Effect of Subgrade, Subbase and Base Materials on the PMED Software Predicted Distresses in Jointed Plain Concrete Pavement

Principal Author:
M. Alauddin Ahammed, Ph.D., P.Eng.
Manager, Pavement and Materials Engineering Section
Manitoba Transportation and Infrastructure
1420- 215 Garry Street, Winnipeg, Manitoba R3C 3P3
Telephone: (204) 792 1338
Email: Alauddin.Ahammed@gov.mb.ca

Co-Authors:
Tim J Smith, M.Sc. Eng., P.Eng.
Senior Director, Built Environment, Transportation and Public Works
Cement Association of Canada
1105-350, rue Sparks Street,
Ottawa, ON K1R 7S8
Telephone: (613) 236 9471- Ext. 212 (O), (613) 882 6415 (C)
E-mail: tsmith@cement.ca

Diana Podborochynski, M.Sc., P.Eng.
Senior Surfacing Standards Engineer, Saskatchewan Ministry of Highways
126-105th Street East, Saskatoon, Canada S7N 1Z3
Telephone: (306) 933-5269
E-mail: Diana.Podborochynski@gov.sk.ca

Jhuma Saha, M.Sc., P.Eng., PMP, P.E.
Pavement Design Engineer, Pavement Engineering Technical Standard Branch
Alberta Transportation and Economic Corridors
Telephone: (780) 644-8630
Email: Jhuma.Saha@gov.ab.ca

Arma Dhaliwal, M.Eng., P.Eng.
Manager – Transportation Asset Management, Pacific Region, Tetra Tech Canada
10th Floor, 885 Dunsmuir Street, Vancouver, B.C. V6C 1N5
Telephone: (778) 945-5745
E-mail: Arma.Dhaliwal@tetratech.com

Julie Roby, M.A.Sc., P.Eng.
Pavement Design Engineer, Ministère des Transports et de la Mobilité durable
800, rue d'Youville, 14e étage, Québec (Québec) G1R 3P4
Téléphone : (418) 643-0800 x24065
E-mail: Julie.Roby@transports.gouv.qc.ca

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Abstract:

Between May 2022 and August 2022, the Transportation Association of Canada (TAC) Mechanistic Empirical (ME) Pavement Design Subcommittee has completed a number of design trials to assess the effect on the AASHTOWare Pavement ME Design (PMED) software predicted distresses in jointed plain concrete pavement (JPCP) due to varying subgrade and subbase and base materials. These trials were run with climatic inputs from nine different climate stations across Canada, five different untreated native subgrade soils/fill, five different soil cement layers, a crushed rock subgrade, six different base (cement treated and granular) materials with varying thickness and two different granular subbase materials.

The results have shown that climate has a significant effect on the predicted IRI and faulting. No design meets the IRI criteria for clay and silt subgrade soils in cold climates. When a crushed rock layer is used as a subgrade, all designs meet the IRI criteria and the effect of underlying native subgrade soils becomes minimal. With native subgrade/fill alone, the predicted IRI decreases as the material physical properties improves. The physical properties of subgrade soils have more influence on the predicted IRI than their stiffness. Inconsistent and unexplainable trends of the predicted faulting at concrete joints were observed for changes in subgrade type. There was no or negligible effect on the predicted transverse cracking due to changes in subgrade material type and variation in climatic exposure. Currently, PMED software is unable to model the stabilized soils as subgrade.

In general, good quality and thicker base layers provide lower IRI and faulting with some inconsistencies. The variations of the predicted transverse cracking for changes in base material type and thickness were inconsistent. Poor quality subbase materials cause a small increase while thicker subbase layers cause an inconsistent variation of the predicted distresses. Significant differences in predicted distresses, with many inconsistencies in the trends, were noted between the PMED software v2.6 and v3.0.

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Introduction

Jointed plain concrete pavement (JPCP) is the most commonly constructed rigid pavement in Canada, and the United States. It consists of a portland cement concrete (PCC) surface layer, which is generally placed over granular or treated base layer (may also include a subbase layer) and native or treated subgrade. Regardless of whether a pavement is composed of asphalt concrete (AC) or PCC surface, its performance, to a varying extent, depends on the characteristics of the underlying layers. However, the underlying layers of a PCC pavement structure have less effect on its structural capacity than AC pavement structures. As PCC is a rigid material, the majority of stresses from the applied traffic loads are distributed within the PCC surface layer itself. Only a small amount of the induced stresses from traffic loading is transmitted into the underlying base (and subbase, if used) and subgrade, if the subgrade foundations consist of compacted and stable materials. For PCC pavements, the main functions of the base and subbase layers are to provide a uniform working platform to build the PCC surface layer, pavement subsurface drainage and frost protection.

However, if the subgrade soils are very weak with low resilient moduli values, expansive and susceptible to shrinkage and/or frost heave, differential settlements of PCC slabs due to changes in moisture and freeze/thaw actions will occur. This could lead to a very rough road surface within a very short period after the construction of concrete pavement, as experienced in Manitoba and Quebec on highway projects several years ago. In addition, joints in the JPCP are the weakest links. A weak subgrade could results in a high stress at the joints, which can contribute to increased faulting and road roughness. The added granular or treated subbase and/or base, and/or treated or select subgrade materials play important roles in such cases for a long lasting JPCP. Therefore, it is important to ensure there is uniform and strong support for the PCC pavement to prevent potential differential settlement and faulting. Another benefit of the base and subbase layers is an increase in the composite modulus of subgrade reaction, k- value, for the pavement structure. In empirical pavement design method such as AASHTO 1993 [1], an increased k-value provides a reduction in the required PCC layer thickness.

To prevent potential migration of fines, from the subgrade, geotextiles can be placed on the subgrade surface before placing the granular layers. Granular base material with low fines or stabilized base or subgrade will reduce or eliminate pumping issues while providing good drainage of pavement. These will reduce or eliminate potential faulting issues for the PCC pavement (at joints and cracks).

The design inputs for the JPCP in the PMED software include the physical and mechanical properties of base and subbase layers and subgrade foundation. The physical properties of unbound materials include dry density, gradation, Atterberg limits, moisture content and soil-water characteristics, while the mechanical properties of unbound and treated materials include the resilient or elastic modulus. The subgrade soils are subjected to a lower stresses than the top layers since the stresses experienced in pavements reduce with depth. This study focuses on how soil type (native and stabilized) and resilient modulus, in combination with changes in base type and climatic conditions, affect the PMED software predicted distresses in JPCP. This study also assesses the effects of granular base course (GBC) modulus (with the same gradation), GBC gradations (with the same modulus), and the subbase material stiffness and gradation on the PMED software predicted distresses. In addition, this study assessed the input option for cement stabilized soil layer into AASHTOWare PMED software and its outcome.

Background

The TAC ME Pavement Design Subcommittee has been evaluating the AASHTOWare PMED software since 2007. A good number of design trials were completed during 2007- 2019 to assess effect of traffic loading, asphalt mix properties, binder and thickness, subgrade, subbase and base materials, and PCC slab and joint designs on the predicted distresses. The analysis and results from some of these trials can be found in different technical papers presented in different conferences. Between May 2021 and January 2022, several new design trials were conducted using PMED software v2.6 to evaluate the effects of subgrade, granular subbase and base materials on the predicted distresses in asphalt pavements. The results of these studies [2, 3] showed that PMED software, which is the latest and most sophisticated pavement design and analysis tool, is still unable to adequately consider the effect of the subgrade and the granular base thickness and stiffness on the asphalt pavement distresses as expected based on the past performance experience.

The design trials undertaken and presented in this paper attempted to determine whether the PMED software is capable to properly account for the effect of subgrade, subbase, and base materials on the distresses in JPCP. Between May 2022 and August 2022, the Subcommittee conducted several sets of design trials with: i) five different untreated native subgrade soils/fill (resilient moduli varied from 25-90

MPa), ii) a 300 mm thick soil cement layer with stabilization of these five different subgrade types, iii) a 300 mm thick layer of crushed rock subgrade combined with these five different types of naïve subgrade soils/fill, iv) six different base (cement treated and granular) materials with varying thickness, v) two different granular subbase materials and vi) different climatic inputs from nine weather stations across Canada. PMED software v2.6/v2.6.1 was used for all these runs. This paper summarizes all the above-described trial results and discusses the effects of different combinations of subgrade, base and subbase layers on the predicted distresses in PCC pavement as well as PMED software limitations for inputting soil cement layers.

Manitoba also completed a limited number of additional design trials (for Winnipeg climatic area) using the PMED software v3.0 to assess the outcome of recent updates to the PMED software by incorporating a model that accounts for the PCC slab and underlying layer interaction as recommended in NCHRP Project 1-51 Report [4].

Findings from Literature Review

Luo et al. [5] summarized a literature review on the influence of subgrade and unbound materials on the performance of PCC pavements. The authors noted that a reduced resilient modulus for unbound layers results in more transverse cracking, higher faulting and reduced smoothness (increased roughness) as compared to an unbound layer with a higher resilient modulus. Zhong 2017 [6] stated that erosion in the base layer at the transverse joints also causes faulting. Increased shear strength within the unbound base layers will reduce transverse cracking, reduce faulting, and improve the smoothness of a PCCP. Likewise, a thicker unbound base layer will reduce transverse cracking, reduce faulting, and improve the smoothness of a PCCP [5, 6].Based on a global sensitivity analysis of PMED software inputs, Schwartz et al. [7] indicated that JPCP faulting and transverse cracking distresses are sensitive to base layer thickness and base layer resilient modulus as well as erodibility and loss of friction. Smoothness was sensitive to resilient modulus and erodibility of base layer.

Both Schwartz et al. [7] and Luo et al. [5] identified the parameters that affect an unbound layer's influence on pavement performance, variation of resilient modulus and shear strength, erosion, and permanent deformation. The authors indicated that granular material strength and resilient modulus depend on the moisture within the layer. Since unbound granular materials are non-homogeneous and anisotropic, they behave non-linearly when subject to high stress and high moisture conditions. However, the current PMED software does not adequately consider the stress dependency, anisotropy and nonlinearity of unbound base and subgrade materials.

