

Performance evaluation of bio-based asphalt pavements

Accelerated pavement testing and field monitoring

Abubeker Ahmed, Jiqing Zhu, Kenneth Olsson, Patryk Witkiewicz and Xiaohu Lu

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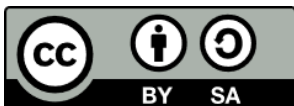
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Titel

Utvärdering av prestanda hos biobaserade asfaltbeläggningar. Accelererad provning och fältförsök

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Project

Bio-based asphalt for sustainable infrastructure

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Vinnova via InfraSweden

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Kort sammanfattning

Denna rapport presenterar resultaten från ett projekt som syftade till att utvärdera prestandan hos asfaltbeläggningar med biobaserade bitumenbindemedel, med fokus på långsiktiga strukturella egenskaper och ytegenskaper. Projektet studerade biobindemedel innehållande talloljebeck och ett polymermodifierat bitumen (PMB) med biogen komponent som alternativ till konventionella bituminösa bindemedel. Både penetrationsbitumen och PMB ingick i projektet.

Försöksprogrammet omfattade fullskaliga accelererade provningar (accelerated pavement testing, APT) med hjälp av en Heavy Vehicle Simulator (HVS) vid VTI:s inomhusanläggning i Linköping, kompletterat med uppföljning av ytans egenskaper på en gång- och cykelväg som anlades i Sundbyberg, Stockholm. Fyra fullskaliga beläggningsskonstruktioner byggdes med asfaltmassor producerade vid asfaltverk. Två referensbeläggningar med penetrationsbitumen respektive PMB samt en beläggning med bitumen/talloljebeck och en beläggning med PMB med biogen komponent. Konstruktionerna instrumenterades med töjningsgivare för asfalt samt temperatursensorer för att mäta temperaturer och dragtöjningar relaterade till utmattningssprickbildning. De fullskaliga proven genomfördes genom upprepade belastningar vid beläggningstemperaturerna 10 °C och 20 °C.

Resultaten från de fullskaliga proven visade att beläggningar med biobaserade bindemedel uppvisade likvärdiga eller förbättrade stabilitetsegenskaper (mindre spårbildning) jämfört med konventionella referensstrukturer, särskilt vid förhöjda temperaturer. De uppmätta dragtöjningarna i asfaltlagrens underkant var generellt lägre eller jämförbara för de biobaserade konstruktionerna, vilket indikerar gynnsamma utmattningsrelaterade förutsättningar. Inga operativa problem observerades vid asfaltproduktion, transport eller läggning, och de biobaserade asfaltmassorna uppvisade god bearbetbarhet och packningsegenskaper.

Gång- och cykelvägen följdes upp under en treårsperiod avseende textur, medelprofildjup (MPD) samt jämnhet, International Roughness Index (IRI). De uppmätta värdena låg under hela uppföljningsperioden inom det intervall som rapporterats för nyanlagda gång- och cykelvägar i Sverige. Sammantaget visar resultaten att biobaserade asfaltbeläggningar är tekniskt genomförbara och utgör ett lovande hållbart alternativ för asfaltbeläggningar utan att kompromissa med prestandan.

Nyckelord

Bioasfalt, penetrationsbitumen, polymermodifierat bitumen (PMB), talloljebeck

Abstract

This report presents the results of a project aimed at evaluating the performance of asphalt pavements incorporating bio-extended bituminous binders, with a focus on long-term structural behaviour and surface characteristics. The project focused on bio-extended penetration-graded bitumen containing Tall Oil Pitch (TOP) and a polymer-modified bitumen (PMB) with a biogenic component as alternatives to conventional bituminous binders. Both penetration-graded bitumen and PMB were investigated.

The experimental program consisted of full-scale accelerated pavement testing (APT) using a Heavy Vehicle Simulator (HVS) at the indoor testing facility of the Swedish National Road and Transport Research Institute (VTI), complemented by surface performance monitoring of a walking and cycling path constructed in Sundbyberg, Stockholm. Four full-scale pavement structures, penetration-graded reference and its bio-extended variant, as well as PMB reference and PMB with biogenic component, were constructed using asphalt mixtures produced in asphalt plants. The pavement structures were instrumented with asphalt strain gauges (ASGs) and temperature sensors to measure temperatures and tensile strains related to fatigue cracking. Rutting performance was evaluated through repeated loading at test temperatures of 10 °C and 20 °C.

The APT results showed that the structures incorporating bio-based binders exhibited similar or improved resistance to permanent deformation compared with conventional reference structures, particularly at the elevated temperature of 20 °C. Measured tensile strains at the bottom of the asphalt layers were generally lower or comparable for bio-based variants, indicating favourable fatigue-related condition. No operational challenges were observed during asphalt production, transportation, or paving, and the bio-based mixtures demonstrated good workability and compaction characteristics.

The walking and cycling path was monitored over a three-year period to assess surface texture and roughness using Mean Profile Depth (MPD) and International Roughness Index (IRI). The measured values remained within the range of reference data for newly paved paths in Sweden throughout the monitoring period. Overall, the results demonstrate the technical feasibility of bio-based asphalt mixtures as a sustainable alternative for asphalt pavements without compromising performance.

Keywords

Bio-asphalt, Penetration-graded bitumen, Polymer-modified bitumen (PMB), Tall oil pitch (TOP)

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Summary

This report presents the results of a project aimed at evaluating the performance of asphalt pavements incorporating bio-extended bituminous binders, with the objective of reducing the climate impact of road infrastructure while maintaining high technical performance. Bitumen containing Tall Oil Pitch (TOP) and a polymer-modified bitumen (PMB) with a biogenic component were evaluated. Both penetration-graded bitumen and PMB were included as references in the investigation.

The study combined full-scale accelerated pavement testing (APT) and field monitoring. Full-scale pavement structures were constructed at the Swedish National Road and Transport Research Institute (VTI) using asphalt mixtures produced in commercial asphalt plants. Four test structures were evaluated: a penetration-graded reference and its bio-extended variant, as well as a PMB reference and its bio-extended variant. The structures were tested using a Heavy Vehicle Simulator (HVS) under controlled indoor conditions. Performance was assessed in terms of resistance to permanent deformation (rutting) and tensile strains at the bottom of the asphalt layers, which are indicative of fatigue cracking initiation.

The full-scale test results showed that pavements incorporating bio-based binders performed similarly to, or better than, the corresponding reference structures. At a test temperature of 10 °C, rutting differences between bio-extended and reference pavements were small, while at 20 °C the bio-based variants exhibited improved resistance to permanent deformation. Measured tensile strains were generally lower or similar for the bio-extended structures, particularly at the elevated temperature, indicating favourable structural performance. No adverse effects were observed during asphalt production, transport, or paving, and the bio-extended mixtures were found to have good workability and compaction characteristics.

To complement the accelerated testing, a walking and cycling path was constructed in Sundbyberg, Stockholm, using a bio-extended asphalt mixture. Surface texture and evenness were monitored over a three-year period using Mean Profile Depth (MPD) and International Roughness Index (IRI). The results showed stable surface characteristics, with MPD and IRI values remaining within the range reported for newly constructed walking and cycling paths in Sweden.

Overall, the project demonstrates that the investigated bio-extended bituminous binders can be successfully used in asphalt pavements without compromising structural or surface performance. The findings support the potential of bio-extended binders as a viable and sustainable alternative in road and pavement applications.

While this project employed full-scale APT testing to evaluate pavement performance with respect to rutting and fatigue-related indicators, further studies under real traffic and environmental conditions are recommended to capture long-term field performance more comprehensively.

Future work should include long-term in-service monitoring of road sections incorporating bio-based binders under varying climatic conditions and traffic levels. Additional research is also recommended to evaluate other performance aspects such as low-temperature cracking, moisture sensitivity, and ageing-related distresses.

