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ORIGINAL RESEARCH PAPER

# Enhancing Pavement Resilience in Canada Through Adaptive Asphalt Binder Selection

**Mohammad Shafiee**[1] · **Morvarid Fattahi**[1] · **Ehsan Roshani**[1]

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## Abstract

Climate change is increasingly posing risks to flexible pavements due to rising temperatures and more frequent and intense extreme heat events. As climate patterns shift from historical norms, the vulnerabilities of these pavements become more evident, threatening transportation infrastructure and economic stability. This paper presents a climate change impact assessment on the SUPERPAVE ® asphalt binder Performance Grade (PG) selection for mix design in Canada. Therefore, a tool was firstly developed named as Performance-Graded Asphalt Cement under a Changing Climate (PGAC3) considering projected temperature conditions. Secondly, the relative impact of climate change on design temperatures was studied under different Representative Concentration Pathway (RCP) scenarios. The findings indicate that projected temperature changes are geographically variable and affect critical design factors differently. Notably, case study simulations for a representative city suggested that adapting PG selection to future climate conditions could potentially extend the pavement service life. These insights underscore the critical need for the Canadian transportation sector to prioritize and implement robust climate adaptation strategies and policies.

**Keywords** Climate Change · Asphalt Binder · Pavement Resiliency · Performance Prediction

## 1 Introduction

Among core public infrastructures, roads deliver critical services to our communities for day-to-day life. Canada's public road network comprises more than 1.13 million lane-kilometres (Four provinces—Ontario, Quebec, Saskatchewan, and Alberta—account for over 75% of the total road length.). Approximately 40% of these roads are paved and the majority of paved roads are constructed using asphaltic materials [1]. The country's road transportation infrastructure spans a vast landmass which often faces harsh climates [2]. Climate change has evidently impacted extreme weather patterns, including their frequency, duration, and intensity [3, 4]. Canada undergoes accelerated and heightened warming compared to the global average. Particularly, the winter season is projected to experience the most significant warming across the country [5]. While mitigating the underlying causes of climate change is imperative, adapting to its ongoing effects is equally crucial [6].

Proactive adaptation measures to choosing the most suitable materials for Hot Mix Asphalt (HMA) layer is essential for maintaining pavement performance and safety under increasingly severe climate conditions [7]. Asphalt binders, which serve as the adhesive agent for aggregates to produce a dense and smooth road surface, are selected based on the Superpave system for Performance-Grade (PG), with climate being the foremost factor to consider among others [8]. To date, many provincial transportation agencies have already incorporated PG zone maps into their pavement design manuals based on historical weather records and recommend utilizing the Long-Term Pavement Performance Bind (LTPPBind Online) [9] web-based tool to confirm the suitable PG type.

However, considering the influence of climate change, depending solely on historical climate data for asphalt binder selection carries the risk of early pavement failures and

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shortened service life due to insufficient resistance to future temperature conditions. Global Climate Models (GCMs), or General Circulation Models, are typically used to develop climate models on a global scale. These complex numerical tools simulate interactions between several components of the Earth system, which includes the atmosphere, oceans, land surfaces, and icy regions including sea ice, glaciers, and permafrost. GCMs help scientists understand and predict how the Earth's climate system will behave in different scenarios by recording these interactions [10]. Nonetheless, there are restrictions to GCM forecasts. GCM outcomes can occasionally show ongoing biases due to oversimplifications or errors in depicting more detailed processes when used for local-scale climates. Additionally, their limited spatial resolution limits their effectiveness for analyzing localized climate changes. Spatial downscaling techniques and bias correction are used to improve GCM data for local usage in order to address these problems [11]. Among various statistical downscaling methods, the Bias-Correction/Constructed Analogues with Quantile mapping reordering (BCCAQ) strategy has been shown to outperform several other statistical downscaling methods, providing high-resolution climate data for regional analyses using GCMs from the Coupled Model Intercomparison Project Phase 5 (CMIP5) [12].

In recent few years, an increasing number of researchers worldwide have explored the potential influence of climate change on asphalt binder PG selection, emphasizing its temporal and regional sensitivity. The literature review suggests several key studies that have investigated this topic as shown in Table 1.

The findings from these studies mainly highlight the necessity for updated PG binder selection criteria that incorporate future climate projections. In Canadian context, there remains a notable gap in a comprehensive assessment of the impact of climate change on asphalt binder PG across provinces and territories. To address this gap, this study focuses on developing and utilizing a new online tool called Performance-Graded Asphalt Cement under a Changing Climate (PGAC3) that integrates climate change data into the PG selection process. Hence, the key objective of this paper is to quantify the relative impact of climate change on the minimum required asphalt binder PG type.

## 2 Methodology

### 2.1 Climate Data and Scenarios

Statistically downscaled data from 24 CMIP5 global climate models, using the BCCAQ, Version 2 method, was used in this study. Two RCP scenarios, 4.5 and 8.5, were considered to account for varying emission levels. That is to say, RCP 4.5 exemplifies low reduction in Greenhouse Gas (GHG) emissions, while RCP 8.5 demonstrates a condition under the impact of 'business as usual' case. In this study, four distinct 20-year design life periods were chosen, labeled as Cycle 1, Cycle 2, Cycle 3, and Cycle 4. Cycle 1 (2000–2019) served as the baseline period for comparison. Cycle 2 (2020–2039), Cycle 3 (2040–2059), and Cycle 4 (2060–2079) represent subsequent periods, each reflecting evolving climate conditions. Also, the geographic scope encompassed the entirety of Canada, with all regions situated approximately below the Arctic Circle.

