Effect of HMA Density, VMA and AC Content on PMED Software Predicted Distresses in Flexible Pavement

M. Alauddin Ahammed, Ph.D., P.Eng. (Principal Author)
Manager, Pavement and Materials Engineering Section
Manitoba Transportation and Infrastructure
Winnipeg, Manitoba
Alauddin.Ahammed@gov.mb.ca

Diana Podborochynski, M.Sc., P.Eng.
Senior Surfacing Standards Engineer
Saskatchewan Ministry of Highways
Saskatoon, Saskatchewan
Diana.Podborochynski@gov.sk.ca

Yuen-Ting Fiona Leung, M.A.Sc., P.Eng.
Pavement Design Engineer, Engineering Materials Office
Ontario Ministry of Transportation
Toronto, Ontario
Fiona.Leung@ontario.ca

Qingfan Liu, PhD, P. Eng
Senior Pavements Engineer
Tetra Tech Canada Inc., Pavement Infrastructure Technologies
Edmonton, Alberta
Qingfan.Liu@tetratech.com

Shawn Lapain, P.Eng.
Senior Geotechnical Engineer/Pavement Specialist
AECOM Canada Ltd.
Ottawa, Ontario
Shawn.Lapain@aecom.com

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Abstract

An empirical pavement design method such as the American Association of State Highway and Transportation Officials (AASHTO) 1993 pavement design guide uses structural layer coefficient (a_i) value to determine thickness of each layer material or to convert a selected layer thickness to structural number (SN). Any change in material composition and properties will affect the a_i value, which will directly affect the required thickness of that layer in a logical manner. However, there are concerns regarding the sensitivity and trends of predicted distresses using the AASHTOWare Pavement Mechanistic-Empirical Design (PMED) software for different design inputs including material properties and the consistency among the PMED software versions. Two sets of design trials were completed between November 2023 and February 2024 in this study, using the latest web version (v3.0) of the PMED software, to assess the effect of hot mix asphalt (HMA) in-place compaction, which ranged from 90 to 97%, and the voids in mineral aggregates (VMA), which ranged from 13 to 17%, on the predicted distresses. Climatic data from nine to ten weather stations across Canada were used.

The analysis showed that a lower density/compaction (increased air voids) in an HMA mat results in an increase of predicted IRI, total and HMA (i.e., asphalt concrete) layer rutting, bottom-up fatigue cracking (BUFC), and thermal cracking (TC), but an inconsistent variation of top-down fatigue cracking (TDFC). Increased VMA and asphalt cement (AC) content results in a reduction of predicted IRI, BUFC, TDFC and TC, and an increase in total and HMA layer rutting. In general, the predicted distresses were shown to be very sensitive to changes in HMA density (air voids), VMA, and AC content. The impact of climatic condition on predicted distresses was not shown to be as expected or practically experienced. This paper presents the details of these trials including trend analyses and findings.

Introduction

Highway agencies across North America and other countries generally favour the use of empirical design methods for flexible pavement design. In many empirical methods, the total pavement structure requirement is established based on design inputs such as subgrade material type/stiffness and traffic loads. The thickness of each layer material is then determined based on the stiffness of each material, which depends on the composition and properties of that material. The design outcomes could be sub-optimal in some cases, but sensitivity and trends of the outcomes from these empirical methods are generally found to be logical. For example, a material with improved quality will always results in a reduced pavement thickness as compared to a poorer quality material. The impact of varied climatic conditions is also reflected in the variations of in-place pavement performance. For example, a particular HMA will experience more rutting in warmer climate than that in a colder climate. There will be higher amount of thermal cracking in colder climates than that in a warmer climate for a given mix and asphalt binder grade.

An example of empirical design approach is the procedure available in the AASHTO 1993 pavement design guide[1], which is still a predominant approach for flexible pavement design. This design approach provides a design structural number (SN) based on subgrade stiffness, design traffic loads and other design inputs for the design of a flexible pavement. The design SN is then converted into the thickness of different layer materials using their structural layer coefficient (a_i) values. The a_i value of each material depends on its elastic or resilient modulus (M_r), which in turns depends on the composition and properties of that respective material. For example, an asphalt mix with 10% air voids (AV) will exhibit a lower elastic modulus and thereby, a lower a_i value than a mix with 7% AV. This will affect the required thickness of a pavement structure when using the AASHTO 1993 pavement design guide.

AASHTOWare PMED software, which has been under development and refinement for over two decades, is the newest and most sophisticated design tool for the design and analysis of various pavements. Despite the robustness of the software in predicting the long term performance of pavements, highway agencies are still facing challenges to implement this software because of concerns related to some models, low sensitivity of the predicted distresses due to some key inputs, inconsistencies in predicted distresses, significant variations in predicted distresses between successive software versions, and the inability to come up with a unique set of calibration factors in each jurisdiction.

The focus of the design trials completed for this study was to evaluate the sensitivity and consistency of the predicted outcomes from the latest version of the PMED software for flexible pavement design. The design trials were completed with several changes to asphalt mix properties and climatic input parameters from selected locations across Canada. The information presented herein may help highway agencies and interested individuals in assessing the suitability of the PMED software for flexible pavement design.

Background

The Transportation Association of Canada (TAC) ME Pavement Design Subcommittee (Subcommittee) has been evaluating the AASHTOWare PMED software since 2007. These evaluations have involved numerous design trials aimed at understanding the impact of different input parameters on distress predictions for various pavement types.

The trials have covered a range of pavement types, including new conventional flexible pavements and rigid pavements, new thin HMA surfaced pavements, and HMA overlays on existing flexible pavements. Several papers have been published to document and share the results of these trials. Notably, the previous design trial results[2,3] have revealed significant differences and inconsistencies in predicted distresses between PMED software versions 2.6 and 3.0, along with unexpected variations in predicted distresses across different climatic conditions. Additionally, inconsistent trends in predicted distresses due to variations in certain design inputs have been observed in those two studies. Considering these undesirable observations and the continued development of the PMED software, the Subcommittee has decided to continue the evaluation of the latest version (currently v3.0) of the software and present the findings in technical meetings and conferences.

Findings from Literary Review

In the PMED software, HMA properties such as density, effective AC content, total AC content, AV, aggregate gradations, etc. are Level 3 input parameters. A NCAT study indicated that HMA in-place density (i.e., % compaction) has a significant impact on the performance of flexible pavements[4]. Inadequate compaction results in a HMA with poor durability, early aging, rutting, raveling, and moisture related stripping due to the ingress of moisture, and other pavement performance issues because of the high amount of VMA and AV. Based on laboratory testing and PMED software predictions, Mogawer et al.[5] also found that higher HMA density improved fatigue and rutting performance.

The effective AC content is determined as the VMA minus AV in a compacted HMA. VMA is the inter-aggregates void space in a compacted HMA, expressed as a percent of total volume of the mix. The VMA should be optimal to ensure that there is sufficient room for asphalt cement (excluding AC absorption by aggerates) plus the required AV in a HMA mix, which can provide adequate coating of aggregates for strong inter-aggregates bond for a stiff and durable mixture and sufficient lubrication for ease of HMA placement, compaction, and finishing. If the VMA is too low, the mix may have durability issues[6]. Alternatively, if VMA is too high for a given AC content, the mix may have stability and other performance issues. An increased AC content for a given AV improves the HMA cracking resistance and durability properties, but it can reduce the HMA's resistance to rutting.

Grebenschikov and Prozzi[7] examined the impact of HMA volumetric properties including effective AC content, VMA, and voids filled with asphalt on rutting using the PMED software. The study concluded that HMA rutting performance predictions from PMED software support laboratory rutting test results using the Hamburg Wheel Tracking Device. It was also concluded that the asphalt layer rutting predicted with the PMED software increased with an increase in VMA.

PMED software Manual of Practice[8] provided guidance to satisfy the desired performance criteria when designing a pavement structure. For example, if alligator cracking (i.e., bottom-up fatigue cracking) needs to be satisfied, then the HMA density should be increased, and AV should be decreased. Alligator cracking and rutting are also affected by the HMA aggregate sizes. For example, to reduce alligator cracking or rutting in the HMA, manufactured fines or crushed aggregate contents should be increased. These aggregate properties cannot be captured simply through Level 3 i.e., gradation, density, AV and AC content inputs in the PMED software.

Wang et al.[9] examined the impact of volumetric properties of asphalt concrete mixtures using FlexPAVE. The program was reported to predict the mechanical responses, fatigue damage, and rut depths in pavement structures analyzed. Using performance test results from laboratory mixed laboratory compacted asphalt mixtures and one plant produced mixture, performance simulations were completed using FlexPAVE. The study concluded that a change of in-place VMA of 0.5 % (i.e., from 16% to 16.5%) would cause the pavement structure to gain approximately two years of fatigue life.

Objective, Scope and Significance

Findings from the literature review indicates that HMA density, AV, AC content, and VMA are important parameters for pavement performance. However, there are limited number of studies that investigated the sensitivity and trends of the PMED software predicted distresses to changes in HMA mix properties, specifically the density, AV, VMA, and AC content. This study assessed the sensitivity and impact of various HMA mix parameters on the predicted distresses using the latest version (v3.0) of the PMED software. The objective of this paper is to present the details of the completed trial results, analysis and findings.

The design trials conducted in this study specifically examined the trends of predicted distresses for varied climatic conditions across Canada, HMA density (% compaction) for a given AC content, and the VMA and AC content in a HMA for a given AV.