Foreword

This report presents the results of a project conducted by VTI in cooperation with industrial partners Skanska and Nynas, as well as the Royal Institute of Technology (KTH). The project was divided into three work packages. Laboratory investigations were carried out in the first work package, whereas full-scale and field investigations were conducted in the second work package. The third work package dealt with the life cycle analysis of pavement structures with bio-based binders. This report specifically presents the results of the second work package. In addition to the in-kind contributions of the partners, the project was financed by the following:

- The Swedish Transport Administration (Trafikverket), via the Industry program BVFF – Bana väg för framtiden, registration number: TRV 2021/79537
- SBUF – Svenska Byggbranschens Utvecklingsfond (The Development Fund of the Swedish Construction Industry), project number: 14070
- Vinnova, via strategic innovation program InfraSweden, registration number: 2022-00166

The Group for Alternative Pavement Materials (Alternativa beläggningskonstruktioner) served as the reference group for the project. The group has representatives from Skanska, Nynas, the Swedish Transport Administration, NCC, Peab Asfalt, Svevia, Total Energies, and VTI, with the following external members:

- Henrik Arnerdal, Swedish Transport Administration
- Mats Wendel, Peab Asfalt
- Mats Jonsson, Svevia
- Lars Jansson, Peab Asfalt
- Krister Persson, Total Energies
- Jonas Ekblad, NCC
- Jenny-Ann Östlund, Nynas
- Kenneth Olsson, Skanska

Microsoft Copilot was used for language editing and to improve readability. The authors reviewed all content and take full responsibility for the published report.

Linköping, June 2026

Abubeker Ahmed
Project leader

Granskare/Examiner

Yared Dinegda, VTI.

De slutsatser och rekommendationer som uttrycks är författarens/författarnas egna och speglar inte nödvändigtvis myndigheten VTI:s uppfattning.

The conclusions and recommendations in the report are those of the author(s) and do not necessarily reflect the views of VTI as a government agency.

Publikationen godkänd för publicering/Publication approved for publication

Björn Kalman, VTI.

1. Introduction

1.1. Background

Several studies have shown that the road transport sector, including the infrastructure construction, maintenance, and operation phases releases a large amount of CO₂ to the environment. Consequently, countries worldwide are implementing various strategies to reduce emissions from the road infrastructure sector. In this regard, the Swedish Transport Administration (Trafikverket) is undertaking various adjustments and is currently evaluating different technologies that can be implemented to reduce emissions related to the road infrastructure.

With regard to the climate impact of road construction processes, various measures such as warm or cold mix asphalt technologies to reduce energy consumption, the use of alternative road materials with a low carbon footprint such as recycled materials, and high-performance (long-lasting) modified pavement materials have been evaluated. Recent investigations have also proposed innovative low-carbon-footprint solutions using renewable plant-based oils, such as tall oil pitch (TOP), from the forest and paper industry. TOP is used to extend bitumen (also referred to as bio-based binder or bio-extended binder) by partially replacing the bitumen binder in asphalt pavements.

Laboratory investigations carried out on selected bio-based binders using TOP found that TOP is fully miscible with bitumen, and that desired standard paving-grade specifications can be achieved for selected base bitumen and TOP dosages. In general, improved performance was observed when using bio-binders (Ingrassia et al., 2020). These investigations are primarily based on laboratory studies of binders and asphalt mixtures, focusing on stiffness and fatigue properties at both binder and mixture levels. A cradle-to-gate carbon footprint analysis of bio-based binders indicated that they have the potential to be carbon-neutral materials (Lu et al., 2020).

Laboratory performance tests on bio-based binders and asphalt mixtures produced with these binders indicated similar or improved overall performance compared with conventional neat binders. Additionally, results from limited full-scale field tests indicated promising performance levels and showed no significant distresses so far. Furthermore, in the field tests, no operational differences were observed with respect to mixing and paving processes. The field tests conducted are relatively newly constructed. It is important to note that long-term durability and performance of asphalt pavements are key aspects of sustainability, as longer pavement life results in less maintenance, lower resource use, reduced energy consumption, and ultimately reduced environmental impacts. Therefore, long-term pavement performance must be considered when estimating life-cycle environmental and economic costs and assessing pavement structural performance.

This report presents results from part of a larger project aimed at evaluating the long-term performance of asphalt mixtures made with bio-based binder. The project consisted of three work packages (WPs). Work Package 1 (WP1) focused on laboratory characterization of bio-based bitumen binders and asphalt mixtures. Work Package 2 (WP2) focused on full-scale evaluation of pavement structures made with bio-based asphalt mixtures using accelerated full-scale testing. The life cycle assessment of the bio-based binders was conducted in WP3. The results of WP1 and WP3 are reported in a separate report (Zhu et al., 2025). This report presents the results of WP2, which focuses on the full-scale evaluation of bio-based asphalt mixtures.

2. Objectives and scope

The main objective of this project is to evaluate the long-term performance of asphalt pavement structures made with bio-based binders by accelerated full-scale testing and field monitoring. Two types of binders are considered. For penetration-graded bitumen, the bio-based binder consists of partially replacing fossil-based bitumen with plant-based bio-oil (TOP). For polymer-modified bitumen (PMB), a PMB containing a biogenic component is used. The focus is on resistance to permanent deformation and fatigue cracking, which are evaluated using full-scale accelerated pavement testing.

Additionally, a walking and cycling path was constructed to evaluate surface characteristics such as texture and roughness.

A key objective is to facilitate and support next-generation road pavement design and construction processes, and to provide the asphalt industry and Swedish Transport Administration with relevant knowledge regarding bio-extended binders.

The outcomes of this project can assist in understanding the effects of bio-based binders, as well as polymer-modified binders containing biogenic components, on full-scale structural behaviour and the long-term development of pavement performance. The project complements laboratory-scale studies and thus contributes to further clarifying the effects of using bio-based binders on life-cycle costs and the long-term climate footprint of these asphalt mixtures.

3. Experimental program

3.1. Overview of the test campaign

The full-scale accelerated pavement testing (APT) program was conducted at the indoor test facility of VTI in Linköping, Sweden. The VTI indoor full-scale test facility consists of three test pits that are 3 m deep, 5 m wide, and 15 m long (Wiman, 2006; Saevarsdottir et al., 2016). The sides and bottom of the test pits are made of concrete. The groundwater level within the test pits can be varied by adding water to the pavement structure through an installation at the bottom of the pit. The pavement structures constructed in the test pits are usually instrumented with various types of sensors, such as strain gauges, temperature sensors, and moisture sensors.

Additionally, a walking and cycling path was constructed to evaluate surface characteristics such as texture and roughness.

The test program focused on two primary performance aspects: structural response and surface condition. Structural response was assessed through strain and rutting measurements on the full-scale APT structures, while surface condition was evaluated through MPD and IRI measurements on the walking and cycling path.

3.2. Full-scale APT

3.2.1. Description of APT structures

Two APT tests were carried out in this study, namely one with penetration-graded bitumen (PEN bitumen) and another one with PMB. In each APT test, two adjacent structures were built and tested simultaneously: a reference structure and a modified structure. Each APT test structure consists of an asphalt surface layer, a bituminous base layer, crushed rock base and subbase layers, over a sand subgrade.

For the PEN bitumen test structures, a dense asphalt layer made with 70/100 penetration bitumen and a nominal maximum aggregate size of 16 mm (ABT 16 70/100) was used as the surface layer, whereas 160/220 penetration bitumen with a nominal maximum aggregate size of 16 mm was used for the bituminous base course (AG 16 160/220). For the PEN reference test structure, neat 70/100 and 160/220 bitumen were used (PEN Ref). For the corresponding PEN bio test structure, the addition of 5% bio-oil to 50/70 penetration bitumen resulted in a 70/100 binder, and the addition of 21% bio-oil to 50/70 base bitumen resulted in a 160/220 bio-based penetration bitumen (PEN Bio). TOP was used as the bio-oil in this project. Details of binder formulation are presented in another VTI report (Zhu et al., 2025).

