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Noise and **E**missions **MO**nitoring and Radical Mitigation

Research and Innovation Action

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Road pavements full-scale testing

WP6, Task 6.3

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Abbreviations and acronyms

Acronym	Description
AC	Asphalt concrete
BB0/4	Asphalt with a majority of aggregates less than 4 mm in diameter
BB0/8	Asphalt with a majority of aggregates less than 8 mm in diameter
BBSG	Béton Bitumineux semi-grenu (or Dense Graded Asphalt Concrete)
BBTM	Very thin asphalt concrete ("Béton bitumineux très mince")
FWD	Falling Weight Deflectometer
CAM	Average traffic aggressiveness coefficient
FWTT	French wheel tracking tester
GB	Grave Bitume (or Gravel with bitumen)
HL	Hydrated lime
ITS	Indirect tensile strength
ITSR	Indirect tensile strength ratio
NE	Equivalent number of reference axles
NPL	Cumulative heavy goods vehicle traffic over the operating period
PA	Porous asphalt
PMB	Polymer-modified bitumen
S1	Section number 1 of the fatigue carousel. It includes a porous asphalt surface layer and is used as a reference in mechanical durability tests.
S2	Section number 2 of the fatigue carousel. This is an experimental asphalt section constructed from innovative peri-urban mixture, and that undergoes mechanical durability testing to over one million load cycles.
S4	Section number 4 of the fatigue carousel. It includes a conventional BBSG surface asphalt layer and is used as the primary reference in mechanical durability tests.
SMA	Stone mastic asphalt
UGM	Unbound granular material

Executive Summary

The report presents the methodology and results corresponding to Task 6.3 of Work package 6 (WP6). The main objective was to evaluate the long term mechanical performance and provide representative samples for assessing the pollutant trapping / degradation capacity of innovative urban and peri-urban mixtures. The mixtures were designed in the laboratory to mitigate road/vehicle related emissions including noise, exhaust gases and microplastics coming from tires' wear and tear. This objective is derived from the challenges defined in the NEMO project description for road infrastructure.

Based on the formulations provided in deliverable D6.2, IFT with the support of UC and M+P for the implementation of new pavements and sample collection then characterization have monitored the mechanical properties of two innovative and two reference asphalt mixtures dedicated to urban and peri-urban roads. Thus, the work carried out can be divided into three main stages related to : i) the industrial production of the asphalt, ii) the construction of the four pavements, and iii) their accelerated testing and follow-up of mechanical properties.

Starting with the asphalt production, it has been demonstrated that industrial amounts (of the order of tons) of asphalt can be produced in asphalt mixing plants from experimental formulations. However, such production requires extra precautions due to the complexity of the formulation and the nature of the materials incorporated. In particular, the addition of low percentages of fines, fibers, and hydrated lime requires the use of heavy protective equipment for handling personnel. Furthermore, the presence of attrition-prone materials of various origins and the lack of aggregate screening in most asphalt plants make it necessary to check and finely recalibrate production before each run.

As for the pavement laying operations, both experimental pavements produced in asphalt mixing plants according to the UC and M+P formulations could be built under realistic conditions. However, as with the production phase, the laying phase requires additional precautions due to the high temperature of the asphalt (up to 150°C) and the high binder content. In particular, due to its two-layer structure, peri-urban asphalt requires special equipment to limit tedious handling operations and prolonged exposure to hot bitumen fumes.

The laboratory results obtained from samples taken immediately after the production and construction phases were in line with the target specifications for the experimental peri-urban pavement, both in terms of durability and structure. In particular, the mechanical resistance values (in terms of complex modulus, rutting depth, strength, etc.) are close to those of reference materials or European standards, and where they are lower, they remain acceptable. Nevertheless, deviations were observed in the urban pavement in terms of thickness and percentage of voids, leading to significantly greater deformation than expected from laboratory measurements.

Finally, mechanical durability monitoring during accelerated testing did not demonstrate any major deterioration of the innovative pavements. In the case of the urban pavement, no significant surface damage was observed and, contrary to laboratory results, no apparent rutting was measured, even under high heat conditions and after 1,000,000 cycles. Deflection and deformation, while slightly higher than the reference pavements, remain broadly comparable. A similar conclusion can be drawn for the peri-urban pavement: no significant surface damage, except for local aggregate stripping. As regards rutting, deflection and deformations, they are similar to or only marginally different from those of the reference pavement.

Keywords

Asphalt mixtures, full-scale testing, mechanical performance, surface properties, pollutant and noise emissions

1 Introduction

The NEMO project is developing a two-pronged strategy to provide radical and innovative solutions to reduce noise and improve air quality in urban areas and along major transportation infrastructure. These two strategies encompass road and rail transport. The first resulted in improved automated remote sensing technologies to detect and identify noisy and polluting vehicles in the traffic flow. The second strategy resulted in a holistic solution to mitigate noise and emissions from passing vehicles, including optimization of road characteristics (texture and grading) and a multifunctional barrier.

Thus, in WP6.2, UC and M+P developed and validated at laboratory scale innovative urban and peri-urban pavement mixtures capable of reducing road/vehicle related emissions, including noise, exhaust and microplastics from tire wear. The main challenge in this work package was to achieve a significant reduction in pollutant and noise emissions while maintaining adequate rolling and skid resistance to ensure a high level of driving safety.