### 2.2 Asphalt Binder Selection

In this study, the National Research Council (NRC)'s Performance-Graded Asphalt Cement under a Changing Climate (PGAC3) tool was utilized [29]. This tool enables the selection of asphalt binder grades by considering projected temperature conditions and is supported by various pavement temperature prediction functions, including the recent LTPP models [9] chosen for this paper as depicted in Eqs. (1–4).

$$\begin{aligned} LPT = & -1.56 + 0.72T_{L,air} - 0.004Lat^2 \\ & + 6.26\log(H + 25) \\ & - Z(4.4 + 0.52\sigma^2_{T,air})^{0.5} \end{aligned} \tag{1}$$

where $LPT$ is the lowest yearly pavement temperature, $T_{L,air}$ is the lowest yearly air temperature, $Lat$ is the latitude, $H$ is the depth into HMA surface, $Z$ is the reliability constant equal to 2.055 for 98% reliability, $\sigma^2_{T,air}$ is standard deviation of lowest yearly air temperature. The 98% reliability threshold aligns with the Ontario Provincial Standard Specifications (OPSS) for Performance Graded Asphalt Cement [30] and is also commonly adopted in equivalent provincial guidelines across Canada to ensure the performance of asphalt binders.

$$HPT = PG_{H,d} + (Z)\left(PG_{H,d}\right)\frac{CVPG}{1000} \tag{2}$$

$$PG_{H,d} = 48.2 + 14DD - 0.96DD^2 - 2RD \tag{3}$$

$$CVPG = 0.000034(Lat - 20)^2RD^2 \tag{4}$$

where $HPT$ is the highest pavement temperature, $CVPG$ is the yearly PG coefficient of variation, $PG_{H,rel}$ is the relative PG value, $DD$ is the Degree Days and $RD$ is the rutting depth.

To narrow the scope to climate impact exclusively, standard loading conditions (less than 3 million Equivalent Single Axle Load (ESAL)) and fast traffic speeds (> 70 km/h) were assumed. As a result, grade bumping, typically recommended for heavy traffic loading or slow speeds,

**Table 1** Overview of previous studies on climate change impacts on PG selection

| Country (A-Z) | Study Area | PG Calculation Method | Climate Change Database | Projection Target Year | Author |
|---|---|---|---|---|---|
| Canada | 16 Cities | LTPP | ECCC[1] & MERRA-2 | 2079 | Shafiee et al. [13] |
| Canada | 16 Cities | LTPP2.1 | Pacific Climate Impacts Consortium | 2100 | Swarna et al. [14] |
| Canada | 10 Cities Across Ontario | LTPP 2.1 & Locally Calibrated Model | GCMs[2] | 2100 | Basit et al. [15] |
| Canada | 17 Cities | LTPP 2.13 | CGCM2A2×4 & Had-CM3B215 | 2050 | Mills et al. [16] |
| Chile | 94 Cities | SHRP6 & LTPP 2.1 & LTPP 3.1 | MIROC57 and WRF8 | 2059 | Delgadillo et al. [17] |
| China | East China | SHRP | ARIMA9 | 2039 | Sheng et al. [18] |
| China | National Scale | SHRP | GCM1[0] | 2059 | Liu et al. [19] |
| Columbia | National Scale | SHRP | CMIP51[1] | 2100 | Gulzar et al. [20] |
| India | National Scale | SHRP | CMIP5 | 2100 | Gulzar et al. [20] |
| Iran | 34 Cities | SHRP/C-SHRP | PROPHET/LSTM1[2]/ ARIMA/EMP1[3] | 2061 | Dadaei et al. [21] |
| Italy | 71 Cities | SHRP | Italian Air Force Meteorological Service | 2033 | Viola et al. [22] |
| Morocco | 30 Cities | LTPP and SHRP | POWER[14] | 2080 | El Haloui et al. [23] |
| South Africa | Tshwane | – | CCAM1[5] | 2060 | Mokoena et al. [24] |
| United Arab Emirates | Sharjah | LTPP and SHRP | MRI-CGCM3 | 2070 | A. Abttan et al. [25] |
| USA | New Jersey | M-IOMM1[6] | CMIP | 2040 | Marath et al. [26] |
| USA | – | SHRP | USHCN1[7] and GCM | 2100 | Underwood et al. [27] |
| USA | 3 Districts in Virginia | – | GHCN1[8] | 2039 | Qiao et al. [28] |

[1] Environmental and Climate Change Canada

[2] Global Circulation Models

3Long Term Pavement Performance

4A2x Experiment from Coupled Global Climate Model 2

[5] B21 Experiment from Hadley Climate Model 3

6The strategic Highway Research Program

7Global warming forecast models

8Weather Research and Forecasting

9The Auto-Regressive Integrated Moving Average

1[0]Global Climate Model

1[1]Coupled Model Intercomparison Project 5

1[2]Long-Short Term Memory

[13] Environmental Master Plan

[14] Prediction of Worldwide Energy Resources

1[5]Conformal-Cubic Atmospheric Model

[6] The Modified Imposed Offset Morphing Method

[7] United States Historical Climatology Network

[8] Global Historical Climatology Network

was not considered in this analysis. The threshold of 3 million ESALs aligns with established practices in pavement design, including guidance from provincial standard specifications and the LTPPBind algorithm, both of which recommend grade bumping for traffic levels exceeding this threshold.

# 3 Analysis and Discussion

## 3.1 Sensitivity Analysis

To demonstrate the combined effect of site's climate factors and latitude on the High Pavement Temperature (HPT) and LPT for PG selection, sensitivity analysis was carried out as shown in Fig. 1a and b, respectively. It is evident from Fig. 1a that higher Degree Days (DD) levels correlate with increased HPT levels. In fact, DD serves as a critical parameter for assessing the combined effects of heat intensity and duration. While mean air temperature is a commonly used metric, it may not always accurately reflect regional climatic variations that influence asphalt performance, especially in regions with significant diurnal or seasonal temperature fluctuations. Regarding the effect of site's latitude on HPT, it was observed that northern regions with even moderate DD levels can still experience high HPT values. Latitude greatly impacts *CVPG*, with minimal variations in southern regions requiring negligible PG adjustments, while significant increases in northern regions demand larger adjustments to address extreme weather risks. As depicted in Fig. 1b, under the assumption of a constant standard deviation of 1, low air temperatures in northern sites emerge as the critical scenario for the lowest pavement temperatures. The nonlinear relationship between latitude and LPT means that as latitude increases, low-temperature conditions worsen, increasing the risk of cracking. This underscores the need for low PG adjustments to account for more extreme temperature fluctuations in colder regions. It is noteworthy that the database in the LTPP low-temperature model covers a limited latitude range, from 41.69 to 51.90 degrees, and low air temperature, from – 41.53 to 4.61°C [31]. This underscores the necessity of a more robust model in future to include a broader range of latitudes and climatic conditions for improved accuracy in pavement temperature predictions.

### 3.2 Predicted Design Temperatures

Accurate design temperature prediction is crucial for selecting a suitable asphalt binder that matches the respective climate, ensuring the design of climate-resilient pavements. Regional differences in warming rates and long-term projections, underscores the need for updated design temperatures that account for the full spectrum of temperature changes anticipated across the country.