For the PMB test structures, only the surface layer was varied, i.e., a standard PMB binder (Nypol 73, 40/100-75) and a bio-PMB binder (Nypol RE73, 40/100-75) were used. A stone mastic asphalt surface mixture with a nominal maximum aggregate size of 16 mm (ABS 16 PMB) was tested. The same type of bituminous base layer with 160/220 penetration bitumen (AG 16 160/220) was used beneath both surface layers.

The asphalt mixtures for the test structures were produced at asphalt plants. The PEN Bio and PEN Ref asphalt mixtures were produced at Skanska's asphalt plant in Vällsta, Stockholm, and transported to the VTI test facility in Linköping. The asphalt mixtures for the PMB Bio and PMB Ref test structures were produced at NCC's asphalt plant in Norrköping.

Figure 1 shows the test structures, including layer thicknesses (in mm) and mixture types. The structures were instrumented with asphalt strain gauges (ASGs) at the bottom of the asphalt layer to measure tensile strains, with three strain gauges installed per section. Temperature sensors were also installed. Figure 2 shows the paving process and the placement of ASGs.

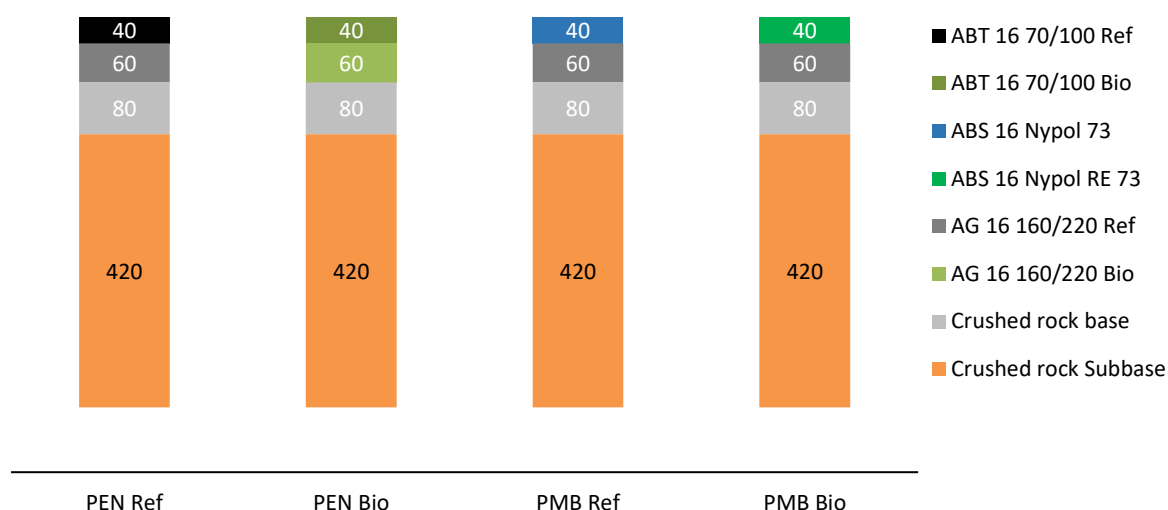


Figure 1. Test structures evaluated in this study.

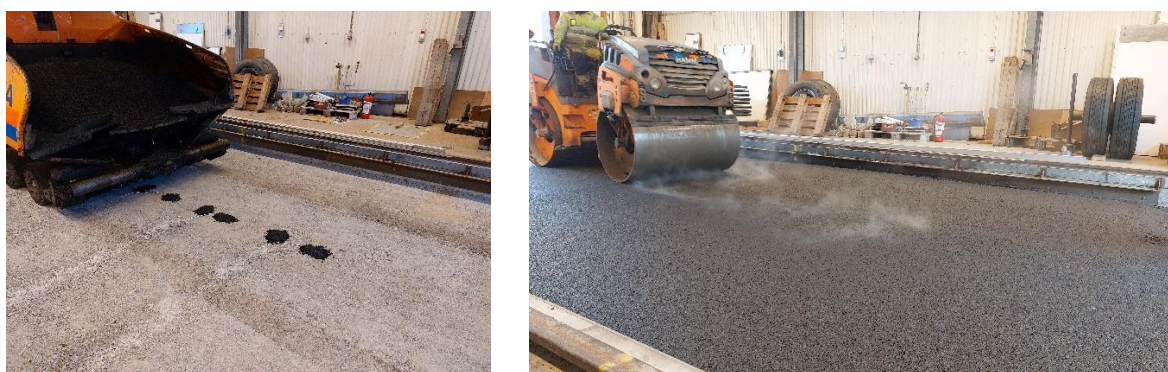


Figure 2. Paving of the test structures.

3.2.2. Test setup and instrumentation

A heavy vehicle simulator (HVS), shown in Figure 3, was used to apply the loads in the APT tests. The following test setups were used for the APT tests. Each test was divided into three stages. The first stage was preloading, which was conducted using a dual-tire assembly at a test temperature of 10 °C. The main objective of the preloading stage was to measure the pavement responses under wheel loads. Response measurements were carried out at various wheel-load positions. The tire pressure and wheel load were kept at 800 kPa and 30 kN, respectively. The preloading was conducted for the first 20 000 load cycles.

Following the completion of the preloading stage, the main test, i.e., the permanent deformation test, was carried out. The main test consisted of two stages, first at 10 °C and subsequently by 20 °C. Each stage was conducted for 250 000 load cycles; thus, the pavement structures were subjected to a total of 500 000 load cycles excluding the 20 000 cycles of preloading. Table 1 presents the test setups and parameters employed in the full-scale tests.



Figure 3. Heavy Vehicle Simulator (HVS). Photo: VTI.

Table 1. Test setup for the full-scale test.

	Preloading	Main test at 10°C	Main test at 20°C
Speed, km/h	12	12	12
Wheel configuration	Dual wheels	Dual wheels	Dual wheels
Wheel load, kN	30	60	60
Tire pressure, kPa	800	800	800
Temperature, °C	10	10	20
Direction of loading	Bidirectional	Bidirectional	Bidirectional
Load of cycles	20 000	250 000	250 000
Distribution	Uniform	Normal	Normal

The test structures were instrumented with ASGs and temperature sensors. The temperature sensors were installed in each asphalt layer, whereas the ASGs were installed at the bottom of the asphalt layers. Asphalt strain was recorded during the preloading stage and throughout the main tests. The asphalt strain data were analysed to assess the condition of the pavement structures.

The ASGs were installed along the centerline of the test structures, in both transverse and longitudinal directions. Six ASG sensors were installed per test pavement structure. Figure 4 shows the top view of the pavement sections and the locations of the ASG sensors. The dashed red line indicates the boundary between adjacent pavement structures.

Rut depth in the pavement structures was measured throughout the main test to assess the development of permanent deformation. A laser-beam-based measurement system was used to measure the transverse profiles, and the rut depth was calculated from the measured profiles.