In WP6.3, the pavement formulations prepared and validated in the laboratory were tested at the actual road scale. In fact, two aspects are addressed that are central to the practical implementation of the formulations. The first is the ability to produce and lay the innovative urban and peri-urban asphalts industrially: *i.e.*, at the scale of an asphalt mixing plant for the production phase and at the scale of tens of meters of pavement for the road construction phase. The second aspect involves the characterization and monitoring of the pavement's mechanical behavior over its entire service life. The conducted tasks include laboratory and field measurements on samples taken at the asphalt mixing plant, during and immediately after the laying of pavements, and during their use in an accelerated pavement testing facility.

The UGE fatigue carousel is one of the largest facilities of its kind in the world and unique in the EU. This large accelerated pavement testing facility allows simultaneous evaluation of the mechanical behavior of conventional (*i.e.*, reference) and experimental pavement mixes to be tested in a shorter period of time. Therefore, a number of load cycles equivalent to 20-30 years of heavy vehicle traffic (i.e. up to 1,000,000 cycles depending on the traffic intensity assumed) is achieved in just a few months, allowing the long-term analysis to be carried out in a timeframe adapted to the NEMO project.

The work carried out in WP 6.3 and detailed here (D6.4) involves multiple and repeated measurements. They aim to provide the most exhaustive and robust assessment possible of the mechanical behavior and evolution of key structural properties of pavements subjected to the simulated heavy vehicle traffic. Measurements therefore cover changes in the density, porosity, deformation, deflection, etc. of the various pavement layers tested in temperate conditions as well as in periods of high temperatures. They are accompanied by visual and/or instrumented observations of surface condition: including the presence of fractures, pull-outs, rutting, etc. Finally, to extend the scope of the current knowledge, the results also bring together measurements rarely carried out with such optimized pavements, like complex modulus measurements.

It is worth mentioning that the carousel was equipped with electric motors before the start of the NEMO project. In addition to evaluating the mechanical durability of the pavement under realistic load conditions and actual weather conditions, the implementation of electric motors allowed for more fine-tuned and consistent operation of the carousel. This furthermore provided access to more accurate measurements of tire and road particulate emissions as well as rolling noise, which will be discussed in Deliverable 6.5.

1.1 Purpose, scope and target group

The results proposed in this deliverable contribute to the overall objective of the NEMO project to achieve a turn-key solution through the implementation of innovative pavement mixtures that improve air quality and reduce noise impacts in EU cities. The formulated urban and peri-urban pavements respond to NEMO objectives number 7, "the development of an integral solution for both urban roads and highways to reduce road vehicle noise and emissions", and in particular number 8, realistic and robust "validation of the new mitigation solutions as a tool to control the acoustic and air quality and reduce their damage on people and environment (impact evaluation)".

The results and conclusions presented in this report are intended for municipalities, local/regional/national road authorities, the scientific community, civil society organization, road/transport network planning agencies, and industry (asphalt producers and road builders).

1.2 Contribution partners

Table 1: Contribution of partners

Partner nº and short name	Contribution
8 -IFT	Asphalt production and implementation, pavement accelerated mechanical durability testing
9 - UC	Formulation of mixes, laboratory tests
2 - M+P	Formulation of mixes, laboratory tests
7 - G21	Dissemination

1.3 Relation to other activities in the project

Table 2: Relation to other activities in the project

Task	Description
6.2	The UC and M+P have developed two innovative asphalt formulations that reduce noise and/or pollutant emissions for urban and peri-urban roads. The industrial production and implementation of these formulations on a real scale is the objective of Task 6.3.
7.2	The new urban mixture developed in Task 6.2 and characterized for mechanical durability in Task 6.3 will be implemented in a pilot section in the city of Florence in Task 7.2.
8.3	The results from Task 6.2 and Task 6.3 in terms of the final formulation of the novel asphalt mixtures, noise level and gas emission reduction will be incorporated to the Life-Cycle-Cost assessment in task 8.3.

2 The accelerated pavement testing facility

2.1 Accelerated pavement testing (APT) facilities

Although pavement designs have progressed in recent years, the evaluation of the long-term performance of pavement structures remains a challenge. Accelerated Pavement Testing (APT) is the controlled application of a wheel loading to a pavement system to determine the response of the pavement in a compressed period of time (Steyn 2012). APT has been used for years to assess the response and performance of road pavement material (Hugo and Epps 2004). Over time the installation causes deterioration of the pavement structure which is monitored by a series of sensors and instruments. The data obtained is analysed and together with laboratory data and field understanding, often leads to improved pavement design; maintenance and managements models. Accelerated loading in APT installations is mainly used to obtain a faster pavement analysis without having to wait for the normal life of the pavement to elapse before typical deterioration occurs (Metcalf 1996). Therefore, the application of accelerated traffic should only shorten the waiting period of the expected deterioration outcome and should not affect the response mechanism of the pavement.

For this reason, APT facilities remain essential tool for the validation of new asphalt mixture designs, due to their ability to perform full-scale tests in shorter times. This is confirmed by the increase of APT facilities in different countries and the upgrading of the existing ones, including new instrumentation and monitoring equipment, and methods for handling and using increasing amounts of data. In addition, efforts are being made towards the standardisation of APT databases to improve and facilitate the cross-comparison of results, exchange of knowledge, as well as to facilitate the use of numerical tools with the achieved data.

