the predicted transverse cracking. Varying climate was shown to have significant effect on the predicted IRI, a lesser effect on the predicted faulting and no or negligible effect on the predicted transverse cracking. The trial results also showed some inconsistencies and significant differences in the predicted distresses between software v2.6 and v3.0.

The trial results using software v3.0 showed that an increase in the PCC thickness results in an increase in the predicted IRI and faulting, which is not expected. An increase in the PCC thickness showed a reduction in the predicted transverse cracking. The trial results also showed that thicker dowels provide a significant reduction in the predicted faulting and IRI, but have no or minimal effect on the predicted transverse cracking. PCC joint spacing showed no or minimal effect on the predicted IRI, a significant effect on the predicted joint faulting for PCC layer thicker than 200 mm and for high CTE values and a significant effect on the predicted transverse cracking. Traffic loading has a small effect on the predicted IRI. The minimum PCC thickness should be 205 mm and CTE should be 8.0x10^{-6}/ºC to produce an impact of traffic loading on the predicted faulting. Transverse cracking is highly sensitive to traffic loading with thinner concrete. Overall, a high CTE value has shown a greater impact on the predicted performance than joint spacing and PCC thickness, which seems to be unreasonable and requires further investigation.

Acknowledgement

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Introduction

PCC mix properties, PCC layer thickness, dowel size (thickness) and joint spacing can have a significant influence on the PCC pavement design and performance. Since PCC mix properties can have a huge effect on both the durability and performance of the concrete pavement, it is important to utilize good quality aggregates that are resistant to alkali silica reaction (ASR) and D-cracking and meet the CSA A23.1 [1] Class C-2 exposure requirements to ensure that the concrete pavement will have the appropriate strength and durability. Compressive strength is another critical concrete property that can influence the concrete pavement performance. Higher compressive strength of a properly designed and constructed concrete generally correlates well with increased durability and service life, as the concrete pavement becomes more resistant to bending and fatigue cracking, and freeze-thaw damage as well as chemical attacks due to reduced permeability.

Hein, D. and Sullivan, S. [2] identified CTE as one of the critical parameters in the design of PCC pavements using the PMED software. The paper also noted that the original CTE data used in the PMED software for the distress prediction models in rigid (PCC) pavements was incorrect due to an error in the AASHTO TP 60-00 test procedure [2, 3], and it is not known to be corrected in any newer versions of the software.

The thickness of concrete pavements is also important parameter as it will have a major effect on the amount of truck traffic the concrete pavement structures can carry. Concrete pavements utilizing shorter joint spacing have proven to perform better than that with larger joint spacing [4]. The shorter joint spacing improves load transfer across joints and reduces shrinkage forces and environmental stresses. For example, the curling and warping stresses due to differential drying and thermal shrinkage are reduced with shorter joint spacing. Bending stresses in unsupported concrete slabs are also reduced by decreasing the joint spacing. In addition, shorter slabs will also have smaller joint openings due contraction of concrete, improve load transfer from slab to slab across the joints due to better aggregate interlock. It should be noted here that the typical spacing between transverse joints is between 3.7 m and 4.5 m for 175 mm (7 in.) to 300 mm (12 in.) thick PCC layer [5].

The function of dowel bars is to provide load transfer between adjacent concrete slabs while allowing for horizontal movement of PCC slabs, to help maintain pavement smoothness and to minimize faulting and cracking. The size (diameter/thickness) of the dowel used will affect the bearing stress at the bottom of the dowel and JPCP performance. Since larger dowels have a greater surface area at the bottom of the dowel, the induced stress on the dowel from applied load at concrete joints will be distributed over a wider contact area under the dowel. This will reduce chance of crushing the concrete under the dowel due to repeated loads and enhance performances of JPCP. Larger size dowels also provide higher resistance to bending.

This paper assesses the impact of the above-specified input parameters on the PMED software predicted distresses in JPCP.

Background

The TAC ME Pavement Design Subcommittee has been evaluating the PMED software since 2007. Numerous design trials were completed between 2007 and 2019 to assess effect of traffic loading, asphalt mix properties, binder and thickness, subgrade, subbase and base materials, and concrete slab and joint designs on the predicted distresses. Recently, the Subcommittee has also completed design trials to assess the effect of subgrade, subbase and base materials on the predicted distresses in JPCP using the PMED software. Results from some of these trials can be found in different technical papers presented elsewhere and this conference.

Between September 2022 and March 2023, five sets of design trials were completed to assess the effect of concrete mix properties such as compressive strength, cementitious materials (cm) content, CTE, water to cementitious materials (*w/c)* ratio and unit weight, concrete slab thickness, dowel size (diameter) and joint spacing on the PMED software predicted distresses. Varying climatic data from nine weather stations across Canada were used in all trials. The combinations of design inputs in the five trial sets were: i) varied concrete mix properties (using v2.6), ii) comparison between predicted distresses using v2.6 and v3.0 for varied concrete mix properties, iii) varied PCC thickness, dowel size and CTE (using v3.0), iv) varied joint spacing, PCC thickness and CTE (using v3.0), and v) varied traffic loading and PCC thickness (using v3.0). Fifty-four (10 with software v2.6 and 44 with software v3.0) design runs were completed for each climate station with different combinations of inputs. A number of additional trials were completed by Manitoba for an in-depth analysis. This paper presents the results of these trials and discusses the issues and suitability of the PMED software for modeling the effect of concrete mix and material properties, thickness, dowel size, joint spacing and traffic loading.

Findings from Literature Review

NCHRP Project 1-47 [6] conducted a sensitivity analysis of distresses predicated by the Mechanistic-Empirical Pavement Design Guide (MEPDG). The study indicated that different input parameters have different levels of sensitivity on the predicted distresses in the JPCP are listed in Table 1.

Table 1. Levels of sensitivity (NCHRP Project 1-47) [6]

Parameters	**Level of Sensitivity for JPCP**	
	Faulting	**Transverse Cracking**
w/c Ratio	Sensitive	Non-Sensitive
Unit Weight	Sensitive	Sensitive
PCC Thickness, Joint Spacing and CTE	Very Sensitive	Very Sensitive
28-day Compressive Strength	Non-Sensitive	Very Sensitive
Dowel Diameter	Sensitive	Non-Sensitive

Hein, D. and Sullivan, S. [2] performed a sensitivity analysis using DARWin-ME software to assess the effect of CTE on concrete pavement performance by varying the CTE value from 7 to 11x10^{-6}/°C. The study showed that the CTE significantly affects the magnitude of predicted IRI, joint faulting, and percent transverse cracking, a higher CTE means higher IRI, joint faulting, and transverse cracking. However, the effect of CTE was less significant for 4.2 m wide slabs as compared with 3.7 m wide slabs in terms of transverse cracking performance. Saboori et al. [7] performed another sensitivity analysis using the PMED software v2.5.3 with three CTE values, 4x10^{-6}/°F, 5x10^{-6}/°F, 6x10^{-6}/°F (7.2x10^{-6}/°C, 9.0x10^{-6}/°C, 10.8x10^{-6}/°C). The results also showed that an increased CTE value causes a significant increase in IRI, joint faulting and transverse cracking.

A sensitivity analysis on the effect of compressive strength was also conducted in the study by Saboori et al. [7] using three different strength values, 32.6 MPa, 39.5 MPa, and 46.4 MPa. The result showed that increased compressive strength reduces the IRI and transverse cracking. In terms of transverse cracking, an increase in compressive strength from 32.6 MPa to 46.6 MPa resulted in a decrease in the transverse cracking from 70% to about 8% in a 40-year design service life. However, the change in compressive strength has a lesser impact on the joint faulting than the transverse cracking.

According to the study by Saboori et al. [7], the effect of increased concrete thickness on the predicted faulting does not match with the expected result for thicker concrete pavement that should have less faulting. It was believed that this outcome is related to the fact that dowel bar diameter of 1.5 in. (38.1 mm) was kept constants for all concrete thicknesses of 7 in., 8 in., and 9 in. (178 mm, 203 mm and 229 mm). A further analysis showed that if the dowel diameter is adjusted for each concrete thickness to 1.00 in., 1.25 in., and 1.5 in. (25.4 mm, 31.8 mm, and 38.1 mm) for 7 in., 8 in., and 9 in. (178 mm, 203 mm and 229 mm) concrete thickness, respectively, the predicted faulting decreases significantly.

A study in Manitoba [8] observed that the required concrete thickness for the JPCP using the PMED software is significantly thinner than that Manitoba usually constructs. In the AASHTO 1993 [9] design method, flexural strength of concrete and joint load transfer efficiency (LTE) have significant contribution on PCC thickness design and pavement performance. The flexural strength depends on the in-place concrete mix and aggregate properties or compressive strength. The LTE) depends on dowel size and spacing, aggregate size and interlock at concrete interface, stiffness of support layers and subgrade.

Pavement performance is significantly influenced by the magnitude and frequency of the vehicular traffic loads. The traffic loading applied to rigid (PCC) pavement structures is distributed over a wider area under the concrete slabs before it is transmitted to the underlying supporting layers [11]. As a result, the traffic load induced responses such as stresses, strains and deflections in the layer below the concrete slabs are relatively smaller as compared to that in flexible pavement structures [12].

The stresses induced in concrete pavement slabs due to traffic loading are sensitive to the loading position relative to the geometry of the slab. This variability has been well quantified using the well-established Westergaard method of analysis. Stresses in a concrete slab are greater when the load is applied near the slab edge or corner, when compared to interior loading conditions. Edge or corner loading must also consider load transfer effects. Consequently, thickness design is influenced by the location of the load relative to the geometry of the pavement. Alternatively, slab geometry can be modified to minimize the imparted stresses by traffic loads [13].

