Tracking GHG Emissions Across the Life Cycle of Asphalt Pavements under Climate Change Considering Quasi-Level 1 Inputs for PMED

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Abstract

As climate change intensifies, developing sustainable and resilient asphalt pavements is crucial to enhance infrastructure durability while reducing their carbon footprint. This study evaluated two asphalt mixes using AASHTOWare Pavement ME Design under future climate scenarios: a standard mix with an unmodified binder and a mix with a polymer-modified binder (PMB). Dynamic modulus testing provided Level-1 mechanical property inputs, offering insights into each mix's performance under variations in temperature and frequency. Additionally, life cycle assessments (LCA) were conducted, incorporating maintenance activities to estimate the long-term greenhouse gas (GHG) emissions associated with each pavement design. Although the PMB mix exhibited higher initial embodied carbon, based on Environmental Product Declarations (EPDs), its enhanced mechanical properties translated into improved predicted performance under future climate conditions, extending pavement service life and reducing annualized GHG emissions. This case study, conducted for an urban pavement setting, demonstrates a comprehensive methodology for evaluating new materials in asphalt pavements. The findings underscore the value of combining advanced material testing, performance simulation and LCA to assess the sustainability and climate resilience of innovative materials for infrastructure solutions.

Introduction

With the ongoing rise in global temperatures due to climate change, Canadian cities are witnessing shifts in weather patterns that may directly affect infrastructure[1,2]. One key element potentially impacted by these changes is the performance of asphalt pavements, which are particularly sensitive to temperature fluctuations[3]. As such, conventional asphalt mixes designed to withstand current temperature conditions might not be sufficient under the increasingly extreme temperatures projected by future climate models[4]. According to studies by the National Research Council (NRC) Canada, temperature increases are expected to influence the longevity and maintenance needs of asphalt pavements[5-7].

Traditionally, the Performance Grade (PG) system has been an effective tool in defining asphalt binder formulations, ensuring resistance to rutting in warmer conditions and cracking in colder months. However, with rising temperatures and the frequency of heatwaves that climate projections suggest, these traditional binders may no longer meet required performance standards, leading to potential issues such as premature rutting, cracking, and accelerated surface roughness[8,9]. A potential solution for adapting asphalt pavements to climate change could be the use of Polymer Modified Binders (PMBs)[10-14]. Unlike conventional asphalt binders, PMBs may be designed to endure a broader range of temperatures, potentially minimizing the risk of heat-induced damage. Their enhanced flexibility and durability make them ideal for Canadian regions, where rising temperatures could pose an increasing challenge to road infrastructure. The World Bank's 2022 report highlights the potential of PMBs in mitigating the vulnerability of road networks to climate change[15]. Consequently, the integration of PMBs may be seen as a key adaptation strategy to strengthen road infrastructure resilience[4]. This stance is echoed by the United Nations Economic Commission for Europe[16], which advocates for the widespread use of PMBs, alongside other measures like advanced drainage systems and permeable pavements, to ensure road network sustainability in a changing climate. Additionally, the World Road Association (PIARC) has expressed support for the use of PMBs as an essential technique to counteract the pavement damage caused by rising temperatures and climate variability[17].

A wide range of studies suggests that SBS is one of the most effective polymers for enhancing asphalt binder performance under climate-stressed conditions[8,18-25.] SBS contributes significantly to increasing

both the stiffness and elasticity of asphalt cement, improving its overall resistance to permanent deformation, thermal cracking, and oxidative aging over time. For instance, Kanabar[26] from Queen's University, Canada, conducted an extensive comparative evaluation of various asphalt modifiers, including SBS, polyphosphoric acid (PPA), and reactive ethylene terpolymer. This research utilized the Bending Beam Rheometer (BBR) to examine the binders' low-temperature cracking potential, and the Multiple Stress Creep Recovery (MSCR) test to assess their capacity to resist permanent deformation under repetitive loading. The results revealed that SBS-modified binders exhibited superior ductility and strain tolerance, which was further validated through the Double-Edge-Notched Tension (DENT) test. Furthermore, Kanabar emphasized the relevance of studying the chemical aging behavior of SBS-enhanced binders. Using Fourier Transform Infrared (FTIR) spectroscopy, this research analyzed the evolution of carbonyl groups over time, suggesting that SBS-modified asphalts may retain more favorable long-term properties than both unmodified and PPA-modified systems,particularly in terms of elastic recovery and thermal resistance[26].

Additional experimental validation comes from research conducted at the University of Waterloo by Aurilio et al.[27, 28], who investigated the mechanical response of SBS binders under fatigue and high-temperature stress conditions. Their findings suggested that SBS may improve fatigue life and rutting resistance, factors that are crucial for Canadian pavements exposed to seasonal temperature fluctuations. Notably, their follow-up work in 2021 questioned the adequacy of conventional low-temperature tests. Instead, they advocated for the use of Linear Amplitude Sweep (LAS) testing, which offers a more nuanced understanding of cracking behaviour under high-strain conditions,an area where SBS modification has reportedly provided clear performance benefits. These tests also supported the idea that the performance improvements might scale with the percentage of SBS used in the binder formulation[27,28].

In addition to mechanical benefits, SBS has been credited with improving moisture susceptibility and other physical durability parameters. For example, mixtures containing 5% SBS reportedly demonstrated significantly better Marshall stability, higher tensile strength, and an improved Tensile Strength Ratio (TSR) compared to unmodified asphalt mixtures. Moreover, SBS-modified pavements were found to exhibit up to 79.8% less rutting and a 39.4% increase in resilient modulus, suggesting longer structural lifespan and potential savings in material use and maintenance[10].

Despite these performance advantages, economic assessments indicate that the initial costs associated with incorporating more climate-resilient binders may be notable. For instance, projections for the European Union estimate that annual expenditures could range from €38.5 million to €135 million between 2040 and 2070, with a potential increase to €65 million to €210 million annually from 2070 to 2100, specifically for the purpose of upgrading asphalt binders to climate-resilient alternatives[16]. However, these cost implications could be justified over the long term by reducing maintenance frequency, improving service reliability, and extending pavement life under evolving climatic conditions. Also, from an environmental standpoint, the GHG implications of PMBs, compared with conventional counterparts, are an important consideration. Understanding the full life-cycle emissions is crucial for guiding the transition to low-carbon, climate-resilient pavement systems.

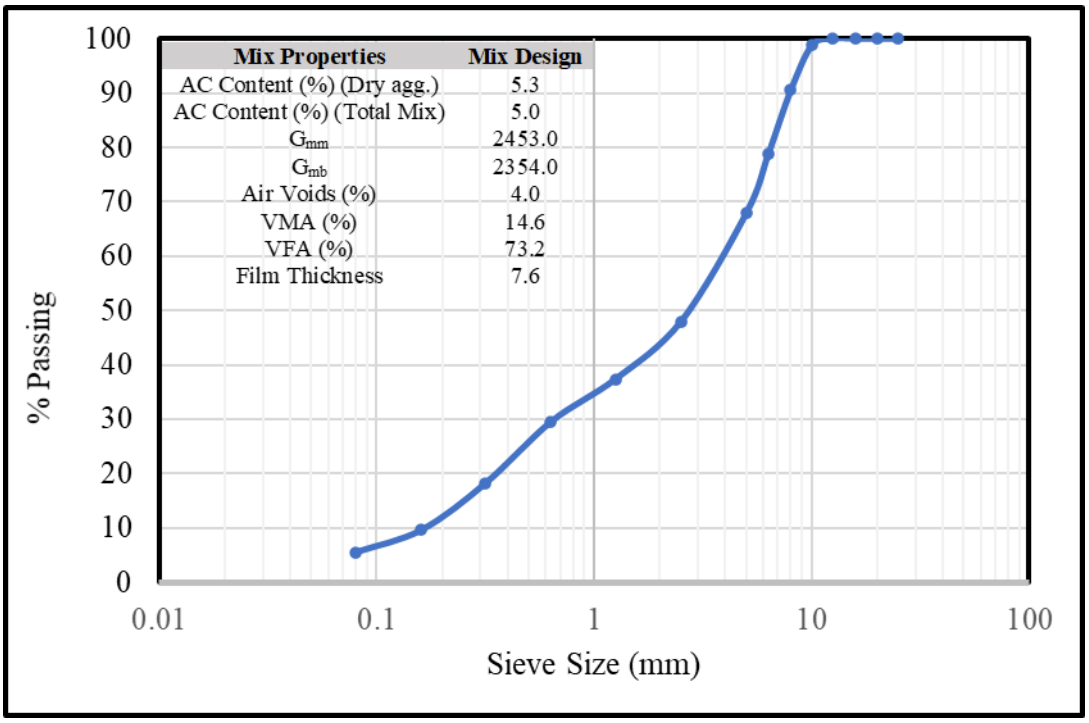
Therefore, the primary objective of this study is to evaluate the performance and environmental impacts of two asphalt mixtures - conventional unmodified binder (UB) and polymer modified biner (PMB). Utilizing AASHTOWare® PMED software, this research simulates the performance of asphalt pavements under projected climate change scenarios, incorporating both Level 1 and Level 3 input parameters. Key performance indicators, such as the International Roughness Index (IRI), were analyzed over the pavement's lifespan to achieve the goal. Additionally, open LCA tools were used in this study to quantify

GHG emissions from initial construction, maintenance and preservation and end-of-life phases for each mix. By comparing the durability and environmental impacts of these alternatives, the study aims to identify sustainable solutions that balance long-term pavement performance with environmental benefit, addressing the challenges imposed by climate change.