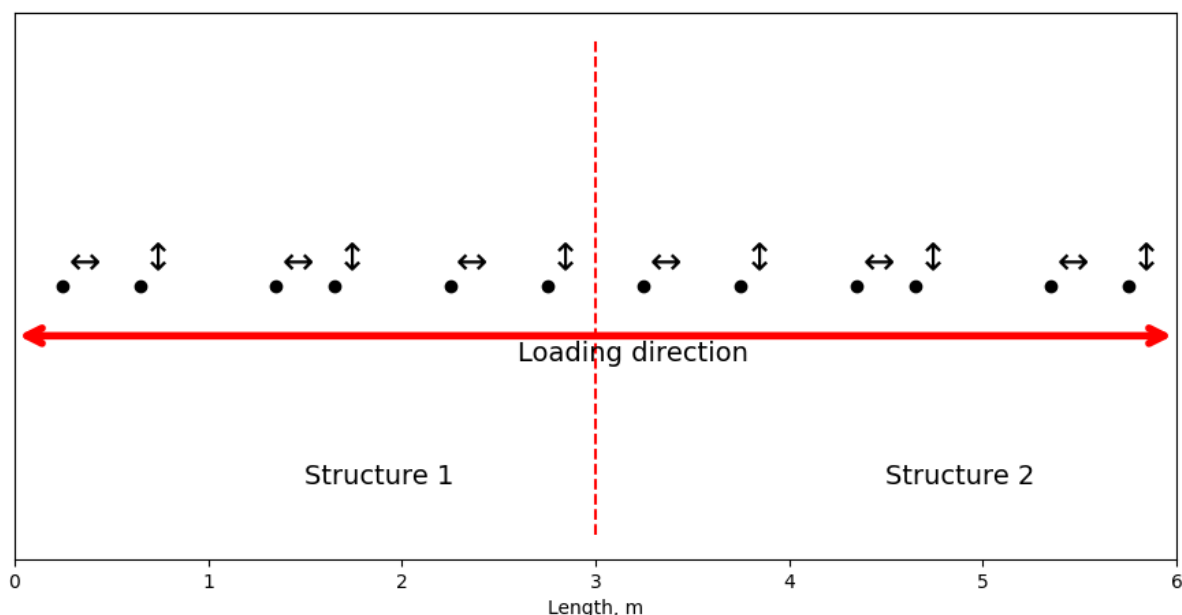


Figure 4. ASG sensor locations (↔ - Longitudinal, ↕ - Transverse).

3.3. Walking and cycling path

3.3.1. Site description and measurement methods

In addition to the APT test structures, a 500 m long walking and cycling path was constructed in October 2023 in Sundbyberg City, Stockholm County. The asphalt surface layer used for the path was similar to that of the PEN Bio APT test structure; however, it also contained reclaimed asphalt material. The surface characteristics and evenness of the path were evaluated in terms of MPD and IRI. The MPD and IRI were measured over three consecutive years (2023 to 2025) following the construction of the path. Figure 5 shows the location of the walking and cycling path.

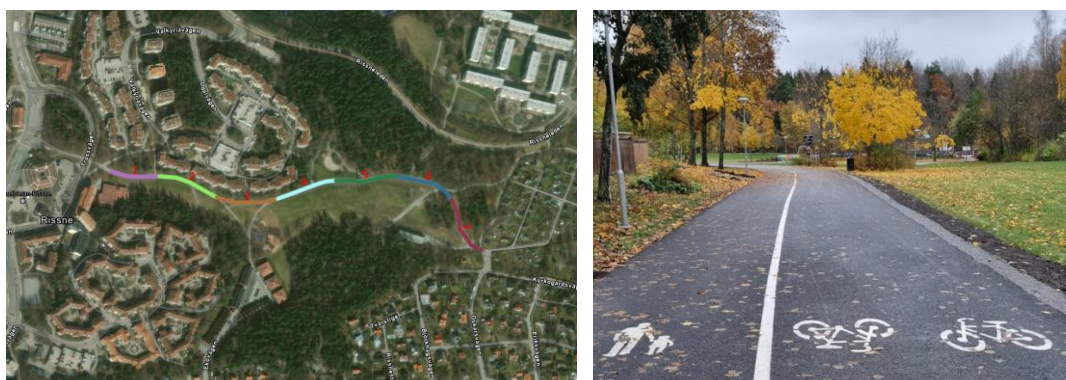


Figure 5. Walking and cycling path in Sundbyberg, Stockholm (Photo: Kenneth Olsson, Skanska).

The surface characteristics of the walking and cycling path were measured using VTI's texture-measuring device (shown in the left image in Figure 6) and a bicycle measurement device (shown in the right image in Figure 6). The texture-measuring device measures the surface texture at intervals of 1 mm. Various texture metrics can be calculated from the measured data, such as MPD, which is commonly used to describe the surface texture of roadways. The bicycle measurement device is equipped with a scanning laser which, together with an accelerometer, enables measurement of the longitudinal road surface profile. From the longitudinal profile, relevant metrics can then be calculated, such as the IRI.



Figure 6. Measurement devices for the walking and cycling path in Sundbyberg, Stockholm (Photo: Mattias Tunholm).

4. Results and discussion

The subsequent sections present the results of the full-scale APT tests as well as the surface measurements from the three-year follow-up of the walking and cycling path. The sections are organized according to the type of test and the metrics considered.

4.1. Full-scale APT structures

The full-scale tests by APT evaluated the resistance to permanent deformation, or rutting, of the tested pavement structures. Additionally, tensile strains at the bottom of the asphalt layers were measured as indicators of resistance to fatigue cracking. Sections 4.1.1 and 4.1.2 present the rutting performance and the measured strains, respectively.

4.1.1. Rutting performance

Figure 7 presents the development of rut depth for the PEN Bio and PEN Ref pavement structures. The solid line represents the average rut depth calculated from three transverse profiles, while the shaded region indicates the 95% confidence interval. During the first half of the test, when the test temperature was 10 °C, no significant difference in rut depth development was observed between the PEN Bio and PEN Ref structures. However, when the test temperature was increased to 20 °C, the PEN Bio structure performed better, exhibiting lower permanent deformation (rutting) at the end of the test. Note that a similar wheel load of 60 kN was applied for both the 10 °C and 20 °C test stages.

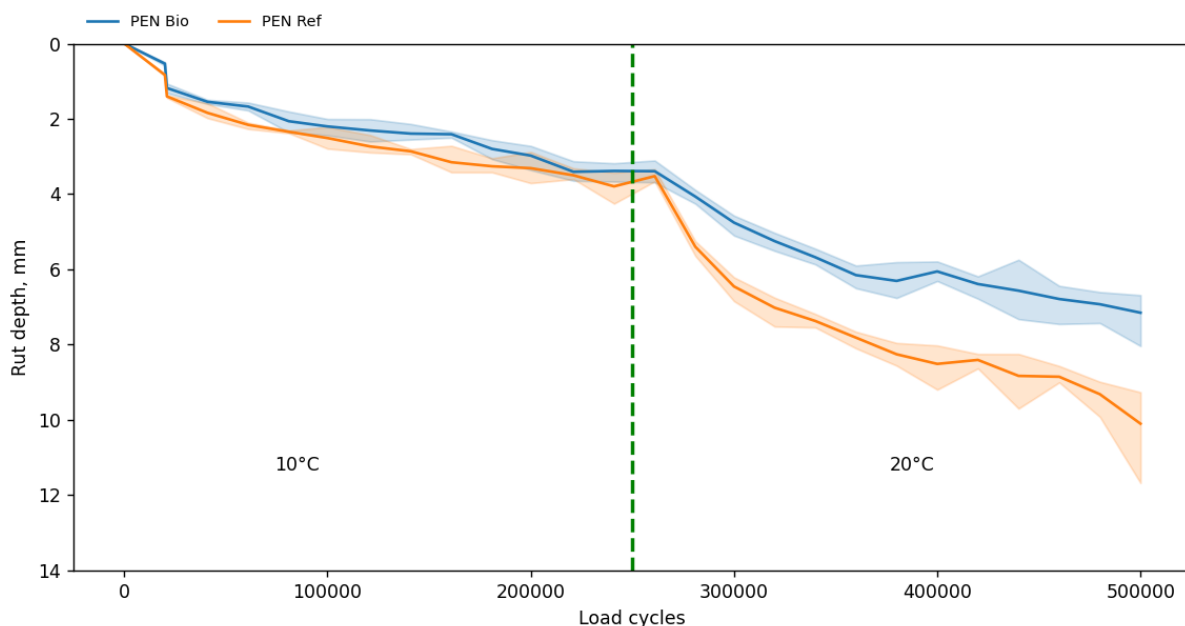


Figure 7. Rut depth evolution for PEN Bio and PEN Ref test structures.