Objective and Significance

Some past studies conducted global sensitivity analysis of the PMED software predicted distresses to concrete mix properties without an in-depth logical analysis, while some other studies indicated low to high sensitivities to some concrete mix properties but no or negligible sensitivities to other concrete mix properties, dowel size, and concrete thickness. Some studies also questioned the adequacy of the PMED software models for concrete with different aggregate types.

The objectives of the TAC ME Pavement Design Subcommittee design trials is to assess further the effect of concrete mix properties as well as other parameters such as joint spacing, dowel size, concrete thickness and traffic loading on the predicted distresses using the software v2.6 and v3.0 (the new web version) in Canadian context. The objective of this paper is to present the details of the completed trial results and analysis. The presented information may help different agencies and other interested individuals in assessing the suitability of the PMED software when designing a concrete pavement structure and/or to develop an appropriate process for design and construction.

Software Versions and Design Trial Inputs

All participants used the PMED software v2.6 and v3.0 with the global calibration coefficients for the design trials. The variable design inputs were: i) Climate: varying climates data from nine climate stations across Canada, ii) PCC mix properties: varying compressive strength, cementitious materials content, CTE, w/c ratio and unit weight (v2.6 and v3.0), iii) Concrete slab and joint: varying joint spacing, dowel size, CTE and slab thickness, and iv) Traffic loading: varying PCC thickness and traffic loading. All other input parameters remained unchanged in all trials: i) Vehicle class distribution and Axle Load Spectra (ALS): Manitoba Level 1; ii) Base layer: 200 mm thick layer of Manitoba's Granular Base Course Type I (GBC-I) with a resilient modulus of 250 MPa; iii) Subgrade materials: Silty sand (AASHTO A-2-4) with resilient modulus of 60 MPa; iv) Design life: 25 years, v) Initial IRI: 0.9 m/km; and vi) Design reliability: 90%.

Selected Climate Stations

As indicated earlier, nine climate stations across Canada with varying weather patterns were used in these trials. Figure 1 shows the general geographic location of the climate stations. The red dots indicate relatively warm while the blue dots indicate relatively cold climates in Canadian context. Table 2 presents the list of climate stations and the summary of the key climate parameters. As shown in the table, there are significant difference in climatic parameters between NARR (v2.6) and MERRA (v3.0) data.

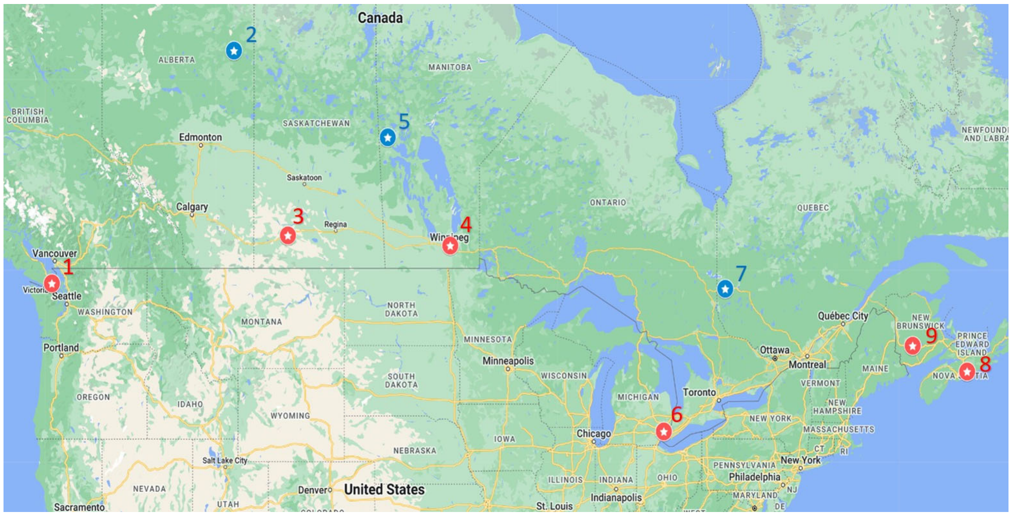

Figure 1. Geographic location of climate stations used in the PMED software trials

Table 2. List of climate stations and climate data summary

NARR vs MERRA Climate Data for Different Climate Stations Across Canada					
Climate Station	**Mean Annual Air Temp., °C**	**Mean Annual Precipitation, mm**	**Mean Annual Number of Wet Days**	**Mean Annual Freezing Index, °C -days**	**Mean Annual No. of Freeze-Thaw Cycles**
1. Victoria, BC	10.6/10.9	1002/1494	221/333	1.1/10.4	1.2/7.2
2. Fort McMurray, AB	1.9/1.4	567/643	241/339	1900/1926	47.2/72.3
3. Swift Current, SK	5.0/5.2	414/444	203/277	1361/1045	50.5/100.5
4. Winnipeg, MB	4.0/3.3	506/623	205/302	1653/1760	36.2/67.6
5. The Pas, MB	1.7/0.4	477/600	219/329	2017/2357	43.4/59.1
6. Windsor, ON	10.0/9.6	776/1094	199/301	383/304	56.7/52.2
7. Rouyn, QC	3.5/2.1	890/1236	240/350	1443/1767	45.4/67.4
8. Halifax, NS	7.8/7.3	801/1584	211/340	432/315	69.8/68.8
9. Fredericton, NB	6.0/5.0	913/1426	220/344	819/996	72.3/81.0

Design Trial Matrix and Trial Results

Each set of design trials included a specific matrix of inputs. The variables in each trial set including their rationale are discussed in the results and discussion section for the convenience of understanding. Due to a large number of climate stations in the trials, only selected climate stations are used to demonstrate the variation of each predicted distress for a clear understanding/visualization of the effect of each variable.

Results and Discussion- Trial Sets #1 and 2: Effect of PCC Mix Properties on the Predicted Distresses

PMED software v2.6 and v3.0 were used for Trial Sets #1 and 2, respectively. Table 3 shows the summary of various concrete mix properties used in Trial Sets #1 and 2. The purposes of these two sets of trials were to: i) evaluate the effect of concrete strength and thermal expansion as well as w/c ratio, cementitious contents, and varying climate on the predicted distresses; ii) evaluate the possible variations in pavement distresses between v2.6 and v3.0. Although an increase in the cementitious materials content or a reduction in the w/c ratio will generally increase the strength of the concrete, these design trials were conducted to assess the impact of each individual variable (Designs 1 through 10) in addition to the combined physical and mechanical properties of concrete (Designs 11 and 12).

Table 3: Concrete mix properties and aggregate types in Trials Sets #1 and 2

Design No.	Notation	Compressive Strength, MPa	Cementitious Contents, kg/m^3	Concrete Aggregate Types	CTE (based on aggregate type), x10^{-6}/ºC	w/c Ratio	Concrete Density, kg/m^3
1	(1) 35MPa-340CM-LS-CTE6.0-WC0.4	35	340	Limestone	6.0	0.40	2350
2	(2) 28MPa-340CM-LS-CTE6.0-WC0.4	28	340	Limestone	6.0	0.40	2350
3	(3) 42MPa-340CM-LS-CTE6.0-WC0.4	42	340	Limestone	6.0	0.40	2350
4	(4) 35MPa-310CM-LS-CTE6.0-WC0.4	35	310	Limestone	6.0	0.40	2350
5	(5) 35MPa-370CM-LS-CTE6.0-WC0.4	35	370	Limestone	6.0	0.40	2350
6	(6) 35MPa-340CM-GR-CTE8.0-WC0.4	35	340	Granite	8.0	0.40	2350
7	(7) 35MPa-340CM-DO-CTE6.0-WC0.4	35	340	Dolomite	10.0	0.40	2350
8	(8) 35MPa-340CM-LS-CTE6.0-WC0.35	35	340	Limestone	6.0	0.35	2350
9	(9) 35MPa-340CM-LS-CTE6.0-WC0.45	35	340	Limestone	6.0	0.45	2350
10	(10) 35MPa-340CM-LS-CTE6.0-WC0.40	35	340	Limestone	6.0	0.40	2250
11	*(11) 28MPa-310CM-LS-CTE6.0-WC0.42	28	310	Limestone	6.0	0.42	2300
12	*(12) 42MPa-370CM-LS-CTE6.0-WC0.37	42	370	Limestone	6.0	0.37	2400

**Not included in Trial Set #1 with software v2.6; designs 1, 2 and 3 = variation of strength; designs 1, 4 and 5 = variation of cementitious materials content; designs 1, 6 and 7 = variation of CTE; designs 1, 8 and 9 = variation of w/c; and designs 1 and 10 = variation of density.*

Effect of PCC Mix Properties on the Predicted Distresses (Software v3.0)

Figures 2 through 4 show the comparative variation of predicted distresses for different concrete mix properties using software v3.0. As shown in Figures 2 and 3, there is a direct relationship between concrete compressive strength and two predicted distresses, IRI and faulting, where a reduction in compressive strength (compare designs 2-1-3) results in a higher IRI and faulting. Higher cementitious materials content (compare designs 4-1-5) leads to higher IRI and faulting, which is questionable and needs further investigation. Furthermore, a higher CTE (compare designs 1-6-7) significantly increases the IRI and faulting values. The results also indicate that an increase in w/c ratio (compare designs 8-1-9) and a reduction in concrete density (compare designs 1-10) contribute to higher IRI and faulting values. The results presented in Figures 2 and 3 show that the IRI and faulting tend to follow similar trends.