Figure 2 compares the projected HPTs under two different climate scenarios, RCP 4.5 and RCP 8.5, across the four time periods. Under the RCP 4.5 scenario, a moderate climate change projection, temperatures gradually increase over time. From 2000 to 2019, HPTs mostly range between 25 and 40°C, particularly in central and southern Canada. By 2020–2039, areas in Alberta, Saskatchewan, Manitoba, and Ontario see temperatures reaching up to 45°C. This warming trend continues into 2040–2059, with HPTs extending further north and reaching between 40 and 50°C. By 2060–2079, large areas in the central provinces exceed 50°C, indicating a substantial rise in temperature.

The RCP 8.5 scenario, representing a more severe climate change projection, shows a much sharper increase in HPTs. From 2000 to 2019, similar trends to RCP 4.5 are observed, but the temperature rise accelerates significantly in subsequent periods. By 2020–2039, many regions already experience temperatures between 40 and 50°C. In 2040–2059, temperatures in large parts of Alberta, Saskatchewan, Manitoba, and Ontario exceed 50°C, with some areas nearing 55°C. By 2060–2079, almost the entire southern half of Canada is projected to experience temperatures above 50°C, with extensive areas reaching up to 55°C.

Figure 3 depicts projected changes in LPTs under RCP 4.5 and RCP 8.5 scenarios, respectively. In the RCP 4.5

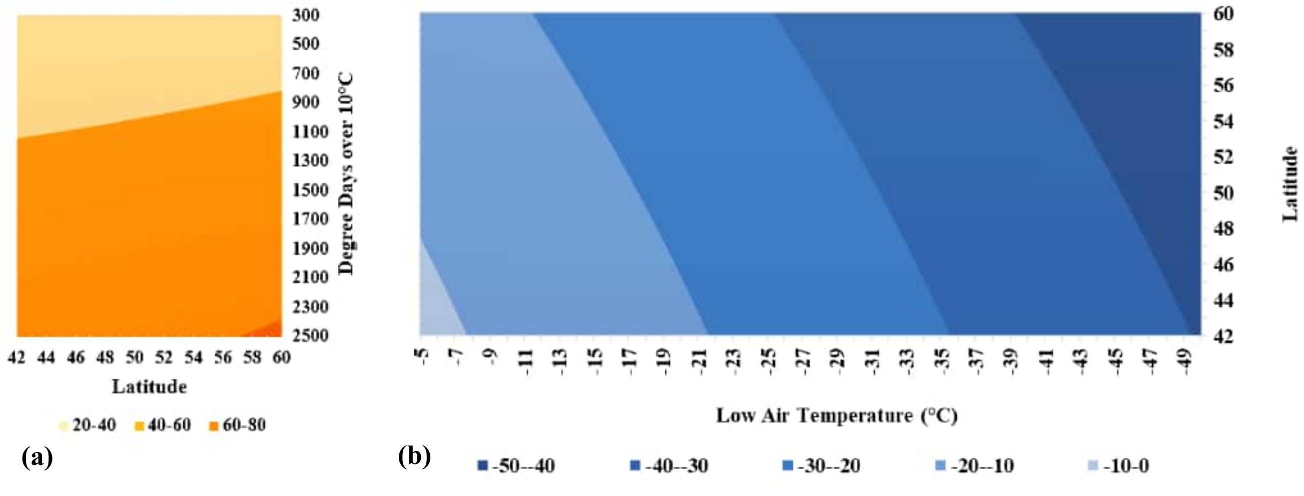


**Fig. 1** Multivariable (2-way) sensitivity analysis graph demonstrating **a** HPT, **b** LPT across various climate and latitude ranges