Methodology

In this study, two plant-produced asphalt mix alternatives for a major collector (truck and bus route) roadway were obtained and analyzed: one utilizing a conventional unmodified asphalt binder (PG 58-28) and the other incorporating an SBS-modified asphalt binder (PG 64-28). Both the mixtures consisted of the same aggregate gradations and volumetric properties, as illustrated in Figure 1.

Figure 1. Aggregate Gradation Curve with Mix Design Properties for Asphalt Mixtures.



Notably, the SBS-modified mix incorporated a specified percentage of SBS (3.5% by weight of the binder) to enhance its performance characteristics. Moreover, incorporating projected climate change data is often a key component of active pavement design, as it ensures the pavement structure can withstand anticipated changes in temperature over its service life. Therefore, two Shared Socioeconomic Pathways (SSPs) scenarios were also considered: SSP5-8.5 and SSP2-4.5. SSP5-8.5 represents a high emissions scenario driven by rapid economic growth, heavy reliance on fossil fuels, and energy-intensive lifestyles, leading to substantial increases in greenhouse gas emissions. And, SSP2-4.5 reflects a moderate emissions pathway based on intermediate socio-economic development and the implementation of climate policies that result in stabilized emissions through mitigation efforts[41]. Daily climate change data was obtained from the outputs of Coupled Model Intercomparison Project Phase 6 (CMIP6) climate model datasets, which have been downscaled and bias-adjusted using Bias Correction / Constructed Analogues with Quantile Mapping (BCCAQ) method[29]. Daily data were then transformed into an hourly format using the method as shown in Equation 1[30].

$$T(t) = (Tmax - Tmin) \times sin[(\pi \times t)/(DL + 4)] + Tmin \quad (1)$$

Where T is temperature at time t after sunrise;
T_{max} is maximum temperature;
T_{min} is the minimum temperature in the morning; and
DL is daylength (in hours)

Furthermore, Hourly Climatic Data (HCD) files were generated and uploaded to the web-based AASHTOWare® Pavement ME Design (PMED) to simulate pavement performance under specific climatic conditions. Performance projections were conducted with projected climate data for a typical urban roadway pavement structure in Edmonton, Alberta, as shown in Table 1. Design inputs included in this study were mainly compiled from the City of Edmonton's guidelines[31]. As identified in the guide, Average Annual Daily Truck Traffic (AADTT) for the major collector roadway was chosen as 1611 for this study, with the following percentage distribution for each vehicle classification: 20.5% for Class 4, 33.8% for Class 5, 9.2% for Class 6, 1.5% for Class 7, 8.9% for Class 8, 22.0% for Class 9, 1.8% for Class 10, 0.7% for Class 11, 0.2% for Class 12, and 1.4% for Class 13. As per the City's specifications the reliability level for the design purpose was 85%. A design life of 20 years was initially considered, with predicted distresses needing to meet a specified threshold value.

Table 1. Pavement Structure Design Inputs for PMED Analysis

Layer	Thicknesses (mm)	Material Type		Modulus (MPa)
Surface Course	80	HT 10mm	PG 64-28 (PMB)	Internally Calculated
			PG 58-28 (UB)	
Binder Course	120	B 20mm	PG 58-28	
Granular Base	300	3-20 Designation		250
Granular Subbase	600	3-80 Designation		200
Subgrade	Semi-infinite	Highly Plastic Clay		35

Based on the information provided, the following target values were used: Initial IRI, 0.9 m/km, Predicted Terminal IRI, 2.3 m/km, Permanent Deformation - AC only, 20 mm, Permanent Deformation - Total Pavement, 20 mm, AC Bottom-up Fatigue Cracking, 20 %, AC Thermal Fracture, 250 m/km. This analysis assumes that traffic is evenly split, with half traveling in each direction. The design considers two lanes in each direction, with 95 percent of commercial vehicle traffic using the design lane. The projected average annual daily truck traffic (AADTT) growth is from 1600 in 2020 to 9500 in 2080, with a compound growth rate of 3%[31]. Additionally, the average operational speed is assumed to be 60 km/h.

Finally, the serviceable life of the initial pavement construction was assessed, including three subsequent 50-mm Mill and Fill (M&F) rehabilitations, performed as needed to maintain performance. It is noteworthy that only major maintenance and rehabilitation activities, specifically the M&F treatments, were considered in this analysis. Routine maintenance actions such as crack sealing, pothole patching, or full-depth reconstruction were not included in the scope of this LCA study. This extended timeframe allows for examining the evolving climate patterns (particularly air temperature) and traffic levels on pavement performance. For LCA, the Environmental Product Declarations (EPD) were sourced from the Acheson Asphalt Plant, operated by Standard General Inc. Edmonton. The details of the EPDs are presented in Table 2. Moreover, TRACI v2.1 methodology was used to assess the environmental impacts in this analysis.

The LCA was conducted in this study to evaluate the GHG emissions generated by asphalt pavement structures incorporating the two mixes - UB and PMB. Two publicly available LCA tools, Athena Pavement LCA and FHWA LCA Pave, were employed to estimate the emissions under two SSP scenarios: SSP2-4.5 and SSP5-8.5. This analysis considered four scenarios and examined key life-cycle stages, including initial construction and maintenance and rehabilitation processes.

As shown in Table 2, the HT 10mm PG 64-28 (PMB) mix generally exhibits slightly higher values across most impact categories compared to the HT 10mm PG 58-28 (UB) mix. This is expected due to the additional processing and materials involved in producing polymer-modified binders. Notably, the Global Warming Potential (GWP-100) for PMB is approximately 10.5% higher than UB, reflecting the higher embodied energy of SBS polymers. The B 20mm PG 58-28 mix, used primarily for binder course, shows lower impacts across all categories, which aligns with its simpler composition and lower binder content.

Table 2. Summary of Environmental Product Declaration (EPD) for Asphalt Mixtures

Impact Category	Potential impact per ton asphalt mixture		
	HT 10mm PG 58-28 (UB)	HT 10mm PG 64-28 (PMB)	B 20mm PG 58-28
Global warming potential (GWP-100)	50.66 kg CO2 Equiv.	56.00 kg CO2 Equiv.	43.12 kg CO2 Equiv.
Ozone depletion potential (ODP)	5.73e-08 kg CFC-11 Equiv.	5.75e-08 kg CFC-11 Equiv.	5.36e-08 kg CFC-11 Equiv.
Eutrophication potential (EP)	3.59e-02 kg N Equiv.	3.94e-02 kg N Equiv.	3.37e-02 kg N Equiv.
Acidification potential (AP)	1.94e-01 kg SO2 Equiv.	2.08e-01 kg SO2 Equiv.	1.68e-01 kg SO2 Equiv.
Photochemical ozone creation potential (POCP)	5.34 kg O3 Equiv.	5.62 kg O3 Equiv.	4.74 kg O3 Equiv.