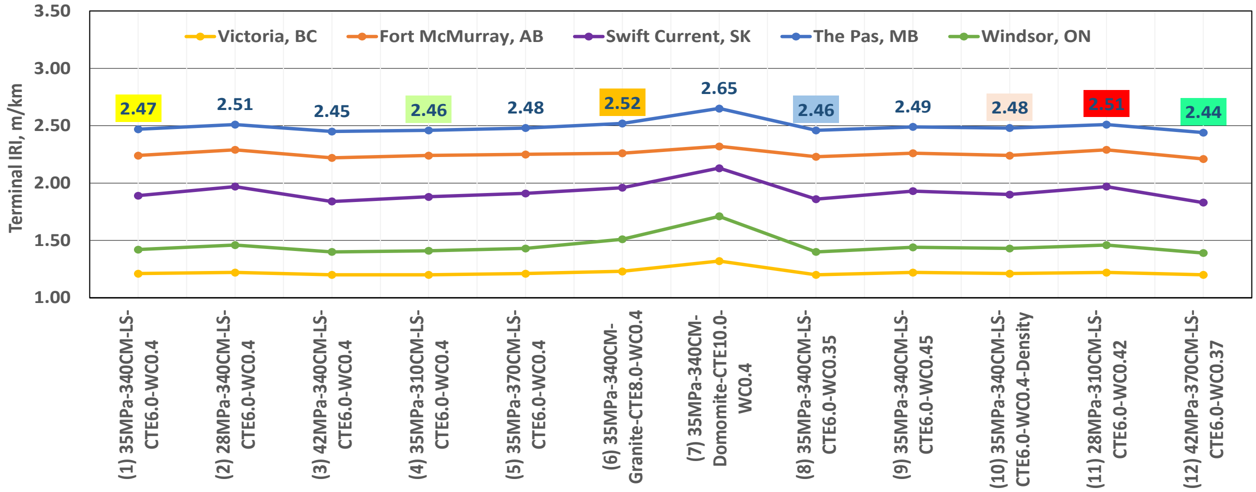

Figure 2. Effect of PCC mix properties on the predicted IRI (v3.0)

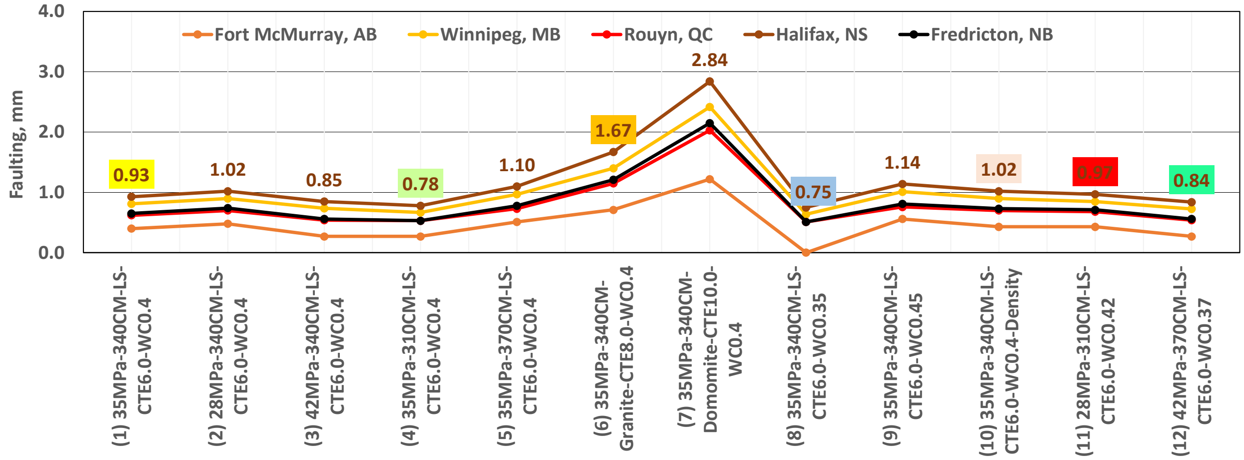

Figure 3. Effect of PCC mix properties on the predicted faulting (v3.0)

Figure 4 shows that among the concrete mix properties, the CTE has a significant effect on the predicted transverse cracking in PCC pavements. Specifically, only a high CTE value (compare designs 1-6-7) of greater than 8.0 x 10^{-6}/ºC appears to have an impact on the predicted transverse cracking. The compressive strength (compare designs 2-1-3) of concrete produces noticeable effect on the predicted transverse cracking. No other changes in the concrete mix properties (e.g., designs 4 vs 5, 8 vs 9 and 1 vs 10) seem to affect significantly the predicted transverse cracking. As expected, climatic conditions play a crucial role in all the predicted distresses as temperature and moisture changes cause significant expansion and contraction of PCC. Overall, good quality concrete improves the performance of concrete pavements in terms of reduced roughness, faulting and cracking (compare designs 11-12 in Figures 2, 3 and 4).

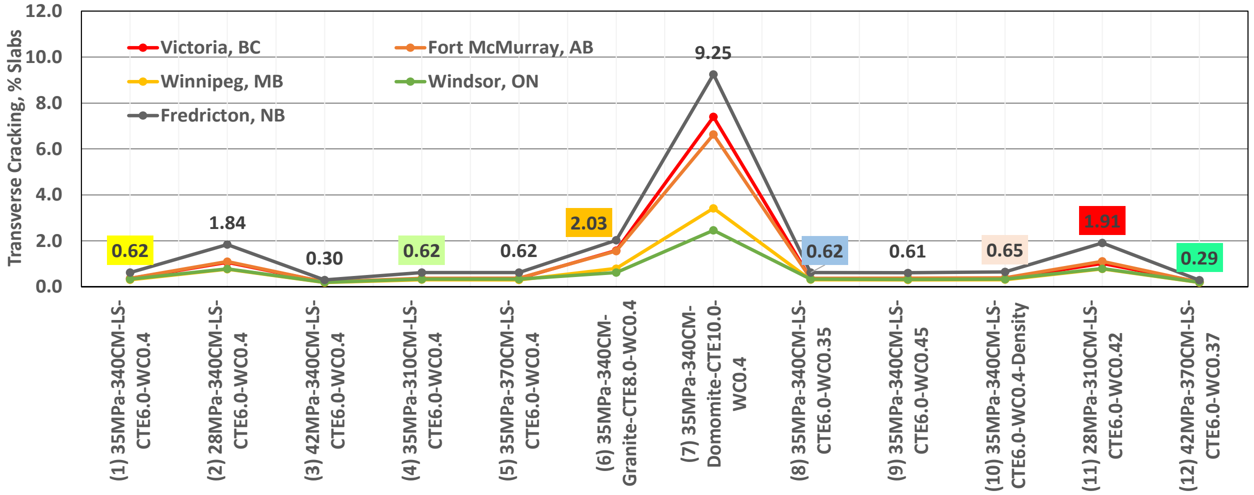

Figure 4. Effect of PCC mix properties on the predicted transverse cracking (v3.0)

Comparison of the Effect of PCC Mix Properties on the Predicted Distresses: Software v3.0 and v2.6

Figures 5 to 7 present comparisons between predicted distresses using two versions of the PMED software, v2.6 and v3.0, for the variation of concrete mix properties. As shown in Figure 5, in general, both versions exhibit similar trends in the predicted IRI, with the exception of the effect of compressive strength. With increased compressive strength, software v2.6 produces higher IRI and faulting (compare designs 2-1-3), which do not seem to be reasonable. However, software v3.0 generally provides higher IRI values and is less sensitive to CTE than that with v2.6 (compare designs 1-6-7).

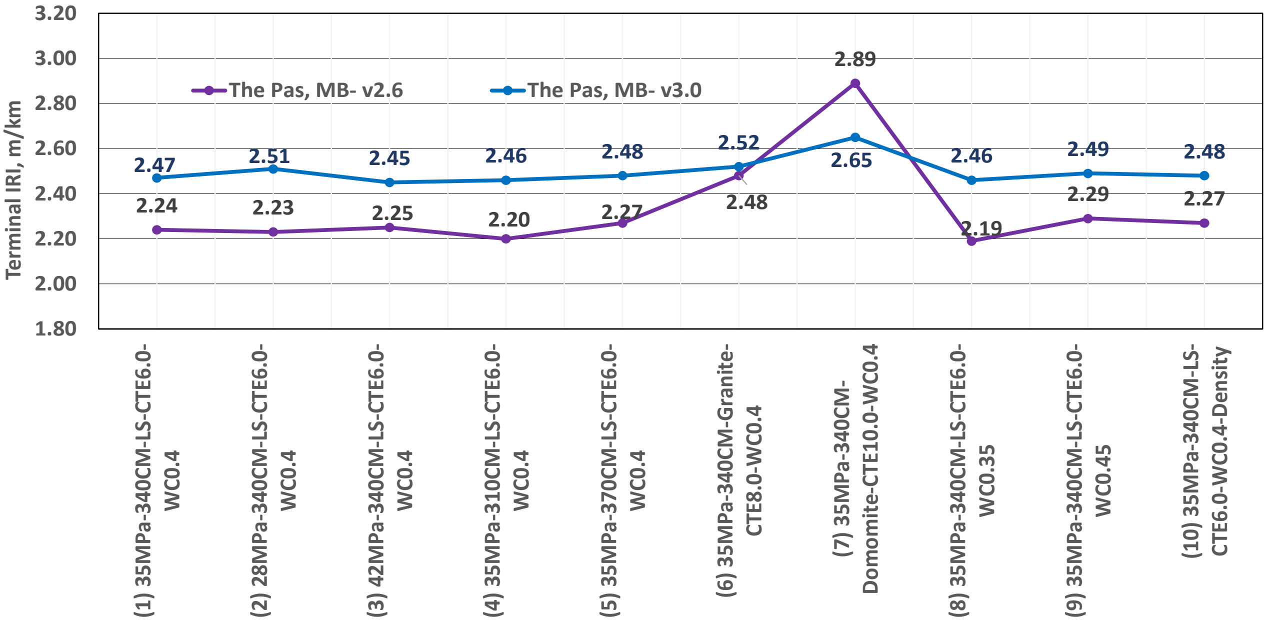

Figure 5. Comparison of the effect of PCC mix properties on the predicted IRI- software v3.0 vs v2.6

As shown in Figure 6, the predicted faulting also follows similar trends using software v2.6 and v3.0 for the variation of concrete mix properties. However, software v3.0 predicts a lower amount of faulting as compared to that with software v2.6, which are reversed trends when compared to the predicted IRI (Figure 5).