APT tests are very important in the validation of new mixture designs developed in the laboratory, due to the real environmental conditions and their ability to apply loads in a controlled manner. This allows research to be taken a step further and to analyse the long-term durability of designs without spending too much time.

Taking all this into account, the APT facility of Gustave Eiffel University (belonging to the Nantes Campus in France) is used for the analysis of the experimental asphalt mixtures previously developed in this project. This institution has been working on APT since the 1980s, when its unique circular testing facility, known as the fatigue carousel, was developed. Since then, they have used their facilities for numerous studies on asphalt mixtures, including reinforcements with grids or biomaterials (bio-recycles asphalt mixtures), among others (Barriera et al. 2021, Nguyen et al. 2021, Hornych et al. 2012, Blanc et al. 2019, Nguyen et al. 2013).

2.2 Carousel's description

The fatigue carrousel of Gustave Eiffel University is an outdoor road traffic simulator designed to study the behaviour of real scale pavements under accelerated heavy traffic. The fatigue carrousel has a diameter of 40 meters and four loading arms, which can each carry loads up to thirteen tons, at a maximum loading speed of 100 km/h (Figure 1). Two months of testing can represent up to 20 years of heavy traffic undergone by a moderate traffic pavement (150 heavy trucks/day). During loading, a lateral wandering of the loads can be applied to simulate the lateral distribution of loads of real traffic.

Figure 1. The IFSTTAR accelerated pavement testing facility

3 Construction of the demonstrator

3.1 Tested sections & pavement structures

3.1.1 Tested sections

A total of four sections were constructed, including two reference sections and two experimental sections. For the four sections, the base course is a layer of GB (Gravel bitumen, or grave bitumen, in French). The wearing course is different for each section. The four sections are:

- 2 references sections, named S1 and S4
  - S1 is a porous asphalt (named BBDr, or Béton bitumineux Drainant)
  - S4 is a French classical bituminous mixture, used for wearing course, named BBSG (Béton Bitumineux Semi-Grenu, in French, or Dense graded asphalt mixture)
- 2 innovative structures, named S2 and S3
  - S2 is the Peri-Urban section
  - S3 is the Urban section

The formulations of the two innovative materials are presented in detail in Deliverable D6.2 entitled "peri-urban experimental mixture" and "urban experimental mixture". These innovative materials for urban and peri-urban roads have been developed by the University of Cantabria. The theoretical particle size distribution for urban and peri-urban road are presented in the ¡Error! La autoreferencia al marcador no es válida. for urban section and Table 4 and for peri-urban section.

Table 3. Theoretical particle size distribution of the aggregates, BB 0/4 Urban

Sieve (mm)	4	2	1	0.5	0.25	0.063
Ophitic 4/2	74.6	0	0	0	0	0
Limestone 2/0	22.9	22.5	13.2	8.3	5.8	3.3
Limestone Filler	2.5	2.5	2.5	2.5	2.5	2.5
Volume (%)	100.0	25.0	15.7	10.8	8.3	5.8
Weight (%)	100.0	24.4	15.4	10.6	8.1	5.7

Table 4. Theoretical particle size distribution of the aggregates, BB0/4 Peri-Urban (top layer)

Sieve (mm)	4	2	1	0.5	0.25	0.063
Ophitic 4/2	81.8	0	0	0	0	0
Limestone 2/0	13.2	13.0	8.5	5.5	3.6	2.0
Hydrated Lime Filler	5.0	5.0	5.0	5.0	5.0	5.0
Volume (%)	100.0	18.0	13.5	10.5	8.6	6.1
Weight (%)	100.0	16.5	12.0	9.0	7.1	4.9

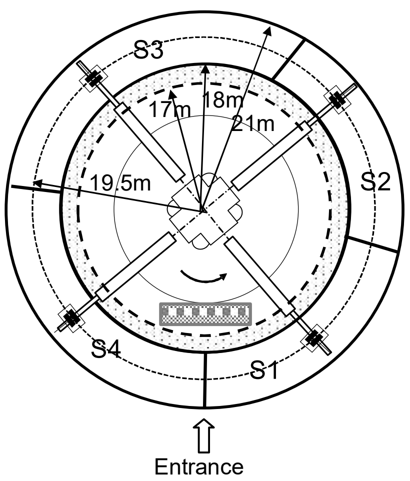
Table 5. Theoretical particle size distribution of the aggregates, BB0/8 Peri-Urban (bottom layer)

Sieve (mm)	8	4	2	1	0.5	0.25	0.063
Ophitic 8/4	81.0	0	0	0	0	0	0
Ophitic 4/2	4.9	4.9	0	0	0	0	0
Limestone 2/0	8.9	8.9	8.8	5.7	3.7	2.4	1.4
Hydrated Lime Filler	5.2	5.2	5.2	5.2	5.2	5.2	5.2
Volume (%)	100.0	19.0	14.0	10.9	8.9	7.6	5.6
Weight (%)	100.0	17.5	12.4	9.4	7.4	6.1	4.4

3.1.2 Pavement structures

The longitudinal, lateral and vertical structures of the pavements are described Figure 2 and Figure 3:

- Subgrade : 2.6m of sand
- 25 cm of Unbound Granular Material (UGM)
- 10 or 12.5 cm of GB (base layer)
- 2.5 or 5 cm of wearing course