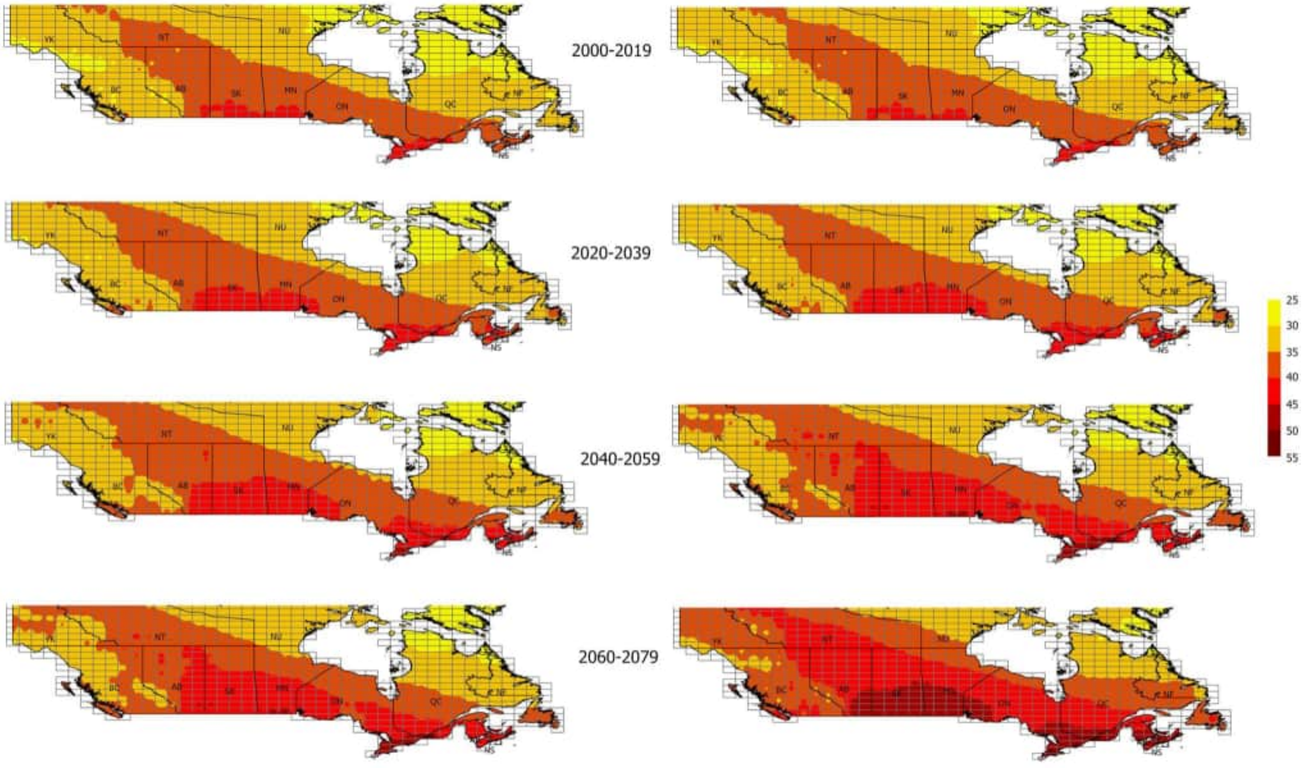


**Fig. 2** Projected HPT Results for RCP4.5 (left) and RCP 8.5 (right) over four analysis cycles

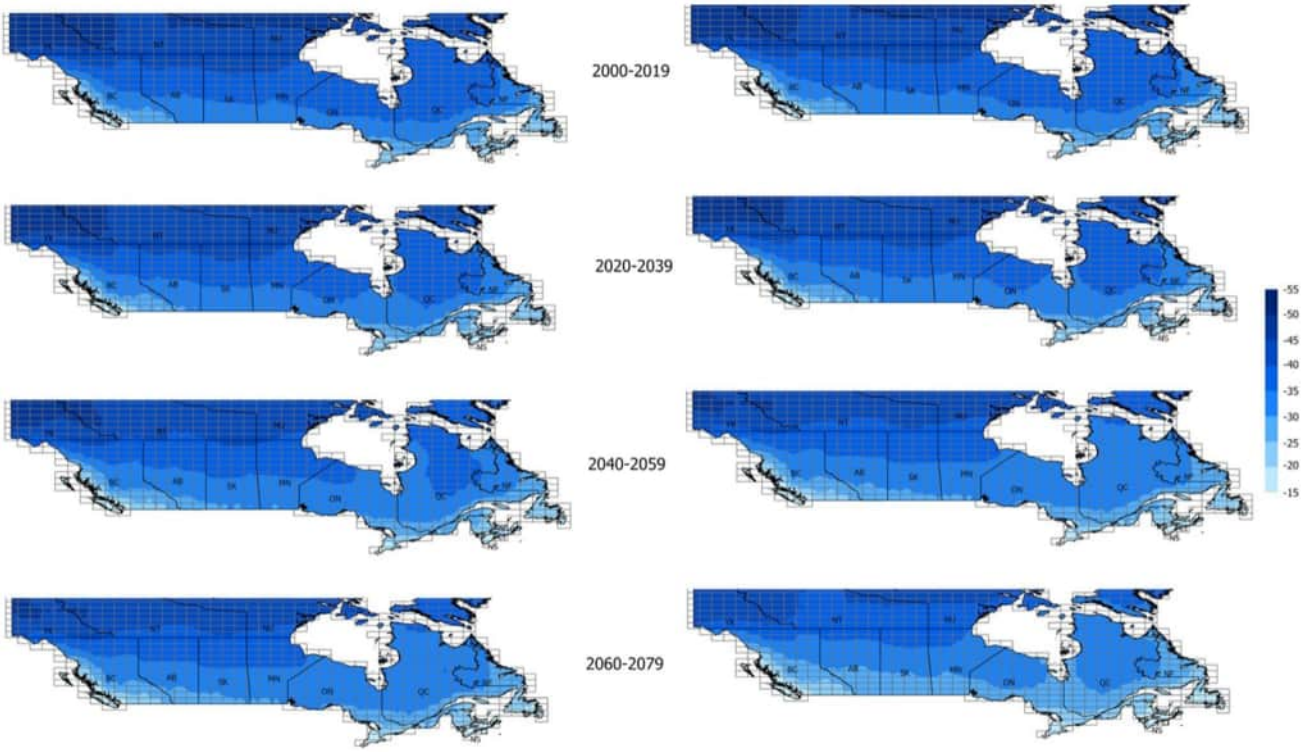


**Fig. 3** Projected LPT Results for RCP4.5 (left) and RCP8.5 (right) over four analysis cycles

scenario, the coldest temperatures during the 2000–2019 period range from – 55°C in northern regions such as Yukon, Northwest Territories, and Nunavut. Central and southern regions experience temperatures between – 25 and – 45°C. By 2020–2039, a warming trend is observed, with northern regions seeing LPTs around – 45 to – 50°C, and central and southern regions warming to – 25°C to – 35°C. This warming trend continues into the 2040–2059 period, with the coldest areas in the north now experiencing temperatures of – 40 to – 45°C, while central and southern regions see temperatures between – 20 and – 30°C. By 2060–2079, northern regions have warmed to around – 35 to – 40°C, with most of Canada experiencing less severe winter conditions, and central and southern regions experiencing LPTs between – 15 and 25°C.

In the RCP 8.5 scenario, the warming trend is more pronounced. During 2000–2019, the coldest LPTs reach – 55°C in northern regions, with central and southern areas experiencing temperatures from – 25 to – 45°C. From 2020 to 2039, the warming trend accelerates, with northern regions showing temperatures primarily around – 45 to – 50°C, and central and southern regions warming to – 25 to – 35°C. By 2040–2059, the coldest temperatures in northern regions are around – 40 to – 45°C, with central and southern regions further warming to – 20 to – 30°C. By 2060–2079, the warming trend is most pronounced under RCP 8.5, with northern regions seeing temperatures around – 35 to – 40°C, and central and southern regions experiencing less severe winter conditions, with temperatures warming to – 15 to – 25°C. Both RCP scenarios indicate a clear warming trend over time, with RCP 8.5 showing a more rapid and pronounced warming compared to RCP 4.5.

These projections suggest asphalt binders may need to accommodate less severe winter temperatures over time, particularly under RCP 8.5. However, it is crucial to remain cautious and continually validate these trends through rigorous field studies and temperature monitoring, as the actual impacts could vary significantly due to regional climate variability. For example, insights from recent local studies [32, 33] have partially demonstrated the utility of LTPP models in projecting pavement temperature trends in Ontario, Canada. Despite some limitations, these models, also used in the PGAC 3 framework, have been validated against Road Weather Information Systems (RWIS) data, a network of roadway sensors that collect real-time weather and pavement data. Validation studies suggest that LTPP models offer reasonably accurate predictions in regional contexts, though their reliability may vary across different geographic and climatic conditions. This highlights the importance of interpreting long-term projections and considering their implications for binder selection in the context of a changing climate.