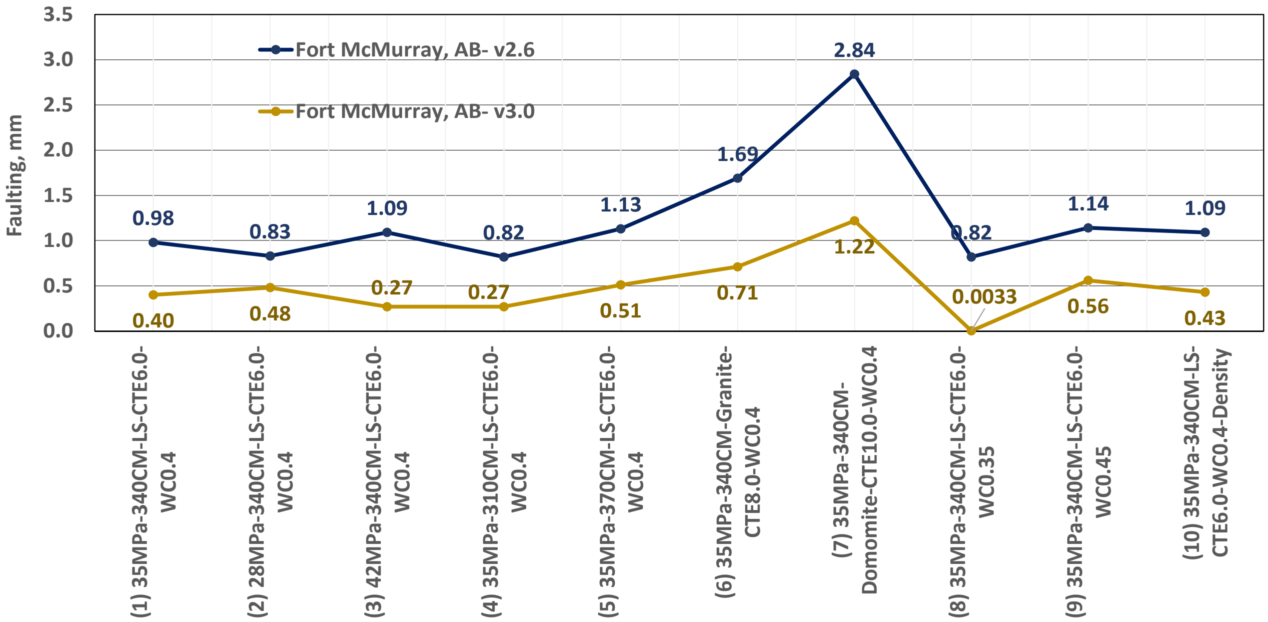

Figure 6. Comparison of the effect of PCC mix properties on the predicted faulting- software v3.0 vs v2.6

The comparison of predicted transverse cracking in Figure 7, between software v3.0 and v2.6, show that the trends are different for most inputs of concrete mix properties. The predicted transverse cracking is influenced by changes in concrete mix properties in software v3.0, but not much in software v2.6. Specifically, software v3.0 exhibits an increase in transverse cracking (compare designs 3-1-2) with weaker concrete (lower compressive strength), whereas software v2.6 shows no effect with changes in compressive strength. Moreover, software v3.0 demonstrates a more significant impact to changes in CTE (compare designs 1-6-7) than software v2.6 on the predicted transverse cracking. Changes in w/c ratio (compare designs 1-8-9) and concrete mix density (compare designs 1-10) have minor effects in software v3.0 whereas software v2.6 shows no effect, and software v3.0 produces a lower amount of transverse cracking than that with software v2.6.

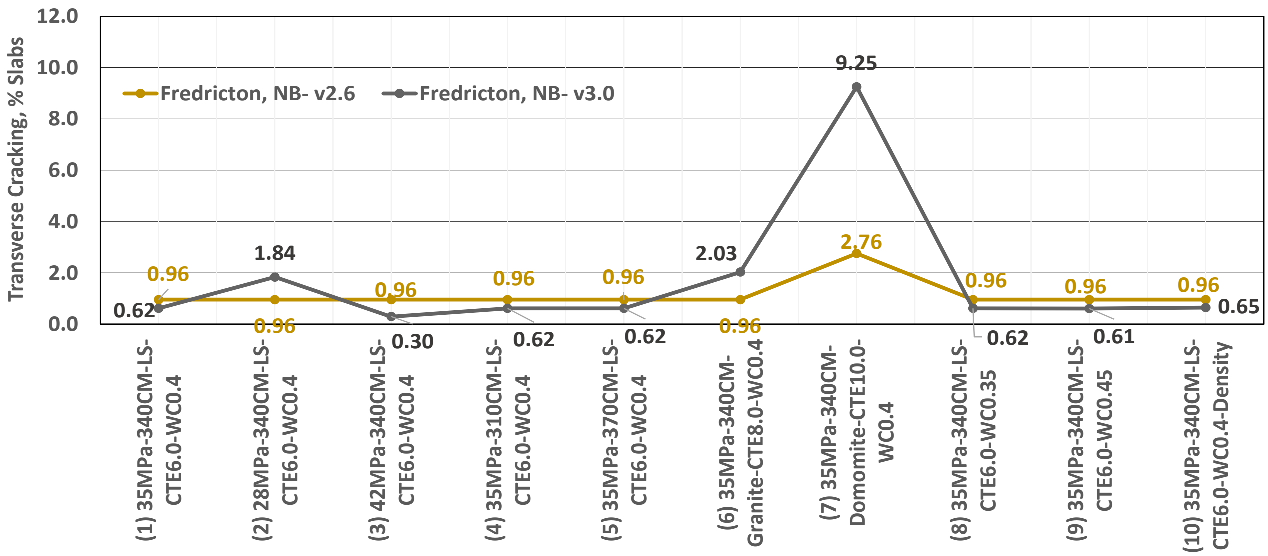

Figure 7. Comparison of the effect of PCC mix properties on transverse cracking- software v3.0 vs v2.6

Results and Discussion- Trial Sets #3 and 4: Effect of PCC Thickness, Dowel Size, Joint Spacing and CTE

The design Trial Sets #3 and #4 aimed to evaluate the effects of PCC slab thickness, dowel size and joint spacing on the predicted distresses in JPCP. To assess the effect of PCC slab thickness, 200 mm, 225 mm and 250 mm thick concrete slabs were used with 28 mm dowels. To assess the effect of dowel size, 28 mm and 32 mm dowels were used with 250 mm thick concrete. To assess the effect of PCC joint spacing, 4.0 m, 4.5 m and 5.0 m joint spacing were used with 200 mm and 250 mm thick concrete and 32 mm dowels. In addition, different aggregate types, with varying CTE values, were used in both trial sets to further assess the influence of CTE on the predicted distresses in combination with the above stated design variables. For the analysis in both trial sets, v3.0 was utilized. Tables 4 and 5 show the variable parameters that were used in Trial Sets #3 and #4, respectively.

Table 4. Variable parameters in Trial Set #3 (joint spacing = 4.5 m)

Design No.	Notation	Aggregate Type	CTE (based on aggregate type), x 10^{-6}/ C	Dowel Size, mm	JPCP Thickness, mm
1	(1) LS-CTE6.0-D28-PCC200	Limestone	6.0	28	200
2	(2) LS-CTE6.0-D28-PCC225	Limestone	6.0	28	225
3	(3) LS-CTE6.0-D28-PCC250	Limestone	6.0	28	250
4	(4) LS-CTE6.0-D32-PCC250	Limestone	6.0	32	250
5	(5) GR-CTE8.0-D28-PCC200	Granite	8.0	28	200
6	(6) GR-CTE8.0-D28-PCC225	Granite	8.0	28	225
7	(7) GR-CTE8.0-D28-PCC250	Granite	8.0	28	250
8	(8) GR-CTE8.0-D32-PCC200	Granite	8.0	32	250
9	(9) DO-CTE10.0-D28-PCC200	Dolomite	10.0	28	200
10	(10) DO-CTE10.0-D28-PCC225	Dolomite	10.0	28	225
11	(11) DO-CTE10.0-D28-PCC250	Dolomite	10.0	28	250
12	(12) DO-CTE10.0-D32-PCC250	Dolomite	10.0	32	250

Table 5. Variable parameters in Trials Set #4 (dowel size = 32 mm)

Design No.	Notations	Aggregate Type	CTE (Based on aggregate type), x 10^{-6}/ºC	JPCP Thickness, mm	Joint Spacing, m
1	(1) LS-CTE6.0- PCC200-JS4.0	Limestone	6.0	200	4.0
2	(2) LS-CTE6.0- PCC200-JS4.5	Limestone	6.0	200	4.5
3	(3) LS-CTE6.0- PCC200-JS5.0	Limestone	6.0	200	5.0
4	(4) LS-CTE6.0- PCC250-JS4.0	Limestone	6.0	250	4.0
5	(5) LS-CTE6.0- PCC250-JS4.5	Limestone	6.0	250	4.5
6	(6) LS-CTE6.0- PCC250-JS5.0	Limestone	6.0	250	5.0
7	(7) DO-CTE10.0- PCC200-JS4.0	Dolomite	10.0	200	4.0
8	(8) DO-CTE10.0- PCC200-JS4.5	Dolomite	10.0	200	4.5
9	(9) DO-CTE10.0- PCC200-JS5.0	Dolomite	10.0	200	5.0
10	(10) DO-CTE10.0- PCC250-JS4.0	Dolomite	10.0	250	4.0
11	(11) DO-CTE10.0- PCC250-JS4.5	Dolomite	10.0	250	4.5
12	(12) DO-CTE10.0- PCC250-JS5.0	Dolomite	10.0	250	5.0

Effect of PCC Thickness, Dowel Size, Joint Spacing and CTE on the Predicted IRI

Figure 8 shows the effect of PCC thickness, dowel size and CTE, while Figure 9 shows the effect of PCC thickness, joint spacing and CTE on the predicted IRI. The results presented in Figure 8 indicate that increased PCC thickness leads to an increase in the predicted IRI with a given dowel size (28 mm) for all CTE values (compare designs 1-2-3, 5-6-7 or 9-10-11). This trend is unexpected as thicker PCC, which has increased aggregate interlock, is typically expected to perform better leading to smoother pavements. The trends in Figure 8 show that for a given PCC thickness (250 mm), a larger diameter dowel bar reduces the predicted IRI (compare design 3-4, 7-8 or 11-12) and the effect is more noticeable for high CTE values (e.g., designs 3-4 vs 11-12). A change in CTE value seem to have the predominant impact on the predicted IRI.