The information presented in this paper may help different agencies and other interested individuals in assessing the suitability of the current version of the PMED software for flexible pavement design.

Software Versions and Trial Inputs

All participants utilized the PMED software version 3.0 with the global calibration coefficients for the design trials. The general design inputs were summarized in Table 1. The varied design inputs for different trial sets can be found in other sections in this paper.

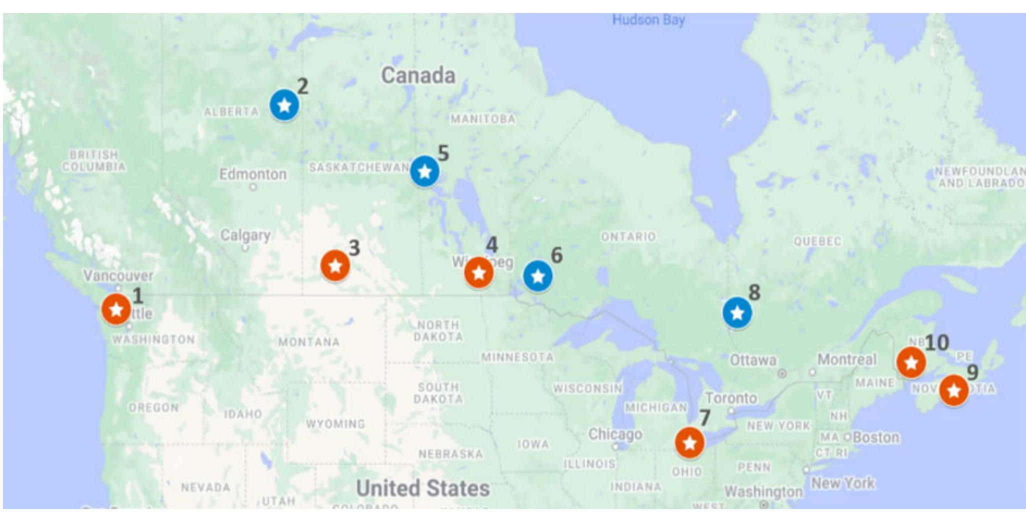
Table 1. General design inputs for design trials

Item		Value Used
Climate Data		MERRA-2 from various climate stations across Canada
HMA Properties		Varying HMA density, AV, AC content, and VMA. All other input parameters remained unchanged in all design trials
Truck Traffic		Two-way 2,500 trucks/day (1,000 trucks/day on the design lane of a four-lane divided highway) and 2% annual growth rate
Design Life		20 years
Initial IRI		0.9 m/km
Design Reliability		90%
Vehicle Class Distribution and Axle Load Spectra		Manitoba Level 1
Pavement Structures	Surface	150 mm of 12.5 mm SuperPave (SP12.5) asphalt concrete with a PG 58-34 asphalt binder (Manitoba Level 3)
	Base	200 mm of Manitoba granular base material (GBC-I) with resilient modulus (Mr) value of 225 MPa (annual representative value)
	Subbase	300 mm of Manitoba granular subbase material (CR-M50) with resilient modulus (Mr) value of 200 MPa (annual representative value)
Subgrade		High plastic clay (AASHTO A-7-6) with a resilient modulus (Mr) value of 35.0 MPa (annual representative value)

Selected Climate Stations

MERRA-2 climate data from 10 climate stations across Canada with varying weather patterns were selected for these design trials. Figure 1 shows the geographic location of the climate stations.

Figure 1. Geographic location of climate stations across Canada



The red dots indicate relatively warmer while the blue dots indicate relatively colder climates in Canadian context. Table 2 presents the list of climate stations and the summary of the key climate parameters. It should be noted here that some of the climatic parameters in the MERRA-2 climate database seem to be unreasonable and do not match with practical observations, especially the frost depths and annual number of wet days.

Table 2. List of climate stations and summary of key climatic parameters over the design life

No.	City/Town, Province (Climate Station)	Mean Annual Air (Min./Max.) Temperature (°C)	Mean Annual Precipitation (mm)	Mean Annual Freezing Index (°C-days) (Frost Depth) (m)	Mean Annual No. of Freeze-Thaw Cycles	Number of Wet Days
1	Victoria, BC (153883)	10.9 (-15.4/29.4)	1502.1	10.8 (0.46)	7.2	332.3
2	Fort McMurray, AB (163119)	0.24 (-47.1/36.9)	629.7	2081.2 (4.40)	66.5	336.7
3	Swift Current, SK (155636)	4.9 (-42.1/37.9)	451.1	998.9 (2.03)	108.6	273.8
4	Winnipeg, MB (155653)	3.47 (-45.9/38.3)	604.5	1754.2 (3.26)	67.6	302.3
5	The Pas, MB (160255)	0.53 (-48.1/37.9)	589.5	2356.7 (7.37)	58.9	328.9
6	Waldhof, ON (156811)	1.3 (-48.9/33.6)	857.5	2130.7 (4.32)	56.8	335.4
7	Wheatly, ON (146461)	9.6 (-21.7/31.6)	1092.4	300.7 (2.04)	52.0	303.7
8	Rouyn, QC (153379)	2.01 (-45.7/31.1)	1226.1	1794.0 (2.74)	67.3	350.3
9	Halifax, NS (149371)	7.3 (-20.1/27.1)	1647.2	315.1 (1.12)	70.0	339.8
10	Fredericton, NB (151094)	5.0 (-36.2/31.8)	1389.4	1027.6 (1.55)	81.2	344.5
Note: The depth to water table was 3.0 m for all climate stations						

Design Trial Matrix

Considering the impacts and importance of the HMA input parameters as stated earlier, design trials were conducted in this study by changing some key HMA input parameters including AV/density (% compaction), VMA, and AC content for each of the selected climate stations. The outcomes of these design trials were then used to assess the impact of the selected input parameters of HMA on the predicted distresses in different climatic conditions. The suitability of the PMED software in predicting the pavement performance and surface distresses as practically expected or experienced was also assessed. The design trials were grouped into two sets:

- Trial Set #1: Varied HMA density (% compaction) that also affected the AV and VMA for a given AC content in nine climatic areas.
- Trial Set #2: Varied VMA and AC content for a given AV in an HMA in 10 climatic areas.

Trial Set # 1 consisted of eight different design runs for each climate station, while Trial Set #2 comprised of five different design runs for each climate station as listed in Table 2. The matrices of varying input parameters of each design trial set are presented in Table 3 and Table 4. To understand the true impacts of selected varied input parameters for the HMA layer, the physical and thermal properties of base, subbase and subgrade materials remained unchanged, and their resilient moduli were fixed to annual representative values for all design runs regardless of variation of climatic and HMA layer inputs. Aggregate gradation for the HMA also remained unchanged in all design runs and climate stations.

Table 3. Trial Set #1: Matrix of varying HMA density, AV and VMA

Design No.	Theoretical Maximum Specific Gravity	Compaction (%)	Density (kg/m^3)	AC Content by Weight of Mix (%)	VMA (%)	AV (%)	Effective AC Content by Volume (%)
1	2.444	97.0	2370	4.8	13.8	3.0	10.8
2	2.444	96.0	2346	4.8	14.6	4.0	10.6
3	2.444	95.0	2322	4.8	15.5	5.0	10.5
4	2.444	94.0	2297	4.8	16.4	6.0	10.4
5	2.444	93.0	2273	4.8	17.3	7.0	10.3
6	2.444	92.0	2248	4.8	18.2	8.0	10.2
7	2.444	91.0	2224	4.8	19.1	9.0	10.1
8	2.444	90.0	2200	4.8	20.0	10.0	10.0

Table 4. Trial Set # 2: Matrix of varying VMA and AC content in HMA

Design No.	Theoretical Maximum Specific Gravity	Compaction (%)	Density (kg/m^3)	AC Content by Weight of Mix (%)	VMA (%)	AV (%)	Effective AC Content by Volume (%)
1	2.497	93.0	2322	4.5	13.0	7.0	6.0
2	2.486	93.0	2312	4.8	14.0	7.0	7.0
3	2.475	93.0	2302	5.1	15.0	7.0	8.0
4	2.464	93.0	2291	5.4	16.0	7.0	9.0
5	2.453	93.0	2281	5.7	17.0	7.0	10.0

Results and Discussion

Tables 5a and 5b present the results of Trial Set #1 for varied density (% compaction) that affected the AV and VMA in the compacted HMA, without changing the theoretical maximum density and AC content. Table 6 presents the results of Trial Set #2 for varied VMA and AC content in the compacted HMA that affected the theorical maximum density, effective AC content, and field density values, without affecting the AV (% compaction). A detailed analysis and discussion are presented in the following sections using graphical trends of the predicted distresses. Only the trends of predicted distresses for representative number of climate stations, from the pool of up to ten climate stations that are used in these two studies, are presented in some figures for an ease of understanding and tracking the changes in trends and the impacts of varied input parameters. These representative climate stations were selected to demonstrate the widespread variation of predicted distresses in differing climatic conditions.