Minnesota uses MnPAVE-Rigid, which is a rigid pavement design procedure based on AASHTO 1993 pavement design procedure. In 2018, Minnesota undertook a project to implement additional features into MnPAVE-Rigid including additional design inputs for base thickness and base materials. This study found that changes to base thickness do not result in significant performance changes in PCC pavements. The study noted that base material gradation may affect damage to PCC pavements and while the effect is small, still it may be included in the PCC pavement design [8].

Using a three-dimensional finite element model called EverFE, developed by the University of Washington and University of Maine, Shaban et al. [9] analysed JPCP structures with varying PCC, base, and subbase thicknesses. The study found that increased thickness of a base layer does not affect bending stresses in the PCC layer. However, the base layer itself showed a slight increase in tensile stresses with increase in its thickness. Increased modulus of elasticity of the base materials resulted in increased tensile stresses in the base layer. An unbound subbase layer underneath the unbound base layer produced a significant reduction in bending stresses in PCC and base layers, with no change in compressive stresses in both layers. The analysis also showed that an increase in the modulus of subgrade reaction decreases the tensile stress at the bottom layer of pavement, while all compressive and tensile stresses at top layer remained unchanged.

NCHRP Project 1-53 [10] looked into possible enhancements to the mechanistic-empirical (ME) models, related to the unbound subgrade and granular base/subbase materials, which are used in the PMED software. The project identified the limitations of the current models and developed or recommended new models to improve the influence of subgrade materials and granular base and subbase material properties as well as thicknesses in the PMED software for both asphalt and rigid pavements. The key aspects of the proposed new models were unbound materials' non-linearity, anisotropy, stress-dependency, moisture sensitivity, freeze-thaw response and suction. The recommendations from this project are not yet implemented in the PMED software.

Jeong and Zollinger [11] characterized key performance factors related to the deterioration of a joint in terms of predicted faulting and found that an increase in subgrade shear strength and subgrade modulus positively affect LTE thereby decrease faulting. A sensitivity analysis of the AASHTO 2002 method by Shahji [12] indicated that increased subgrade modulus significantly enhances the load transfer efficiency (LTE) for larger crack widths, thus reducing transverse cracking. The analysis also noted that the predicted smoothness improves (i.e., IRI decreases) with increased subgrade modulus. An increase in subgrade shear strength increases the resistance to transverse cracking based on the 2008 AASHTO Mechanistic-empirical pavement design guide [13].

An analysis by Bakhsh [14] demonstrated that improvement of the subgrade shear strength could improve smoothness. Higher subgrade shear strength also helps improve resistance to faulting [15]. Improvement of subgrade shear strength would improve IRI performance as faulting induced by erosion damage is reduced with increased shear strength [15].

A sensitivity analysis at the University of California [16] for the JPCP distress prediction models observed that the gravel and sand (A-1-a), and sand (A-3) subgrade soils provide nearly identical performance in terms of transverse cracking while the clay (A-5) subgrade perform the best. However, the clay subgrade resulted in higher faulting and IRI.

Objective and Significance

The findings from literature review indicates some issues or limitations in the models related to subgrade soils, and unbound granular base/subbase that are incorporated into the PMED software. The TAC ME Pavement Design Subcommittee User Group has performed several coordinated design trials to evaluate the latest versions (v2.6/2.6.1 and 3.0) of the PMED software under Canadian environmental conditions and material types. The objective of this paper is to present the trial results, analysis, and findings from these design trials. The presented information may help different agencies and other interested individuals in assessing the suitability of the latest versions of the PMED software when designing PCC pavement structures and varying subgrade, base, and subbase materials characteristics.

Software Versions and Design Trial Inputs

All participants used the PMED software v2.6 or v2.6.1 with the NARR climate data and global calibration coefficients for the design trials. These trials were completed before the release of software v3.0. As such a limited number of additional design trials were completed by Manitoba using software v3.0 with MERRA climate data. Two sets of design trials with varying inputs from different subgrade (varying physical properties and resilient modulus), and base and subbase (varying physical properties, resilient modulus and thickness) were completed. Climatic data from nine areas across Canada were used in both trial sets. Other key input parameters that remained unchanged in all design trials are: i) Vehicle class distribution and Axle Load Spectra (ALS)(Manitoba Level 1), ii) PCC joint spacing (4.5 m) and panel width (4.3 m), iii) PCC mix with a 35 MPa compressive strength, 340 kg/m^3 cementitious materials (cm) and 0.40 water to cementitious materials ratio (w/cm), iv) Design life (25 years), v) Initial IRI (1.0 m/km) and vi) Design reliability (90%).

PCC Trial Set #1 looked at the effect of subgrade on the predicted distresses. The variable inputs in the design trials included the following: five untreated subgrade materials; five soil cement subgrade materials (300 mm thick); 300 mm crushed rock (CR-M50) subgrade. The fixed inputs, in addition to the ones noted above, for this design trial set included the following: design lane traffic loading of 1,000 trucks with a 2-way total of 2,500 trucks/day (20.74 million equivalent single axle loads or ESALs over the design life), 250 mm thick PCC surface layer, 32 mm diameter dowels and 200 mm thick granular base layer with a resilient modulus (Mr) value of 250 MPa.

PCC Trial Set #2 looked at the effect of base and subbase materials on the predicted distresses. The variable inputs in the design trials included the following: five different base materials (cement stabilized and unbound granular), two different subbase materials (unbound granular), and varying thickness of base and subbase materials. The fixed inputs, in addition to the ones noted above, for these design trials included the following: design lane traffic loading of 2,000 trucks per day (41.48 million ESALs over the design life), 200 mm thick PCC surface, 28 mm diameter dowels and silty sand (A-2-4) subgrade with a Mr of 60 MPa.

Selected Climate Stations

NARR/MERRA data from nine climate stations across Canada with varying weather patterns were selected for the trials. Figure 1 shows the general geographic location of the climate stations. The red dots indicate relatively warmer while the blue dots indicate relatively colder climates in Canadian context. Table 1 presents the list of climate stations and the summary of the key climatic parameters. Table 1 shows noticeable difference in climatic indices between NARR and MERRA.

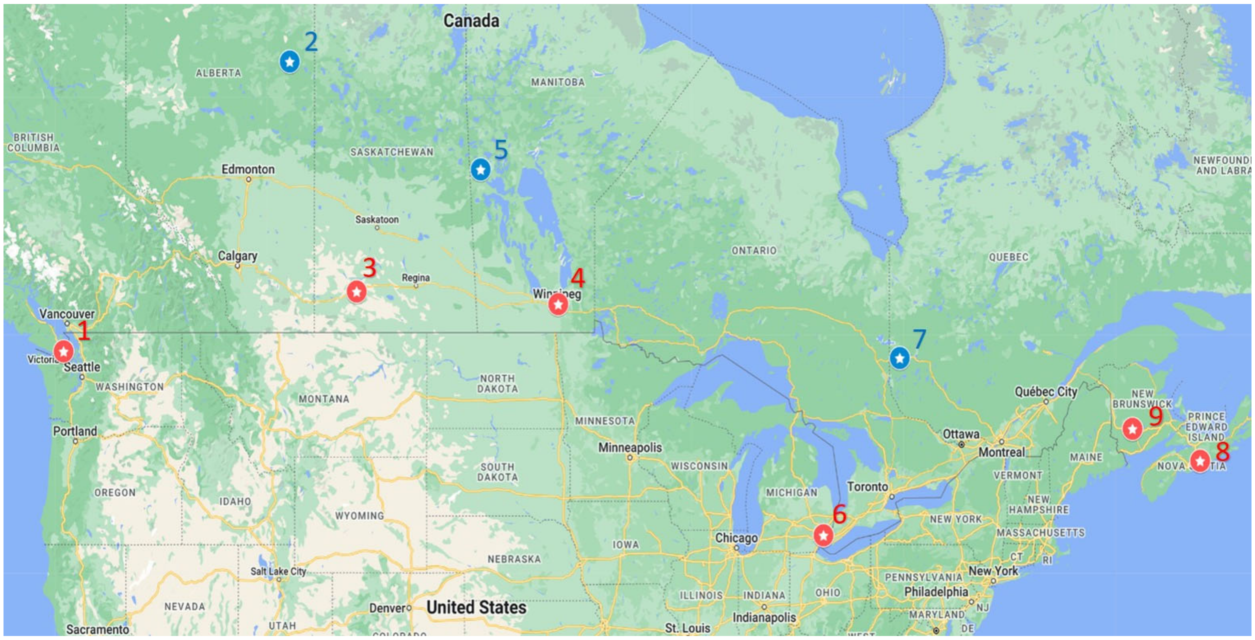

Figure 1. Geographic location of climate stations used in the PMED software trials

Table 1. List of climate stations and climate data summary (NARR/MERRA climate data)

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

PCC Trial Set #1 included 15 design runs for each climatic area and focused on the effect of subgrade materials. Table 2 below shows the subgrade materials inputs that were varied for the various runs. All other input values were held constant to evaluate the effect of changing the subgrade parameters.

The resilient moduli values of untreated (native) subgrade represent typical values obtained through backcalculation from falling weight deflectometer (FWD) deflection data collected from Manitoba highways. The modulus (Mr) value for granular fill (A-1-b) subgrade was estimated from soaked California Bearing Ratio (CBR) test in Manitoba while the modulus value of CR-M50 was determined in laboratory in

Manitoba. The Mr values of treated subgrade were estimated based on limited test data on Manitoba soils and professional judgement.

Table 2. Variable inputs for design runs in Trial Set #1

Design No.	Stabilized or Crushed Rock Subgrade	Stabilized or Crushed Rock Subgrade Mr, MPa	Stabilized or Crushed Rock Subgrade Thickness, mm	Native Subgrade Type	Native Subgrade Mr, MPa
1	N/A	25	N/A	A-7-6 (HP Clay)	25
2	N/A	40	N/A	A-6 (LP Clay)	40
3	N/A	40	N/A	A-4 (Sandy Silt)	40
4	N/A	60	N/A	A-2-4 (Silty Sand)	60
5	N/A	90	N/A	A-1-b (Gran. Fill)	90
6	Soil Cement (A-7-6)	85	300	A-7-6 (HP Clay)	25
7	Soil Cement (A-6)	85	300	A-6 (LP Clay)	40
8	Soil Cement (A-4)	85	300	A-4 (Sandy Silt)	40
9	Soil Cement (A-2-4)	85	300	A-2-4 (Silty Sand)	60
10	Soil Cement (A-1-b)	130	300	A-1-b (Gran. Fill)	90
11	Crushed Rock (CR-M50)	300	300	A-7-6 (HP Clay)	25
12	Crushed Rock (CR-M50)	300	300	A-6 (LP Clay)	40
13	Crushed Rock (CR-M50)	300	300	A-4 (Sandy Silt)	40
14	Crushed Rock (CR-M50)	300	300	A-2-4 (Silty Sand)	60
15	Crushed Rock (CR-M50)	300	300	A-1-b (Gran. Fill)	90

N/A = Not Applicable, CR-50 = Manitoba 50 mm minus crushed rock subbase or fill, HP = high plastic, LP = low plastic

PCC Trial Set #2 included 16 design runs for each climatic area and focused on granular base and subbase materials. Table 3 below shows the design inputs that were varied for the various runs. All other input values were held constant to evaluate the effect of changing the base and subbase parameters.