Structure	Mixes	Length
S1	5 cm Porous asphalt (BBDr) (Ref) +10 cm GB3	25 m
S2	2.5cm BB 0/4 + 2.5cm BB 0/8 + 10 cm GB3 (Peri-urban)	25 m
S3	2.5 cm BB0/4 + 12.5 cm GB3 (Urban)	35 m
S4	5 cm BBSG (Ref) + 10 cm GB3	37.5 m

Figure 2. Implantation of the tested sections on the carousel

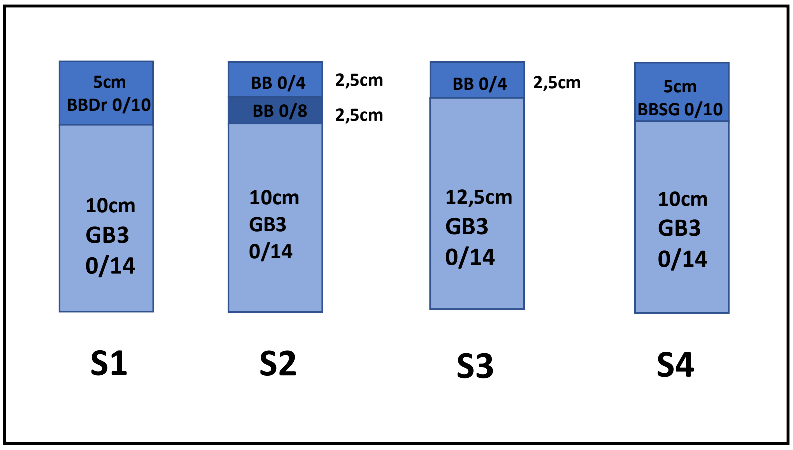


Figure 3. Pavement structures

3.2 Construction

3.2.1 Mix production

The asphalt mixes used on the carousel in the NEMO project were produced in a Colas batch mixing plant. This type of plant allowed us to be flexible in the production of the formulas used in this test. In fact, since the formulas provided by the University of Cantabria were specific, we had to adapt the way certain materials were introduced during the manufacturing process.

The formulation studies carried out in Spain were performed with granular materials that had been previously sieved in the laboratory. Therefore, the aggregates commonly referred to as "downgraded" in a granular fraction were removed. The materials delivered from the Spanish quarry and sent to the asphalt plant in France for the industrial production of the test sections were not screened. As a result, the size distribution curves of aggregates used in the formulation and industrial production stages differed significantly. The asphalt manufacturer had to adjust the percentages of each component to best match the formulas provided by the University of Cantabria.

Table 6 shows the theoretical formulas provided by the University of Cantabria (named LAB formulation) and the formulas adjusted by the asphalt manufacturer (named theoretical for plant). It can be clearly seen that the LAB formulation and the theoretical formulation for plant were very different in their size distribution curves, as the final proportions show large deviations. Despite these significant deviations, it was still possible to recalibrate the actual grading curves to the theoretical grading curves.

It should also be noted that some granular fractions were removed to achieve this result. These fractions consisted of the 0/2 fraction in the peri-urban BB0/4 formulation and the 2/4 fraction in the peri-urban BB0/8 formulation.

Table 6. Comparison between the laboratory formulations proposed by the University of Cantabria and theoretical formulations for plant achieved by Colas

		LAB formulation		Theoretical for plant	
		Fraction	Percentage of passing	Fraction	Percentage of passing
S2 (Peri-Urban)	BB 0/4	0/2	13.1	0/2	-
		2/4	83.4	2/4	89.1
		Hydrated lime filler	3.6	Hydrated lime filler	4.4
		Bitumen	6.50	Bitumen	6.50
	BB 0/8	0/2	8.8	0/2	6.0
		2/4	5.0	2/4	-
		4/8	82.5	4/8	84.5
		Hydrated lime filler	3.7	Hydrated lime filler	3.5
		Bitumen	6.00	Bitumen	6.00
S3 (Urban)	BB 0/4	0/2	22.4	0/2	7.0
		2/4	75.2	2/4	93.2
		Limestone filler	2.4	Limestone filler	5.0
		Bitumen	4.80	Bitumen	4.80

Due to their low percentage and weight, hydrated lime and limestone filler were introduced directly into the asphalt plant mixer, which required manual bagging of hydrated lime and limestone filler (Figure 4). An important question is whether this manual material preparation step can be performed if the innovative mixture is to be prepared on a larger scale. This is all the more important as the quantities to be manually prepared depend on the local (and therefore highly variable) attrition characteristics of the coarsest fractions of the aggregates used, as well as on the type of asphalt mixing plant. It therefore seems necessary to further optimize and validate methods for the preparation of fine fractions.

Figure 4. Bagging and loading belt of the plant

3.2.2 Paving

Below are illustrations of the various stages of construction of the reference and experimental pavements from the asphalt mix produced industrially at the plant. The illustrations are presented in chronological order, starting with the first (deepest) layers and ending with the wearing courses.

The GB mix was paved the 4th of October 2022 at the fatigue carousel facility of the Gustave Eiffel University in Nantes (Figure 5).

Figure 5. Pictures of GB paving operation

The Peri-urban mixes were paved the 6th of October 2022.