Table 5a. Summary of predicted distresses for Trial Set #1: Impacts of HMA density (BC, AB, SK, MB-Winnipeg)

Project Location	Design No.	Trial Designation	IRI (m/km)	Total Rutting (mm)	HMA Rutting (mm)	BUFC (%)	TC (m/km)	TDFC (%)
Victoria, BC	1	97%Comp._3%AV_13.8%VMA	2.20	9.46	3.56	1.45	40.97	11.32
	2	96%Comp._4%AV_14.6%VMA	2.21	9.61	3.70	1.46	40.97	11.28
	3	95%Comp._5%AV_15.5%VMA	2.21	9.81	3.88	1.51	40.97	10.74
	4	94% Comp._6% AV_16.4% VMA	2.21	10.09	4.14	1.78	40.97	9.12
	5	93% Comp._7% AV_17.3% VMA	2.20	10.41	4.44	4.10	40.97	6.43
	6	92% Comp._8% AV_18.2% VMA	2.23	10.81	4.81	16.63	40.97	4.84
	7	91% Comp._9% AV_19.1% VMA	2.30	11.23	5.20	27.54	40.97	4.69
	8	90% Comp._10% AV_20.0% VMA	2.43	11.78	5.71	42.08	40.97	4.69
Fort McMurray, AB	1	97%Comp._3%AV_13.8%VMA	2.44	14.23	8.20	1.46	40.97	14.17
	2	96%Comp._4%AV_14.6%VMA	2.44	14.52	8.48	1.50	40.97	14.17
	3	95%Comp._5%AV_15.5%VMA	2.46	14.98	8.92	1.72	40.97	14.31
	4	94% Comp._6% AV_16.4% VMA	2.48	15.56	9.47	3.67	40.97	5.16
	5	93% Comp._7% AV_17.3% VMA	2.50	16.27	10.16	15.70	40.97	16.93
	6	92% Comp._8% AV_18.2% VMA	2.53	17.12	10.98	26.75	40.97	17.87
	7	91% Comp._9% AV_19.1% VMA	2.66	18.10	11.93	40.18	40.98	16.57
	8	90% Comp._10% AV_20.0% VMA	2.91	19.26	13.05	61.01	134.54	16.54
Swift Current, SK	1	97%Comp._3%AV_13.8%VMA	2.26	8.78	2.90	1.45	40.97	14.13
	2	96%Comp._4%AV_14.6%VMA	2.26	8.89	3.00	1.46	40.97	14.13
	3	95%Comp._5%AV_15.5%VMA	2.27	9.06	3.15	1.49	40.98	14.32
	4	94% Comp._6% AV_16.4% VMA	2.28	9.28	3.35	1.62	40.99	15.22
	5	93% Comp._7% AV_17.3% VMA	2.29	9.55	3.58	2.53	41.02	16.74
	6	92% Comp._8% AV_18.2% VMA	2.31	9.86	3.87	10.35	42.16	17.52
	7	91% Comp._9% AV_19.1% VMA	2.31	10.23	4.20	23.07	44.31	15.76
	8	90% Comp._10% AV_20.0% VMA	2.40	10.66	4.60	34.22	52.70	15.70
Winnipeg, MB	1	97%Comp._3%AV_13.8%VMA	2.30	9.26	3.34	1.45	40.97	14.13
	2	96%Comp._4%AV_14.6%VMA	2.31	9.38	3.45	1.46	40.98	14.13
	3	95%Comp._5%AV_15.5%VMA	2.31	9.58	3.63	1.51	41.09	14.31
	4	94% Comp._6% AV_16.4% VMA	2.32	9.82	3.85	1.73	41.66	15.20
	5	93% Comp._7% AV_17.3% VMA	2.34	10.13	4.13	3.58	42.64	16.88
	6	92% Comp._8% AV_18.2% VMA	2.36	10.49	4.46	15.11	56.75	17.48
	7	91% Comp._9% AV_19.1% VMA	2.39	10.90	4.84	26.23	82.71	15.66
	8	90% Comp._10% AV_20.0% VMA	2.56	11.38	5.29	39.37	169.04	15.60

IRI = International roughness index, BUFC = bottom-up fatigue cracking, TC = transverse cracking, TDFC = top-down fatigue cracking

Table 5b. Summary of predicted distresses for Trial Set #1: Impacts of HMA density (MB-The Pas, ON-Wheatley, QC, NB and NS)

Project Location	Design No.	Trial Designation	IRI (m/km)	Total Rutting (mm)	HMA Rutting (mm)	BUFC (%)	TC (m/km)	TDFC (%)
The Pas, MB	1	97%Comp._3%AV_13.8%VMA	2.31	9.44	3.50	1.45	40.97	14.16
	2	96%Comp._4%AV_14.6%VMA	2.32	9.59	3.64	1.46	40.97	14.14
	3	95%Comp._5%AV_15.5%VMA	2.32	9.77	3.80	1.51	40.97	14.36
	4	94% Comp._6% AV_16.4% VMA	2.34	10.04	4.05	1.76	40.97	15.29
	5	93% Comp._7% AV_17.3% VMA	2.35	10.34	4.33	3.83	40.98	17.01
	6	92% Comp._8% AV_18.2% VMA	2.37	10.71	4.67	15.79	41.12	17.70
	7	91% Comp._9% AV_19.1% VMA	2.38	11.12	5.04	26.64	41.68	16.17
	8	90% Comp._10% AV_20.0% VMA	2.56	11.61	5.50	40.18	148.76	16.13
Wheatley, ON	1	97%Comp._3%AV_13.8%VMA	2.28	9.27	3.37	1.45	40.97	13.72
	2	96%Comp._4%AV_14.6%VMA	2.28	9.42	3.51	1.46	40.97	13.72
	3	95%Comp._5%AV_15.5%VMA	2.29	9.61	3.68	1.51	40.97	13.73
	4	94% Comp._6% AV_16.4% VMA	2.30	9.84	3.88	1.76	40.97	14.26
	5	93% Comp._7% AV_17.3% VMA	2.31	10.12	4.14	3.83	40.97	14.88
	6	92% Comp._8% AV_18.2% VMA	2.31	10.48	4.47	15.97	40.97	12.88
	7	91% Comp._9% AV_19.1% VMA	2.35	10.87	4.83	26.87	40.97	8.99
	8	90% Comp._10% AV_20.0% VMA	2.47	11.32	5.24	40.68	40.97	8.86
Rouyn, QC	1	97%Comp._3%AV_13.8%VMA	2.50	15.62	9.59	1.46	40.97	14.14
	2	96%Comp._4%AV_14.6%VMA	2.51	15.96	9.91	1.51	40.97	14.14
	3	95%Comp._5%AV_15.5%VMA	2.53	16.49	10.43	1.76	40.97	14.28
	4	94% Comp._6% AV_16.4% VMA	2.55	17.17	11.08	4.16	40.97	15.10
	5	93% Comp._7% AV_17.3% VMA	2.58	18.00	11.88	17.08	40.97	16.77
	6	92% Comp._8% AV_18.2% VMA	2.62	18.99	12.84	27.87	40.99	17.58
	7	91% Comp._9% AV_19.1% VMA	2.76	20.16	13.97	42.18	41.02	15.89
	8	90% Comp._10% AV_20.0% VMA	2.95	21.50	15.28	63.21	41.52	15.83
Fredericton, NB	1	97%Comp._3%AV_13.8%VMA	2.51	16.25	10.19	1.46	40.97	14.07
	2	96%Comp._4%AV_14.6%VMA	2.52	16.59	10.52	1.53	40.97	14.07
	3	95%Comp._5%AV_15.5%VMA	2.53	17.16	11.06	1.93	40.97	14.14
	4	94% Comp._6% AV_16.4% VMA	2.56	17.83	11.71	6.18	40.97	14.95
	5	93% Comp._7% AV_17.3% VMA	2.58	18.64	12.50	20.27	40.97	16.46
	6	92% Comp._8% AV_18.2% VMA	2.65	19.67	13.49	31.05	40.97	16.99
	7	91% Comp._9% AV_19.1% VMA	2.81	20.85	14.63	47.70	40.97	14.58
	8	90% Comp._10% AV_20.0% VMA	3.01	22.14	15.89	70.11	40.97	14.50
Halifax, NS	1	97%Comp._3%AV_13.8%VMA	2.34	10.13	2.60	1.45	40.97	13.85
	2	96%Comp._4%AV_14.6%VMA	2.35	10.24	2.68	1.46	40.97	14.54
	3	95%Comp._5%AV_15.5%VMA	2.36	10.40	2.82	1.49	40.97	15.64
	4	94% Comp._6% AV_16.4% VMA	2.34	10.60	3.00	1.65	40.97	11.12
	5	93% Comp._7% AV_17.3% VMA	2.34	10.85	3.22	2.82	40.97	11.00
	6	92% Comp._8% AV_18.2% VMA	2.35	11.15	3.48	12.03	40.97	10.88
	7	91% Comp._9% AV_19.1% VMA	2.39	11.49	3.79	24.35	40.97	10.75
	8	90% Comp._10% AV_20.0% VMA	2.49	11.89	4.15	36.55	40.97	10.62

IRI = International roughness index, BUFC = bottom-up fatigue cracking, TC = transverse cracking, TDFC = top-down fatigue cracking

Table 6. Summary of predicted distresses for Trial Set #2: Impacts of VMA and AC content