Cement stabilized base is a default material in the PMED software with default modulus value. OGDL is a cement treated Open Graded Drainage Layer from Ontario with typical modulus value. MB GBC- I is Manitoba's new granular base material with 25 mm maximum sized aggregates and 4.9% fines (passing 0.075 mm sieve). MB Old Gran. A is Manitoba's old Granular A material with 19 mm maximum sized aggregates and 12.4% fines. Silty sand is a natural granular material. SK subbase is a fine graded sandy subbase material used in Saskatchewan. Table 4 shows the physical properties of base and subbase materials. The Mr for GBC-I, Gran. A and CR-M50 are typical values obtained through laboratory testing. The Mr of silty sand represents typical value determined through backcalculation from FWD deflection data. The Mr of SK subbase material was estimated based on professional judgement.

Table 3. Variable inputs for design runs in Trial Set #2

Design No.	Cement Stabilized Base Thickness, mm	Cement Stabilized Base Modulus, MPa	GBC Type	GBC Thickness, mm	GBC Mr, MPa	GSBC Type	GSBC Thickness, mm	GSBC Mr, MPa
1	100	13790	MB GBC- I	200	250	N/A	N/A	N/A
2	100	5170 (OGDL)	MB GBC- I	200	250	N/A	N/A	N/A
3	N/A	N/A	MB GBC- I	200	250	N/A	N/A	N/A
4	N/A	N/A	MB GBC- I	200	125	N/A	N/A	N/A
5	N/A	N/A	MB Old Gran. A	200	125	N/A	N/A	N/A
6	N/A	N/A	A-2-4 (Silty Sand)	200	70	N/A	N/A	N/A
7	N/A	N/A	MB GBC- I	100	250	CR-M50	200	200
8	N/A	N/A	MB GBC- I	100	250	SK Subbase	200	100
9	200	13790	MB GBC- I	200	250	N/A	N/A	N/A
10	200	5170	MB GBC- I	200	250	N/A	N/A	N/A
11	N/A	N/A	MB GBC- I	500	250	N/A	N/A	N/A
12	N/A	N/A	MB GBC- I	500	125	N/A	N/A	N/A
13	N/A	N/A	MB Old Gran. A	500	125	N/A	N/A	N/A
14	N/A	N/A	A-2-4 (Silty Sand)	500	70	N/A	N/A	N/A
15	N/A	N/A	MB GBC- I	100	250	CR-M50	500	200
16	N/A	N/A	MB GBC- I	100	250	SK Subbase	500	100

GBC = Granular Base Course, MB = Manitoba, GSBC = Granular Subbase Course, CR-M50 = Crushed Rock Minus 50 mm.

Table 4. Physical properties of base and subbase materials

Base/Subbase Materials	Erodibility Index	Minus 4.75 mm, %	Minus 0.075 mm, %	Density, kg/m^3	Moisture Content, %	LL, %	PI, %
Cement stabilized base (Default)	1						
OGDL (ON)	2						
GBC- I (MB)	3	55	4.9	2240	7.1	13	0
Gran. A (MB Old)	4	61	12.4	2240	8.5	20	4
A-2-4 (Silty Sand)	5	91.0	22.0	1764	15.3	18	3
CR- M50 (MB SB)	N/A	29.6	7.8	2065	6.8	NP	NP
SK Subbase	N/A	87	7.0	1989	9.2	25	6

N/A = Not Applicable, CR-50 = Manitoba 50 mm minus crushed rock subbase, LL = liquid limit, PI = plasticity index, NP = non-plastic

Results and Discussion: Effect of Subgrade Materials (Trial Set 1)

Effect of subgrade materials on the predicted IRI

Figures 2a and 2b show the trends of the PMED software v2.6 predicted IRI with the variations of subgrade material types and stiffness in different climatic areas. The numbers in brackets on the horizontal axis indicate the resilient moduli values, cement refers to soil-cement and CR refers to crushed rock layer. As shown in Figure 2a, the predicted IRI decreases as the physical properties or stiffness of native subgrade soils improves from Class A-7-6 (Mr = 25 MPa) to Class A-1-b (Mr = 90 MPa). The A-6 and A-4 soils had the same Mr = 40 MPa value but different physical properties. A reduction of the predicted IRI (e.g., 3.23 m/km at The Pas) for A-4 subgrade from the predicted IRI for the A-6 subgrade (e.g., 3.78 m/km at The

Pas) indicates that the physical properties (gradation and soil indices) of subgrade materials have significant effect on the predicted IRI.

As shown in Figure 2a and 2b, there is a significant effect of varying climatic conditions on the PMED software predicted IRI. No design meets the IRI criteria for high plastic clay (A-7-6), low plastic clay (A-6) and sandy silt (A-4) subgrade soils in cold climates like The Pas (MB), Fort McMurray (AB), Winnipeg (MB), Rouyn (QC) and Swift Current (SK). In no-freeze climate zone, e.g., in Victoria (BC), soil types and stiffness has minimal effect on the predicted IRI, which seems to be due to a very low freezing index and freeze-thaw cycles in Victoria. Similar trend applies to the predicted faulting as well.

As shown in Figure 2a, the addition of a 300 mm thick soil-cement layer to the native subgrade soils, which increased the resilient modulus of native soils from 25-90 MPa to 85-130 MPa, did not provide any significant reduction to the predicted IRI, which is unexpected. For example, for a high plastic clay soil in The Pas (MB), the predicted IRI decreased from 4.06 m/km to 4.04 m/km after adding 300 mm soil-cement layer, which is practically not a considerable change. Similar minor changes are observed for other subgrade soil types with the addition of soil-cement layers. These indicate that stiffer subgrade do not have significant effect on the predicted IRI and the variations of predicted IRI among the subgrade soils are mainly associated with their physical properties. In cold climates, subgrade soils with better physical properties such as low fines content is more helpful than the stiffer subgrade soils.

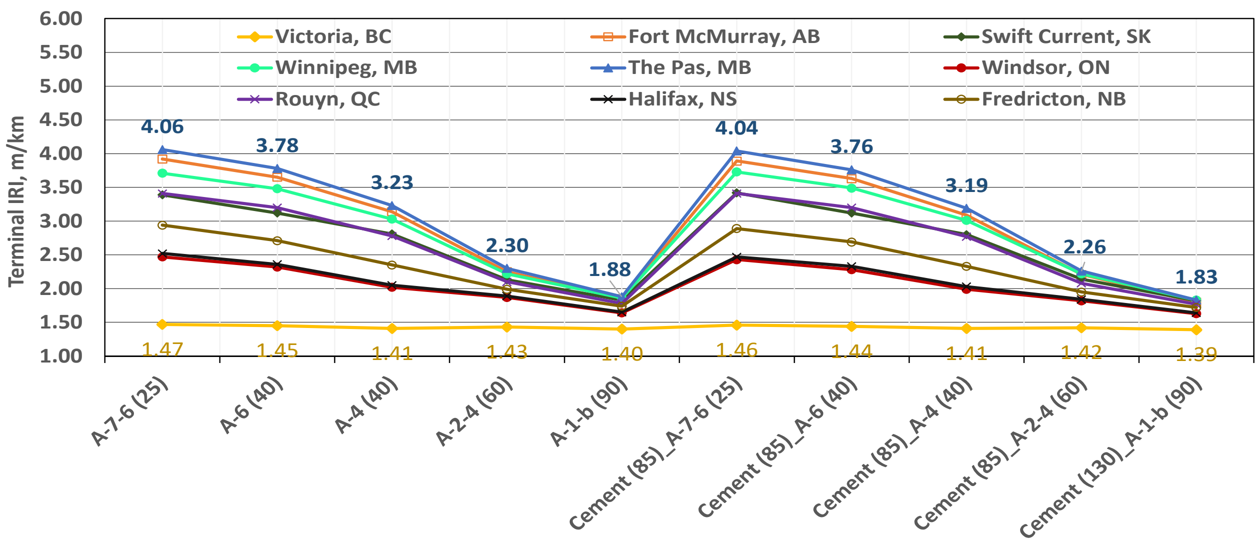

Figure 2a. Trends of the predicted IRI with variations of subgrade materials (native vs soil-cement)

It was also noted that PMED software only allows soil-cement as a sandwich layer between subbase and base or base and surface layers without inputs for gradation and soil characteristics (e.g., moisture, plasticity and soil-moisture properties). Soil-cement materials can be input as subgrade with high stiffness values. However, gradation and soil characteristics of the treated soils are still required in the later case, which is not realistic inputs for soil-cements. Since the PMED software is unable to properly model the soil-cement layer as subgrade, the subsequent discussion in this paper excluded all results and analysis related to soil-cement.

As shown in Figure 2b, when a layer of select granular subgrade i.e., 300 mm CR-M50 was added to the pavement structure, all designs met the IRI criteria in all climatic areas across Canada. The effect of native subgrade soils underlying the CR-M50 layer then became minimal. As shown in Figure 2b, IRI varied from 1.82 to 1.86 m/km among the native subgrade materials placed under a CR-M50 subgrade layer for The Pas (MB) area. The trends in Figure 2b also indicate that subgrade soils with better physical properties, specifically low fine contents, will reduce the predicted roughness in cold climates with freezing and thawing issues.