Similarly, the full-scale test results of the PMB Bio and PMB Ref structures are presented in Figure 8. As for the results of the PEN Bio and PEN Ref structures, the differences between the two PMB structures were not significant for the test conducted at 10 °C. However, for the test at 20 °C, the PMB Bio exhibited significantly better performance compared with the standard PMB. The main difference between the PMB test structures is the surface layer. The same asphalt base layer made of 160/220 penetration bitumen was placed beneath the stone mastic asphalt (SMA or ABS) PMB Bio and PMB Ref surface layers.

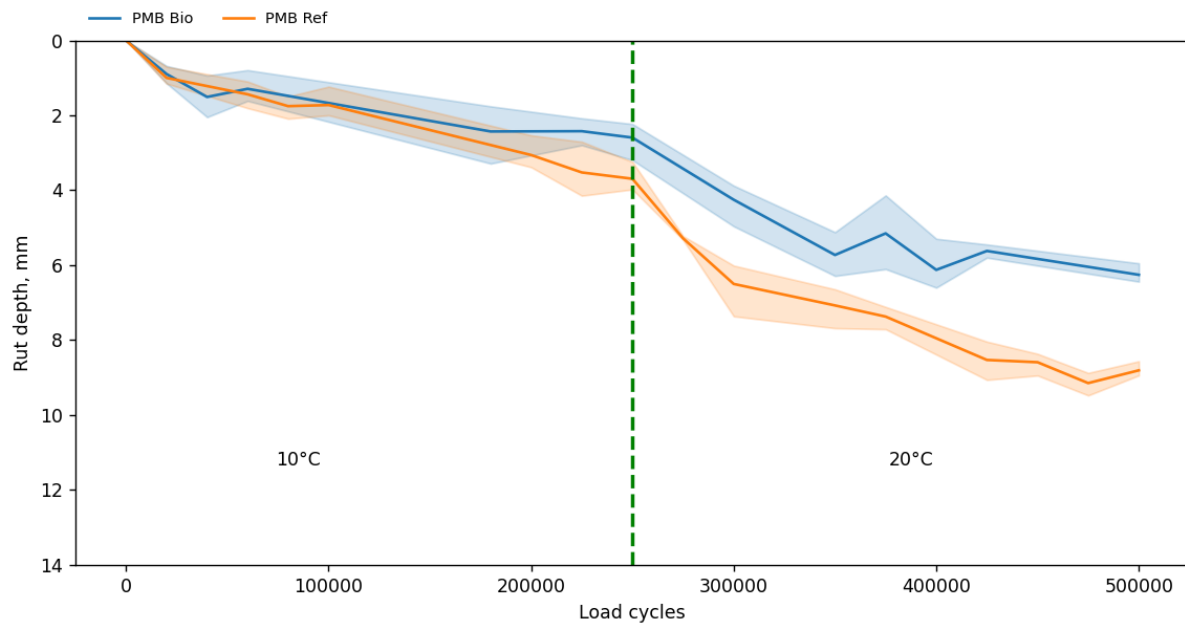


Figure 8. Rut depth evolution for PMB Bio and PMB Ref test structures.

The measured rut depths are in good agreement with the permanent deformation resistance obtained from laboratory cyclic compression test, which is comparable to the Flow Number test (AASHTO T378-17), as reported by Zhu et al. (2025). The stiffness modulus of the mixtures at 20 °C is presented in Figure 9. As shown, a slight increase in stiffness was observed for the bio-based surface course layer (ABT16 70/100) and the AG16 160/220 mixture, with the exception of the PMB mixtures. The permanent deformation tests further indicated that the bio-based mixtures exhibited slightly improved resistance to rutting (Figure 10).

This improvement is particularly evident for the AG16 160/220 mixture, which contains a relatively higher amount of TOP, as well as for the bio-based PMB mixtures. Both the PMB Bio (Nypol RE 73) and the PMB Ref (Nypol 73) mixtures demonstrated superior resistance to permanent deformation compared to the other mixtures as indicated by the cyclic compression laboratory tests (Figure 10).

Thus, the enhanced rutting performance observed in the full-scale tests for PEN Bio may be attributed to the improved deformation resistance of the AG16 160/220 Bio mixture, since no significant difference in the resistance to permanent deformation of the surface layers (ABT16 70/100 Ref and ABT16 70/100 Bio) was observed in the laboratory tests. In addition, the PMB Bio surface layer may also have contributed to the improved rutting performance of the PMB Bio structure, considering that both PMB Bio and PMB Ref were constructed on similar underlying layers.

Note that, for the PMB mixtures, a dense-graded PMB asphalt mixture was used in the laboratory tests as reported by Zhu et al. (2025), whereas a stone mastic asphalt (SMA or ABS) PMB mixture was used in the full-scale APT test with PMB structures. However, similar types of PMB binders were used in both cases.

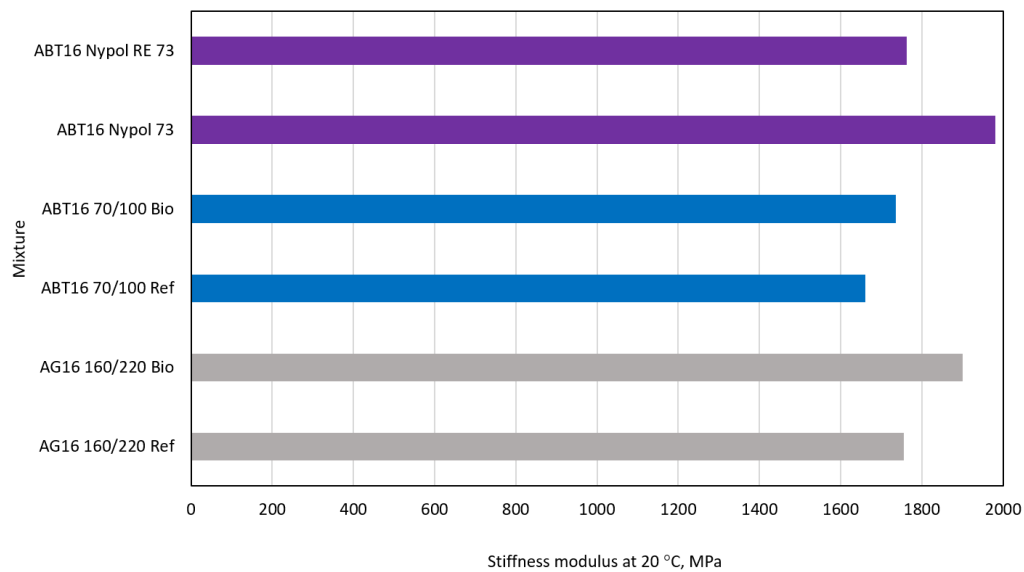


Figure 9. Stiffness modulus of the asphalt mixtures at 20 °C.