Project Location	Design No.	Trial Designation	IRI (m/km)	Total Rutting (mm)	HMA Rutting (mm)	BUFC (%)	TC (m/km)	TDFC (%)
Victoria, BC	1	VMA 13.0%-AC 4.5%-Eff. AC 6%	2.33	9.26	3.39	38.67	40.97	8.56
	2	VMA 14.0%-AC 4.8%-Eff. AC 7%	2.25	9.58	3.68	27.02	40.97	8.64
	3	VMA 15.0%-AC 5.1%-Eff. AC 8%	2.21	9.83	3.90	19.74	40.97	8.68
	4	VMA 16.0%-AC 5.4%-Eff. AC 9%	2.21	10.08	4.14	11.23	40.97	8.72
	5	VMA 17.0%-AC 5.7%-Eff. AC	2.21	10.33	4.36	5.07	40.97	8.84
Fort McMurray, AB	1	VMA 13.0%-AC 4.5%-Eff. AC 6%	2.95	14.06	8.05	71.81	284.16	15.99
	2	VMA 14.0%-AC 4.8%-Eff. AC 7%	2.63	14.75	8.71	47.40	41.35	15.77
	3	VMA 15.0%-AC 5.1%-Eff. AC 8%	2.53	15.38	9.32	32.69	41.02	15.61
	4	VMA 16.0%-AC 5.4%-Eff. AC 9%	2.49	15.96	9.87	24.61	40.98	15.36
	5	VMA 17.0%-AC 5.7%-Eff. AC	2.50	16.53	10.41	18.22	40.97	15.20
Swift Current, SK	1	VMA 13.0%-AC 4.5%-Eff. AC 6%	2.43	8.77	2.91	32.69	212.07	16.04
	2	VMA 14.0%-AC 4.8%-Eff. AC 7%	2.29	9.04	3.15	23.35	67.50	15.80
	3	VMA 15.0%-AC 5.1%-Eff. AC 8%	2.28	9.28	3.37	15.11	49.14	15.61
	4	VMA 16.0%-AC 5.4%-Eff. AC 9%	2.28	9.51	3.57	6.82	42.84	15.45
	5	VMA 17.0%-AC 5.7%-Eff. AC	2.29	9.73	3.77	3.22	41.44	15.26
Winnipeg, MB	1	VMA 13.0%-AC 4.5%-Eff. AC 6%	2.66	9.04	3.15	36.95	462.85	16.08
	2	VMA 14.0%-AC 4.8%-Eff. AC 7%	2.41	9.33	3.41	25.96	181.65	15.83
	3	VMA 15.0%-AC 5.1%-Eff. AC 8%	2.35	9.60	3.65	18.59	90.38	15.64
	4	VMA 16.0%-AC 5.4%-Eff. AC 9%	2.33	9.84	3.87	9.91	51.79	15.50
	5	VMA 17.0%-AC 5.7%-Eff. AC	2.33	10.07	4.07	4.41	44.12	15.29
The Pas, MB	1	VMA 13.0%-AC 4.5%-Eff. AC 6%	2.61	9.23	3.32	38.06	353.22	16.16
	2	VMA 14.0%-AC 4.8%-Eff. AC 7%	2.40	9.52	3.58	26.54	148.49	15.99
	3	VMA 15.0%-AC 5.1%-Eff. AC 8%	2.33	9.80	3.84	19.26	41.82	15.77
	4	VMA 16.0%-AC 5.4%-Eff. AC 9%	2.34	10.05	4.06	10.59	41.03	15.57
	5	VMA 17.0%-AC 5.7%-Eff. AC	2.34	10.27	4.26	4.72	40.98	15.39
Wheatley, ON	1	VMA 13.0%-AC 4.5%-Eff. AC 6%	2.39	9.09	3.22	38.06	40.97	14.80
	2	VMA 14.0%-AC 4.8%-Eff. AC 7%	2.30	9.35	3.45	26.51	40.97	14.67
	3	VMA 15.0%-AC 5.1%-Eff. AC 8%	2.29	9.62	3.69	19.26	40.97	14.54
	4	VMA 16.0%-AC 5.4%-Eff. AC 9%	2.30	9.85	3.89	10.59	40.97	14.42
	5	VMA 17.0%-AC 5.7%-Eff. AC	2.30	10.09	4.11	4.78	40.97	14.32
Waldof, ON	1	VMA 13.0%-AC 4.5%-Eff. AC 6%	2.71	10.42	4.50	48.20	303.89	16.13
	2	VMA 14.0%-AC 4.8%-Eff. AC 7%	2.50	10.82	4.86	32.18	148.21	15.89
	3	VMA 15.0%-AC 5.1%-Eff. AC 8%	2.38	11.17	5.19	23.86	41.90	15.69
	4	VMA 16.0%-AC 5.4%-Eff. AC 9%	2.39	11.50	5.50	16.79	41.03	15.50
	5	VMA 17.0%-AC 5.7%-Eff. AC	2.40	11.83	5.81	8.70	40.99	15.30
Rouyn, QC	1	VMA 13.0%-AC 4.5%-Eff. AC 6%	2.89	15.05	9.05	74.21	46.53	16.04
	2	VMA 14.0%-AC 4.8%-Eff. AC 7%	2.71	15.83	9.80	49.60	41.51	15.80
	3	VMA 15.0%-AC 5.1%-Eff. AC 8%	2.60	16.53	10.46	33.82	41.03	15.63
	4	VMA 16.0%-AC 5.4%-Eff. AC 9%	2.56	17.19	11.11	25.40	40.98	15.36
	5	VMA 17.0%-AC 5.7%-Eff. AC	2.56	17.82	11.70	19.19	40.97	15.20
Fredericton, NB	1	VMA 13.0%-AC 4.5%-Eff. AC 6%	2.94	15.58	9.55	81.41	40.97	15.86
	2	VMA 14.0%-AC 4.8%-Eff. AC 7%	2.77	16.37	10.31	56.30	40.97	15.64
	3	VMA 15.0%-AC 5.1%-Eff. AC 8%	2.64	17.04	10.95	38.26	40.97	15.47
	4	VMA 16.0%-AC 5.4%-Eff. AC 9%	2.58	17.75	11.63	28.20	40.97	15.26
	5	VMA 17.0%-AC 5.7%-Eff. AC	2.57	18.36	12.22	22.00	40.97	15.07
Halifax, NS	1	VMA 13.0%-AC 4.5%-Eff. AC 6%	2.41	9.95	2.45	32.49	40.97	15.16
	2	VMA 14.0%-AC 4.8%-Eff. AC 7%	2.36	10.19	2.64	23.31	40.97	15.03
	3	VMA 15.0%-AC 5.1%-Eff. AC 8%	2.36	10.40	2.83	15.21	40.97	14.83
	4	VMA 16.0%-AC 5.4%-Eff. AC 9%	2.36	10.61	3.00	6.99	40.97	14.69
	5	VMA 17.0%-AC 5.7%-Eff. AC	2.36	10.79	3.16	3.27	40.97	14.54

IRI = International roughness index, BUFC = bottom-up fatigue cracking, TC = transverse cracking, TDFC = top-down fatigue cracking

Trial Set # 1: Effect of Varied HMA Density and VMA

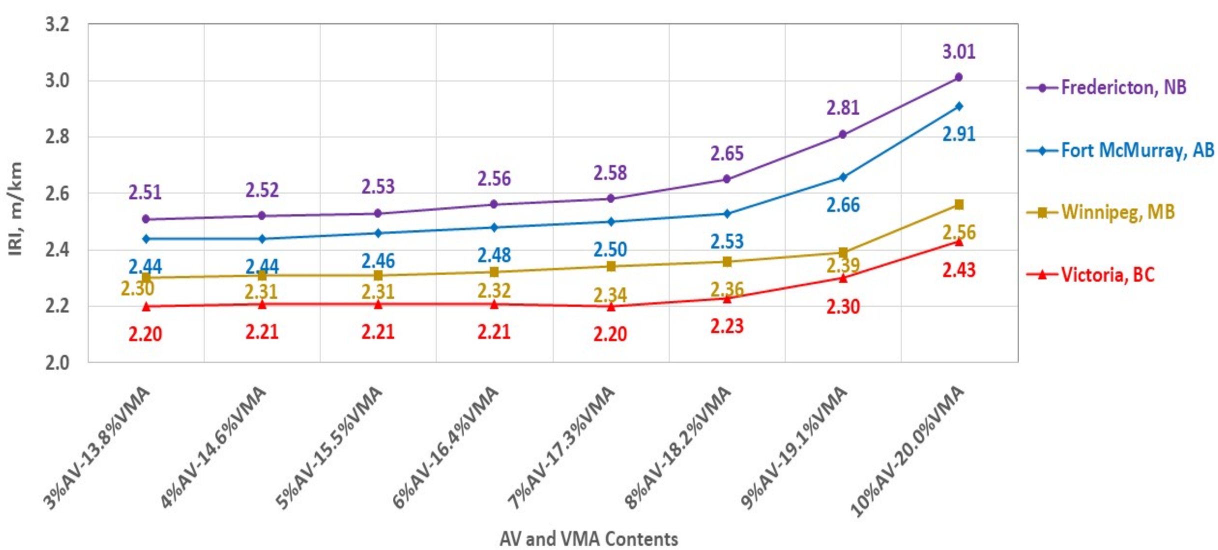
The trends of the predicted distresses for changes in AV/density (% compaction) and VMA without changing AC content are presented in Figures 2 to 7 below.

Impact on Predicted IRI

As shown in Figure 2, a reduction in HMA compaction, which causes an increase in the AV and VMA, results in an increase in the predicted IRI in each climatic area. The increase in IRI with increased AV and VMA is more noticeable when the AV exceed 7%. Such trends seem to be reasonable because a HMA with poor compaction (low density) experiences higher distresses such as cracking and rutting, which may translate into increased road surface roughness.