Figure 6. Pictures of paving operation for the 1st layer of Peri-Urban section (BB 0/8)

Figure 7. Pictures of paving operation for the 2nd layer of Peri-Urban section (BB 0/4)

The Urban mix was paved the 6th of October 2022.

Figure 8. Pictures of paving operation for the Urban section (BB 0/4)

Oral feedback from the workers involved in the paving operation highlighted several critical aspects on the implementation of the experimental pavements. First, and especially for the peri-urban pavement, it was necessary to prepare and then transport the mixes quickly to ensure proper adhesion between the two layers that make up the wearing course. The temperature at the interface between them had to be close to 150°C. In addition, due to the relatively high bitumen content (close to 6.0%), the peri-urban and, to a lesser extent, the urban mixes proved to be relatively sticky to the workers' hand tools.

This shows that, in addition to the mixing stage at the plant, the paving stage should also be optimized. Finally, due to the higher temperatures and percentages of bitumen required, the operators reported greater discomfort with the odorous compounds (probably volatile organic compounds) released during the work.

3.2.3 Final composition of the mixes produced in plant

Table 7 presents the final compositions of the asphalt mixtures produced in plant for the full scale test.

The temperatures at the plant outlet are shown in the table below. Particular care was taken to ensure that the temperature at which the peri-urban asphalt was applied was above 150°C. For this reason, production for both layers was shipped simultaneously.

Table 7. Binder content and size of aggregates of mixes produced in plant (control measurements)

Mixes	S1 (Porous asphalt)	S2 (0/8 Peri-Urban)	S2 (0/4 Peri-Urban)	S3 (0/4 Urban)	S4 (BBSG)	GB
Binder content	4.76%	5.90%	6.31%	4.74%	5.56%	4.42%
2 mm	17%	12%	18%	25%	30%	35%
4 mm	19%	24%	78%	81%	41%	50%
6.3 mm	31%	76%	100%	100%	55%	61%
10 mm	86%	100%	-	-	90%	73%
14 mm	100%	-	-	-	100%	94%
20 mm	-				-	100%
Filler	5.2%	5.4%	5.30%	6.0%	6.7%	7.6%
Laying T°	164°C	166°C	164°C	172°C	178°C	

Figure 9, Figure 10 and Figure 11 exhibit the final aggregates size distribution curves of the various formulations produced by the plant compared to the theoretical target size distribution curves for each type of asphalt. The final grading curves of the different asphalts manufactured in the plant are referred to as “obtain with plant”. The laboratory formulation are named “LAB formulation” and the theoretical formulation for plant are named “Theoretical for plant”.