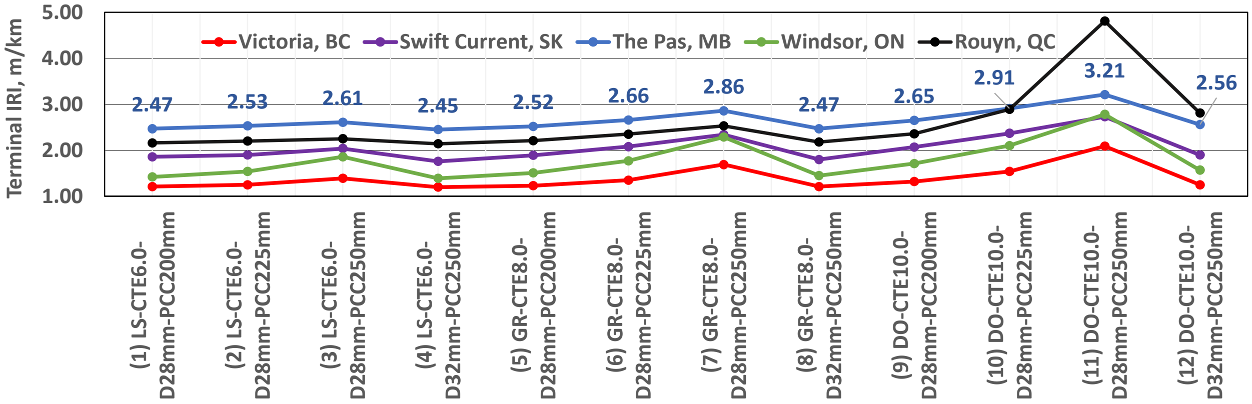

Figure 8. Effect of PCC thickness, dowel size and CTE on the predicted IRI (Trial Set #3)

The results presented in Figure 9 indicate that PCC joint spacing has no or negligible effect on the predicted IRI for a given dowel size (32 mm), except for the high CTE ($10x10^{-6}$/ºC) and thick PCC (250 mm) combinations (compare designs 1 with 2 and 3, and 10 with 11 and 12). In practice, a shorter joint spacing should mean a better aggregate interlock due to reduced joint opening and reduced IRI for a long period.

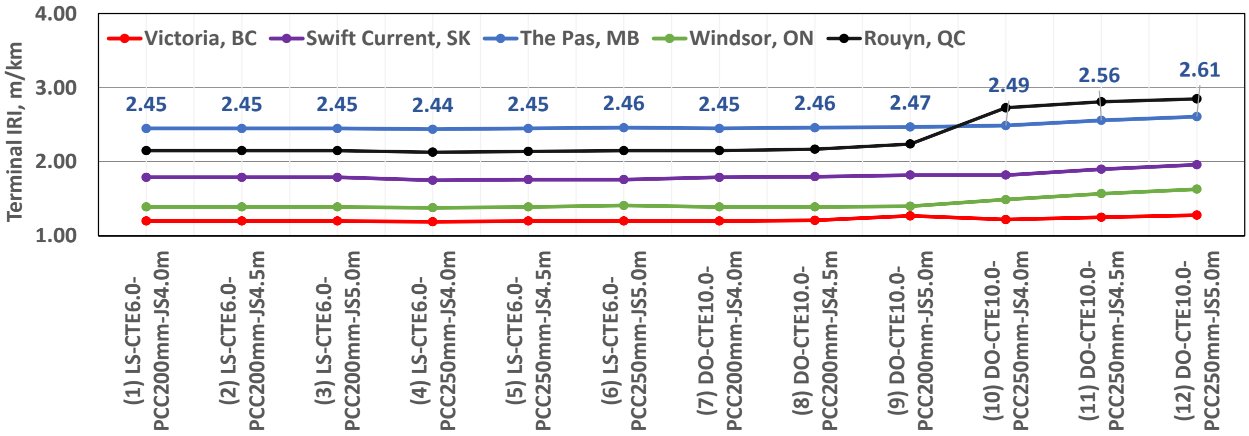

Figure 9. Effect of PCC thickness, joint spacing and CTE on the predicted IRI (Trial Set #4)

Effect of PCC Thickness, Dowel Size, Joint Spacing and CTE on the Predicted Faulting

Figure 10 shows the effect of PCC thickness, dowel size and CTE, while Figure 11 shows the effect of PCC thickness, joint spacing and CTE on the predicted faulting. The trends in Figure 10 indicate that increased PCC thickness leads to an increase in faulting for a given 28 mm thick dowel regardless of CTE values (compare designs 1-2-3, 5-6-7 and 9-10-11). This trend is unexpected as thicker PCC is expected to reduce faulting due to improved aggregate interlock and load transfer efficiencies across joints. While aggregate interlock and LTE parameters are inputs in the faulting prediction model in the PMED software [10], additional trials in Manitoba and discussion with the software developer (Applied Research Associates) revealed that the dowel size should be increased with increased PCC thickness to materialize the benefits of increased PCC thickness. However, this trend requires further investigation because it may not reflect the actual field experience with thicker concrete for a given dowel size.

The trends in Figure 10 show that for a given PCC thickness (250 mm), larger diameter dowel bars substantially reduces the predicted faulting (compare designs 3-4, 7-8 or 11-12) and the effect is more pronounced for high CTE values (e.g., designs 3-4 vs 11-12). A change in CTE values seem to have the most significant impact on the predicted faulting as well.

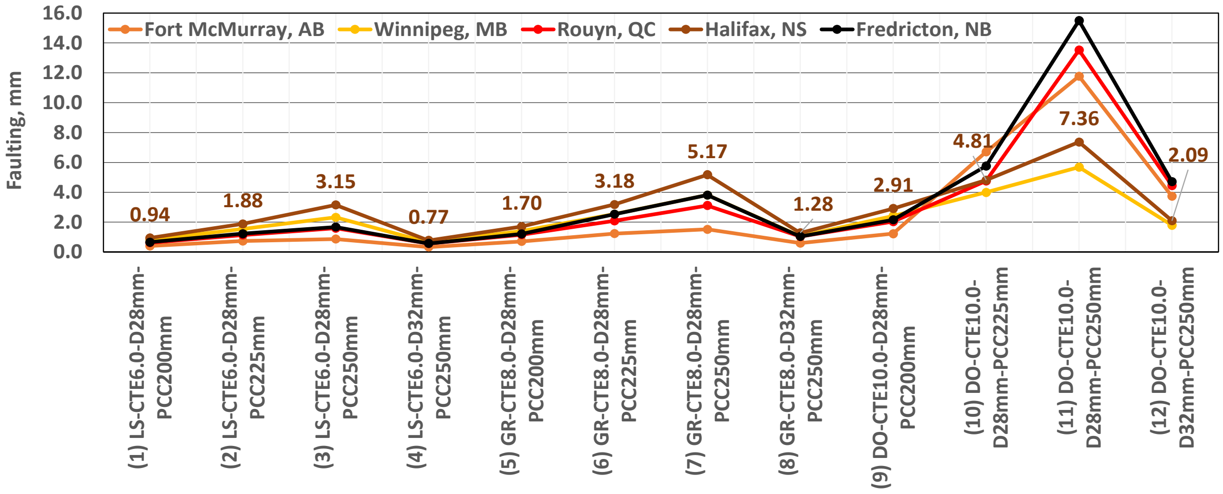

Figure 10. Effect of PCC thickness, dowel size and CTE on the predicted faulting (Trial Set #3)

The results presented in Figure 11 indicate that PCC joint spacing has noticeable effect on the predicted faulting (compare designs 4-5-6, 7-8-9 or 10-11-12) for a given dowel size (32 mm), except for the low CTE (6x10^{-6}/ºC) and thin PCC (200 mm) combinations (compare designs 1-2-3). The effect of joint spacing on the predicted faulting is very high in the case thick (250 mm) PCC and high CTE (10x10^{-6}/ºC) combinations (e.g., designs 10, 11 and 12 vs designs 4, 5 and 6).   .