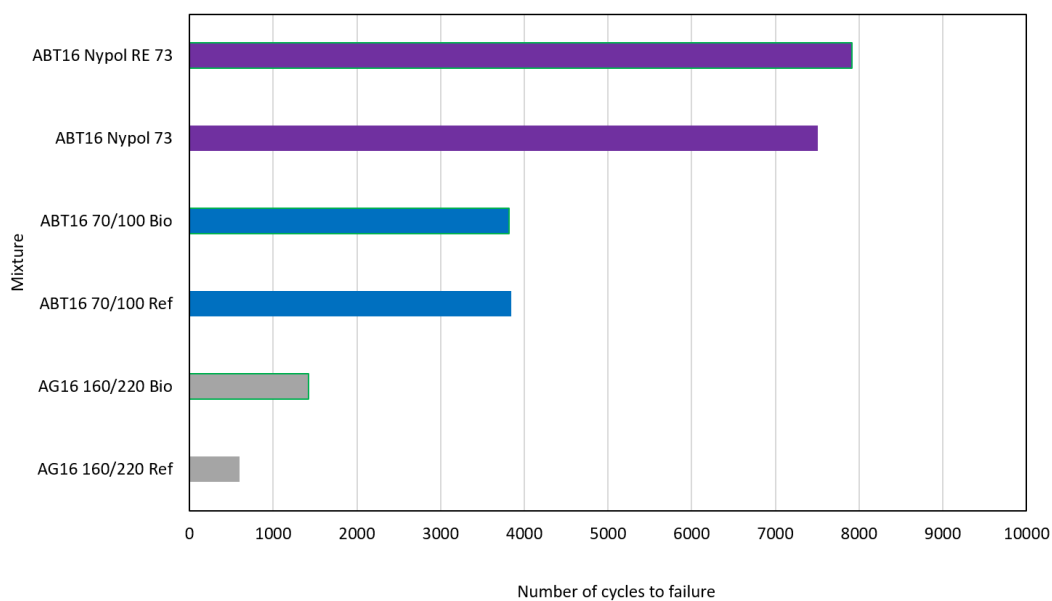


Figure 10. Permanent deformation resistance of the asphalt mixtures (Flow Number at 50 °C).

4.1.2. Strain response results

The measured transverse and longitudinal strains at the bottom of the asphalt layers for the PEN and PMB test structures are shown in Figure 11 and Figure 12, respectively. The figures present the average measured strains after 20 000 load cycles, representing the initial test condition at 10 °C, and after 500 000 load cycles, representing the end condition at 20 °C. The black lines represent the 95% confidence interval. Note that some of the measurements exhibited larger scatter. The measurements were carried out for different load cases.

As can be observed from the figures, in most cases the PEN Bio and PMB Bio structures exhibited relatively lower transverse and longitudinal strains for all load cases compared to the corresponding reference structures. This effect is particularly evident at the test temperature of 20 °C. The results are consistent with the permanent deformation tests presented in the previous sections and indicate that the PEN Bio and PMB Bio structures exhibited superior or comparable performance compared to their respective standard variants.

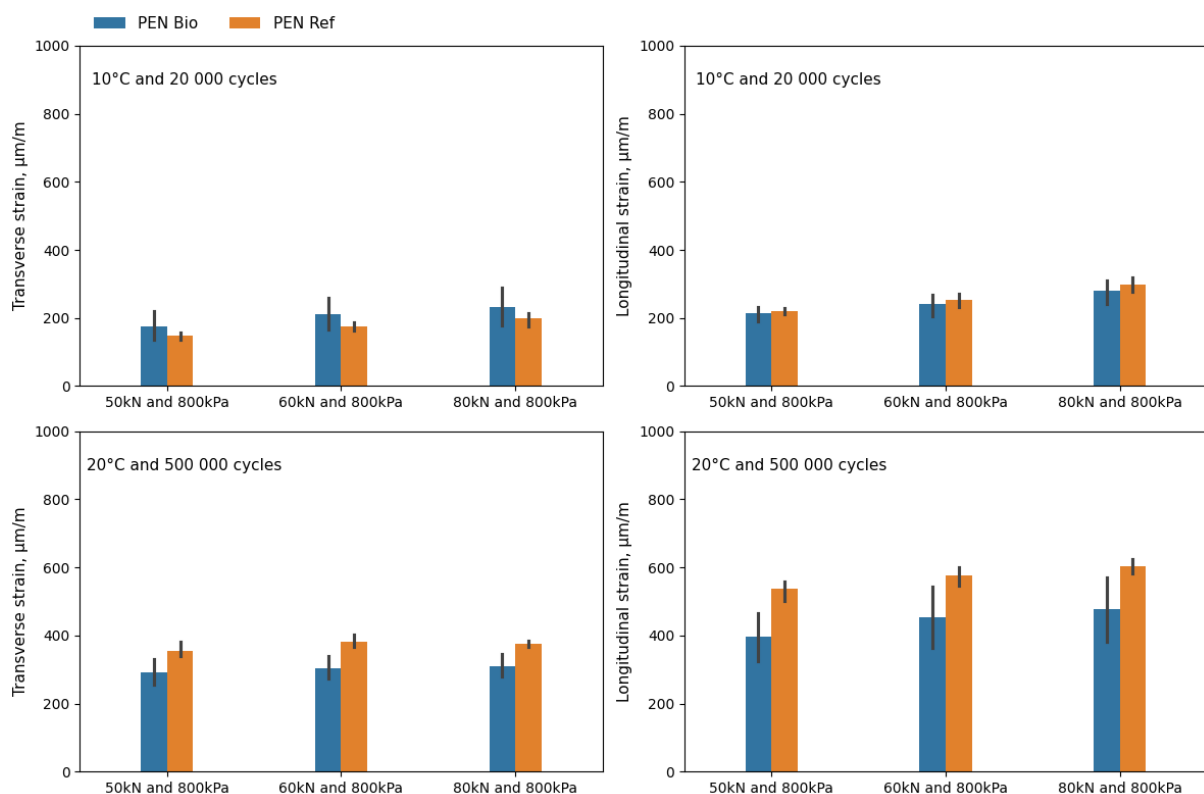


Figure 11. Measured transverse and longitudinal strains for PEN Bio and PEN Ref test structures.

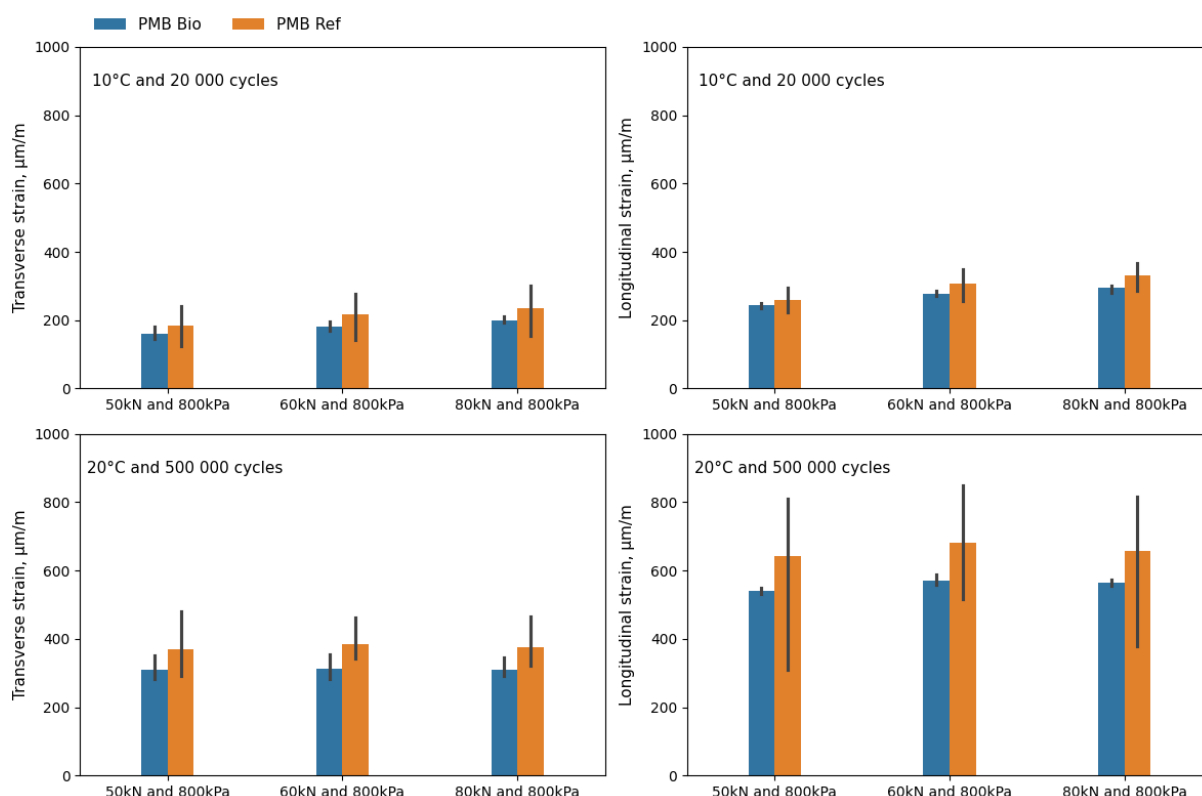


Figure 12. Measured transverse and longitudinal strains for PMB Bio and PMB Ref test structures.