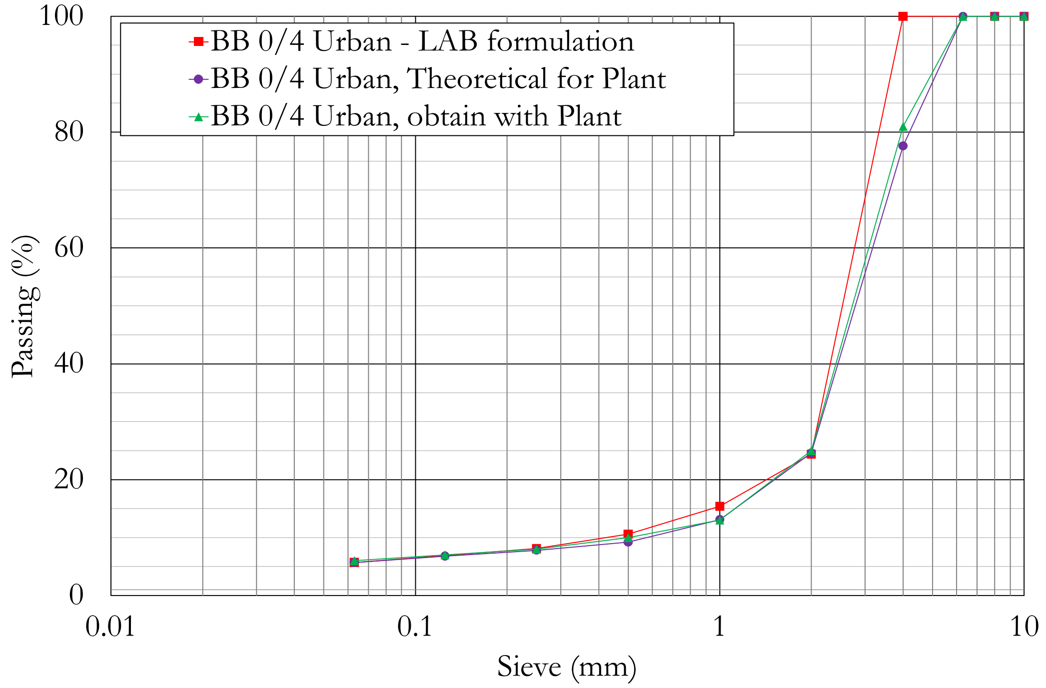


Figure 9. Size distribution curves for Urban BB 0/4 mixture

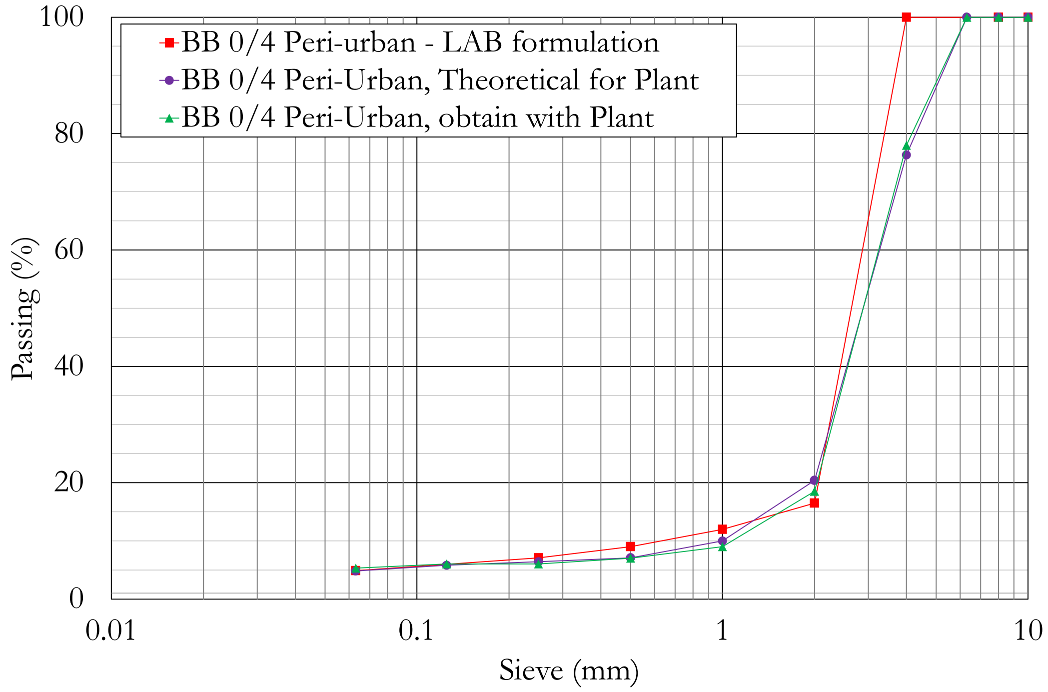


Figure 10. Size distribution curves for Peri-urban BB 0/4 mixture

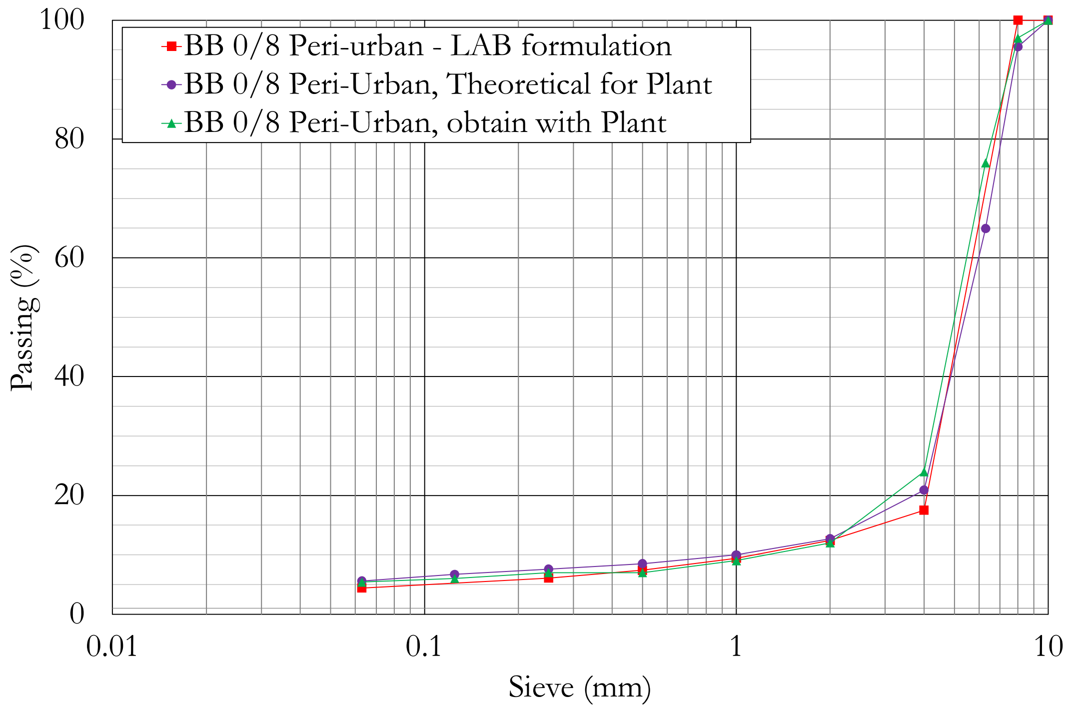


Figure 11. Size distribution curves for Peri-urban BB 0/8 mixture

4 Measurements made after construction

4.1 Thickness of the constructed layers

Actual layer thicknesses were measured at each stage of the pavement construction using topographic surveys (Table 8) and core samples.