### 3.3 Impacts on Asphalt Binder PG Selection

With respect to the high-temperature grade (XX), the progression from Cycle 1 through Cycle 4 shows an increasing trend in the number of grids undergoing grade changes, indicating a direct response to rising temperatures. According to Fig. 4, by mid and late century, more grids mainly in southern Ontario could experience changes in high-temperature grade under RCP 4.5. However, under RCP 8.5 scenario, as shown in Fig. 4, these changes could exacerbate, with a notable 54 affected grids by Cycle 4, spanning multiple provinces with a concentration in southern Prairies and central Canada.

Regarding the low-temperature grade (YY), the impact is more pronounced from the onset, with 89 grids showing changes from Cycle 1 to Cycle 2 under RCP4.5, as illustrated in Fig. 5. This pattern intensifies with 179 grids changing in the subsequent cycle, highlighting a widespread impact across provinces, with parts of Quebec and Ontario being the most affected. The RCP8.5 scenario further amplifies these changes, with 131 grids affected from Cycle 1 to Cycle 2, escalating to 248 and then 256 grids in subsequent cycles, as shown in Fig. 5. It is important to note that, due to winter warming, some regions may no longer experience very cold temperatures. However, using PG grades with a low-end temperature grade above -22 (e.g., PG XX-16 or PG XX-10) may lead to some issues as limited experience indicates an increased risk of block cracking with – 16 or – 10 grades.

Solely from a climate standpoint, PG 46-34 binder was found to be the most common grade, covering about 38% of the grid cells by the last cycle (2060–2079) under RCP 8.5. In total, four binders (PG 46-28, 46-34, 46-40, and 46-46) cover about 85% of the entire grid cells. Stiffer binders, such as PG 58-22, PG 52-22, and PG 52-28, will be in high demand in Southern Ontario, Quebec, and the Prairies. Particularly, these regions are heavily populated and have dense road networks. Although grade bumping current paper does not consider, it must be factored into future mixture designs when necessary for the heavy traffic in these regions to ensure satisfactory performance. It is important to consider the limitations imposed by the relatively coarse temperature increments of 6 °C used in the PG grading system. Given this broad range, it may be beneficial to recommend optional grade bumping for locations situated near the grid borders, close to the boundary of a grid that requires a stiffer PG binder. These areas may benefit from one increase in binder grade (+ 6 °C), which is likely to double the stiffness of the binder according to literature [34].

### 3.4 Case Study: Comparative Assessment of Pavement Life

Drawing from the previous section, this part of the study is articulated to assess the effectiveness of the proposed climate