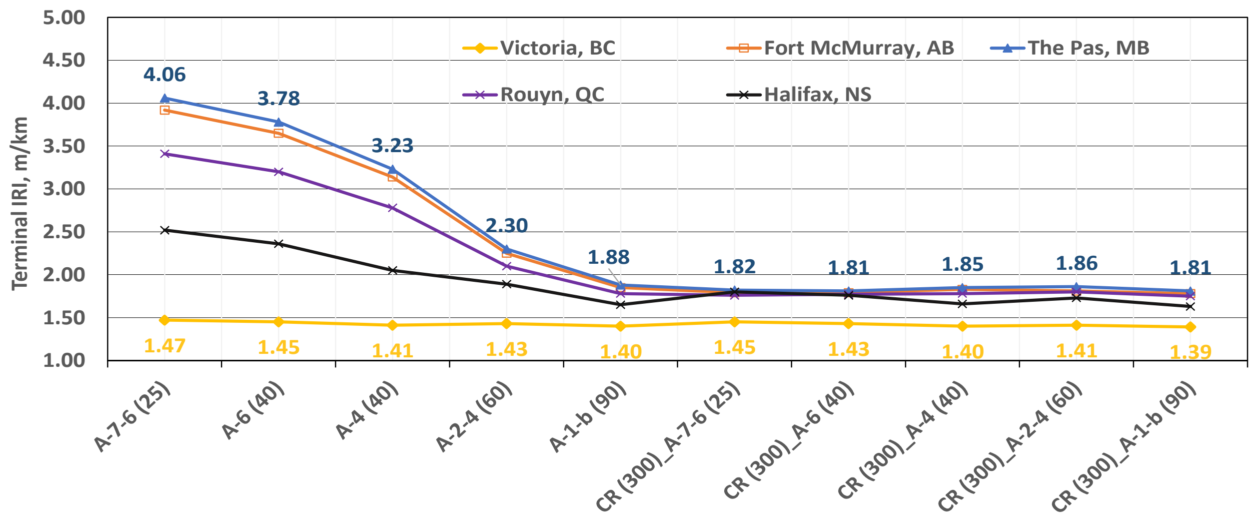

Figure 2b. Trends of the predicted IRI with variations of subgrade materials (native vs granular subgrade)

Figure 3 presents a comparison of the predicted IRI between the PMED software v2.6 and v3.0 for different subgrade combinations. As shown in the figure, software v3.0 provides higher IRI values than that with v2.6 for poor quality (i.e., clay and silt) subgrade soils. The trend reverses for good quality (i.e., sand, gravel and rock) subgrade soils where software v3.0 provides lower IRI values than that with v2.6. While some differences in the predicted distresses between v2.6 and 3.0 are expected due to the incorporation of PCC-granular base interaction model in v3.0 and recalibration of models using MERRA climate data, which provides higher freezing index and number of freeze-thaw cycles than NARR climate data, the reasons for the switch in the trend is unclear and requires further investigation.

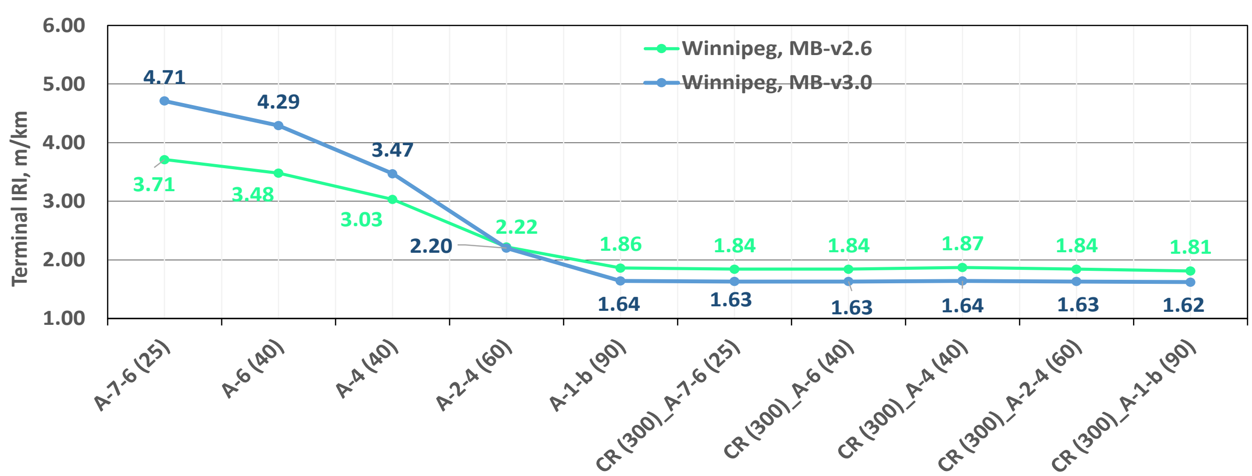

Figure 3. Trends of the predicted IRI with variations of subgrade materials (Software v2.6 vs v3.0)

Effect of subgrade materials on the predicted faulting

Figure 4 shows the variations of the PMED software v2.6 predicted faulting at PCC joints with the variations of subgrade material types and stiffness at select (for clear view of trends) climatic areas. As shown in the figure, the variations of the predicted faulting are inconsistent among the subgrade soil types and climatic areas. These trends are unexpected and difficult to explain.

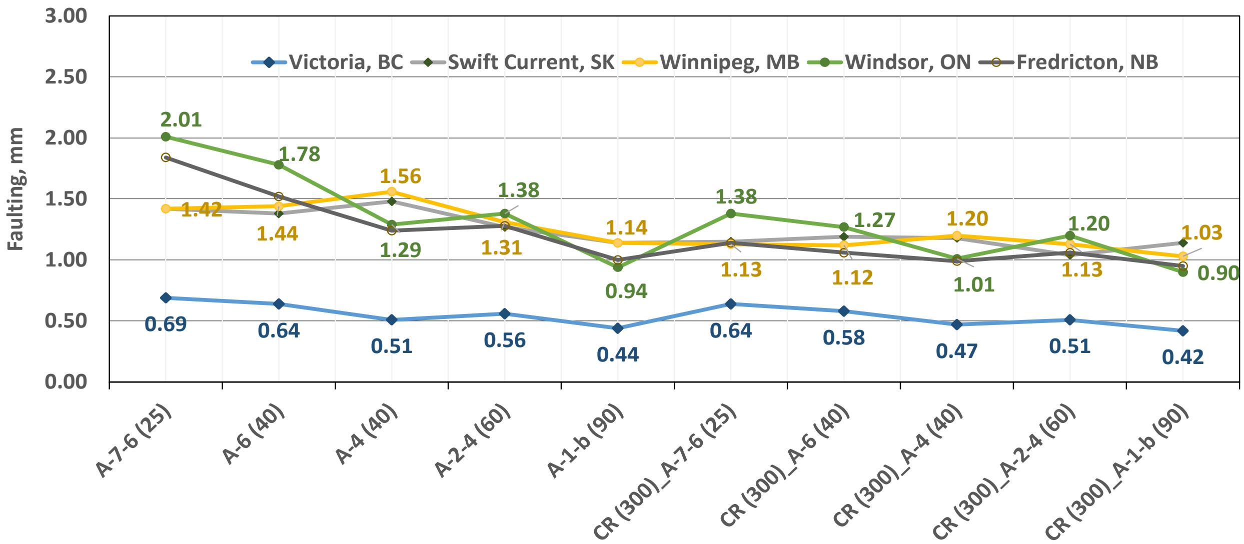

Figure 4. Trends of the predicted faulting with variations of subgrade materials (native vs granular subgrade)

Figure 5 presents a comparison of the predicted faulting at PCC joints between the PMED software v2.6 and v3.0 for different subgrade combinations. As shown in the figure, the predicted faulting using software v2.6 and v3.0 seems to follow similar trends. However, software v3.0 provided lower amount of faulting than that using software v2.6.

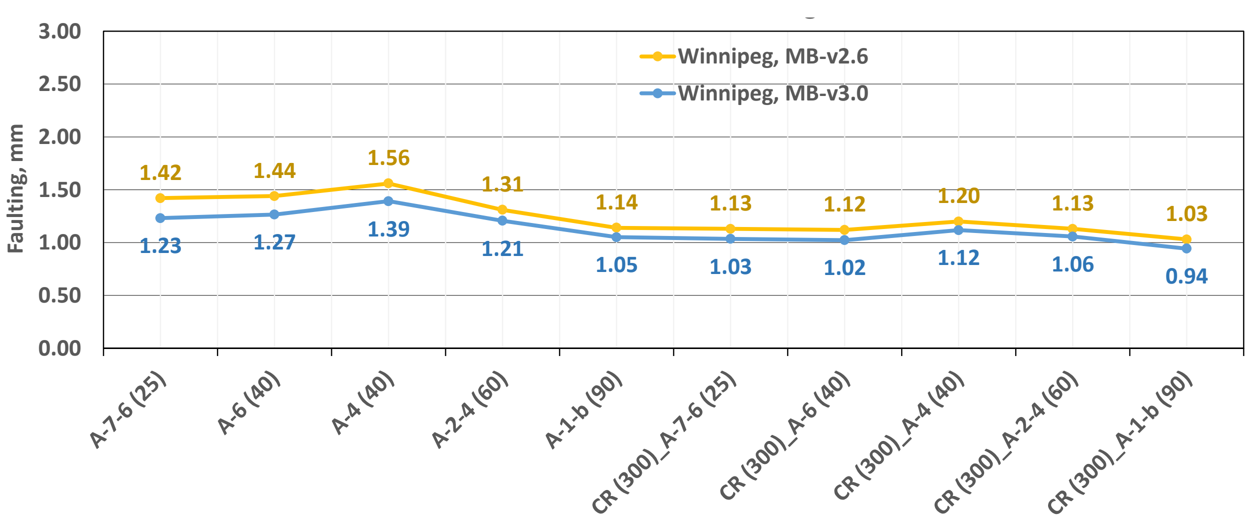

Figure 5. Trends of the predicted faulting with variations of subgrade materials (software v2.6 vs v3.0)

Effect of subgrade materials on the predicted transverse cracking

Figure 6 shows the variations of the predicted transverse cracking in PCC pavements with the variations of subgrade material types and stiffness at different climatic areas using PMED software v2.6. As shown in the figure, subgrade type did not provide any difference in predicted transverse cracking (remained at 0.96% of slab) regardless of climatic conditions and subgrade type or stiffness.