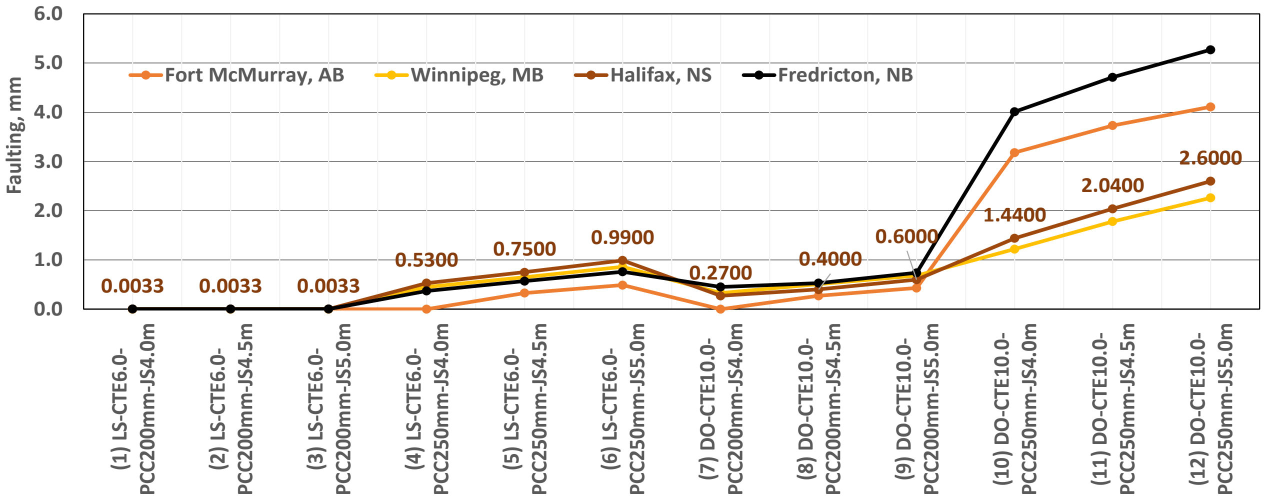

Figure 11. Effect of PCC thickness, joint spacing and CTE on the predicted faulting (Trial Set #4)

Effect of PCC Thickness, Dowel Size, Joint Spacing and CTE on the Predicted Transverse Cracking

Figure 12 shows the effect of PCC thickness, dowel size and CTE, while Figure 13 shows the effect of PCC thickness, joint spacing and CTE on the predicted transverse cracking. The trends in Figure 12 indicate that for a given 28 mm dowel, transverse cracking decreases with an increase in PCC thickness, regardless of CTE values (compare designs 1-2-3, 5-6-7 and 9-10-11). The trends in Figure 12 show that for a given PCC thickness (250 mm), larger diameter dowel bars have no effect on the predicted transverse cracking when the CTE values are 6x10^{-6}/ºC and 10x10^{-6}/ºC (compare designs 3-4 and 11-12), but larger diameter dowel bars have some effect when the CTE value is 8x10^{-6}/ºC (compare designs 7-8). These trends seem to be inconsistent and unexpected.

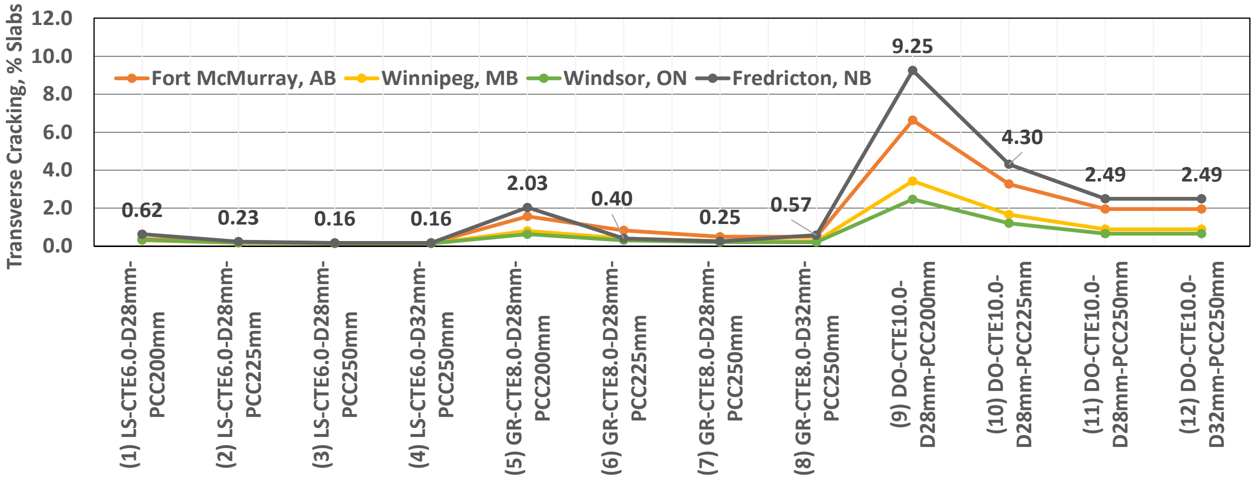

Figure 12. Effect of PCC thickness, dowel size and CTE on the predicted transverse cracking (Trial Set #3)

The trends in Figure 13 indicate that PCC joint spacing has noticeable effect on the predicted transverse cracking (compare designs 1-2-3) for a given dowel size (32 mm). The effect is very significant for thin PCC and high CTE combinations. For example, a very high variation of transverse cracking among designs 7-8-9 with a PCC thickness of 200 mm and CTE of 10.0x10^{-6}/ºC CTE vs a low variation of transverse cracking among designs 4-5-6 with a PCC thickness of 250 mm and CTE of 6.0x10^{-6}/ºC.

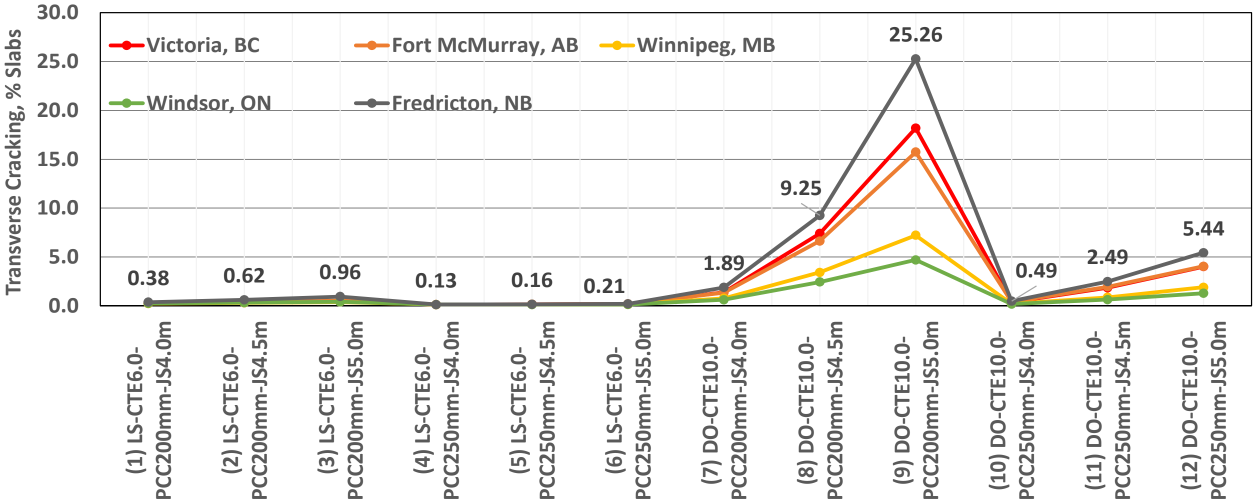

Figure 13. Effect of PCC thickness, joint spacing and CTE on transverse cracking (Trial Set #4)

In-Depth Assessment of the Effect of PCC Thickness, Joint Spacing and CTE

The results in Trial Sets #3 and #4 indicate that the effect of PCC thickness, joint spacing and CTE on the predicted distresses in JPCP are interrelated. Therefore, additional design trials were completed by Manitoba for "The Pas" climatic area to perform an in-depth assessment of the effect of these critical parameters for JPCP designs and to determine the thresholds of input values that will produce appreciable impact on the predicted distresses in JPCP. Since 32 mm size dowel bars are typically used by most agencies, these additional trials were completed using 32 mm dowel bars only. Table 6 shows the results of these additional trials.

As shown in Table 6, the predicted IRI shows a noticeable change only with input combinations of minimum CTE value of 10.0x10^{-6}/ºC, PCC thickness of 200 mm and joint spacing of 5.0 m (refer to designs 1-26). The predicted faulting shows a change only with input combinations of minimum CTE value of 6.0x10^{-6}/ºC, PCC thickness of 215 mm and joint spacing of 4.5 (refer to designs 1-6); CTE value of 8.0x10^{-6}/ºC, PCC thickness of 205 mm and joint spacing of 4.5 m (refer to designs 14-18); CTE value of 8.8x10^{-6}/ºC, PCC thickness of 200 mm and joint spacing of 5.0 m (refer to designs 20-22); or CTE value of 8.8x10^{-6}/ºC, PCC thickness of 205 mm and joint spacing of 4.5 m (refer to designs 20, 21 and 23). All combinations of inputs parameters were shown to produce an impact on the predicted transverse cracking.

Table 6 also shows that the input combinations of highest CTE, thickest PCC and largest joint spacing among the design trials provided the highest impact on the predicted faulting (refer to design 29). The input combinations of highest CTE, thinnest PCC and largest joint spacing among the design trials provided the highest impact on the predicted transverse cracking (refer to design 26). Overall, the results presented in Table 6 indicate that with typical 4.5 m joint spacing, 32 mm dowel bars and software default CTE value of 8.8x10^{-6}/ºC, the minimum thickness of PCC should be 205 mm when using the PMED software. This analysis further shows that CTE has a greater impact on the predicted performance than PCC joint layout and thickness when using the PMED software, which is questionable and requires further investigation.