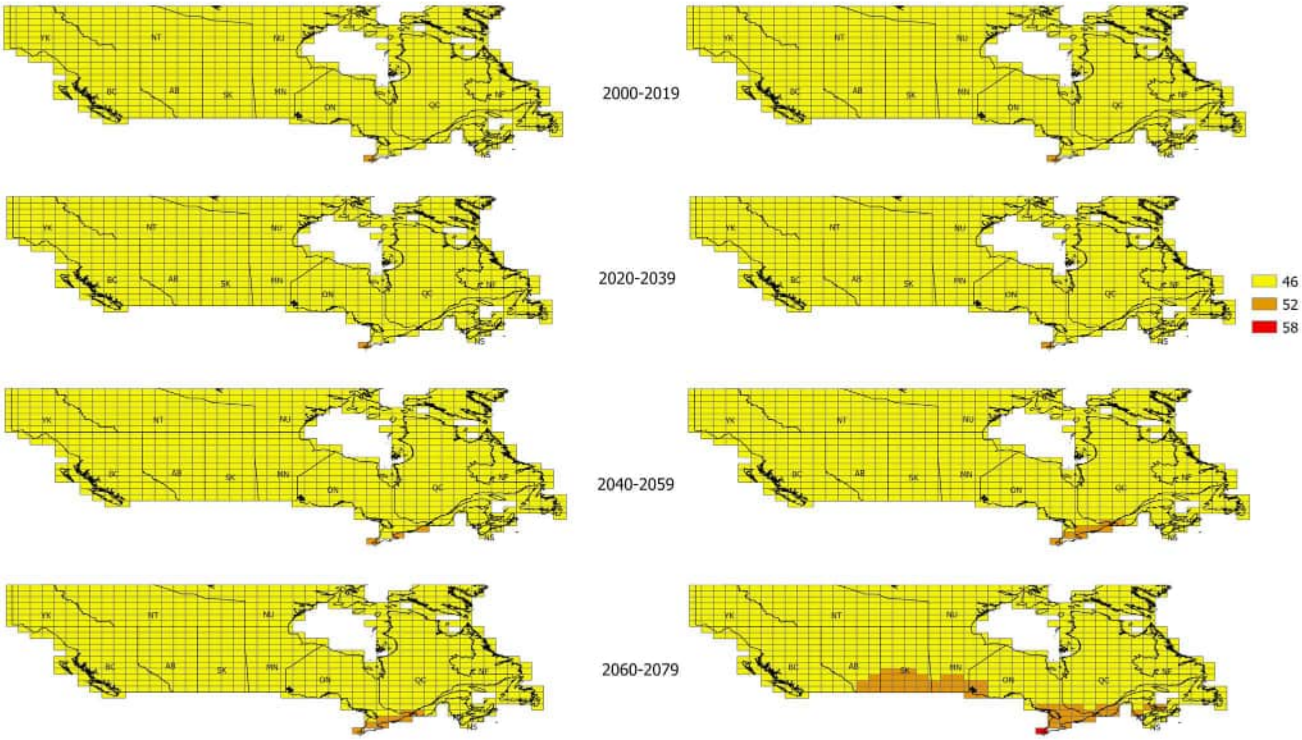


**Fig. 4** PGXX results under RCP 4.5 (left) and RCP 8.5 (right), reflecting changes over analysis cycles

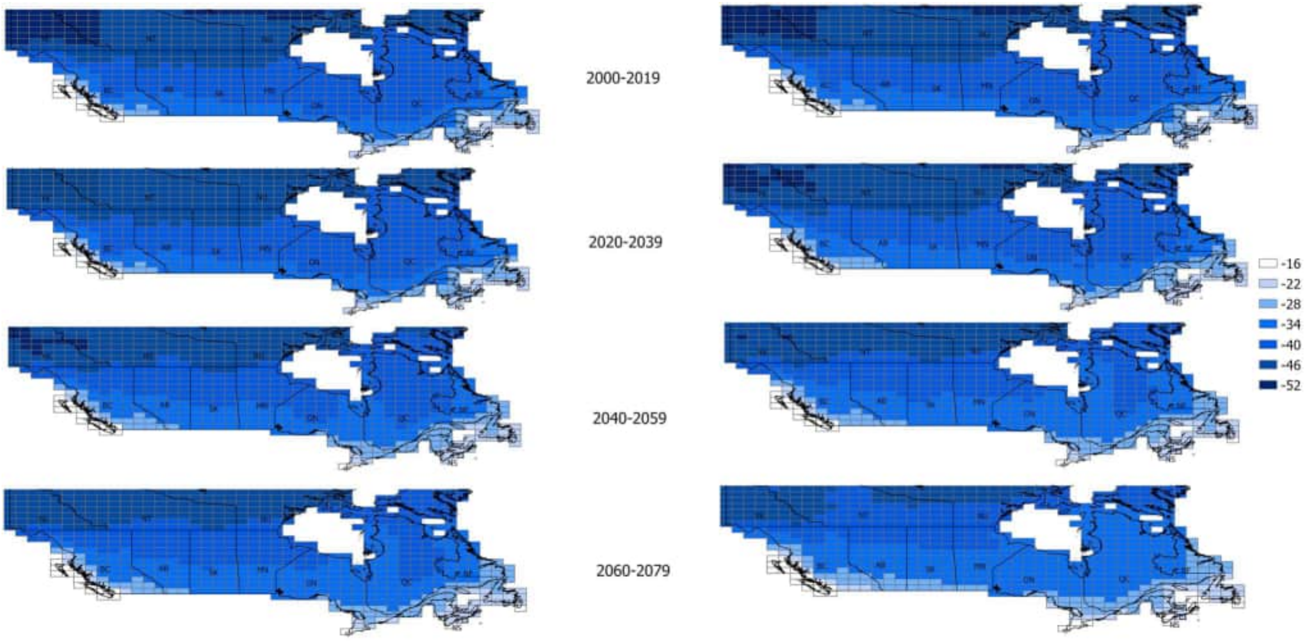


**Fig. 5** PGYY Results for RCP4.5 (left) and RCP8.5 (right), reflecting changes over analysis cycles

change adaptation strategy—the adjustment of asphalt binder PG grades—within the broader context of pavement life. Windsor in southwestern Ontario was selected as case study site for this analysis, to examine the impact of adjusted asphalt binder PG grades on pavement life. A typical flexible pavement composed of a 180 mm asphalt concrete layer on top of 300 mm granular material over a strong subgrade with a resilient modulus of 50 MPa was assumed. A nominated in-service Weighted Mean Annual Pavement Temperature (*WMAPT*) according to the Shell Pavement Design Manual approach [35], was first calculated before estimating a representative asphalt layer modulus. Equations (5–7) show the steps involved in establishing *WMAPT*.

$$WF = 10^{\left(-1.224+0.06508T_{air}-0.000145T_{air}^{2}\right)} \tag{5}$$

$$WMAAT = 19.66 + 16.91\log WF + 0.3117 * (\log WF)^{2} \tag{6}$$

$$WMAPT = -12.4 + \frac{6.32(WMAAT)}{\ln(WMAAT)} \tag{7}$$

In which *WF* is the temperature weighting factor for each month, $T_{air}$ is the monthly average air temperature and *WMAAT* is the Weighted Mean Annual Air temperature.

As depicted in Fig. 6, the WMAPT is projected to increase with higher air temperatures, particularly under RCP 8.5 compared to RCP 4.5. In order to predict the asphalt modulus corresponding to each WMAPT, Witczak's approximation method was then used as shown in Eq. (8).

$$\begin{aligned} logE^{*} = {} & -1.25 + 0.029\rho_{200} - 0.0018\left(\rho_{200}\right)^{2} \\ & - 0.0028\rho_{4} - 0.058V_{a} - 0.822\frac{V_{beff}}{V_{beff} + V_{a}} \\ & + \frac{3.872 - 0.0021\rho_{4} + 0.004\rho_{38} - 0.000017\left(\rho_{38}\right)^{2} + 0.0055\rho_{34}}{1 + e^{(-0.603313-0.313351log(f)-0.3935321log(\eta))}} \end{aligned} \tag{8}$$

where, $E^{*}$ is the dynamic modulus of the mix ($10^{5}psi$), $f$ is the loading frequency (Hz), $\rho_{200}$ is % passing the 0.075 mm sieve, $\rho_{4}$ is % retaining on the 4.76 mm sieve, $\rho_{38}$ is % passing the 9.5 mm sieve, and $\rho_{34}$ is % passing the 19 mm sieve, $V_{\mathrm{beff}}$ is the % effective asphalt content, $V_{\mathrm{a}}$ is the % air voids (by volume of mix) and $\eta$ is the binder viscosity at temperature of interest ($10^{6}$ P) which was separately estimated using Eq. (9).

$$\log\log\eta = A + VTS\log T_{R} \tag{9}$$

where $\eta$ is the binder viscosity (cP), A and viscosity temperature sensitivity (VTS) constants are regression parameters related to each PG type, extracted from the Mechanistic-Empirical Pavement Design Guide (MEPDG) [36], and $T_{R}$ is the degrees Rankine.

Tensile strains at the bottom of asphalt layer, $\varepsilon_{t}$, and compressive strain on top of subgrade, $\varepsilon_{c}$,were predicted using ILLI-PAVE algorithm. Equation (10) represents the algorithm based on a 9000-lb (40.1-kN) circular load with a contact pressure of 80 psi (552 kPa), equivalent to one dual wheel of the standard 18,000-lb (81-kN) single-axle load [37].

$$\begin{aligned} \log\varepsilon_{t} = {} & 2.9496 + 0.1289h_{1} - \frac{0.5195}{h_{1}}\log h_{2} \\ & - 0.0807h_{1}\log E_{1} - 0.0408\log K_{1} \end{aligned} \tag{10}$$

$$\log\varepsilon_{c} = 4.5040 + 0.0738h_{1} - 0.0334h_{2} - 0.3267\log E_{1} - 0.0231K_{1} \tag{11}$$

in which $\varepsilon_{t}$ and $\varepsilon_{c}$ are in *microinch* per *inch*, $h_{1}$ is the asphalt layer thickness in *inches*, $h_{2}$ is the base thickness in *inches*, $E_{1}$ is the asphalt modulus in *ksi*, and $K_{1}$ is the break-point resilient modulus of subgrade in *ksi*. Finally, the Asphalt Institute's failure criteria for fatigue cracking of 20% of the total area, as shown in Eq. (12), and rutting of 0.5 inch, as shown in Eq. (13), were used to calculate the $N_{f}$ and $N_{d}$ which are the allowable numbers of load repetitions.