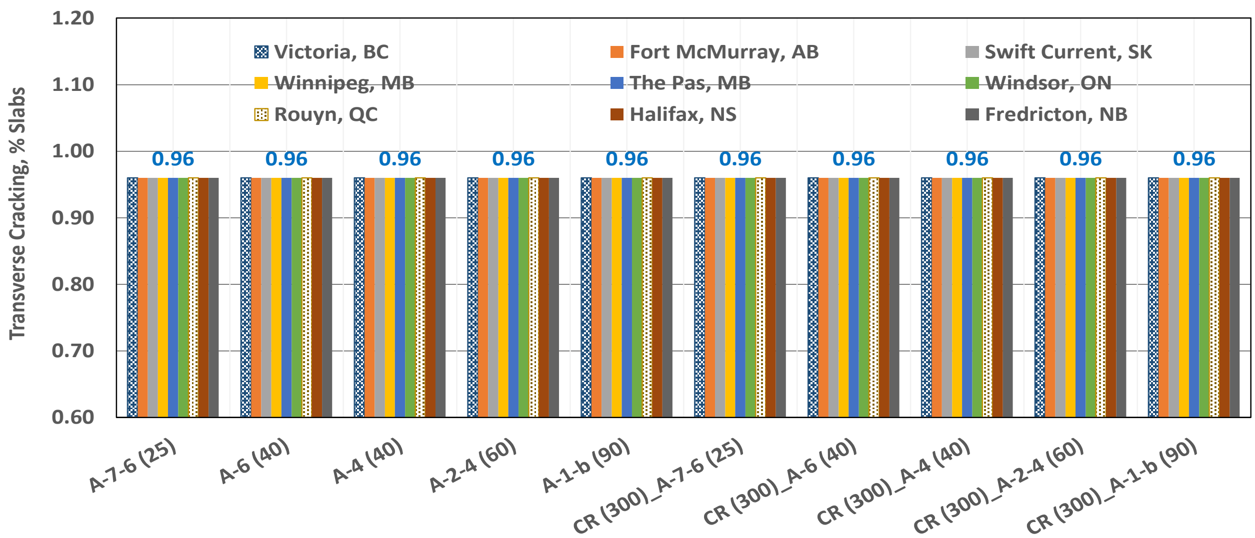

Figure 6. Trends of transverse cracking with variations of subgrade materials (native vs granular subgrade)

Figure 7 presents a comparison of the predicted transverse cracking between the PMED software v2.6 and v3.0 for different subgrade combinations. As shown in the figure, software v3.0 provided consistently lower amount of transverse cracking than that using software v2.6. However, the predicted transverse cracking slightly varied among the subgrade types with the use of software v3.0. In general, a good quality subgrade provides higher transverse cracking when using the PMED software v3.0, except for the A-2-4 subgrade, which shows a drop in transverse cracking as compared to the A-4 subgrade (A-2-4 has a lower density than the A-4), but still higher than that for the A-7-6 and A-6 subgrade soils. This trend seems to be questionable.

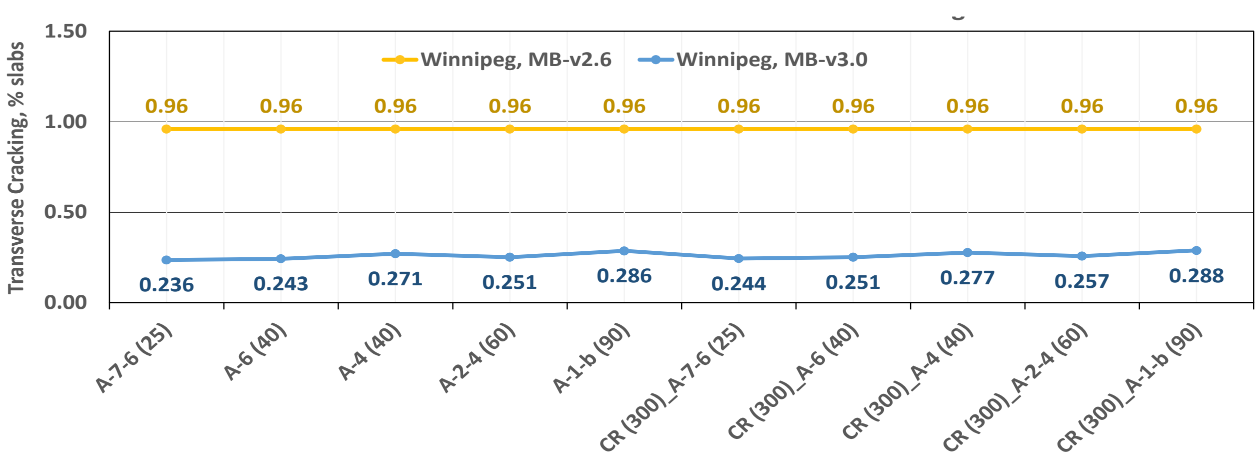

Figure 7. Trends of transverse cracking with variations of subgrade materials (software v2.6 vs v3.0)

Results and Discussion: Effect of Base and Subbase Materials (Trial Set 2)

Although design trials were completed for nine climatic areas across Canada, the charts presented in this section show data from select climate stations for better visualization of the results and trends. The notations in the figures refer to the following:

Run #	Notation	Description	Run #	Notation	Description
1	100CSB-200GSB	100 mm cement stabilized base and 200 mm granular subbase	9	200CSB-200GSB	200 mm cement stabilized base and 200 mm granular subbase
2	100CT OGDL-200GSB	100 mm cement treated open graded drainage layer and 200 mm granular subbase	10	200CT OGDL-200GSB	200 mm cement treated open graded drainage layer and 200 mm granular subbase
3	200GBC I-250MPa	200 mm granular base course Type I with a resilient modulus of 250 MPa	11	500GBC I-250MPa	500 mm granular base course Type I with a resilient modulus of 250 MPa
4	200GBC I-125MPa	200 mm granular base course Type I with a resilient modulus of 250 MPa	12	500GBC I-125MPa	500 mm granular base course Type I with a resilient modulus of 250 MPa
5	200A-base-125MPa	200 mm granular A base with a resilient modulus of 125 MPa	13	500A base-125MPa	500 mm granular A base with a resilient modulus of 125 MPa
6	200Silty Sand-70MPa	200 mm silty sand natural aggregate base with a resilient modulus of 70 MPa	14	500Silty Sand-70MPa	500 mm silty sand natural aggregate base with a resilient modulus of 70 MPa
7	200 CR-M50-200MPa	200 mm minus 50 mm crushed rock subbase with a resilient modulus of 200 MPa	15	500 CR-M50-200MPa	500 mm minus 50 mm crushed rock subbase with a resilient modulus of 200 MPa
8	200SK-SB-100MPa	200 mm fine graded subbase from SK with a resilient modulus of 100 MPa	16	500SK-SB-100MPa	500 mm fine graded subbase from SK with a resilient modulus of 100 MPa

Effect base materials on the predicted IRI

The variations of the PMED software v2.6 predicted IRI with variations of base material type and layer thickness are shown in Figure 8. As shown in the figure, in general, weaker or poor quality base material provides higher IRI with some exceptions depending on the climatic conditions, e.g. Halifax area. In Halifax, the GBC- I and Granular A base with a low modulus (Mr = 125 MPa) were shown to provide lower IRI (2.22 m/km and 2.30 m/km, respectively) than that (2.34 m/km) for the GBC- I with a high modulus (Mr. = 250 MPa). Figure 8 also shows that IRI generally reduces with increased thickness of base layers and climatic condition has a significant effect on predicted IRI.

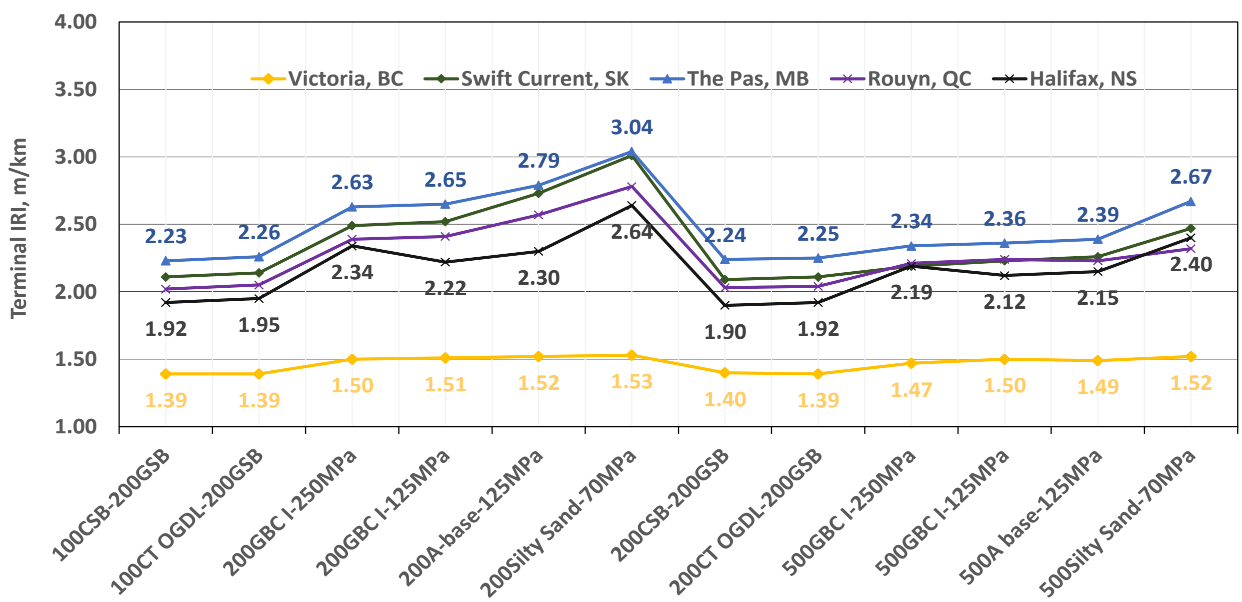

Figure 8. Trends of the predicted IRI with variations of base layer materials and thickness (v2.6)

As shown in Figure 8, the effect of base material stiffness on the predicted IRI seems to be small. For example, at The Pas (MB) area, 200 mm GBC- I provided an IRI of 2.63 m/km when the Mr was 250 MPa and an IRI of 2.65 m/km when the Mr was 125 MPa with same physical properties. The physical properties of base materials seem to have greater impact on the predicted IRI than its stiffness. For example, for The Pas (MB) area, 200 mm GBC- I provided an IRI of 2.65 m/km whereas 200 mm Granular A provided an IRI of 2.79 m/km with the same Mr value of 125 MPa, but with different physical properties. The effect of increased thickness of treated base materials on the predicted IRI seems to be negligible or counter intuitive. For example, an increase in the CTB thickness from 100 mm to 200 mm in The Pas resulted in an increase of IRI from 2.23 m/km to 2.24 m/km. The effect of increased thickness of granular base materials on the predicted IRI was not as high as expected but was noticeable. For example, an increase in the GBC-I (Mr = 250 MPa) thickness from 200 mm to 500 mm in The Pas resulted in a decrease of IRI from 2.63 to 2.34 m/km.