When the predicted IRI values are compared among the selected climatic areas included this study, Fort McMurray and Winnipeg with cold winter (winter temperature ≤-40 °C and freezing index ≥1,600 deg. C-day), high summer temperature (>35 °C) and low precipitation (≤700 mm) are shown to produce higher IRI values than Victoria with warm winter weather (winter temperature >-30 °C and a negligible freezing index of 10.8 deg. C-day), low summer temperature (≤30 °C) and high precipitation (>1,200 mm). These trends seem to be reasonable because a high freezing index value, high amount rutting and high amount cracking (which are input parameters in the IRI prediction model) may yield a high IRI value. However, Fredericton with moderate winter weather (winter temperature between -30 to -39 °C and freezing index between 800 to <1,600 deg. C-day), moderate summer temperature (>30 to 35 °C) and high precipitation (>1,200 mm) is shown to provide the highest IRI value. Further investigation is required to understand such complex effect of different input parameters on the predicted IRI and its accuracy in terms of actual field performance.

Figure 2. Effect of AV and VMA in HMA on predicted IRI

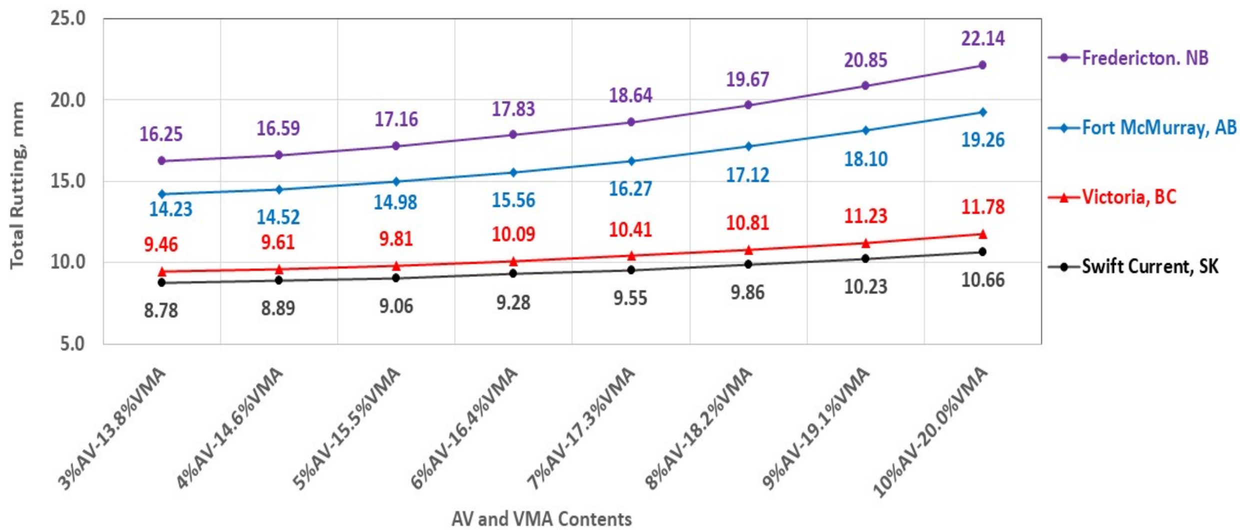


Impact on Predicted Total Rutting

Figure 3 shows that a reduction in HMA compaction (an increase in the AV and VMA) results in a gradual increase in the predicted total rutting (permanent deformation) in each climatic area, which is reasonable.

However, when the predicted total rutting values are compared among climatic areas, Fredericton with moderate summer temperature and high amount of precipitation provided the highest amount of rutting, while Swift Current with high summer temperature and low amount of precipitation provided the lowest rutting value. Alternatively, Victoria with high amount of precipitation and low summer temperature provided lower rutting than Fredericton. Given that the properties of base, subbase and subgrade remained unchanged, the reason(s) for such trends of the predicted total rutting among climatic areas could not be explained based on the available data.

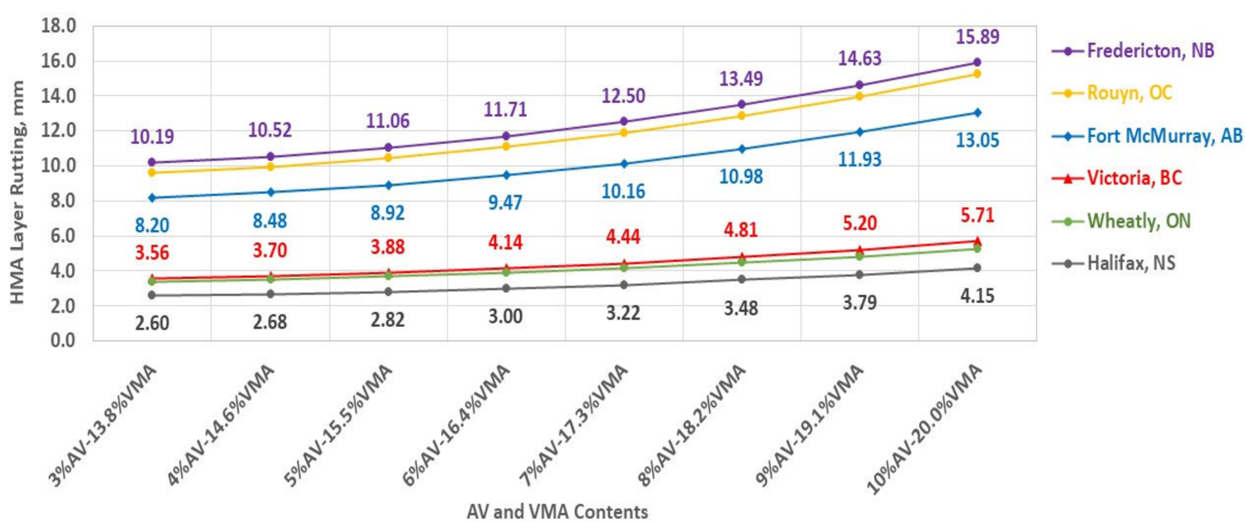
Figure 3. Effect of AV and VMA in HMA on predicted total rutting



Impact on Predicted HMA Layer Rutting

The trends of the predicted HMA layer rutting for the variations of HMA mat density (% compaction) are shown in Figure 4. As shown in the figure, the predicted HMA layer rutting follows similar trends as the total rutting for the reduction in HMA compaction (increase in the AV and VMA) in each climatic area, which is reasonable.

Figure 4. Effect of AV and VMA in HMA on predicted HMA layer rutting

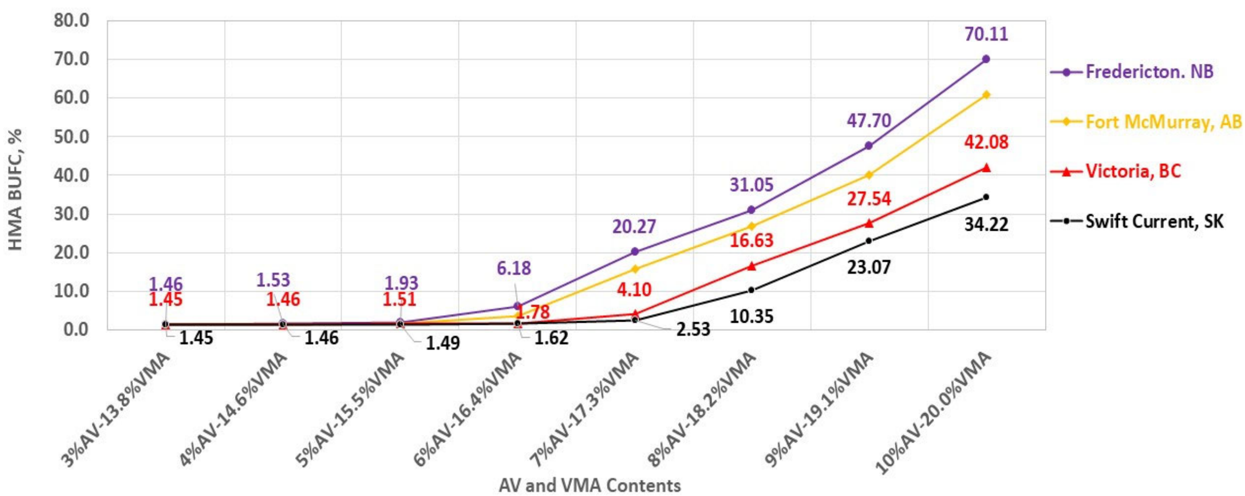


When the predicted HMA layer rutting values are compared among climatic areas, Fredericton (with moderate summer temperature and high amount of precipitation) provided the highest HMA layer rutting as in the case of total rutting. However, the lowest value of HMA layer rutting is observed for Halifax with low summer temperature and the highest amount of precipitation, which is different from the lowest amount of total rutting observed in Swift Current. As in the case of total rutting, the reason(s) for such trends of the predicted HMA layer rutting among climatic areas could not be explained based on the available data.

Impact on Predicted HMA BUFC

Figure 5 shows the trends of the predicted HMA BUFC for the variations of HMA mat AV and VMA. As shown in the figure, the predicted BUFC increases slightly for an increase in the AV up to 5% in each climatic area. The predicted BUFC increases dramatically for an increase in AV exceeding 6% i.e., when the HMA compaction is less than 94% of the theoretical maximum density. However, the figure shows that climatic condition in Fredericton (moderate winter and summer temperatures) produces significantly higher BUFC (which is the highest among the climate stations) than that in Swift Current (which has the lowest BUFC among the climate stations) with low (cold) winter and high summer temperatures.