Laboratory Test Results

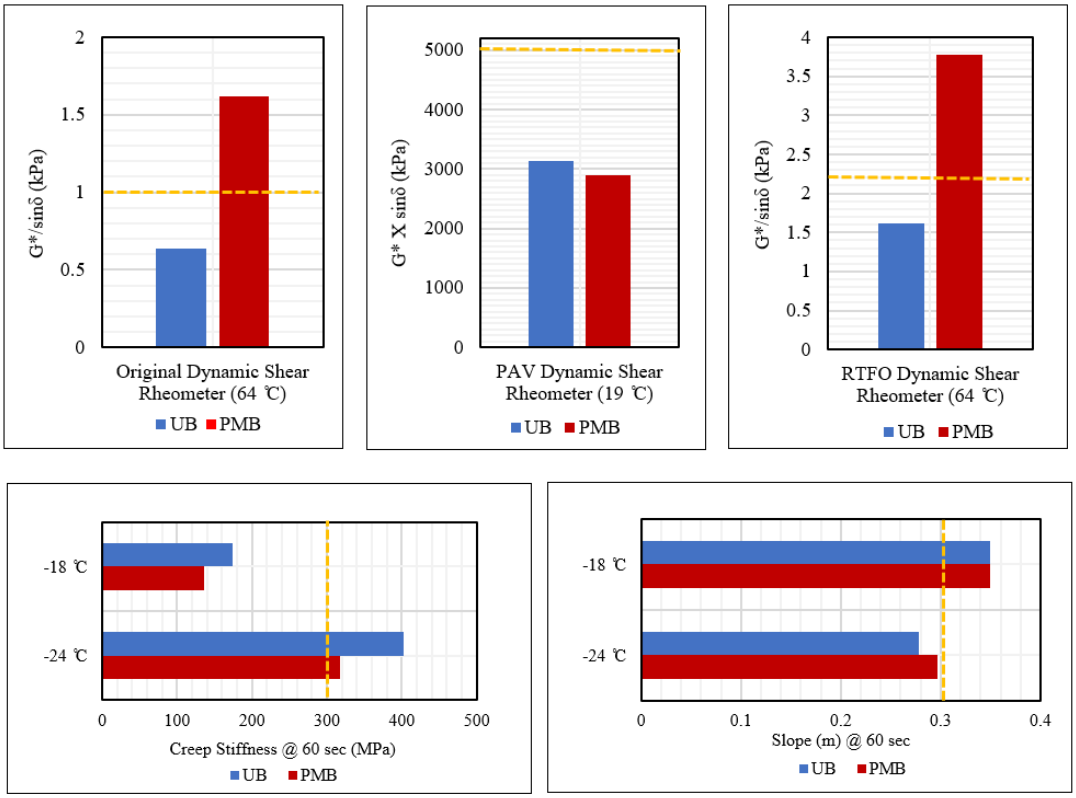
Asphalt Binder Properties

As shown in Figure 2, for the DSR test at 64°C on original condition samples, rutting resistance is evaluated based on G*/sin(δ), where the minimum required value is 1.00 kPa, as per AASHTO M 320-17[32]. PMB exceeds this threshold at 1.62 kPa, indicating improved resistance to rutting, while UB fell below the limit at 0.64 kPa, suggesting reduced performance under high temperatures. In the RTFO-aged condition, the threshold for G*/sin δ is increased to 2.20 kPa. PMB achieved 3.77 kPa, exceeding the requirement, while UB remained below the limit at 1.62 kPa, indicating greater susceptibility to rutting after short-term aging.

For intermediate temperature performance, PAV-aged binders are tested using DSR following AASHTO T 315-16[33], where failure occurs if G*·sin(δ) surpasses 5000 kPa. Both UB (3,140 kPa) and PMB (2,900 kPa) were well below this limit, suggesting that both binders may retain adequate flexibility after long-term aging. At low temperatures, binder performance is assessed using a bending beam rheometer (BBR) as per AASHTO T 313-16[34], with criteria based on creep stiffness (S ≤ 300 MPa) and relaxation capability (m-value ≥ 0.300) at a loading time of 60 seconds. At -18°C, both binders remained within acceptable limits (UB: 174 MPa, PMB: 136 MPa). However, at -24°C, UB exceeded the stiffness threshold at 403 MPa, indicating a higher risk of thermal cracking, whereas PMB remained within the acceptable range at 317

MPa. The m-value at -24°C, also indicated reduced relaxation capability for UB, suggesting increased brittleness in extremely cold conditions.

Figure 2. Rheological Properties for UB and PMB



The results indicate that PMB provides improved high-temperature performance, making it suitable for regions with heavy traffic loads and elevated temperatures. UB exhibits better thermal flexibility but is more prone to rutting and aging. The exceedance of the stiffness threshold at -24°C suggests that UB is more vulnerable to thermal cracking in colder climates.

Asphalt Mix's Dynamic Modulus Test

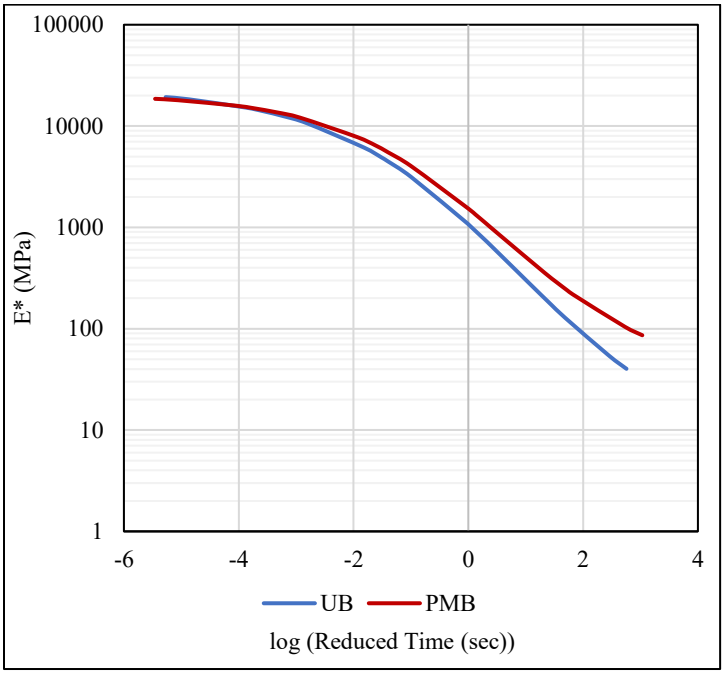
Dynamic modulus testing was conducted in accordance with AASHTO T 342-22[35], as shown in Figure 3, using cylindrical HMA specimens (100 mm diameter × 150 mm height) prepared with a Superpave Gyratory Compactor following AASHTO T 312[36]. Specimens were cored and sawed for dimensional accuracy and tested in a servo-hydraulic system equipped with an environmental chamber. Three LVDTs were mounted at 120° intervals to measure axial strain. Testing was performed at five temperatures (−10°C, 4°C, 21°C, 37°C, and 54°C) and six loading frequencies (25, 10, 5, 1, 0.5, and 0.1 Hz) under controlled sinusoidal compressive stress without lateral confinement. Before testing, each specimen was conditioned at the target temperature for a duration specified in the standard to ensure uniform thermal distribution. The applied stress and the resulting recoverable axial strain were recorded to calculate the dynamic modulus and phase angle. The collected data was subsequently analyzed to develop the dynamic modulus master curve, which characterizes the material's stiffness over a range of temperatures and loading rates.

Figure 3. Dynamic modulus test setup in Universal Testing Machine (UTM)

As can be seen in Figure 4, at very low reduced times, corresponding to high-frequency loading or low-temperature conditions, both asphalt mixes with UB and PMB exhibit high stiffness values around 10,000 MPa. This behavior is characteristic of asphalt binders in cold climates or under rapid traffic loading, where the material likely remains predominantly elastic. The similarity in modulus in this region suggests that both binders could provide adequate structural integrity at low temperatures; however, stress relaxation properties must also be considered for thermal cracking resistance. As the reduced time increases, representing moderate temperatures and loading rates, a divergence in stiffness behaviour becomes apparent. Mix samples with PMB consistently exhibits higher modulus values compared to UB, implying greater rigidity and potentially enhanced resistance to deformation under operational conditions.

This observation suggests that PMB might be more suitable for applications where resistance to rutting and load-associated permanent deformation is a primary concern, particularly in high-temperature environments. At high reduced time values, which simulate prolonged loading durations or high-temperature conditions, both binders tend to demonstrate a significant reduction in modulus, indicating increased susceptibility to viscous flow and permanent deformation. However, samples with PMB retains a higher modulus than UB, supporting its high-temperature stability. Conversely, mix samples with UB exhibits a more pronounced decline in stiffness, suggesting enhanced flexibility, which could contribute to improved resistance against thermal cracking in cold climates. The slope of the master curve provides additional insight into binder behavior across temperature and loading conditions. PMB mix samples exhibits a more gradual decline in stiffness, implying possible greater stability across different loading times and a potentially reduced risk of permanent deformation at high temperatures.