Figure 9 compares the predicted IRI for various base materials using PMED software v2.6 and v3.0. As shown in the figure, there are negligible differences in the predicted IRI between software v2.6 and v3.0 in the case of stabilized base layers, regardless of their physical properties, moduli and thicknesses. For thinner (200 mm) granular base layer, software v3.0 provides lower IRI than that with v2.6 and the difference in predicted IRI between software v2.6 and v3.0 increases for inferior (poor) quality granular base materials. For thicker (500 mm) granular base layer, there are small but inconsistent differences or variations of the predicted IRI between software v3.0 and v2.6. Overall, the predicted IRI using software v3.0 is less sensitive, than that with v2.6 to changes in base material physical properties, stiffness and thickness, which does not seem to reflect the field performance expectation.

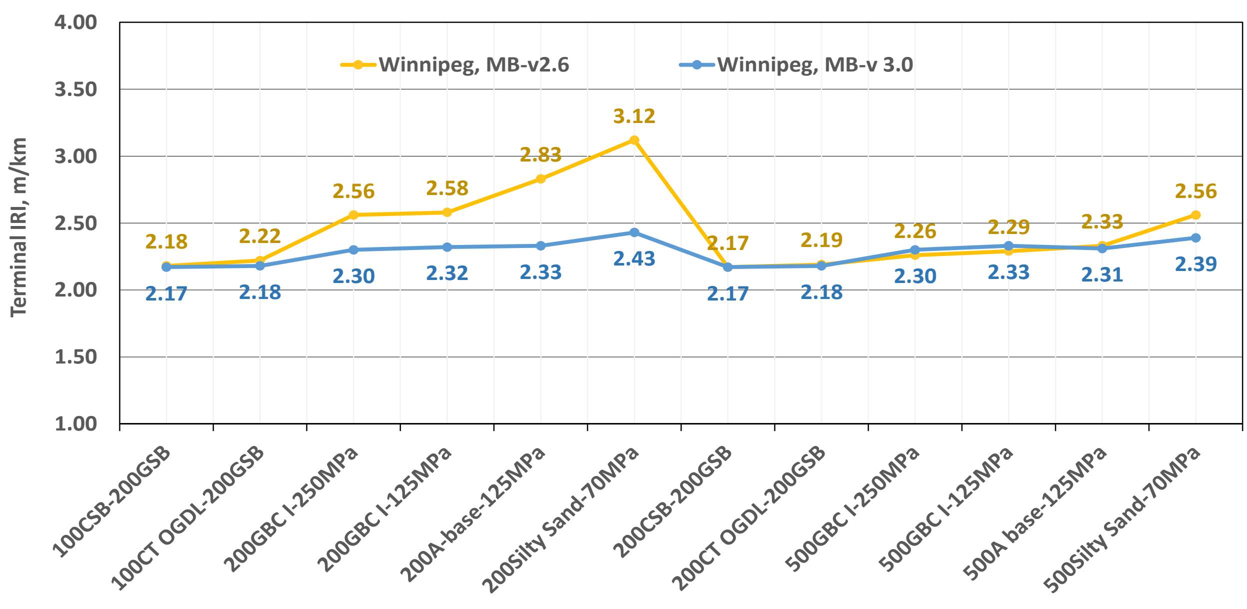

Figure 9. Trends of the predicted IRI with variations of base layer materials and thickness (v2.6 vs v3.0)

Effect of base materials on the predicted faulting

Figure 10 shows the trends of the PMED software v2.6 predicted faulting with variations of base material type and layer thickness. As shown in the figure, weaker or poor quality granular base materials produces higher faulting. The predicted faulting significantly reduces with increased thickness of granular base layer and climatic condition has a significant effect on the predicted faulting. The effects of varying stiffness and thickness of cement stabilized or treated base layers were shown to be small or inconsistent. The effects of granular base material properties on the predicted faulting were shown to be more pronounced (e.g., 200GBC I-125MPa vs 200A-base-125MPa) than that of their stiffness (e.g., 200GBC I-250MPa vs 200GBC I-125MPa). The effects of increased thickness of granular base materials on the predicted faulting were shown to be stronger (e.g., 200GBC I-250MPa vs 500GBC I-250MPa) than the effects of physical properties and stiffness.

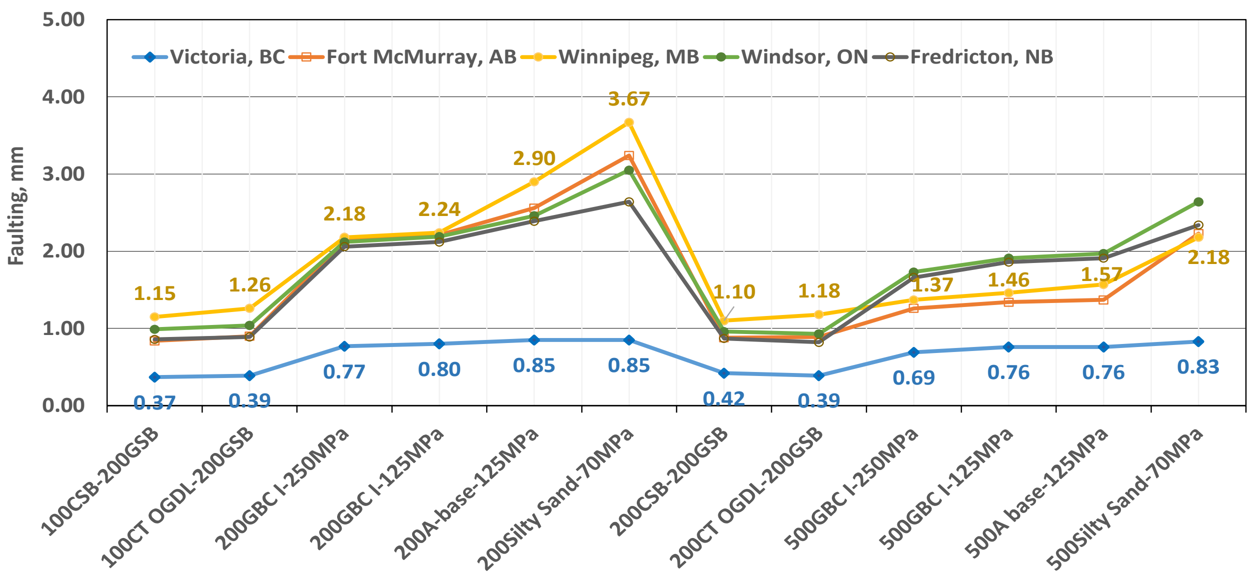

Figure 10. Trends of the predicted faulting with variations of base layer materials and thickness (v2.6)

Figure 11 compares the predicted faulting for various base materials using PMED software v2.6 and v3.0. As shown in the figure, the predicted faulting with software v2.6 and v3.0 follows similar trends for thinner base layers, but software v3.0 provides consistently lower faulting than that with v2.6. The trend reverses or becomes inconsistent for thicker base layers. The trends in Figure 11 shows that the software v3.0 predicted faulting increases with increased thickness of good quality (CSB, OGDL and GBC-I) base materials, while the predicted faulting decreases with increased thickness of poor quality (A-base and Silty Sand) base materials. Such a trend of the predicted faulting using the software v3.0 does not seem to reflect the practical experience. It also shows that the software v3.0 is worse than the software v2.6 in terms of taking into account the effect of base materials.

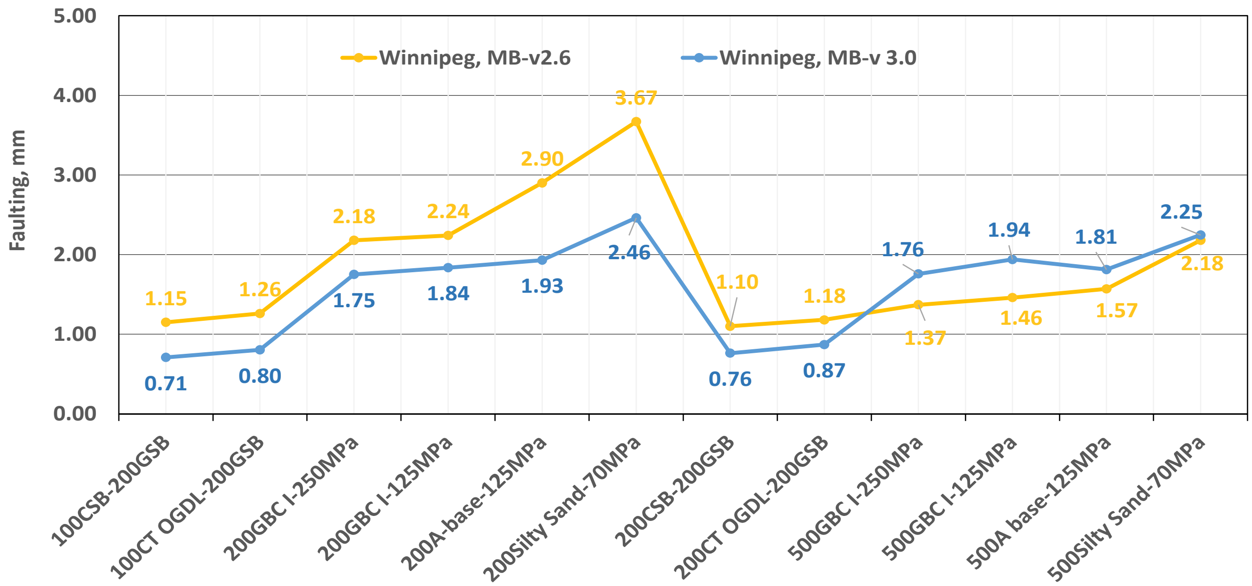

Figure 11. Trends of faulting with variations of base layer materials and thickness (v2.6 vs v3.0)

Effect of base materials on the predicted transverse cracking

The variations of the PMED software v2.6 predicted transverse cracking with variations of base material type and layer thickness are shown in Figure 12. As shown in the figure, there are inconsistent variations of predicted transverse cracking among the base materials and climatic exposures, which are unexpected and difficult to explain.