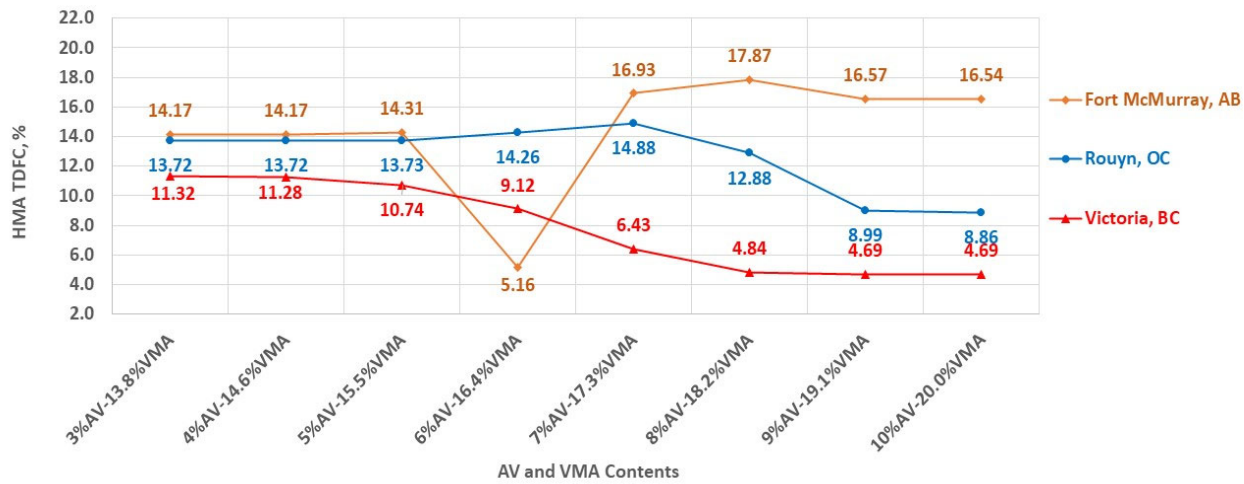
Figure 5. Effect of AV and VMA in HMA on predicted BUFC



Impact on Predicted HMA TDFC

The trends of the predicted HMA TDFC for the variations of HMA mat AV and VMA are shown in Figure 6. As shown in the figure, the predicted TDFC remains unchanged or increases for an increase in the AV up to 5% in Fort McMurray and 7% in Rouyn. The predicted TDFC reduces for an increase in the AV exceeding these values for these example stations. The predicted TDFC reduces for any increase in the AV in Victoria. The trends of the predicted HMA TDFC among AV and climatic areas are inconsistent.

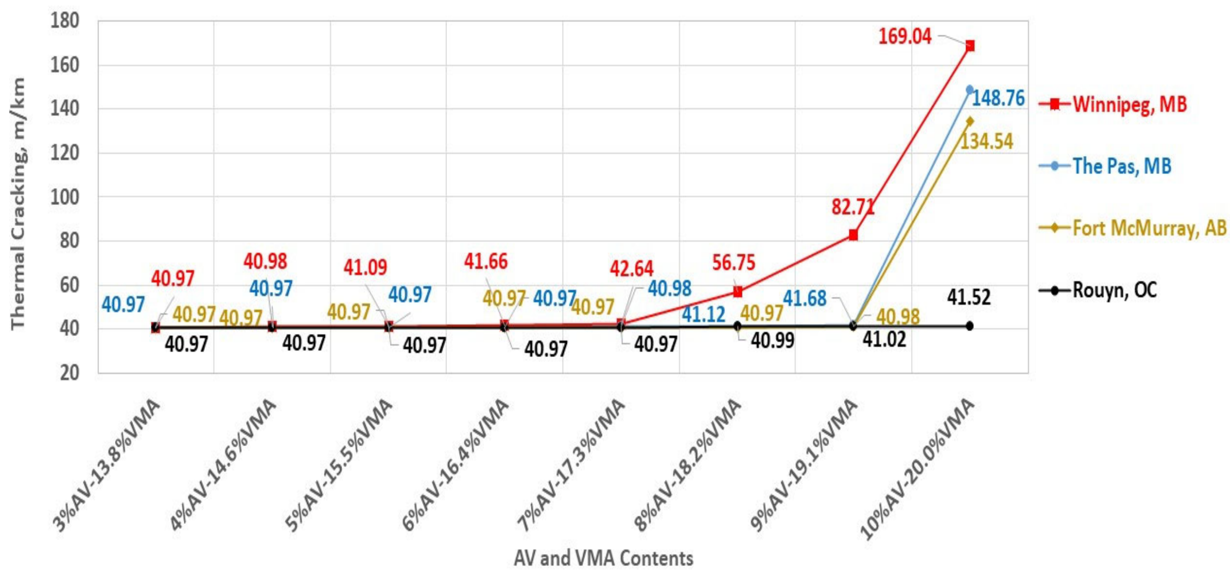
Figure 6. Effect of AV and VMA in HMA on predicted TDFC



Impact on Predicted HMA Thermal Cracking

The trends of the predicted thermal cracking (TC) in HMA layer for the variations of HMA mat AV and VMA are shown in Figure 7. As shown in the figure, there are negligible or no increase in the predicted TC for an increase in the AV up to 7% in some climatic areas (e.g., in Winnipeg) and up to 9% in some climatic areas (e.g., in Fort McMurray and The Pas) while there is no change in the TC in some other climatic areas (e.g., Rouyn) regardless of the AV. An AV exceeding 7% significantly affected the predicted TC in some climatic areas (e.g., in Winnipeg). Colder climatic areas, like The Pas and Fort McMurray, produce less TC as compared to relatively warmer climatic areas (e.g., in Winnipeg). These trends among AV and climatic areas are inconsistent and unexpected as a HMA in colder climates typically experiences more thermal cracking than a warmer climatic area.

Figure 7. Effect of AV and VMA in HMA on predicted thermal cracking



Trial Set # 2: Effect of Varied HMA AC Content and VMA

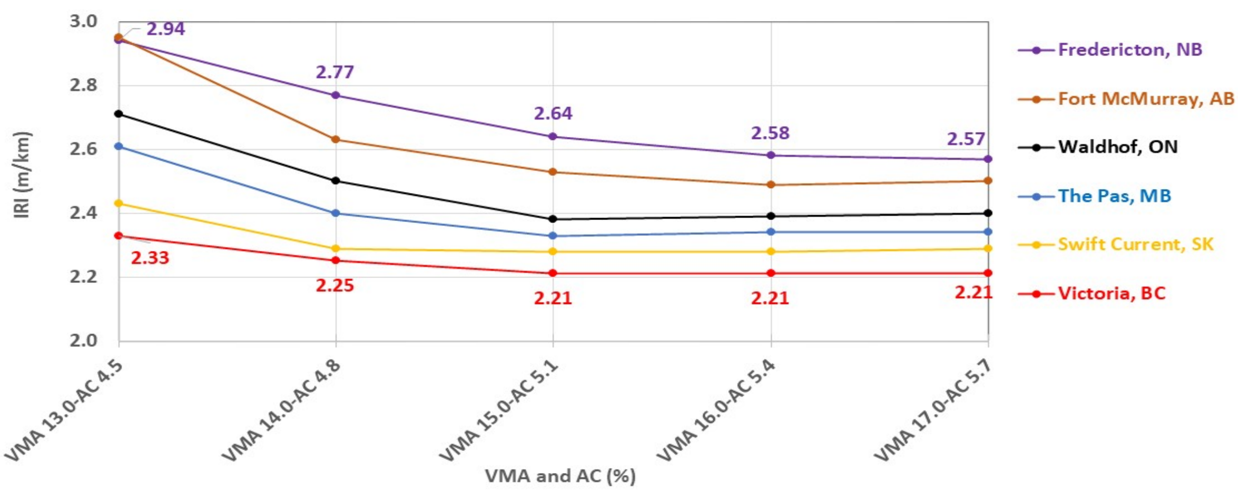
The trends of the PMED software predicted distresses in flexible pavement for varied AC content and VMA with no change in AV (% compaction) are presented in Figures 8 to 13.

Impact on Predicted IRI

The trends of the PMED software predicted IRI for selected climatic areas for the variation of VMA and AC content in HMA, which affect the effective AC content, are shown Figure 9. As shown in the figure, the predicted IRI reduces with an increase in AC content in each climatic area. As shown in the figure, the predicted IRI reduces with an increase in AC content in each climatic area. There is an increase in the amount of rutting in each climatic area (see Figure 8) for an increase in AC content, which should result in an increase in IRI for an increase in AC content. However, an increase in the AC content results in a reduction in the amount of cracking and the reduction in the amount of cracking is more significant than the increase in the amount of rutting. This may justify the trend of reduced IRI with an increase in AC content in each climatic area.

As in the case of Trial Set #1, weather conditions in Fredericton produced the highest and Victoria produced the lowest IRI values. This further emphasizes the need for more extensive investigation into the effect of various inputs on the predicted IRI and accuracy of the IRI prediction model.