4.2. Walking and cycling path

The subsequent sections present the results from a three-year follow-up of the surface characteristics (MPD and IRI) of the walking and cycling path in Sundbyberg, Stockholm.

4.2.1. MPD results

Figure 13 presents the measured MPD along the walking and cycling path for the measurement years 2023, 2024, and 2025. The average MPD is shown in Figure 14. Relatively lower MPD values were measured in 2024 and 2025 compared to the measurements from 2023. The average MPD values are compared with a range of acceptable MPD values from newly paved walking and cycling paths in Sweden reported in the literature (Niska et al., 2025), which are shown as a pink shaded area. As can be seen from Figure 14, the measured MPD values of the walking and cycling path with bio-extended binder fall well within the range of the reference data.

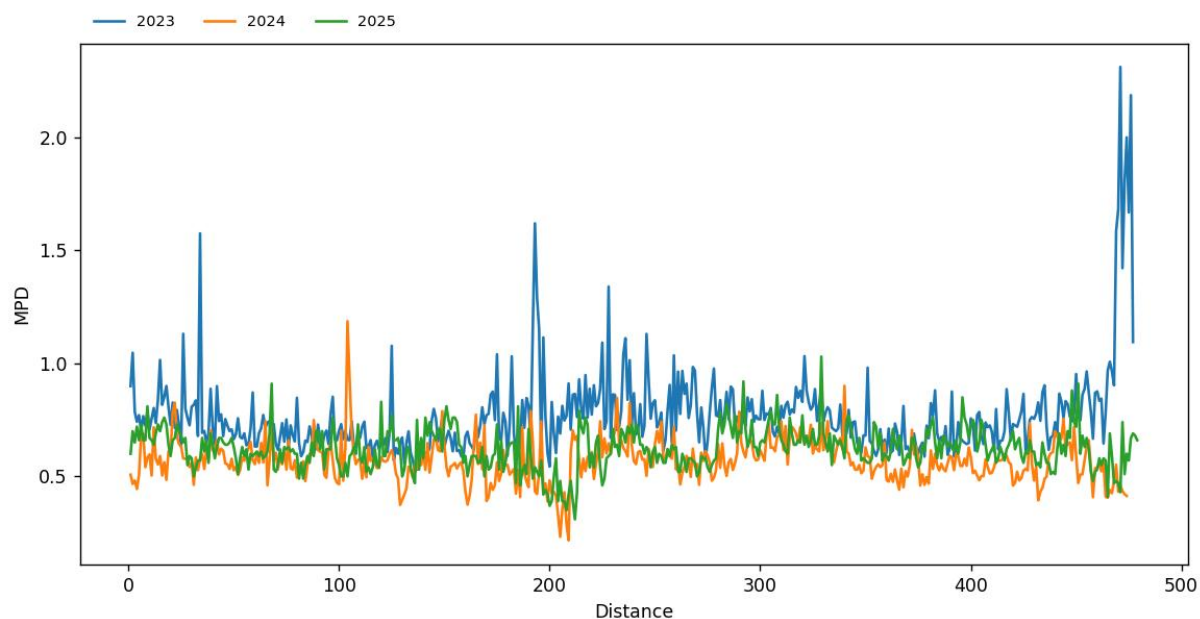


Figure 13. Measured MPD of the walking and cycling path for years 2023, 2024, and 2025.

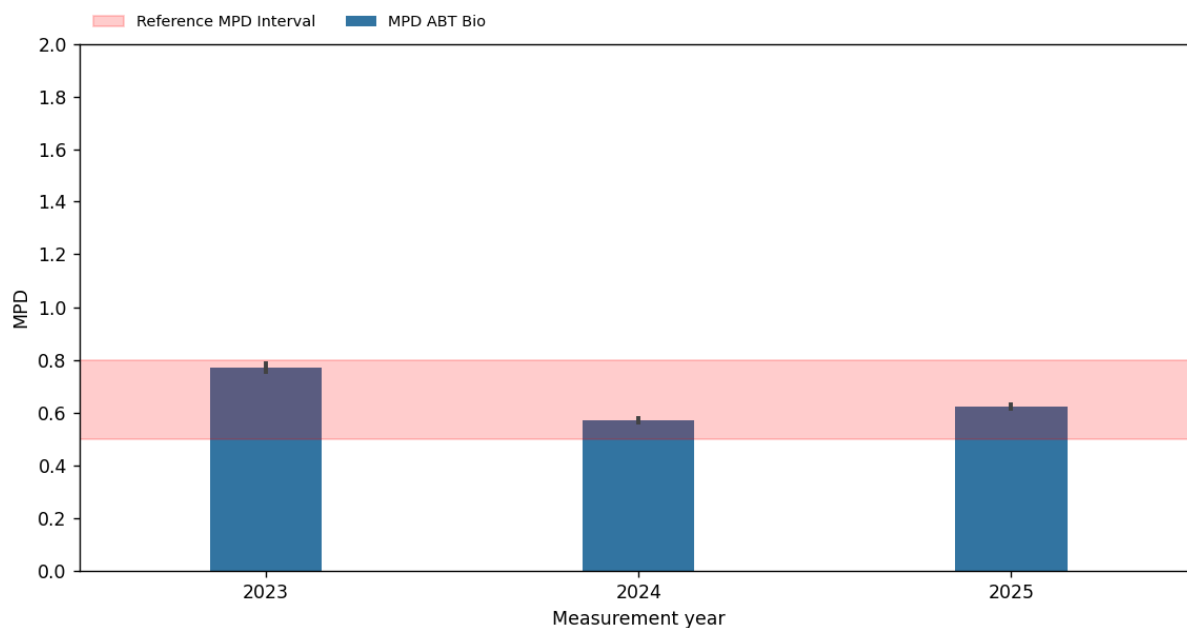


Figure 14. Measured average MPD of the walking and cycling path for years 2023, 2024, and 2025.

4.2.2. IRI results

The measured IRI values along the walking and cycling path for the measurement years 2023, 2024, and 2025 are shown in Figure 15. Figure 16 shows the average IRI for each measurement year. The average IRI values are also compared with a reference range of IRI values from newly paved walking and cycling paths in Sweden reported in the literature (Niska et al., 2025), shown as a pink shaded area. As can be seen from Figure 16, the measured IRI values of the walking and cycling path with bio-extended binder are well within the range of the reference data.