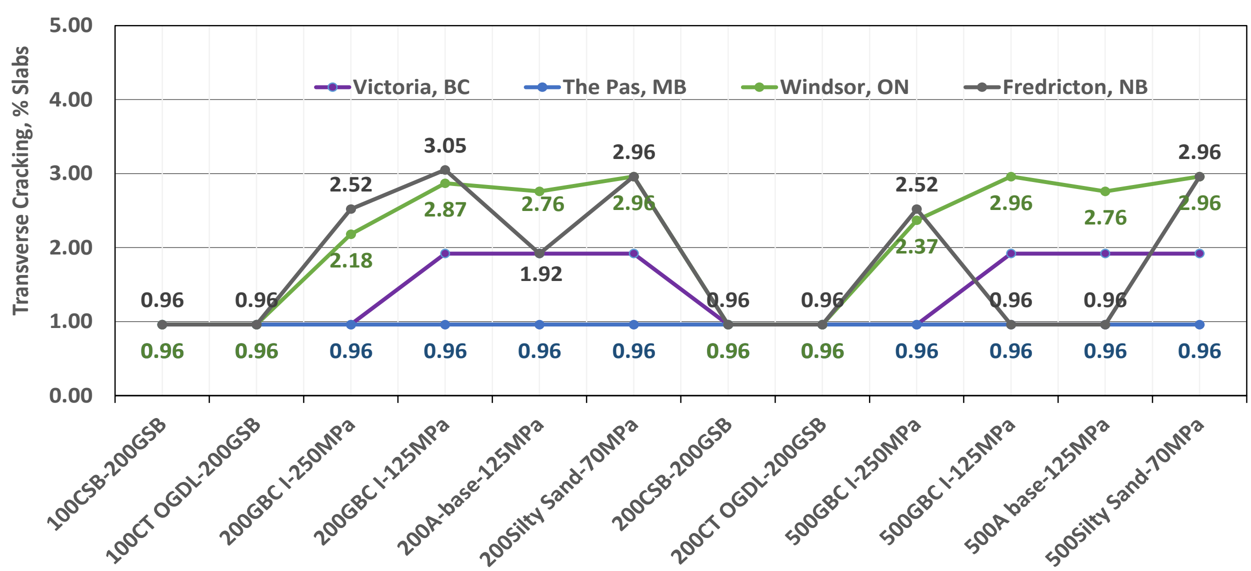

Figure 12. Trends of the predicted transverse cracking with variations of base layer materials and thickness

Figure 13 compares the predicted transverse cracking for various base materials using PMED software v2.6 and v3.0. As shown in the figure, software v3.0 produces higher amount of transverse cracking than that with the software v2.6 with an unexpectedly high amount of transverse cracking for stabilized or treated base (CSB and OGDL) materials. The variations of the predicted transverse cracking, using the software v3.0, with the variations of base material properties, stiffness and layer thickness were also shown to be inconsistent. This further indicates that software v3.0 also does not meet the expectation.

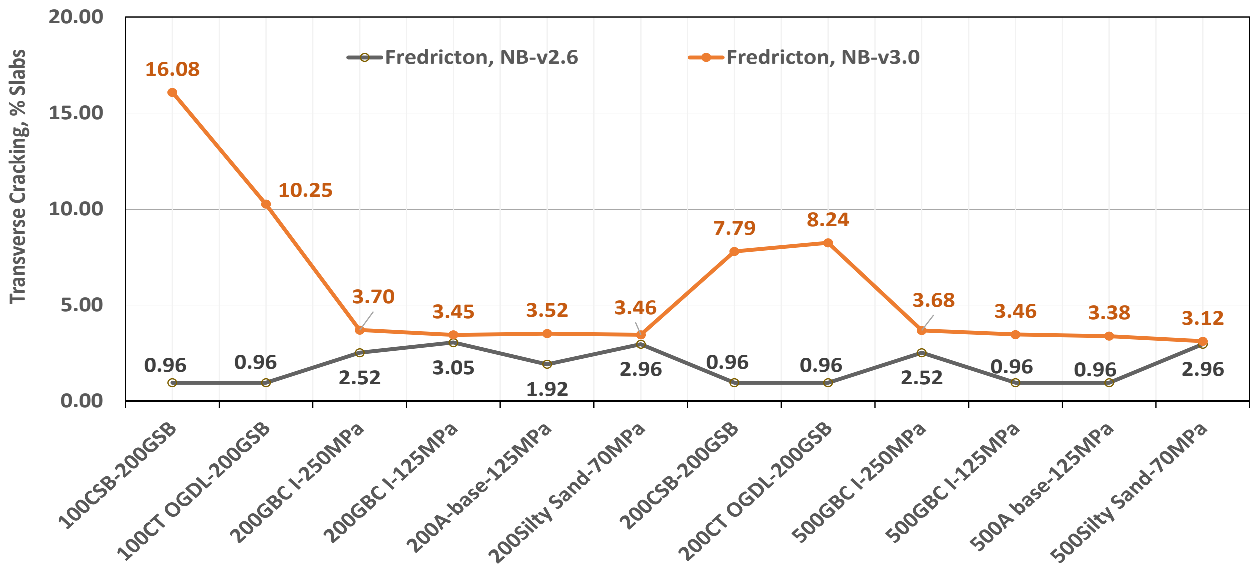

Figure 13. Trends of transverse cracking with variations of base layer materials and thickness (v2.6 vs v3.0)

Effect of subbase materials on the predicted distresses

Figures 14 to 16 show the variations of the PMED software v2.6 predicted distresses with the variations of subbase material type and layer thickness. As shown in Figure 14, in general, poor quality subbase causes slight increase in IRI and thicker subbase cause slight reduction in IRI, except for warm climate like Victoria, where the predicted IRI remained the same or increased with an increase in subbase thickness. The impacts of increased subbase thickness on the predicted IRI seem to be inconsistent among the subbase types and climatic areas.

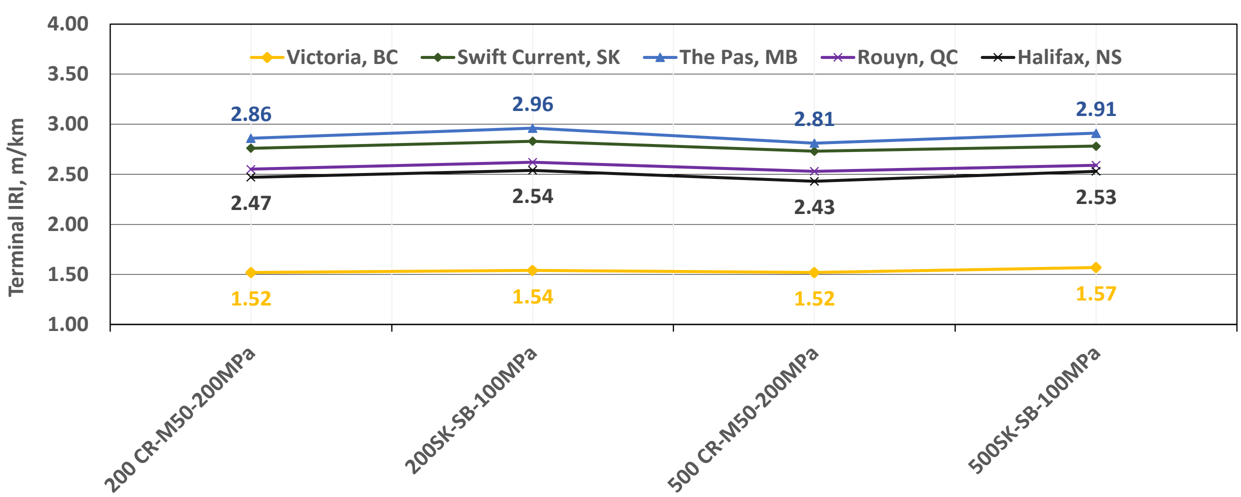

Figure 14. Trends of the predicted IRI with variations of subbase layer materials and thickness (v2.6)

Figure 15 shows that poor quality subbase causes slightly higher faulting and thicker subbase causes slight reduction in the predicted faulting, except for warm climate like Victoria, where the predicted faulting remained unchanged or increased with increased thickness of subbase layer. The trends of the predicted faulting for increased thickness of subbase layer seem to be inconsistent among different climatic areas.

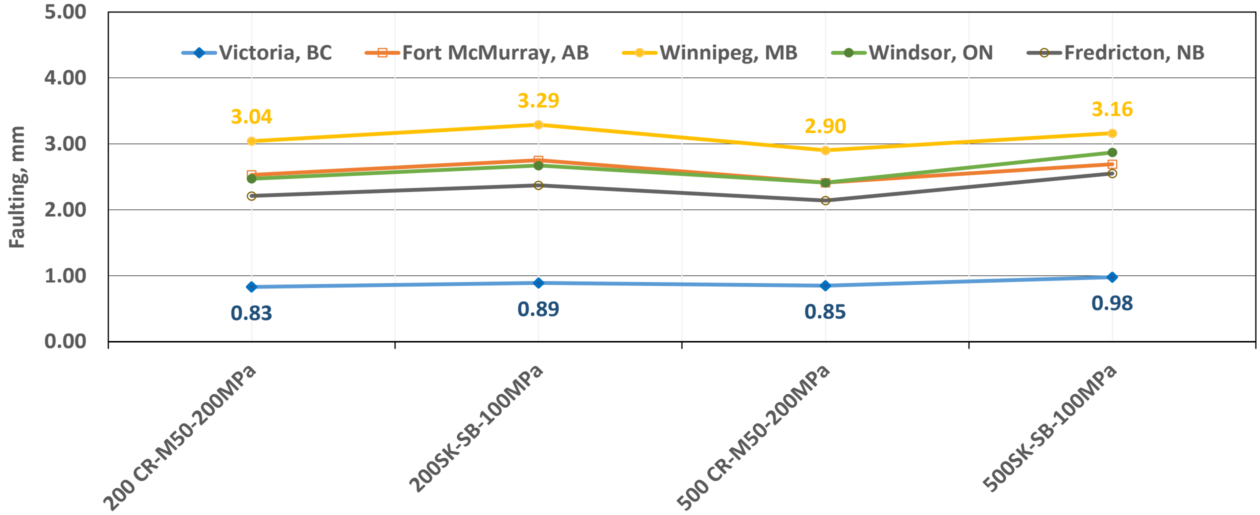

Figure 15. Trends of the predicted faulting with variations of subbase layer materials and thickness (v2.6)

Figure 16 shows that, in general, poor quality subbase results in slightly higher transverse cracking with some inconsistencies among climatic areas, e.g., Fort McMurray (AB), where the predicted transverse cracking (2.37%) remains unchanged for 500 mm thick CR-M50 and 500 mm thick SK subbase. With a thicker subbase layer, there is a slight increase or no change in the predicted cracking. For example, the predicted transverse cracking (3.90%) remained unchanged between 200 mm thick layer of CR-M50 and 500 mm of CR-M50 in Winnipeg area. Such trends of the predicted transverse cracking for changes in subbase materials seem to be inconsistent among climatic areas.