Figure 4. Dynamic modulus (|E*|) master curve for UB and PMB binders at a reference temperature of 21 ◦C.



Hamburg wheel-track test

The HWT Testing of lab-compacted asphalt mixtures was conducted in accordance with AASHTO T 324-23[37], which evaluates the rutting and moisture susceptibility of HMA. This standardized test method measures the rate of permanent deformation under repeated wheel loading while specimens are submerged in a temperature-controlled water bath (Figure 5).

Figure 5. HWT test setup in wet mode

Lab-compacted HMA specimens were prepared using the SGC in accordance with AASHTO T 312[36]. Cylindrical specimens with a diameter of 150 mm and a thickness of at least twice the nominal maximum aggregate size, typically between 60 and 62 mm, were tested. Prior to testing, the specimens were conditioned in a water bath at a target temperature of 50°C to ensure thermal equilibrium. The water bath temperature was maintained within ±1.0°C, with specimens fully submerged in circulating water to simulate field moisture exposure.

During testing, the steel wheel repeatedly traversed the specimen, inducing rutting due to accumulated deformation. A LVDT continuously measured the rut depth at the centre of the wheel's path at intervals of every 400 passes. The relationship between rut depth and the number of wheel passes was plotted to assess performance, with an abrupt increase in deformation indicating the potential stripping of the asphalt binder from the aggregate. The visual condition of the asphalt specimens before and after HWT testing is shown in Figures 6 and 7, illustrating the extent of rutting and surface damage for UB and PMB mixes, respectively.

Figure 6. UB-AC mix specimens before and after HWT test

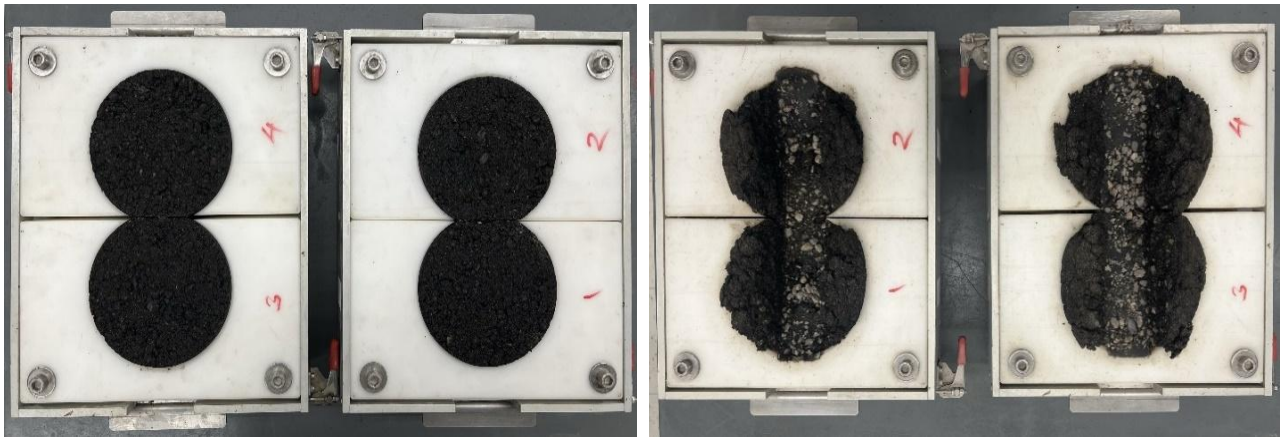
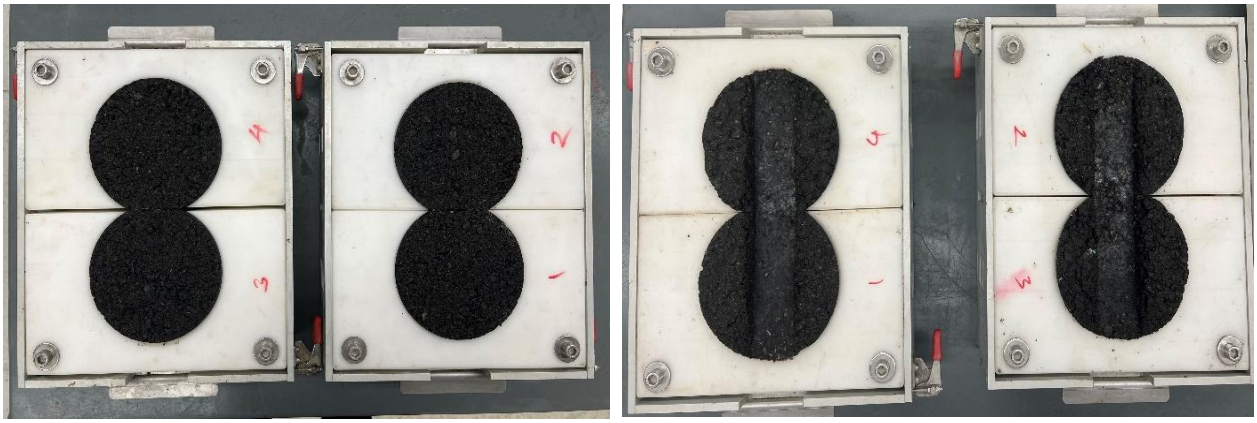


Figure 7. PMB-AC mix specimens before and after HWT test



The HWT test provides a measure of the rutting and moisture susceptibility of asphalt mixes, particularly in regions that experience high temperatures and significant moisture exposure. The performance of the asphalt mixes is typically assessed by measuring the rut depth after a set number of wheel passes. One of the most crucial markers in these tests is the Stripping Inflection Point (SIP), which can indicate the onset of moisture damage. If the SIP occurs before 10,000 passes, the mix is often considered susceptible to moisture damage, potentially leading to premature failure[38]. Also, the Rutting Resistance Index (RRI)[38] is calculated using Eq. (2). A higher RRI generally indicates better rutting resistance and performance under wheel tracking conditions.

$$RRI = N \times (1 - RD) \quad (2)$$

Where RRI is the rutting resistance index (in.)
N is the number of cycles at the test's completion
RD is the rut depth at the test's completion (in.)

The asphalt mix specimens with UB, both S1 and S2, exhibited relatively early stripping inflection points (SIP) at 5252 and 6732 passes (Figure 8). These early SIPs, accompanied by final rut depths exceeding 12 mm and low Rutting Resistance Index (RRI) values of 3275 and 4556 inches, suggest that mixes with UB may have limited durability under moisture susceptibility and repeated loading. The results indicate moderate rutting resistance and possible susceptibility to early-stage moisture-induced damage, implying they might be less suitable for environments with frequent moisture exposure or high traffic loads. Alternatively, as shown in Figure 9, the mixes with PMB demonstrated markedly superior performance. With no observed SIP even after the full 20,000 passes, the mixes exhibited significantly lower rut depths,5.13 mm and 3.79 mm, and much higher RRI values of 15,957 and 17,013 inches. These figures highlight their strong resistance to permanent deformation and moisture damage.

The performance gap between the two binders is visually evident in the rutting depth graphs, where PG 58-28 samples shows a sharp post-SIP rutting increase, and PG 64-28 curves remain gradual and stable throughout. The enhanced performance of mixes with PMB could be attributed to its polymer-modified composition, which may improve elasticity, stiffness at elevated temperatures, and resistance to moisture-induced stripping. These attributes suggest PMB could be a more resilient and long-lasting option for regions facing extreme temperature variations and high traffic demands. While UB might still be appropriate for milder climates or lower-stress applications, PMB appears to offer greater long-term durability and potentially reduced maintenance needs. The notable difference in RRI values,more than fivefold in favor of PMB, underscores its capacity to withstand both environmental and mechanical stresses, possibly making it a strong alternative for sustainable pavement design under changing climatic conditions.