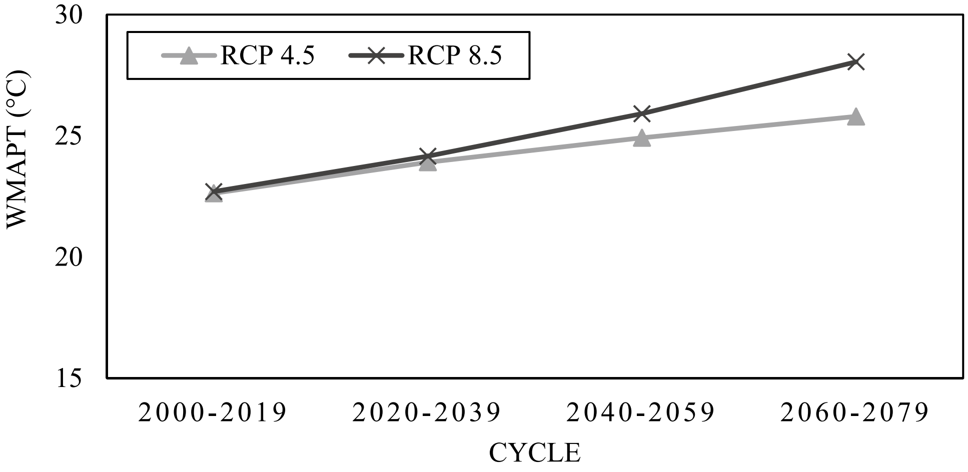


**Fig. 6** Calculated Weighted Mean Annual Pavement Temperature (WMAPT) for Windsor, Ontario

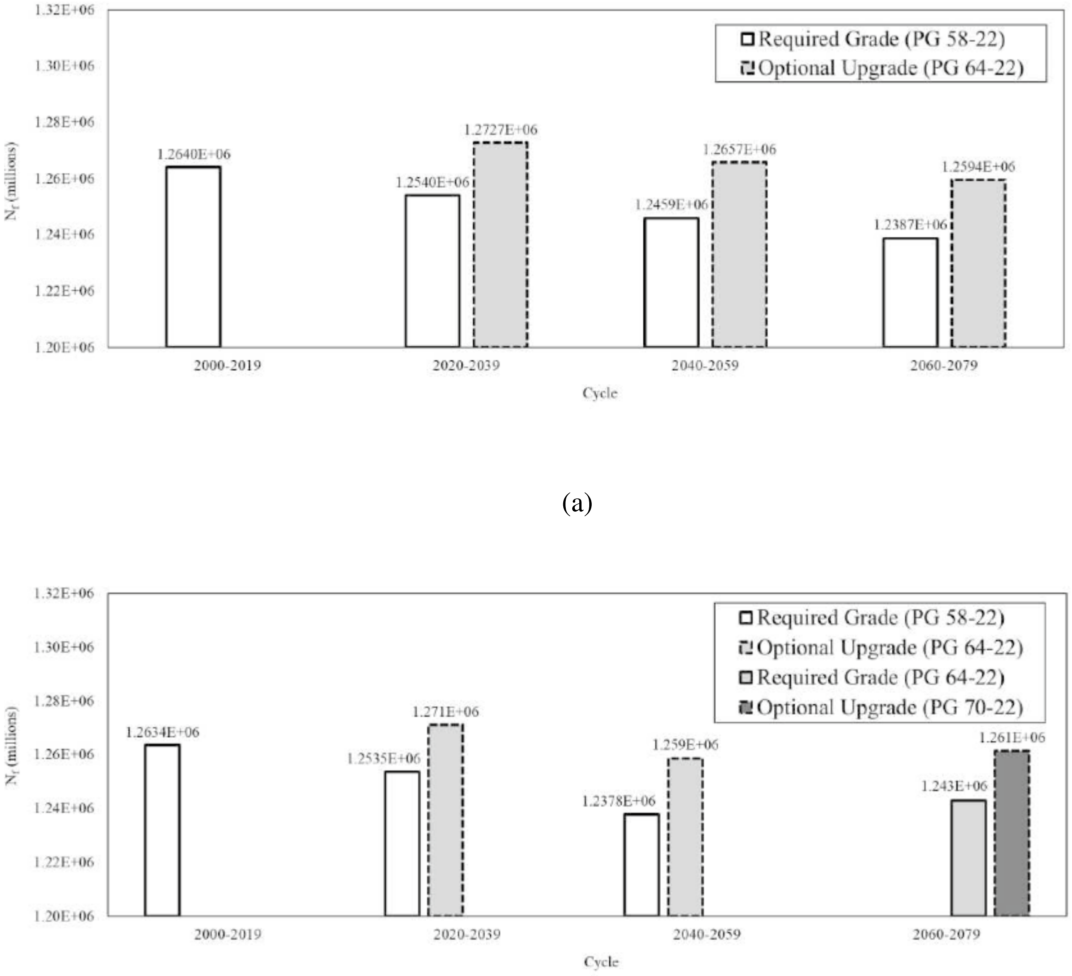
$$N_f = f_1(\epsilon_t)^{-f_2}(E_1)^{-f_3} \tag{12}$$

$$N_d = f_4(\epsilon_c)^{-f_5} \tag{13}$$

where, $f_1$, $f_2$, $f_3$, $f_4$ and $f_5$ are constant values suggested to be 0.0796, 3.291, 0.854, $1.365 \times 10^{-9}$ and 4.477 respectively.

Figure 7 a, under RCP 4.5, demonstrates that PG 58-22 meets the minimum climate requirements in future. However, opting for an optional upgrade to PG 64-22, rather than adhering to the climate-mandated PG 58-22, enhances the fatigue resistance of the pavement under projected future climate conditions. In other words, continued adherence to PG 58-22 in this case may still lead to a reduction in pavement service life over time. Figure 7b illustrates the performance under RCP 8.5, where PG 58-22 remains suitable for climate conditions until the period 2040–2059, yielding comparable benefits with the optional upgrade to PG 64-22. However, beyond 2060–2079, PG 58-22 fails to meet climate requirements, necessitating the adoption of PG 64-22. Similarly, opting for an optional upgrade to PG 70-22 during this phase enhances the pavement's fatigue life significantly.