Table 6. In-depth assessment of the effect of PCC thickness, joint spacing and CTE

Design No.	Configurations	IRI, m/km	Faulting, mm	Transverse Cracking, % Slabs
1	CTE6.0-PCC200mm-JS4.0m	2.45	0.0033	0.23
2	CTE6.0-PCC200mm-JS4.5m	2.45	0.0033	0.30
3	CTE6.0-PCC200mm-JS5.0m	2.45	0.0033	0.39
4	CTE6.0-PCC210mm-JS4.5m	2.45	0.0033	0.22
5	CTE6.0-PCC215mm-JS4.0m	2.45	0.0033	0.16
6	CTE6.0-PCC215mm-JS4.5m	2.45	0.2738	0.19
7	CTE6.0-PCC220mm-JS4.5m	2.45	0.3318	0.17
8	CTE6.0-PCC225mm-JS4.0m	2.44	0.2738	0.14
9	CTE6.0-PCC225mm-JS4.5m	2.45	0.4037	0.16
10	CTE6.0-PCC225mm-JS5.0m	2.45	0.5446	0.19
11	CTE6.0-PCC250mm-JS4.0m	2.44	0.4037	0.13
12	CTE6.0-PCC250mm-JS4.5m	2.45	0.5869	0.14
13	CTE6.0-PCC250mm-JS5.0m	2.46	0.7948	0.15
14	CTE8.0-PCC200mm-JS4.0m	2.45	0.0033	0.34
15	CTE8.0-PCC200mm-JS4.5m	2.45	0.0033	0.73
16	CTE8.0-PCC200mm-JS5.0m	2.45	0.0033	1.26
17	CTE8.0-PCC205mm-JS4.0m	2.45	0.0033	0.29
18	CTE8.0-PCC205mm-JS4.5m	2.45	0.2738	0.63
19	CTE8.0-PCC210mm-JS4.5m	2.45	0.4037	0.54
20	CTE8.8-PCC200mm-JS4.0m	2.45	0.0033	0.44
21	CTE8.8-PCC200mm-JS4.5m	2.45	0.0033	1.28
22	CTE8.8-PCC200mm-JS5.0m	2.45	0.3318	2.35
23	CTE8.8-PCC205mm-JS4.5m	2.45	0.3719	1.09
24	CTE10.0-PCC200mm-JS4.0m	2.45	0.2738	0.73
25	CTE10.0-PCC200mm-JS4.5m	2.46	0.4306	2.98
26	CTE10.0-PCC200mm-JS5.0m	2.47	0.5869	6.08
27	CTE10.0-PCC250mm-JS4.0m	2.49	1.0634	0.21
28	CTE10.0-PCC250mm-JS4.5m	2.56	1.5809	0.80
29	CTE10.0-PCC250mm-JS5.0m	2.61	2.0270	1.69

Results and Discussion- Trial Set #5: Effect of PCC Thickness and Traffic Loading

Trial Set #5 aimed to evaluate the effects of concrete thickness and traffic loading on the predicted distresses in PCC pavements. The selected PCC thickness were 225 mm and 250 mm and traffic loading varied from 2,500 to 20,000 trucks per day. The software default CTE value of 8.8 x 10^{-6}/ºC (dolomite aggregates) was used in these trials. The joint spacing and dowel size remained constant at typical 4.5 m and 32 mm, respectively. For all design trials, software v3.0 was utilized. Table 7 shows the variable parameters that were used in Trial Set #5.

Table 7. Variable parameters in Trial Set #5

Design No.	Notation	JPCP Thickness, mm	Total AADTT	AADTT on Design Lane
1	(1) PCC225mm-AADTT2500	225	2,500	1,000
2	(2) PCC225mm-AADTT5000	225	5,000	2,000
3	(3) PCC225mm-AADTT10000	225	10,000	4,000
4	(4) PCC225mm-AADTT20000	225	20,000	8,000
5	(5) PCC250mm-AADTT2500	250	2,500	1,000
6	(6) PCC250mm-AADTT5000	250	5,000	2,000
7	(7) PCC250mm-AADTT10000	250	10,000	4,000
8	(8) PCC250mm-AADTT20000	250	20,000	8,000

AADTT = Annual Average Daily Truck Traffic

Effect of PCC Thickness and Traffic Loading on the Predicted IRI

Figure 14 shows the variation of the predicted IRI with the variation of PCC thickness and traffic loading. As shown in the figure, traffic loading has small effect on the predicted IRI. For example, by increasing truck traffic volume from 2,500 to 20,000 per day, i.e., increasing the traffic loading by eight times (compare designs 1-4), the predicted IRI increases from 2.45 to 2.57 m/km for a 225 mm thick PCC layer over 25 years. Such a small effect for this huge increase in traffic loading does not seem to be reasonable or as expected. It also does not align with the effect of traffic loading on the predicted faulting (refer to Figure 15) because if the faulting goes up, there should be a corresponding increase in IRI as faulting causes roughness in PCC pavements.

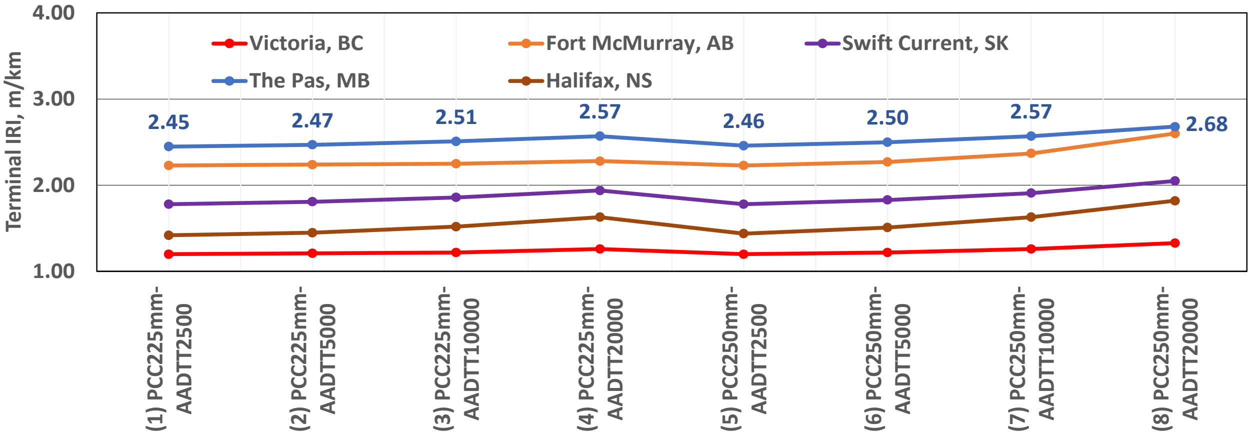

Figure 14. Effect of PCC thickness and traffic loading on the predicted IRI (Trial Set #5)

Effect of PCC Thickness and Traffic Loading on the Predicted Faulting

The variations of the predicted faulting with the variations of PCC thickness and traffic loading for two different PCC thicknesses are shown in Figure 15. As shown in the figure, traffic loading has noticeable impact on the predicted faulting for 225 mm thick concrete (compare designs 1-4). The impact of increased traffic loading on the predicted faulting for 250 mm thick concrete i.e., thicker concrete seems to be more significant than that of 225 mm concrete (compare designs 5-8 with 1-4). Figure 15 once again shows that the increased PCC thickness causes increased faulting for the same traffic loading and dowel size, which seems to be unreasonable.

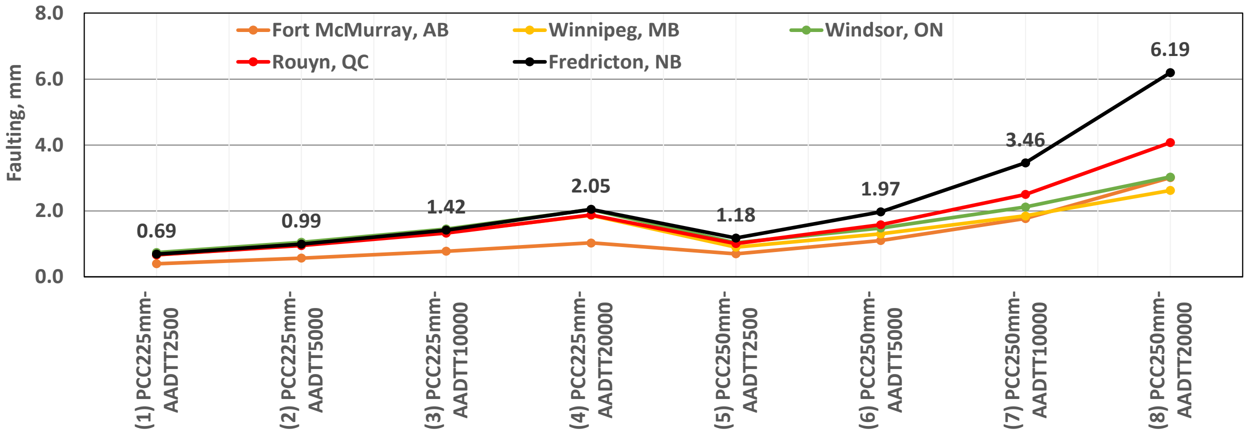

Figure 15. Effect of PCC thickness and traffic loading on the predicted faulting (Trial Set #5)

Effect of PCC Thickness and Traffic Loading on the Predicted Transverse Cracking

Figure 16 shows the variation of predicted transverse cracking with the variation of PCC thickness and traffic loading for two different PCC thicknesses. As shown in the figure, traffic loading has significant impact on transverse cracking for 225 mm thick PCC layer (compare designs 1-4). The impact of increased traffic loading on the predicted transverse cracking for 250 mm thick PCC layer i.e., a thicker PCC layer seems to less significant than that of 225 mm concrete (compare designs 5-8 with 1-4). Figure 16 once again shows that increased PCC thickness causes reduced transverse cracking for a given traffic loading.