Table 8. Thicknesses of the different layers

		S1 (Porous asphalt)	S2 (Peri-Urban)	S3 (Urban)	S4 (BBSG)
Wearing layer	Average measured thickness	5.4 cm (+/- 0.3 cm)	5.6 cm (+/- 0.3 cm)	3.4 cm (+/- 0.5 cm)	4.8 cm (+/- 0.4cm)
	Min / Max	5.0 / 5.9 cm	5.2 / 6.1 cm	2.8 / 5.5 cm	3.5 / 5.5 cm
GB layer	Average measured thickness	10.3 cm (+/-0.8cm)	11.0cm (+/- 0.4cm)	12.8 cm (+/- 0.6cm)	11.2 cm (+/- 0.6 cm)
	Min / Max	9.1 / 11.5 cm	10.3 /11.5 cm	10.8 / 13.5 cm	10.2/13.2 cm
UGM layer	Average measured thickness	22.4 cm (+/- 1.6 cm)	24.4 cm (+/- 2.4 cm)	26.0 cm (+/-1.1 cm)	25.8 cm (+/- 1.4 cm)
	Min / Max	19.9/ 25.1 cm	20.8/ 26.9 cm	24.1/ 28.3 cm	23.1/ 30.1 cm

The thicknesses of the different layers are very homogeneous and closed to the target values, except for the Urban layer, which is significantly thicker than the target: mean thickness of 3.4 cm instead of 2.5 cm.

4.2 Coring

Three cores were taken on each section (outside the wheel path) to qualify and evaluate the initial void values of the surface layer (wearing course) and GB layers. In Figure 12, the location of the cores is indicated by a red cross.

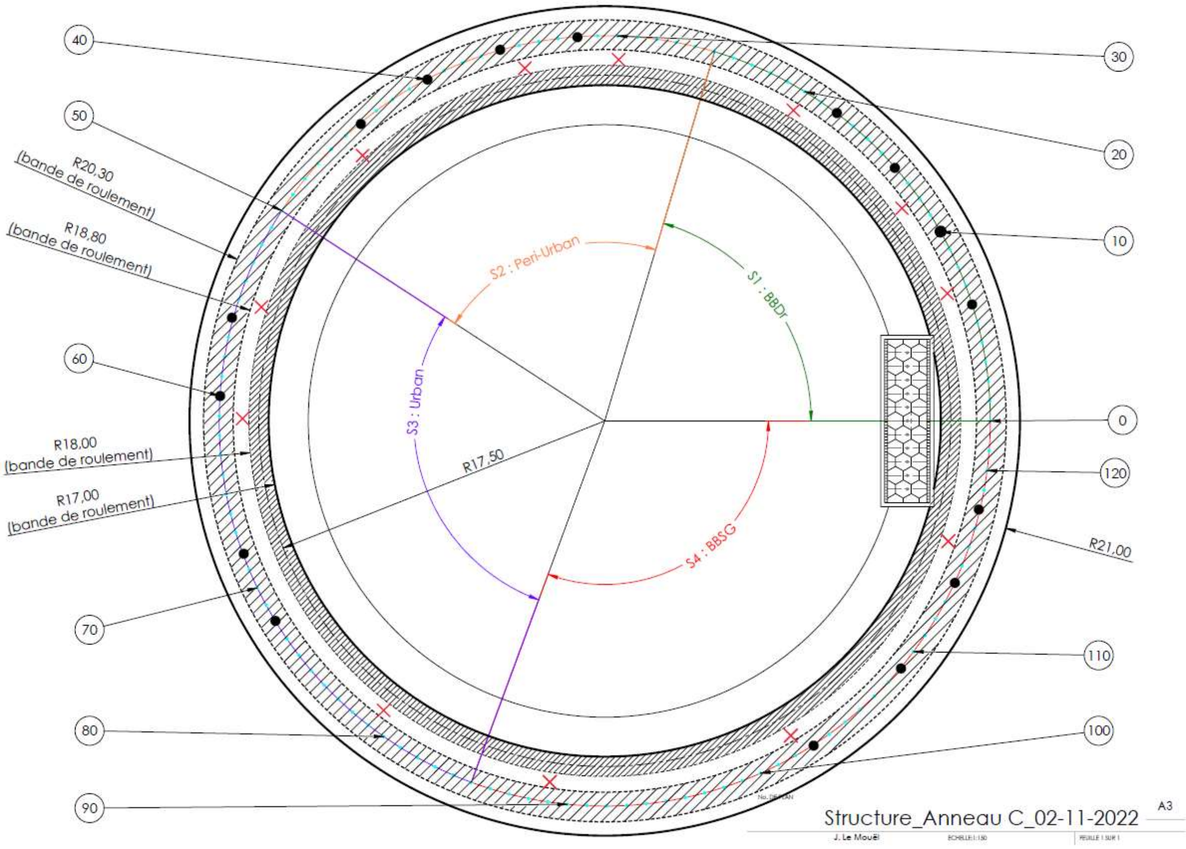
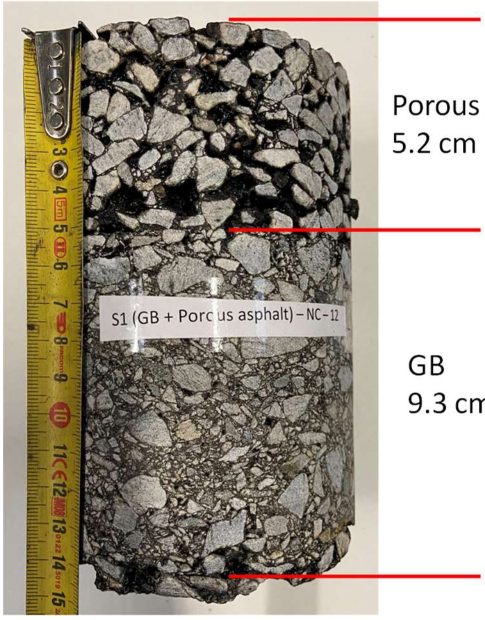
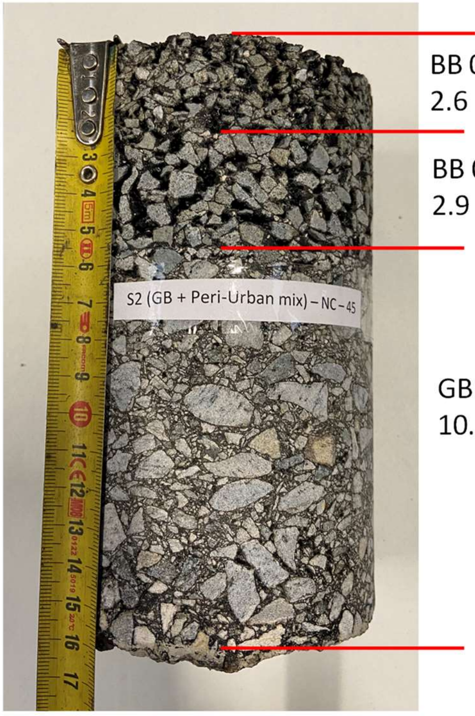