When considering the impacts of climate change, rutting emerges as an even more critical performance indicator due to its strong dependence on temperature. At elevated temperatures, the binder transitions from an elastic to a more viscous state, reducing its ability to resist permanent deformation. As climate change raises temperatures, the decreased stiffness of asphalt increases its susceptibility to rutting under heavy vehicle loads [38–40]. This may lead to poor driving conditions, including an elevated risk of hydroplaning due to water accumulation in ruts and reduced vehicle handling [41]. As shown in Fig. 8a under the RCP 4.5 scenario, the performance of PG 58-22 declines as temperatures rises in subsequent cycles. Meanwhile, a precautionary upgrade to PG 64-22, accounting for the warmer



(a)

(b)

**Fig. 7** Predicted fatigue cracking life under **a** RCP4.5 and **b** RCP8.5

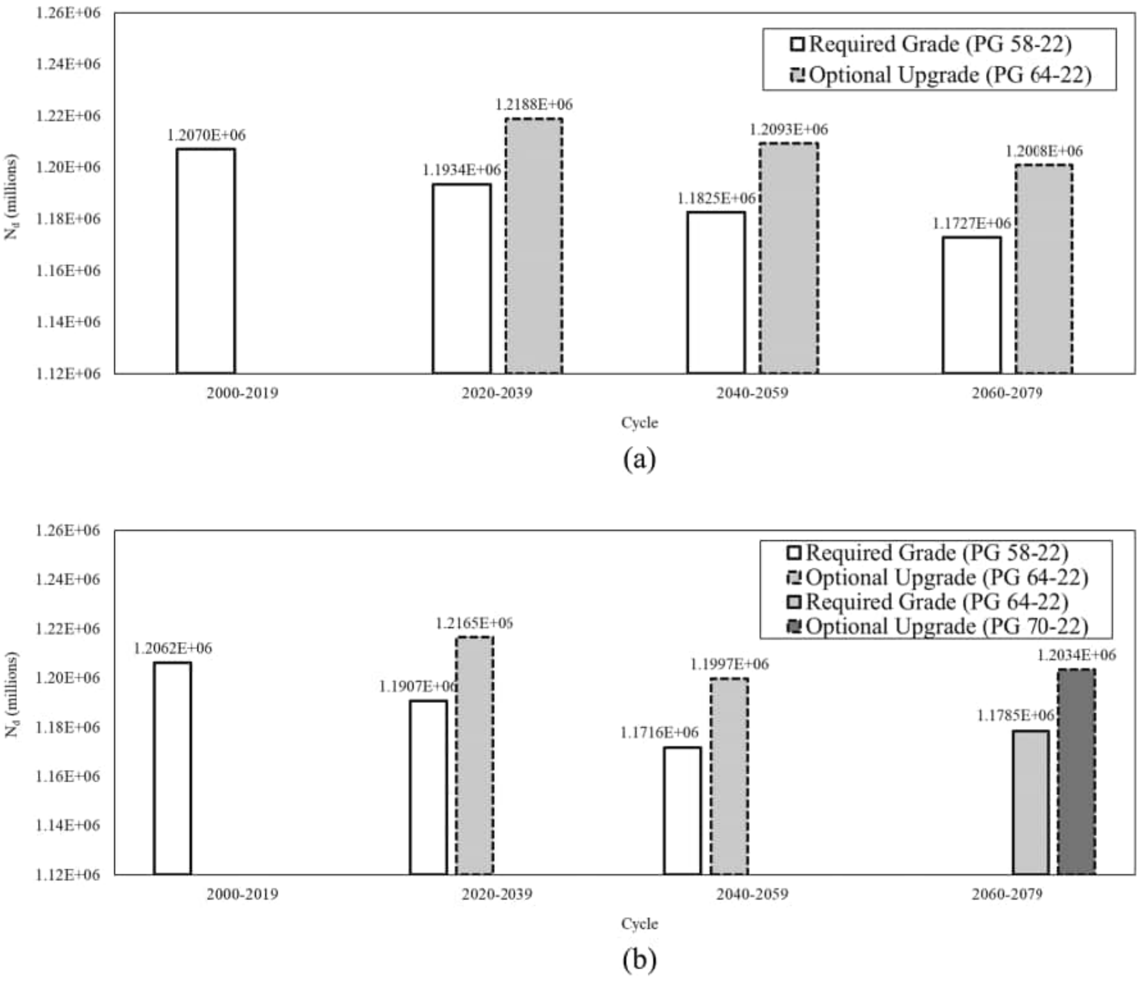


**Fig. 8** Predicted rutting life under **a** RCP4.5 and **b** RCP8.5

conditions, enhances the pavement's rutting resistance during cycles 2, 3, and 4. Similarly, Fig. 8b under the more severe RCP 8.5 scenario reveals a comparable trend, albeit with a shorter time frame for PG 58-22's effectiveness. The option of transitioning to PG 64-22 during cycles 2 and 3 significantly improves rutting resistance, aligning with the projected climatic demands. By cycle 4, PG 64-22 becomes a necessary choice, while an optional upgrade to PG 70-22 further enhances rutting resistance, ensuring sustained performance under extreme warming conditions.

The above case study demonstrates that proactive upgrades to PG could extend service life under projected future climate conditions. While current standards may meet existing climate requirements, they are likely inadequate for long-term performance under evolving climate scenarios. This adaptive strategy is applicable to other regions with similar climate projections, providing a framework for enhancing pavement resilience and sustainability in the face of climate change.

## 4 Conclusions

This paper evaluated the relative impact of climate change on minimum required PG for asphalt pavement in Canada via Performance-Graded Asphalt Cement under a Changing Climate (PGAC3) tool with focusing on short, medium and long-term future. Results showed that some of the examined regions may require adjustments depending on the RCP scenarios. The case study conducted also illustrated the potential performance benefits of upgrading binder grades in line with projected temperature shifts. Integrating climate projections into asphalt binder selection is essential for developing resilient asphalt mixes. Overall, this approach not only enhances the performance of pavements but also aligns with broader goals of sustainable development.

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**Data Availability** Data analyzed in this study were a re-analysis of existing data, which are openly available at locations cited in the reference section.

## Declarations

**Conflict of interest** The authors declare there are no competing interests.

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