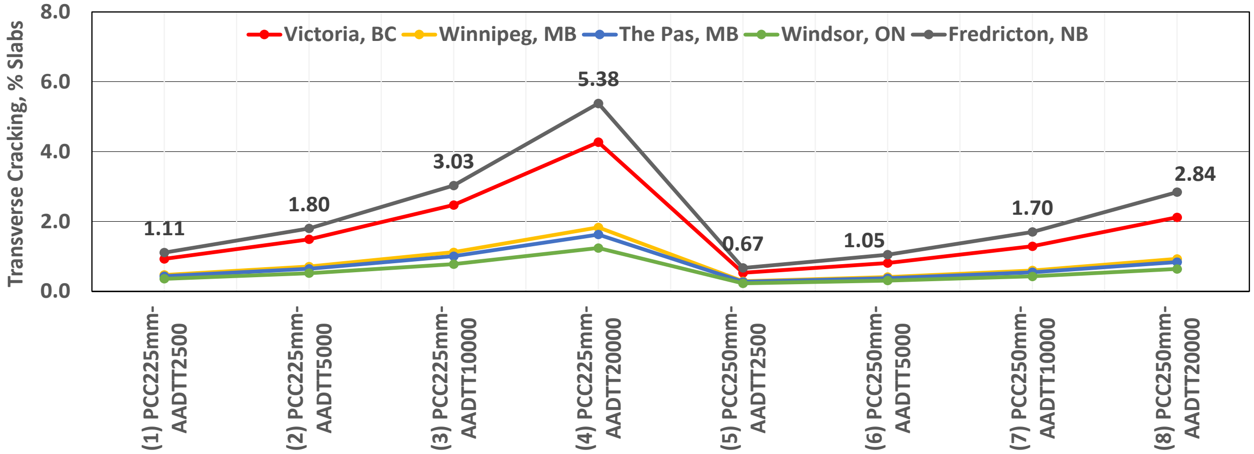

Figure 16. Effect of PCC thickness and traffic loading on the predicted transverse cracking (Trial Set #5)

In-Depth Assessment of the Effect of PCC Thickness, Traffic Loading and CTE

The results in Trial Sets #3 and #4 indicate that the effect of PCC thickness, joint spacing and CTE on the predicted distresses in JPCP are interrelated (refer to Table 6). CTE was also shown to produce significant impacts on the predicted distresses in all preceding trials (Trial Sets #1 through #4). However, Trial Set #5 did not include CTE as a variable in the design inputs. Therefore, Manitoba completed a number of additional design trials for "The Pas" climatic area to perform an in-depth assessment of the effect of traffic loading, PCC thickness and CTE combinations for JPCP designs and to determine the thresholds of input values that will produce real or considerable impact on the predicted distresses in JPCP. The typical 32 mm diameter dowel bars and 4.5 m joint spacing were used in these additional trials as well.

Table 8 shows the results of the additional in-depth analysis by Manitoba. As shown in the table, there is no or negligible change in the predicted IRI for CTE values in the range of 6.0x10^{-6}/ºC to 8.0x10^{-6}/ºC, PCC thickness up to 205 mm and traffic loading in the range of 2,500 (1,000 on the design lane) to 20,000 (8,000 on the design lane) trucks/day (refer to designs 1-20). There is a minor change in the predicted IRI when the CTE value is 8.8x10^{-6}/ºC, PCC thickness is 205 mm and traffic loading is 20,000 trucks/day (refer to designs 20 vs 21).

As indicated in Table 8, the predicted faulting shows a change with input combinations of minimum CTE value of 8.8x10^{-6}/ºC, PCC thickness of 205 mm and AADTT of 2,500 (1,000 trucks/day on the design lane) (refer to designs 1-6); CTE value of 8.0x10^{-6}/ºC, PCC thickness of 205 mm and AADTT of ≥5,000 (≥2,000 trucks/day on the design lane) (refer to designs 7-11 and 13-16); or CTE value of 6.0x10^{-6}/ºC, PCC thickness of 225 mm and AADTT of ≥2,500 (≥1,000 trucks/day on the design lane) (refer to designs 22 and 24). All combinations of these three inputs parameters were shown to produce an impact on the predicted transverse cracking.

Table 8. In-depth assessment of the effect of PCC thickness, traffic loading and CTE

Design No.	**PCC Design**	**IRI, m/km**	**Faulting, mm**	**Transverse Cracking, % Slabs**
1	PCC205mm-AADTT2500-CTE 6.0	2.45	0.0033	0.20
2	PCC205mm-AADTT2500-CTE 7.0	2.45	0.0033	0.26
3	PCC205mm-AADTT2500-CTE 7.5	2.45	0.0033	0.32
4	PCC205mm-AADTT2500-CTE 8.0	2.45	0.0033	0.42
5	PCC200mm-AADTT2500-CTE 8.8	2.45	0.0033	0.81
6	PCC205mm-AADTT2500-CTE 8.8	2.45	0.2738	0.70
7	PCC200mm-AADTT5000-CTE6.0	2.45	0.0033	0.30
8	PCC205mm-AADTT5000-CTE 6.0	2.45	0.0033	0.26
9	PCC205mm-AADTT5000-CTE 7.0	2.45	0.0033	0.36
10	PCC200mm-AADTT5000-CTE8.0	2.45	0.0033	0.73
11	PCC205mm-AADTT5000-CTE 8.0	2.45	0.2738	0.63
12	PCC205mm-AADTT5000-CTE 8.8	2.45	0.3719	1.09
13	PCC205mm-AADTT10000-CTE 6.0	2.45	0.0033	0.35
14	PCC205mm-AADTT10000-CTE 7.0	2.45	0.0033	0.52
15	PCC200mm-AADTT10000-CTE 8.0	2.45	0.0033	1.16
16	PCC205mm-AADTT10000-CTE 8.0	2.45	0.3300	0.97
17	PCC205mm-AADTT20000-CTE 6.0	2.45	0.0033	0.50
18	PCC205mm-AADTT20000-CTE 7.0	2.45	0.0033	0.79
19	PCC200mm-AADTT20000-CTE 8.0	2.45	0.0033	1.89
20	PCC205mm-AADTT20000-CTE 8.0	2.45	0.4306	1.57
21	PCC205mm-AADTT20000-CTE 8.8	2.47	0.6684	2.98
22	PCC225mm-AADTT2500-CTE 6.0	2.44	0.2738	0.15
23	PCC225mm-AADTT2500-CTE 8.8	2.45	0.5869	0.43
24	PCC225mm-AADTT5000-CTE6.0	2.45	0.4037	0.16

The results presented in Table 8 further indicate that with typical 4.5 m joint spacing, 32 mm dowel bars and software default CTE value of $8.8\text{x}10^{-6}$/ºC, the minimum thickness of PCC should be 205 mm when using the PMED software. A lower CTE value of $8.0\text{x}10^{-6}$/ºC will work with 205 mm thick PCC when the design lane AADTT is 1,000 or higher. A CTE value of as low as $6.0\text{x}10^{-6}$/ºC will work with the design lane AADTT of 1,000 or higher when the PCC thickness is ≥225 mm.

Summary and Conclusions

This paper presented the results and analysis of design trials completed to assess the effects of PCC mix properties, slab thickness, dowel diameter, joint spacing, traffic loading and CTE on the PMED software predicted distresses in JPCP. Based on the presented trial results and analysis, the key findings and conclusions can be summarized as follows:

1. Overall, better quality concrete results in improved performance of JPCP in terms of predicted IRI, faulting and transverse cracking in PMED software v3.0.
2. With software v3.0, a higher strength of PCC mix results in lower IRI, faulting and transverse cracking. An increased amount of cementitious materials content result in increased IRI and faulting, but no noticeable effect on the transverse cracking. A higher w/c results in higher IRI and faulting, but no or minimal effect on transverse cracking. A lower density of PCC mix results in higher IRI (negligible), faulting and transverse cracking.
3. The results using the software v3.0 for different inputs of concrete mix properties are significantly different from results using the software v2.6. Software v3.0 generally provides higher IRI values than that with software v2.6. In contrast, software v3.0 predicts lower amounts of faulting as compared to that with software v2.6. The predicted transverse cracking are different between software v2.6 and v3.0 for most inputs of PCC mix properties.
4. An increase in PCC thickness results in an increase in the predicted IRI and faulting, which seem to be unreasonable because an increased concrete thickness is known to provide a smoother pavement with reduced faulting due to improved aggregate interlock. An increase in PCC thickness shows a reduction in the predicted transverse cracking, which is a logical trend.
5. Dowels smaller than 32 mm in diameter cause high amount distresses regardless of CTE values. Larger dowels provide a significant reduction in faulting and IRI, but have no or minimal effect on the predicted transverse cracking.
6. PCC joint spacing shows no effect on the predicted IRI, unless the concrete is 225 mm or thicker and/or CTE value is $>8.8\text{x}10^{-6}$/ºC. PCC joint spacing shows no effect on the predicted joint faulting, unless the concrete is 215 mm or thicker (with low CTE), or CTE value is $>8.0\text{x}10^{-6}$/ºC with 205 mm or thicker concrete. PCC joint spacing shows a significant effect on transverse cracking regardless of concrete thickness and CTE values. In practice, a shorter joint spacing should improve aggregate interlock due to less opening of the joints during expansion and contraction, which should result in reduced faulting. The predicted IRI should also be lower with a shorter joint spacing because joint faulting affects the pavement smoothness.

7. Traffic loading has a small effect on the predicted IRI and significant effect on faulting and cracking. These trends are difficult to explain or understand because when faulting goes up, there should be a corresponding increase in IRI value as faulting affects pavement smoothness. The predicted faulting is highly sensitive to traffic loading with thicker concrete, which seems to be unreasonable because an increased concrete thickness is known to reduce the faulting due to improved aggregate interlock. The results and analysis have indicated that the minimum PCC

thickness should be 205 mm and CTE should be 8.0x10^{-6}/ºC to produce an impact of traffic loading on the predicted faulting. The predicted transverse cracking is highly sensitive to traffic loading with thinner concrete.

8. Overall, the CTE has shown a greater impact on the predicted performance than joint spacing and PCC thickness, which seems to be unreasonable and requires further investigation.

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