Figure 8. HWT rutting depth for asphalt mix samples with UB

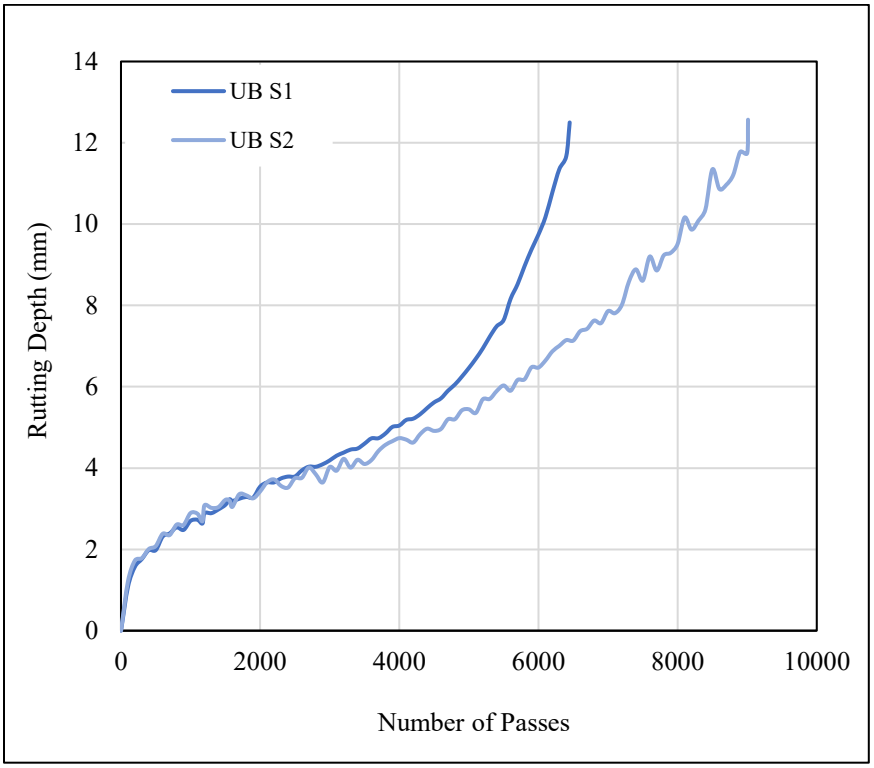
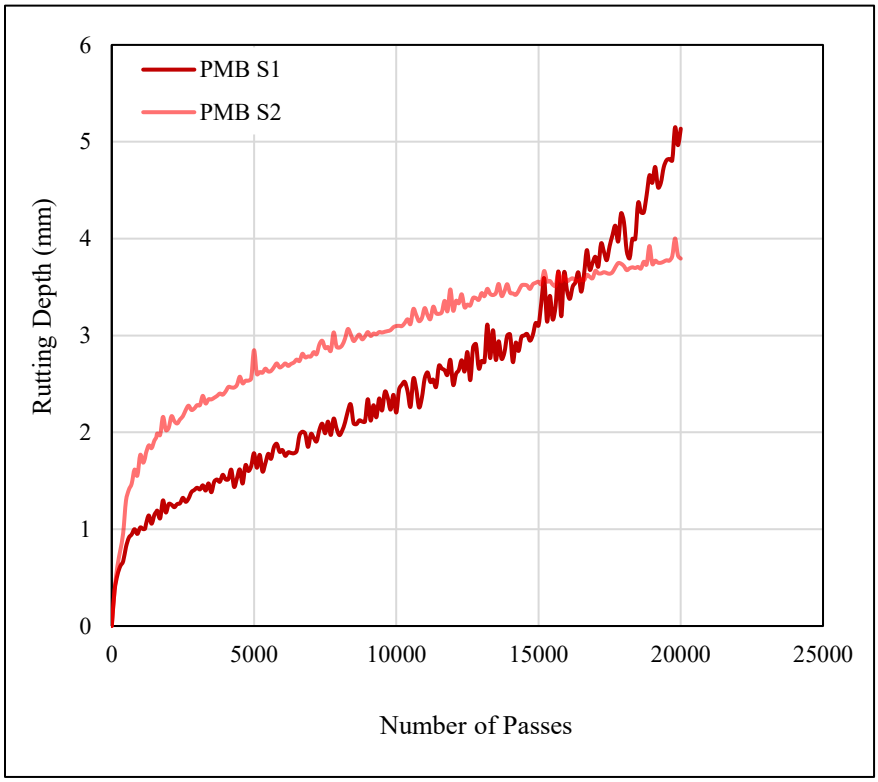


Figure 9. HWT rutting depth for asphalt mix samples with PMB

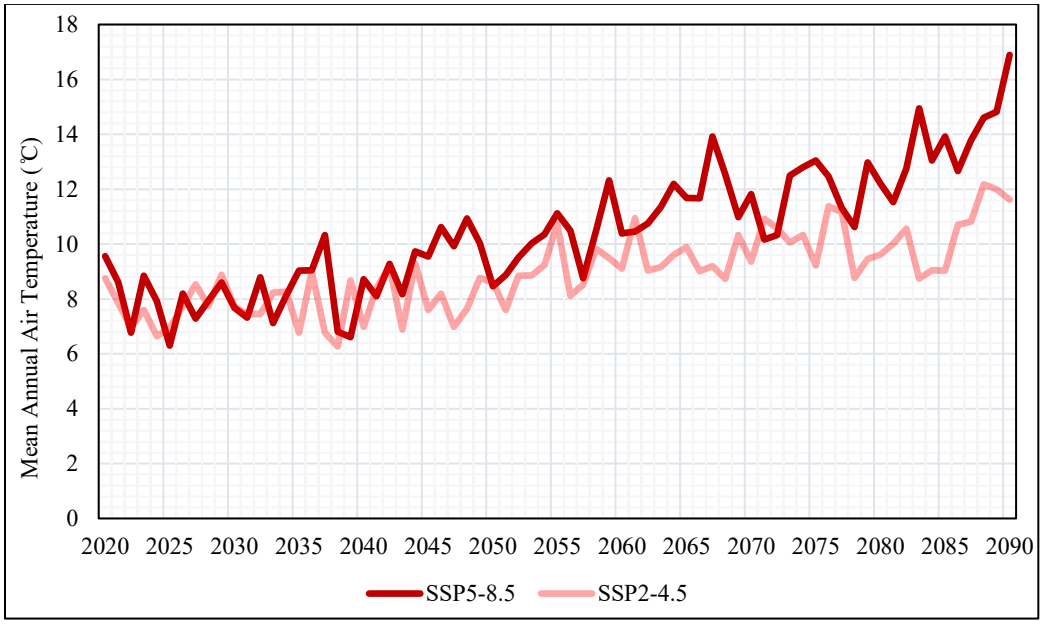


Predicted Performance Under Changing Climate

Climate Change Projection

Figure 10 illustrates the projected Mean Annual Air Temperature (MAAT) trends for Edmonton (AB), from 2020 to 2090 under two climate scenarios, SSP5-8.5 and SSP2-4.5. Both scenarios suggest a general increase in MAAT, though SSP5-8.5 appears to exhibit a more pronounced rise. Temperature variability is observed across the timeline, while SSP5-8.5 showing a steeper upward trend, particularly in the latter half of the century.

Figure 10. Projected MAAT Trends for Edmonton (AB) under SSP2-4.5 and SSP5-8.5



Under SSP5-8.5, MAAT could increase from approximately 9.5°C in 2020 to around 16.9°C by 2090, reflecting a potential rise of about 7.3°C over seven decades. In contrast, SSP2-4.5 starts just above 8.5°C in 2020 and follows a more gradual trajectory, potentially reaching approximately 11.6°C by 2090. The divergence between the two scenarios becomes more apparent after 2050, likely reflecting the influence of different emissions pathways. While SSP5-8.5 suggests a more substantial warming trend, SSP2-4.5 projects a slower, steadier increase.

These projected temperature increases may have important implications for pavement performance and asphalt binder selection. As the MAAT rises, the frequency and intensity of extreme temperature events could also increase, potentially leading to premature pavement distresses such as rutting, bleeding, and surface softening. The upward trend in MAAT, especially under the SSP5-8.5 scenario, suggests that pavement surfaces might increasingly experience temperatures that exceed the typical performance thresholds of PG 58-28. In this context, adopting more climate-resilient alternatives such as PMB may be warranted to enhance long-term durability. The performance simulations presented in this study indicate that PMB (PG 64-28), due to its enhanced high-temperature stiffness and elasticity, might offer improved resistance under future climate conditions. Overall, these findings highlight the need to consider

projected temperature trends when selecting binder grades to maintain pavement performance and durability.