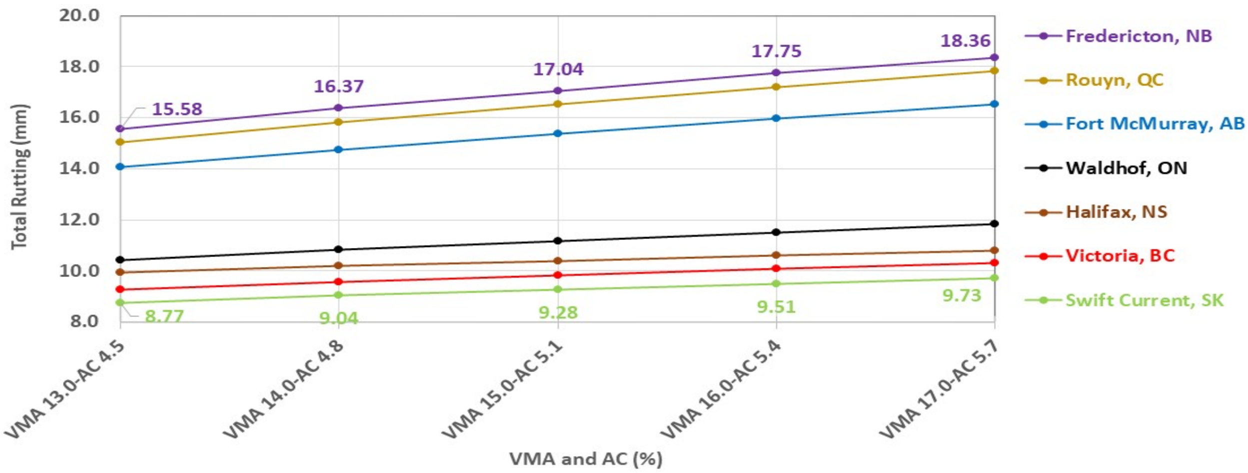
Figure 8. Effect of VMA and AC content in HMA on predicted IRI



Impact on Predicted Total Rutting

Figure 9 shows that the predicted total rutting gradually increases with an increase in VMA and AC content in each climatic area, which is reasonable. As in the case of Trial Set #1, Fredericton with a moderate summer temperature and high precipitation provided the highest amount of rutting, while Swift Current with high summer temperature and low precipitation provided the lowest rutting value. Fort McMurray, with similar summer temperature and low precipitation as Swift Current, provided much higher rutting than that in Swift Current. Alternatively, Victoria and Halifax with high amounts of precipitation and low summer temperatures provided lower rutting than Fredericton. Given that the properties of base, subbase and subgrade remained unchanged, as in the Case of Trial Set #1, the reason(s) for such trends of the predicted total rutting among climatic areas could not be explained based on the available data.

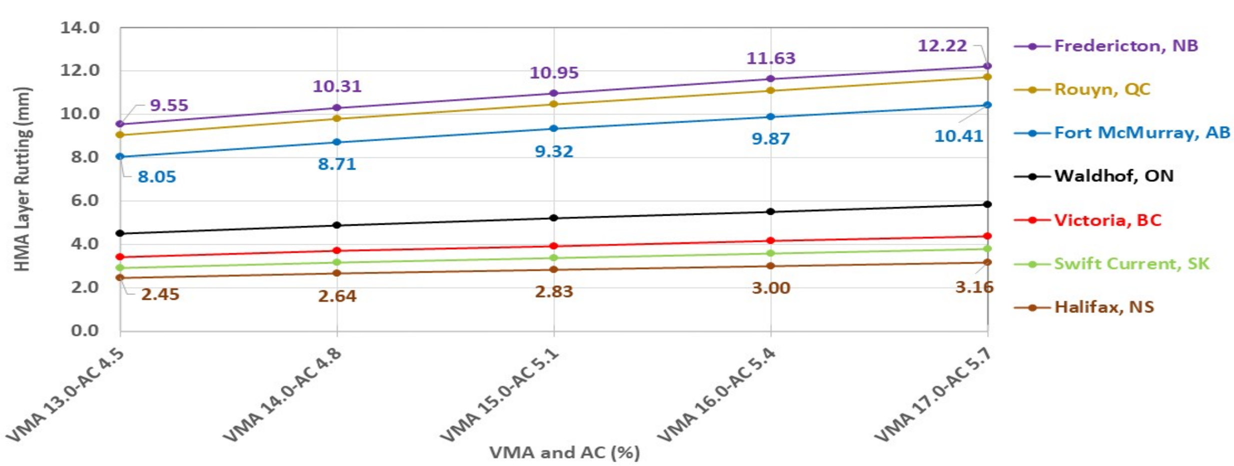
Figure 9. Effect of VMA and AC content in HMA on predicted total rutting



Impact on HMA Layer Rutting

The trends of the predicted HMA rutting for the variations of VMA and AC content are shown in Figure 10. As shown in the figure, the predicted HMA layer rutting follows similar trends as the total rutting for the increase in the AC content in each climatic area, which is reasonable. However, when the predicted HMA layer rutting values are compared among climatic areas, Fredericton (with moderate summer temperature and high amount of precipitation) provided the highest value of HMA layer rutting as in the case of total rutting (also same as Trial Set #1). However, the lowest value of HMA layer rutting is observed for Halifax with low summer temperature and the highest amount of precipitation (same as Trial Set #1). As in the case of total rutting, the reason(s) for such trends of the predicted HMA layer rutting among climatic areas could not be explained based on available data.

Figure 10. Effect of VMA and AC content in HMA on predicted HMA layer rutting

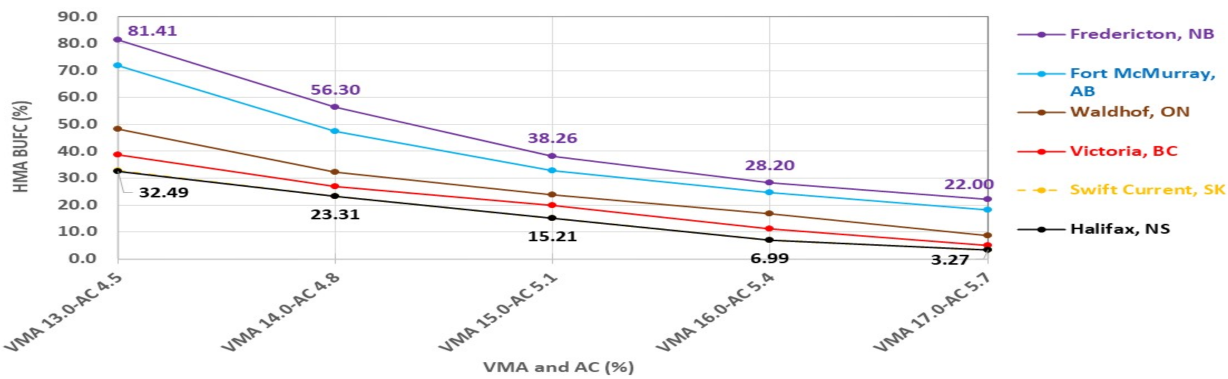


Impact on Predicted HMA BUFC

Figure 11 shows the trends of the predicted HMA BUFC for the variations of VMA and AC content in asphalt mixes. As shown in the figure, the predicted BUFC decreases with an increase in the AC content in each climatic area, which is a reasonable trend. However, the figure shows that climatic condition in

Fredericton (moderate winter and summer temperatures) produces significantly higher BUFC (which is the highest among the climate stations) than that in Halifax with warmer winter and low summer temperatures (which produced the lowest BUFC among the climate stations) and Swift Current with cold winter and hot summer.

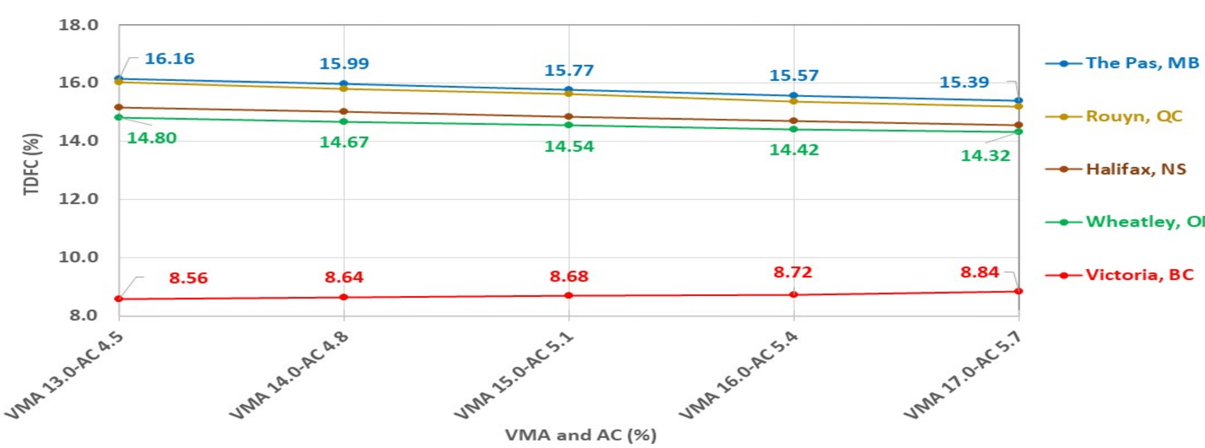
Figure 11. Effect of VMA AC content in HMA on predicted BUFC



Impact on Predicted HMA TDFC

The trends of the predicted HMA TDFC for the variations of VMA and AC content are shown in Figure 12. As shown in the figure, the predicted TDFC increases for an increase in the AC content in Victoria, it reduces for an increase in the AC content in other climatic areas. Such opposing trends among climatic areas are inconsistent. The highest TDFC in The Pas with a low winter and hot summer temperatures while the lowest TDFC in Victoria with low summer and winter temperatures requires further investigation.