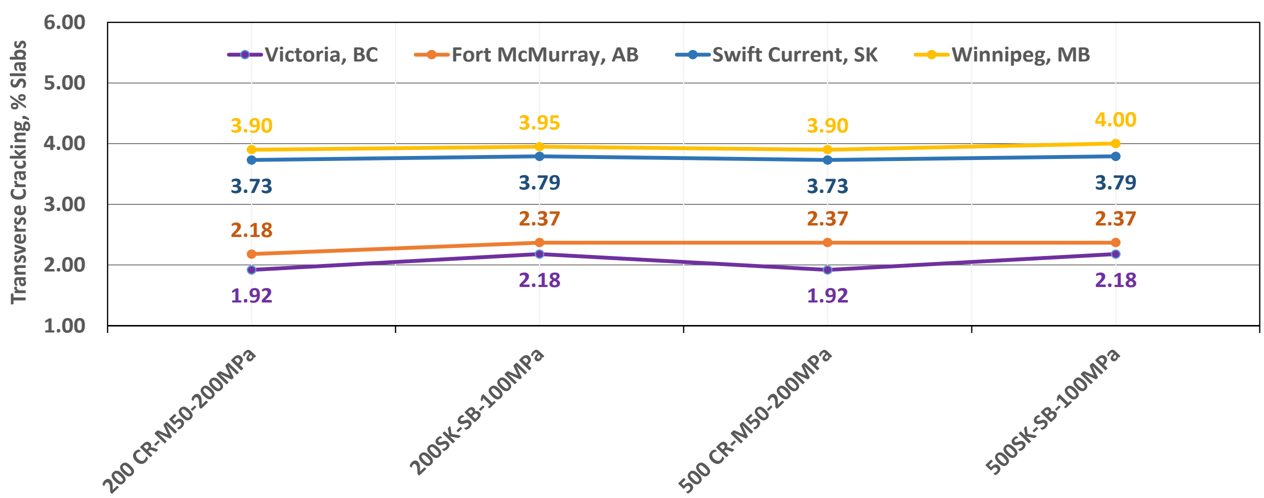

Figure 16. Trends of the transverse cracking with variations of subbase layer materials and thickness (v2.6)

Summary of Findings

This study examined the impact of different subgrade soil types (native and stabilized) including their physical and mechanical properties, different base (granular and stabilized) material types including their physical and mechanical properties, different granular subbase materials and varying climatic exposures across Canada on the predicted distresses in JPCP using the AASHTOWare PMED software. The predicted distresses using PMED software v2.6 and v3.0 were also compared. Based on the results and analysis presented in this paper, the key findings can be summarized as follows:

1) The physical properties (gradation and soil indices) of subgrade materials and climatic conditions have significant effect on the predicted IRI. No design meets the IRI criteria for clay (A-7-6/A-6) and silt (A-4) subgrade soils in cold climates. If a granular layer is used as subgrade, all designs meet the IRI criteria and then the effect of underlying native subgrade becomes minimal.
2) Stiffer subgrade does not have significant benefit in terms of predicted IRI and, in a given climatic condition, the variations of predicted IRI among the subgrade soils are mainly associated with their physical properties. In cold climates, subgrade soils with better physical properties such as low fines content will be more helpful than the stiffer subgrade soils.
3) The predicted faulting for the variation of subgrade materials and climatic exposures was inconsistent and difficult to explain.
4) Subgrade type has no effect on the predicted transverse cracking with software v2.6. The predicted transverse cracking using software v3.0 shows minor variations among the subgrade types, which seem to be related to the new concrete-granular base interaction model.
5) Soil cements cannot be modeled properly as subgrade below the granular subbase. Although they can be input as subgrade with high stiffness values, gradation and soil characteristics of the treated soils are still required, which are not realistic inputs for soil-cement materials.
6) In general, good quality and thicker base/subbase provide reduction in IRI and faulting with some inconsistences. The variations of predicted transverse cracking among the base materials and climatic exposures were inconsistent.
7) The effect of base material stiffness on the predicted IRI seems to be small. The effect of base material physical properties on the predicted IRI seems to be stronger than its stiffness. The effect of increased thickness of treated base materials on the predicted IRI seems to be negligible or counter intuitive. The effect of increased thickness of granular base materials on the predicted IRI was not as high as expected but noticeable.
8) The effects of varying stiffness and thickness of cement stabilized or treated base layers were shown to be small or inconsistent. The effects of granular base material properties on the predicted faulting were shown to be more pronounced than their stiffness. The effects of increased thickness of granular base materials on the predicted faulting were shown to be stronger than the effects of physical properties and stiffness.
9) Poor quality subbase causes slight increase in IRI and faulting and thicker subbase causes slight reduction in IRI and faulting with some inconsistencies.
10) Poor quality subbase results in slightly higher transverse cracking and thicker subbase causes slight increase or no change in predicted cracking with some inconsistencies.
11) There were some inconsistencies and significant difference in the predicted distresses between software v2.6 and v3.0 for the variations of both subgrade and base materials inputs.
12) Some trends or values of the predicted distresses using the software v3.0 for the variation of base materials inputs do not seem to reflect the practical experience. It was also noted that software v3.0 is worse than the software v2.6 in terms of taking into account the effect of base materials.

References

[1] AASHTO 1993. "*AASHTO Guide for Design of Pavement Structure*." American Association of State Highway and Transportation Officials, Washington, D.C.

[2] Ahammed, M. A. et al. 2022. *"Sensitivity of the Pavement ME Design Software Predicted Distresses in Flexible Pavements to Granular Base Materials."* Proceedings of the 2022 Annual Conference of the Transportation Association of Canada, Innovations in Pavement Management, Engineering and Technologies Session, Edmonton, AB.

[3] Ahammed, M. A. et al. 2022. *"Sensitivity of the Pavement ME Design Software Predicted Distresses in Flexible Pavements to Subgrade Soils and Granular Subbase Materials."* Proceedings of the 2022 Annual Conference of the Transportation Association of Canada, Innovations in Pavement Management, Engineering and Technologies Session, Edmonton, AB.

[4] NCHRP 01-51, 2017. "*A Model for Incorporating Slab/Underlying Layer Interaction into the MEPDG Concrete Pavement Analysis Procedures*". The National Cooperative Highway Research Program (NCHRP), Transportation Research Board, National Academies of Sciences, Engineering, and Medicine, Washington D.C.

[5] Luo X. et al. 2017*. "Mechanistic-Empirical Models for Better Consideration of Subgrade and Unbound Layers Influence on Pavement Performance."* Elsevier, Science Direct. Transportation Geotechnics, Volume 13. pp 52-68.

[6] Zhong, J. 2017. "*Rigid Pavement: Ontario Calibration of the Mechanistic-Empirical Pavement Design Guide Prediction models,"* University of Waterloo thesis, Waterloo, Canada.

[7] Schwart, C.W. et al. 2011. *"Sensitivity Evaluation of MEPDG Performance Predictions."* Final report, NCHRP 1-47. Transportation Research Board of the National Academics, Washington, D.C.

[8] Tompkins, D. 2018. "*MnPAVE-Rigid 2.0- Research Project Report*." Final Report 2018-17. Minnesota, US.

[9] Shaban et al. 2020. *"Effect of Pavement Foundation Materials on Rigid Pavement Response."* 3rd International Conference on Engineering Science, Institute of Physics (IOP) Conference Series: Materials Science and Engineering, 671 (2020) 012085, Bristol, United Kingdom.

[10] NCHRP 1-53, 2019. *"Proposed Enhancements to Pavement ME Design: Improved Consideration of the Influence of Subgrade and Unbound Layers on Pavement Performance."* The National Cooperative Highway Research Program (NCHRP), Transportation Research Board, National Academies of Sciences, Engineering, and Medicine, Washington D.C.

[11] Jeong, J.H., and D.G. Zollinger. 2001. *"Characterization of Stiffness Parameters in Design of Continuously Reinforced and Jointed Pavements."* Transportation Research Record: Journal of the Transportation Research Board, No. 1778, pp. 54–63.

[12] Shahji, S. 2006. *"Sensitivity Analysis of AASHTO's 2002 Flexible and Rigid Pavement Design Methods."* Master of Sc. in the Dept. of Civil & Environmental Engineering, College of Engineering and Computer Science. University of Central Florida. Orlando, FL.

[13] AASHTO, 2008. *"Mechanistic-Empirical Pavement Design Guide—A Manual of Practice."* Interim Edition, American Association of State Highway and Transportation Officials, Washington, DC.

[14] Bakhsh, K.N. 2014. *"Design Methodology for Subgrades and Bases under Concrete Roads and Parking Lots."* PhD diss., Texas A&M University, College Station, TX.

[15] Bakhsh, K.N., and D. Zollinger. 2014. *"Faulting Prediction Model for Design of Concrete Pavement Structures."* Pavement Materials, Structures, and Performance, pp. 327–342.

[16] Saboori, A., Harvey, J., Lea, J., Wu, R., & Mateos, A. 2021. *"Pavement ME Sensitivity Analysis (Version 2.5.3)*." UC Davis: University of California Pavement Research Center.