AASHTOWARE PMED simulations

Analysis using quasi-level 1 inputs

Figure 11 illustrates the progression of pavement roughness, indicated by IRI, for UB under SSP2-4.5 and SSP5-8.5 scenarios based on PMED simulations. The simulations were performed using Quasi-level 1 inputs, incorporating dynamic modulus test results obtained from laboratory investigations. Both scenarios show a steady increase in IRI following initial construction in 2020, with periodic maintenance interventions occurring upon reaching the critical threshold of 2.3 m/km. These interventions were modeled as 50-mm Mill and Fill (M&F) rehabilitations, which effectively restore the IRI to near-initial levels after each cycle.

Under SSP2-4.5, the IRI gradually increases, reaching approximately 1.8 m/km by 2033 and surpassing the 2.3 m/km threshold by 2042, requiring the first M&F intervention after 22 years. Subsequent interventions occur in 2056 and 2069, suggesting an estimated service life of 62 years. The deterioration pattern follows a cyclical trend, with M&F interventions effectively restoring the pavement condition after each cycle. Similarly, under SSP5-8.5, the IRI follows a broadly comparable trajectory but with a moderately accelerated deterioration rate, likely due to increased environmental stress. The threshold is reached by 2041, prompting the first M&F intervention, followed by cycles in 2055 and 2068. The total service life is estimated to be about 61 years, marginally shorter than SSP2-4.5, consistent with the projected harsher climate conditions.

The performance of PMB for SSP2-4.5 and SSP5-8.5 scenarios is illustrated in Figure 12 through their IRI progression over time. After the initial construction in 2020, the IRI predictions for both sections began to rise steadily. By 2033, the IRI for SSP2-4.5 approaches 1.7 m/km, while for SSP5-8.5, it is slightly higher. By 2043, the IRI for SSP2-4.5 reach the critical threshold of 2.3 m/km, prompting the first M&F intervention 23 years after construction. In the case of SSP5-8.5, the first M&F intervention occurred 22 years after the initial construction. These maintenances restore the IRI to roughly 1.3 m/km for both sections. Furthermore, for SSP2-4.5, the IRI again reaches the threshold in 2058, followed by subsequent M&F interventions in 2072 and 2085. Similarly, SSP5-8.5 follows nearly the same timeline for the interventions, though its IRI tends to reach the threshold slightly faster between cycles. The total service life is estimated at 65 years for SSP2-4.5 and 63 years for SSP5-8.5, indicating that PMB may offer better long-term performance under milder climate scenarios.

The analysis suggests that PMB-treated pavements may exhibit a longer service life than conventional mixes, potentially indicating enhanced durability. The results also indicate a slightly higher rate of IRI progression for SSP5-8.5 compared to SSP2-4.5, which could be influenced by variations in climate stress or binder properties. However, the overall performance of PMB appears to contribute to a possible reduction in the frequency of major rehabilitation events compared to untreated pavements.

Figure 11. Predicted IRI Trends for UB for SSP5-8.5 and SSP2-4.5 Scenarios

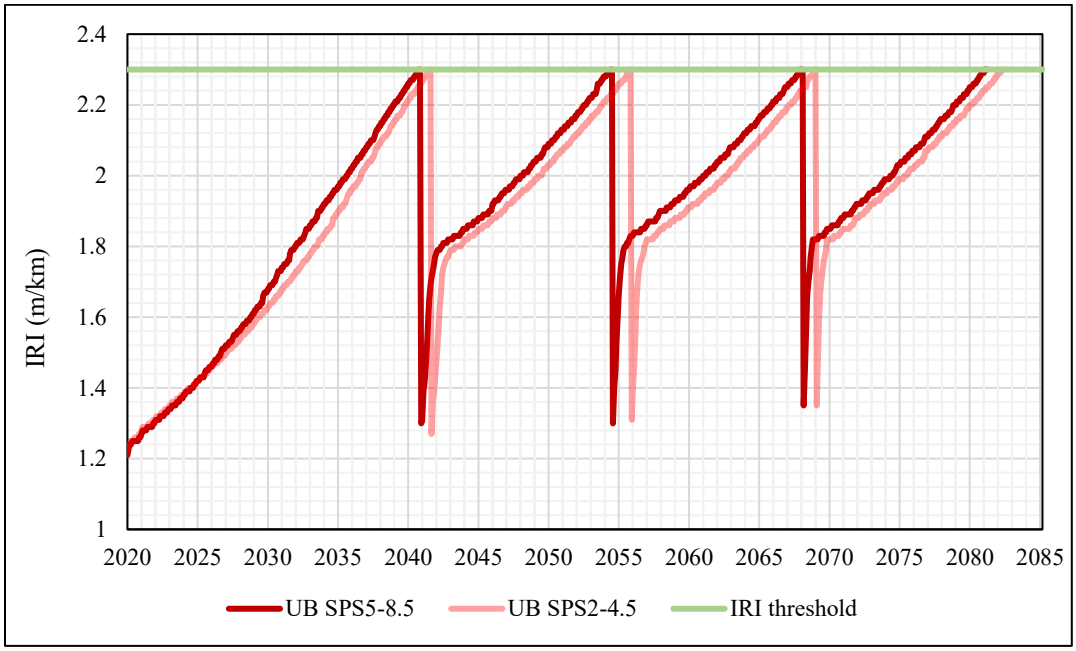
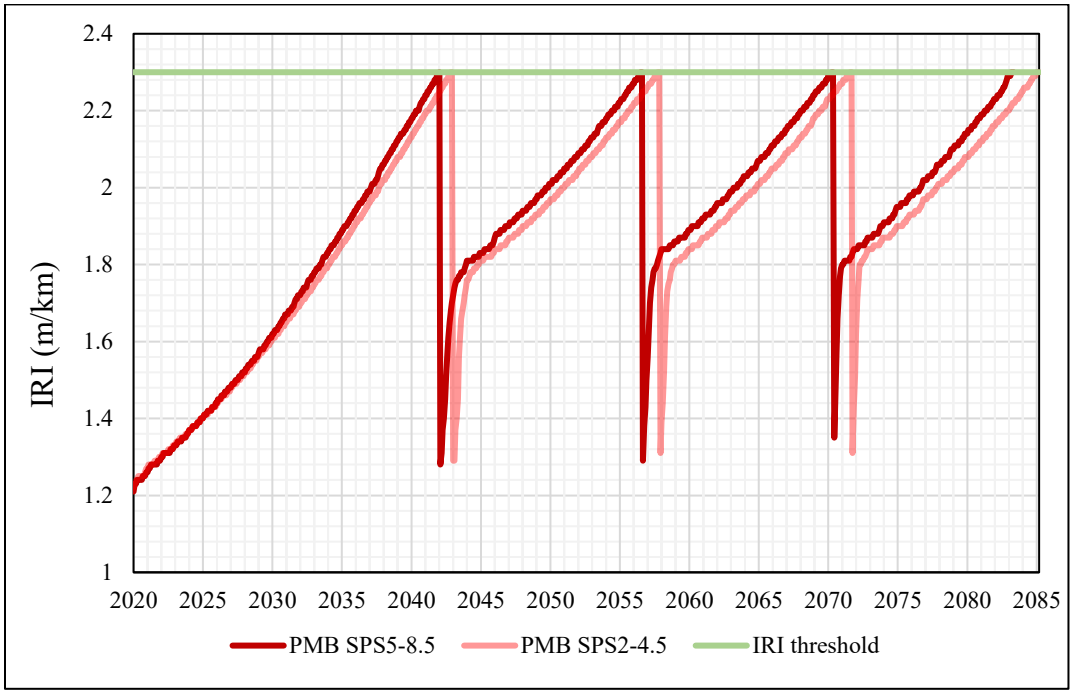


Figure 12. Predicted IRI Trends for PMB for SSP5-8.5 and SSP2-4.5 Scenarios



Analysis using level 3 inputs

In addition to Level 1 input simulations, comparative analysis was performed using Level 3 inputs. Level 3 inputs are based on default or "best-estimated" values, typically derived from global or regional data with similar characteristics[39]. While less project-specific, Level 3 inputs offer reduced testing and data

collection costs[39]. By contrasting Level 1 and Level 3 results, this study evaluates potential variations in projected pavement performance, particularly in service life and deterioration rates under differing input conditions.