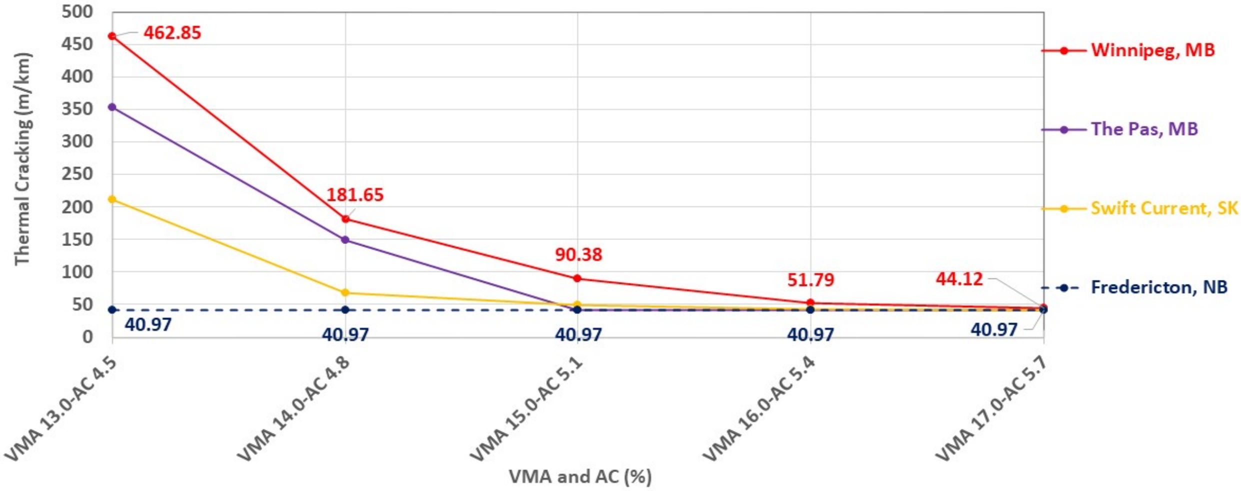
Figure 12. Effect of VMA and AC content in HMA on predicted TDFC



Impact on Predicted HMA Thermal Cracking

The trends of the predicted thermal cracking (TC) in HMA layer for the variations of VMA and AC content are shown in Figure 13. As shown in the figure, there are significant decreases in predicted TC with an increase in AC content in some climatic areas. However, in past studies, the authors did not notice a noticeable effect of AC binder grade on the predicted TC. In this study, HMA AC contents have shown significant impact on the predicted TC in some climatic areas. However, a negligible effect of AC content in other climatic areas like Fredericton do not align with the typical trends as specified above. Colder climatic areas (e.g., The Pas) produce less TC as compared to that in relatively warmer climatic areas (e.g., in Winnipeg). These trends among AC content values and climatic areas are inconsistent and unexpected as a higher amount of TC are observed in colder climates for a given HMA and asphalt binder grade.

Figure 13. Effect of VMA and AC content in HMA on predicted thermal cracking



Statistical Analysis

A multiple regression analysis was conducted to assess the relative impacts and statistical significance of selected variables that are expected to practically affect the predicted distresses. A variable that provided illogical (impractical) impact on a predicted distress or its presence produced an impractical impact of another key variable on that predicted distress was excluded (e.g., the blank cells in Table 7) from the multiple regression analysis for that distress type. The summary of statistical analysis is presented in Table 7. The key observations from this statistical analysis are presented below:

1) Predicted IRI: Precipitation, freezing index, total rutting, total (bottom up plus top down) fatigue cracking and thermal cracking are significant variables. This finding matches with the IRI prediction model. However, the impacts of precipitation and freezing index are minimal or negligible. The total rutting is shown to have higher impact than fatigue and thermal cracking on the predicted IRI value. Since the predicted rutting and cracking are also dependent on these climatic parameters, these climatic parameters may be redundant in the IRI prediction model.
2) Predicted Total and HMA Layer Rutting: Lower winter temperature causes significant increase in rutting, which is unreasonable. The impact of high summer temperature is statistically insignificant. Precipitation has statistically significant impact on the predicted rutting. The number of wet days is statistically significant at >95% confidence level for the total rutting, but it has smaller and less significant (at 93% confidence level) effect of the HMA layer rutting. Increased HMA density results in statistically significant decrease in rutting. The impact of AV content in a HMA on the predicted rutting is logical but not statistically significant. An increased AC content causes large increase in rutting, although statistically significant at 92 to 94% confidence level.
3) Predicted Fatigue Cracking: Low winter temperature causes statistically significant increase in BUFC and TDFC. Alternatively, although not statistically significant at ≥95% confidence level, higher summer temperature causes increase in BUFC and reduction in TDFC. Higher precipitation

causes increase in both BUFC and TDFC, but they are not statistically significant at ≥95% confidence level. The number of wet days causes statistically insignificant increase in BUFC, but statistically significant reduction in TDFC. An increase in HMA density results in a reduction (statistically significant at 90% confidence level) in BUFC, but a statistically significant (at 95% confidence level) increase in TDFC, which is questionable. An increase in HMA density results in a reduction (statistically significant at 90% confidence level) in BUFC, but a statistically significant (at >95% confidence level) increase in TDFC. An increase in AV in a HMA results in a statistically significant (at >95% confidence level) reduction in both BUFC and TDFC. An increase in AC content results in a statistically significant (at >95% confidence level) reduction in BUFC, but the reduction in TDFC is not statistically significant at ≥90% confidence level.

4) Predicted Thermal Cracking: A low winter temperature and high freezing index result in statistically insignificant increase in thermal cracking. An increased HMA density causes statistically significant (at >95% confidence level) increase in thermal cracking. Although not statistically significant at ≥90% confidence level, an increased AV in a HMA causes noticeable increase in thermal cracking. Finally, an increased AC content results in a substantial reduction of thermal cracking, which is statistically significant at >95% confidence level.

Table 7. Summary of statistical analysis

Predicted Distresses	Terminal IRI		Total Rutting, mm		HMA Rutting		BUFC (%)		TDFC (%)		TC (m/km)	
	Coeff.	*P-value*	*Coeff.*	*P-value*	*Coeff.*	*P-value*	*Coeff.*	*P-value*	*Coeff.*	*P-value*	*Coeff.*	*P-value*
Intercept	1.82215	0.00000										
Min. Air Temp. (oC)			-0.24835	0.00000	-0.24125	0.00000	-0.37279	0.04100	-0.25788	0.00000	-0.15072	0.90426
Max. Air Temp. (oC)			0.22240	0.31588	0.35199	0.14528	1.49588	0.17080	-0.27394	0.19702		
Precipitation (mm)	0.00005	0.00808	0.00842	0.00044	0.00876	0.00075	0.02175	0.05984	0.00180	0.42014		
Freezing Index (oC-days)	0.00004	0.00022									0.01631	0.39532
# of Wet Days			0.03056	0.05828	0.03130	0.07417	0.09466	0.23062	-0.05033	0.00131		
HMA Density (kg/m^3)			-0.01190	0.00148	-0.01592	0.00011	-0.02968	0.10132	0.01214	0.00073	0.08443	0.00001
HMA AV (%)			0.20575	0.13402	0.07337	0.62160	4.68057	0.00000	0.25901	0.04933	2.82421	0.27392
Eff. Binder, %			0.35750	0.00899	0.27590	0.06174	-6.44446	0.00000	-0.11143	0.38813	-18.95253	0.00000
Total Rutting, mm	0.02809	0.00000										
Total Fatigue Cracking	0.00423	0.00000										
Thermal Cracking	0.00058	0.00000										

Green: Logical or statistically significant impact at ≥95% confidence level; Blue: Logical impact and statistically significant at ≥90% to <95% confidence levels; Brown: Logical impact, but not statistically significant at ≥90% confidence level; Yellow: Inconsistent or questionable impact; and Red: Illogical trend of the impact.

Conclusions

This study evaluated the effect of AV (HMA density/compaction), VMA, and AC content in HMA on the PMED software predicted distresses in flexible pavement in 10 different climatic areas of Canada. The key findings are summarized below:

1. Reduced density and increased AV in an HMA result in an increase of predicted IRI, total rutting, HMA layer rutting, BUFC and thermal cracking, and an inconsistent variation of TDFC.
2. Increased VMA and AC content result in a reduction of predicted IRI, BUFC and TC, a reduction of predicted TDFC with some inconsistencies, and an increase of total and HMA layer rutting.

3. In general, the predicted distresses were shown to be very sensitive to changes in HMA density, air voids and AC content.
4. An increased AC content was shown to be more helpful in reducing the thermal cracking than a reduced AV and asphalt binder performance grade.
5. The impact of climatic condition on predicted distresses did not seem to align well with the expected or experienced performance of pavements in some cases. More investigation is required to determine the consistency of the impact of climatic condition on PMED software predicted distresses because climatic conditions have a considerable practical impact on pavement performance.
6. The climatic variables (namely, freezing index and precipitation) in the IRI prediction model seem to be redundant.

The results and analyses of this study can be a useful reference to agencies and consultants that may consider using PMED software in flexible pavement designs, validating the predicted distresses or calibrating the models.

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