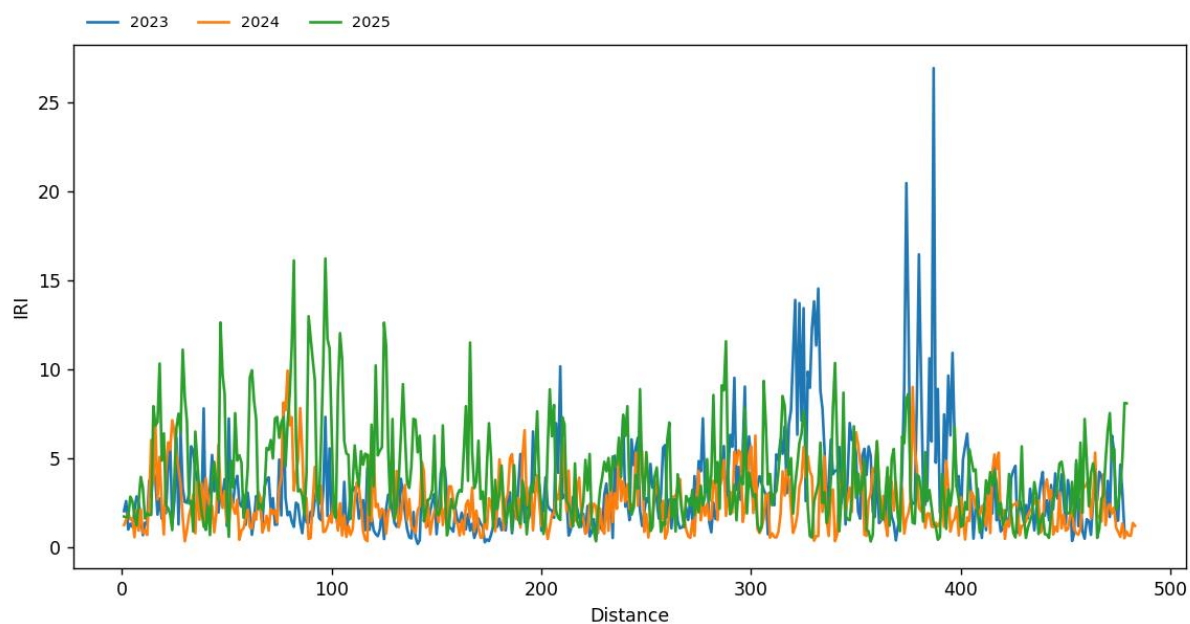


Figure 15. Measured IRI of the walking and cycling path for years 2023, 2024 and 2025.

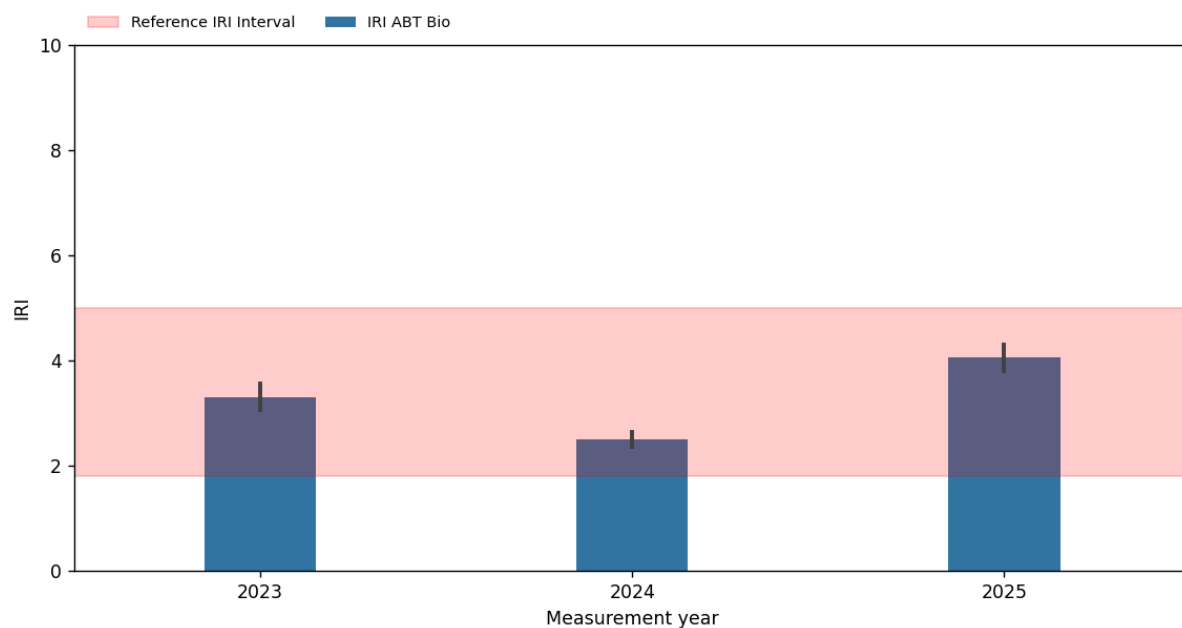


Figure 16. Measured average IRI of the walking and cycling path for years 2023, 2024 and 2025.

5. Conclusions

5.1. Summary

This project evaluated the structural performance of asphalt pavement structures incorporating bio-based binders, with a focus on resistance to permanent deformation (rutting) and indicators of fatigue performance. Both penetration-graded bitumen and PMB were investigated. The evaluation was conducted using full-scale APT with a HVS, for which asphalt mixtures produced at asphalt plants were transported to an indoor test facility and used to construct full-scale pavement structures.

In total, four full-scale pavement structures, comprising a penetration-graded reference and its bio-based variant, as well as a PMB reference and its biogenic-containing variant, were constructed and tested. The structures were instrumented with strain gauges at the bottom of the asphalt layers to monitor tensile strains associated with fatigue cracking initiation.

The APT results demonstrated that asphalt mixtures incorporating bio-extended binders exhibited similar or improved performance compared with their corresponding reference mixtures. In particular, both PEN Bio and PMB Bio structures showed comparable rutting performance at 10 °C and improved resistance to permanent deformation at 20 °C. Measured tensile strains at the bottom of the asphalt layers were generally lower or comparable for the bio-based structures, especially at the elevated test temperature, indicating favourable fatigue-related condition.

In addition to the APT tests, a walking and cycling path was constructed in Sundbyberg, Stockholm, to evaluate the early field ageing and surface performance of bio-based asphalt mixtures under real service conditions. Surface texture and roughness were monitored over a three-year period using MPD and IRI. The measured MPD and IRI values remained within the range reported in the literature for newly paved walking and cycling paths in Sweden and showed no adverse trends over time.

Furthermore, no significant differences were observed in terms of asphalt production, transportation, or paving operations when using bio-extended binders. On the contrary, the bio-extended mixtures were generally observed to be easier to compact, indicating good workability in practical applications.

5.2. Limitations

The results show that bio-based binders can be successfully used in asphalt pavement without compromising structural or surface performance. The favourable rutting resistance observed at higher temperatures highlights the potential of bio-based binders in changing climates where temperature-related distress is a concern.

However, the study is subject to several limitations. The APT tests were conducted in an indoor facility under controlled environmental conditions, which cannot fully replicate the variability of in-service field conditions such as seasonal temperature cycles, moisture variations, and traffic. In addition, although the walking and cycling path provided valuable field data, the monitoring period is still relatively short compared to the full-service life of asphalt pavements.

The scope of the project was also limited to specific binder types, bio-oil dosages, and mixture designs. Therefore, the findings should be interpreted within the context of the materials and configurations investigated.

5.3. Recommendations for future work

While this project employed full-scale APT testing to evaluate pavement performance with respect to rutting and fatigue-related indicators, further studies under real traffic and environmental conditions are recommended to capture long-term field performance more comprehensively.

Future work should include long-term in-service monitoring of road sections incorporating bio-based binders under varying climatic conditions and traffic levels. Additional research is also recommended to evaluate other field performance aspects such as low-temperature cracking, moisture sensitivity, and ageing-related distresses.

Moreover, extending the evaluation to a broader range of bio-oil types, base bitumen, and dosage levels would contribute to establishing more general design recommendations. Continued investigation into life-cycle costs and long-term climate impacts, including maintenance and rehabilitation phases, is also recommended to support wider implementation of bio-based binders in sustainable pavement design.

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