Figures 13 and 14 depict the IRI trends for UB and PMB under both SSP scenarios. For UB under SSP2-4.5 (Figure 13), the IRI shows a steady increase after initial construction in 2020, reaching approximately 1.8 m/km by 2030 and surpassing the 2.3 m/km threshold by 2039. This necessitates the first M&F intervention after 19 years, with subsequent cycles in 2053 and 2064, suggesting a service life of approximately 53 years. Under SSP5-8.5, UB exhibits a similar but marginally accelerated deterioration pattern, reaching the threshold by 2039 with interventions in 2052 and 2062. The estimated service life of 52 years reflects the heightened environmental stresses modeled in PMED simulations.

Figure 13. Predicted IRI Trends for UB for SSP5-8.5 and SSP2-4.5 Scenarios

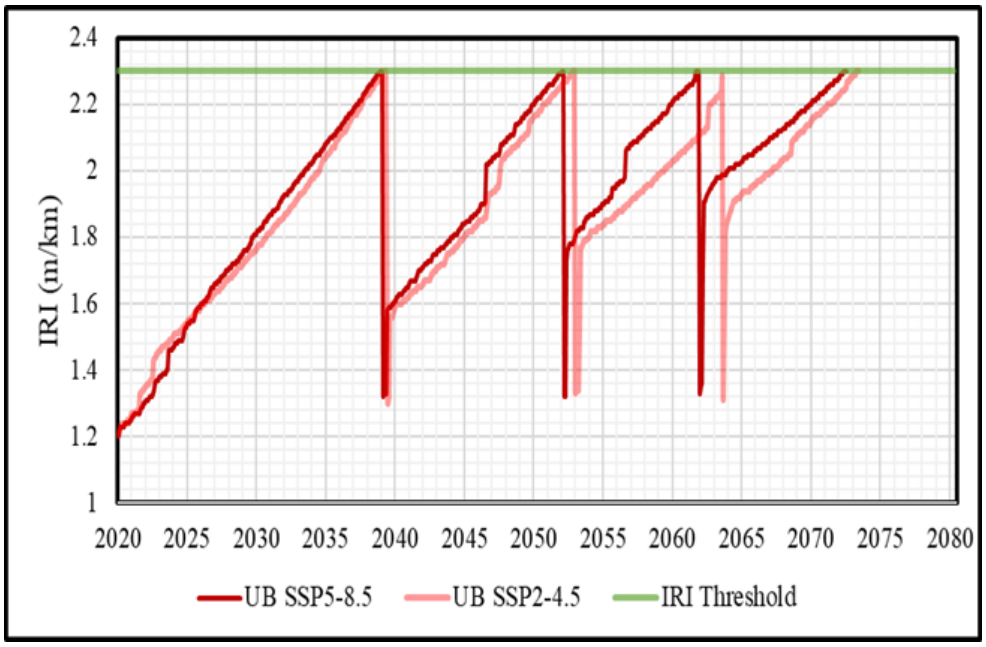
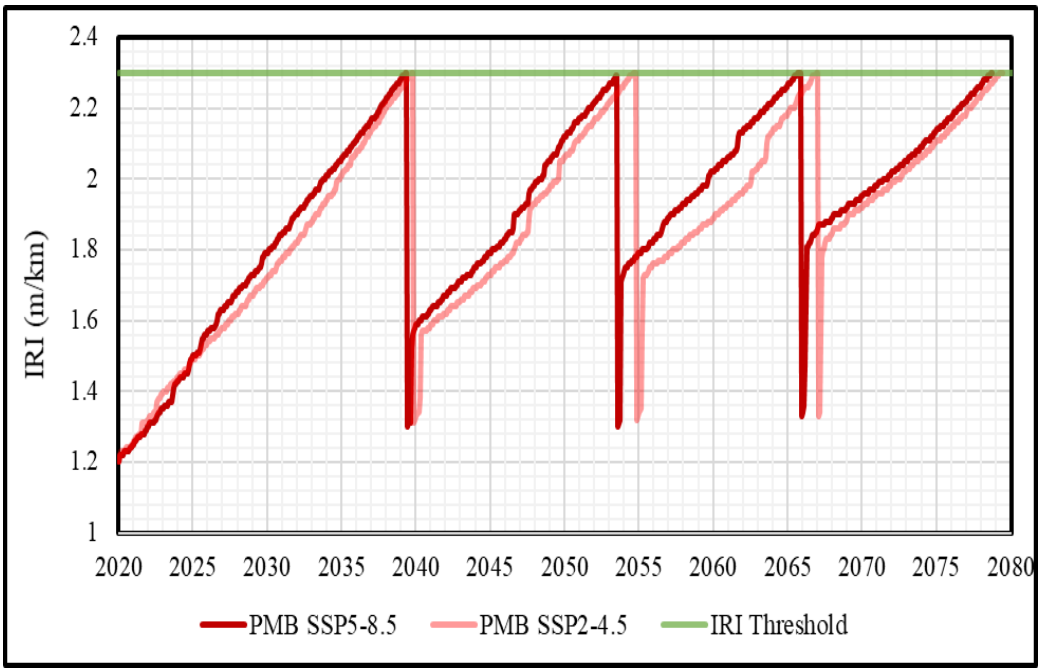


Figure 14 shows the IRI progression for PMB under both SSP scenarios. Both scenarios display similar deterioration patterns, reaching the 2.3 m/km threshold 19 years after initial construction (2039). Following M&F maintenance that restores IRI to approximately 1.3 m/km, SSP2-4.5 requires subsequent interventions in 2055 and 2067, yielding a total service life of 59 years. In comparison, SSP5-8.5 demonstrates slightly accelerated deterioration, with a projected service life of 58 years. The service life predictions derived from PMED simulations using Level 1 and Level 3 inputs reveal notable differences, which appear to be influenced by the type and quality of input data. These differences are also evident when comparing the results for UB and PMB under the two SSP scenarios.

Simulations using quasi-Level 1 input consistently suggest a longer service life. For example, under the SSP2-4.5 scenario, the predicted service life for UB was approximately 62 years, with Mill & Fill maintenance interventions occurring 22 years after initial construction, followed by subsequent treatments at 14 and 13 years after the preceding intervention, respectively. The extended service life could reflect the more detailed characterization of material properties, which likely provides a better understanding of the pavement's performance under actual conditions. On the other hand, when Level 3

inputs, derived from default or "best-estimated" values based on regional or global data were used, the predicted service life for UB was shorter, estimated at about 53 years. This difference probably stems from the generalized nature of Level 3 inputs, which may not fully capture the specific characteristics of the material. A similar trend was observed for PMB. Under the SSP2-4.5 scenario, the predicted service life using Level 1 inputs was approximately 65 years, compared to 58 years with Level 3 inputs. Notably, the Witczak E* predictive model, commonly employed in PMED for Level 3 analysis, utilizes aggregate gradation, binder viscosity, and mixture volumetrics to approximate E*, serving as a default input method[40]. While the Witczak model offers a cost-effective approach for preliminary design, its accuracy might vary depending on the specific characteristics of the asphalt mixture.

Figure 14. Predicted IRI Trends for PMB for SSP5-8.5 and SSP2-4.5 Scenarios



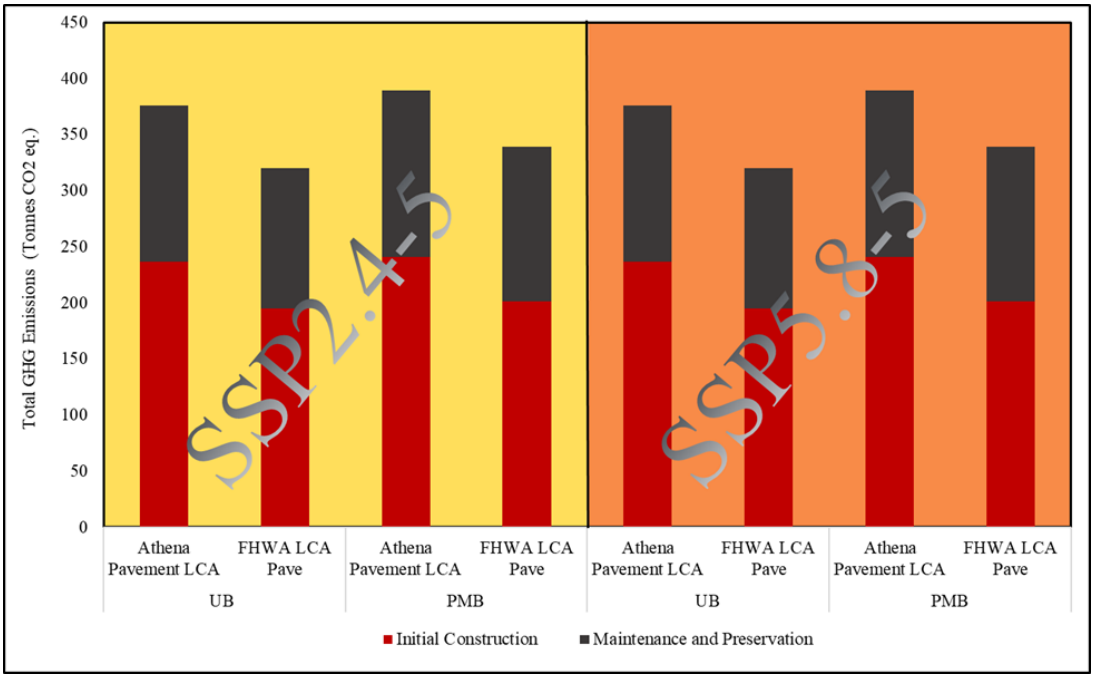
This difference was also evident under the more severe climate conditions of SSP5-8.5. For UB in that scenario, Level 1 inputs yielded a service life of about 61 years, while Level 3 inputs predicted only 52 years. For PMB, the corresponding service lives were 63 years (Level 1) and 58 years (Level 3). These variations highlight the influence of more refined material characterization in Level 1 inputs, such as laboratory-derived properties, which enable more accurate simulation of pavement performance.

In summary, while Level 3 inputs offer a cost-effective approach for preliminary design, they may generally provide less reliable predictions than Level 1 inputs for pavement service life[42]. Level 1 inputs, which are based on direct laboratory measurements, tend to yield more reliable predictions of long-term pavement performance. Overall, the results underscore the importance of using site-specific, laboratory-derived data for projects where accurate service life prediction is critical for ensuring pavement durability and performance over time.

GHG Implications Analysis

As shown in Figure 15, in terms of total GHG emissions and in case of UB for the SSP2-4.5 scenario, the Athena Pavement LCA estimated 236.60 tonnes CO_2-eq emissions during the initial construction phase. These emissions appear to primarily arise from raw material extraction, manufacturing, transportation, and construction of the pavement structure. The maintenance and preservation phase added another 139.47 tonnes CO_2-eq likely due to recurring Mill & Fill operations over the pavement's lifespan. Thus, the total emissions assessed by Athena Pavement LCA amounted to 376.07 tonnes CO_2-eq for the SSP2-4.5 scenario. However, the FHWA LCA Pave assessment reported lower emissions for UB in the SSP2-4.5 scenario; the initial construction phase accounted for 194.98 tonnes CO_2-eq, and the maintenance and preservation 125.27 tonnes CO_2-eq leading to total emissions of 320.25 tonnes CO_2-eq. For the SSP5-8.5 scenario, both Athena Pavement LCA and FHWA LCA Pave resulted in the same emissions as their respective calculations for the SSP2-4.5 scenario.

Figure 15. Estimated total GHG Emissions (in tonnes CO_2-eq)

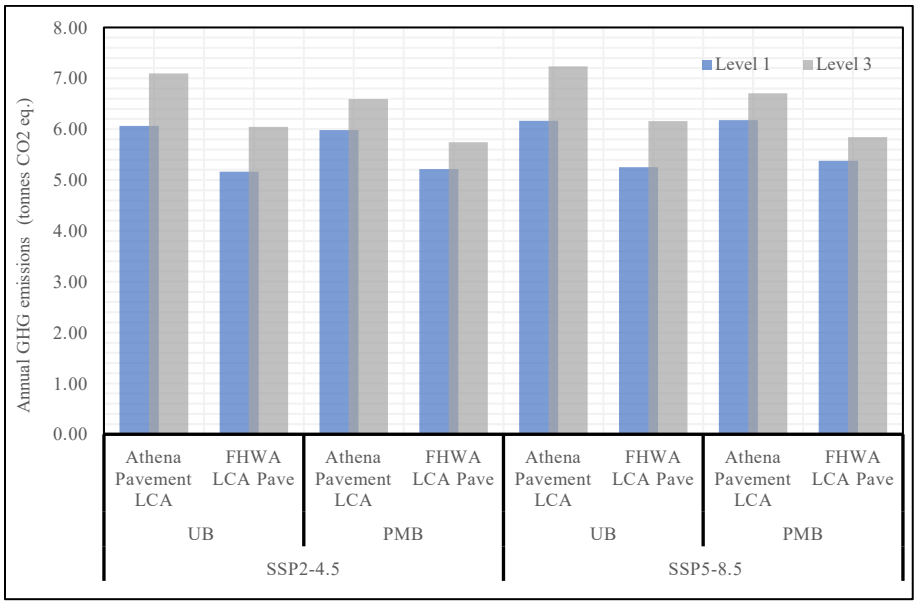


In the case of the SSP2-4.5 scenario with PMB, Athena Pavement LCA estimated 241.09 tonnes CO_2-eq for the initial construction phase. Maintenance and preservation contributed 147.89 tonnes CO_2-eq, potentially reflecting emissions from Mill & Fill operations using SBS-modified materials. The total emissions for SSP2-4.5 with PMB, as assessed by Athena, were 388.98 tonnes CO_2-eq. FHWA LCA Pave estimated 201.42 tonnes CO_2-eq for the initial construction phase and 137.54 tonnes CO_2-eq for maintenance and preservation, resulting in total emissions of 338.96 tonnes CO_2-eq. For the SSP5-8.5 scenario, both tools seem to report identical values to SSP2-4.5 for PMB. These discrepancies in results may arise from differences in methodological frameworks and the specificity of the underlying data sources used by each tool.

The annual GHG emissions are derived by dividing the total GHG emissions by the service life of the pavement, as determined through PMED. As shown in Figure 16, using Level 1 inputs in PMED, pavements

with UB under SSP2-4.5 (with a service life of 62 years), had an annual emission at 6.07 tonnes CO_2-eq as estimated with Athena Pavement LCA, or 5.17 tonnes CO_2-eq as estimated with FHWA LCA Pave. Whereas under SSP5-8.5, with a slightly shorter service life of 61 years, the annual emissions were 6.17 tonnes CO_2-eq when using Athena Pavement LCA or 5.25 tonnes CO_2-eq when using FHWA LCA Pave. On the other hand, for pavements with PMB under SSP2-4.5, the service life was 65 years. Consequently, annual emissions were at 5.98 tonnes CO_2-eq when using Athena Pavement LCA, compared to FHWA LCA Pave's estimate of 5.21 tonnes CO_2-eq. Under SSP5-8.5 (service life 63 years), Athena reported annual emissions of 6.17 tonnes CO_2-eq, while FHWA estimated 5.38 tonnes CO_2-eq.

Figure 16. Comparison of Annual GHG Emissions Using Level 1 and Level 3 Inputs



As expected, the longer service life of pavements with PMB , appears to reduce their annualized emissions compared to pavements with UB, even though their total emissions are higher overall. This suggests that to serve the same amount of traffic and climatic stressors, the environmental price in terms of annual GHG emissions could be rather lower when using PMB. With respect to Level 3 inputs, annual GHG emissions were higher due to underestimation of service life. This highlights the importance of utilizing the laboratory-derived Level 1 inputs which likely generate more accurate service life estimation and eventually enhanced emissions estimations for resiliency and sustainability assessments. However, it should be noted that some uncertainties may exist, and additional research could help verify these patterns across a broader range of scenarios.

Conclusions

In conclusion, this study evaluates the performance of asphalt pavement under projected climate change scenarios by integrating climate modeling, laboratory performance testing, and LCA. The use of SSP2-4.5 and SSP5-8.5 climate scenarios allowed for the assessment of temperature-related stresses on pavement materials, while performance-based laboratory tests, including dynamic modulus, and HWT, provided detailed insights into the mechanical behavior of both unmodified binders (UB) and polymer-modified binders (PMB). This combination of empirical testing and scenario-based analysis enabled a more informed assessment of pavement responses to projected environmental conditions.

The study leveraged Level 1 input data, derived from laboratory measurements, to improve the accuracy of pavement service life predictions and therefore GHG emission estimates. The comparative analysis between Level 1 and Level 3 inputs demonstrated the value of high-resolution data in reducing uncertainty and enhancing the reliability of performance and environmental assessments. This approach underscores the importance of integrating empirical laboratory data with predictive modeling when evaluating infrastructure materials in the context of long-term sustainability and climate resilience.

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