Figure 12. The location of the collected cores is marked with red crosses

Figure 13 shows the photographs of the various cores taken. Only one photo per section is provided. The rest of the photographs are presented in the Appendix titled "Pictures of the cores".



Section 1 (Porous asphalt + GB)



Section 2 (Peri-Urban : BB0/4 + BB 0/8 + GB)

Section 3 (Urban : BB 0/4 + GB)

Section 4 (BBSG + GB)

Figure 13. Pictures of the cores

Height of the sample and void percentage were measured on each sample and the obtained data is given in the Table 9.

Table 9. Height and void percentage of the samples taken on each section of the fatigue carousel

	Surface layer		GB layer	
	Thickness	Void percentage	Thickness	Void percentage
S1, Porous asphalt	5.5 cm (+/-0.4 cm)	20.4% (+/-1.8%)	9.0 cm (+/-0.9 cm)	4.7% (+/-0.3%)
S2, peri-urban mix BB0/8	3.0 cm (+/-0.1 cm)	22.6% (+/-1.4%)	9.7 cm (+/-0.6 cm)	4.2% (+/-0.15%)
S2, peri-urban mix BB0/4	2.8 cm (+/-0.2 cm)	22.0% (+/-0.1%)		
S3, Urban mix, BB0/4	3 cm (+/-0.2 cm)	23.3% (+/-0.7%)	11.7 cm (+/-0.6 cm)	4.4% (+/-0.15%)
S4, BBSG	4.8 cm (+/-0.3 cm)	8.4% (+/- 1.0%)	10.6 cm (+/-0.4 cm)	4.3% (+/-0.6%)

For the LAB formulation, the void percentages were :

- 16.2% for the Urban mixture
- 22.2% for the peri-urban mixture 0/4
- 23.1% for the peri-urban mixture 0/8

The void percentages of the field materials are closed to the LAB formulation for the peri-urban mixture, and higher than the LAB formulation for the urban mixture.

4.3 Bearing capacity

The subgrade includes a sand layer, and an unbound granular (UGM) subbase, consisting of one former layer with a thickness of about 25 cm. The bearing capacity of the subgrade was measured at different positions on each structure by means of dynamic plate load test (Figure 14) (NF P94-117-2), which gave average values between 103 and 125 MPa for the soil, and between 157 and 170 MPa on top of the UGM layer (see). The four sections of the carousel were found to be very consistent.

Table 10. Bearing capacity of the different structures

Measurement of bearing capacity (top of UGM) with dynamic plate load		S1 (Porous asphalt)	S2 (Peri-Urban)	S3 (Urban)	S4 (BBSG)
UGM	Average bearing capacity	160 MPa (+/- 13 MPa)	170 MPa (+/-11 MPa)	157 MPa (+/-24 MPa)	157 MPa (+/- 9MPa)
	Min / Max	134/183 MPa	149/184 MPa	128/179 MPa	141/172 MPa
Soil	Average bearing capacity	114 MPa (+/- 5MPa)	125 MPa (+/- 17 MPa)	117 MPa (+/-24 MPa)	103 MPa (+/- 19 MPa)
	Min / Max	108/119 MPa	100/137 MPa	78 / 154 MPa	65/126 MPa

Figure 14. Measurement of bearing capacity (top of UGM) with dynamic plate load

5 Laboratory tests

5.1 IFT Laboratory tests on loose mixtures from plant and cores

All the materials produced in plant were characterised in laboratory using complex modulus test and, for the surface layers, rutting test (using a French wheel tracking tester).

The specimens were prepared from loose materials collected during the production stage. The materials were compacted using a slab compactor with rubber-tire wheels (EN 12697-33) to produced:

- 600mm by 400mm and 120 mm thick slabs for complex modulus test (after compaction, the slabs were sawn to produced specimens).
- 500mm by 180mm and 50mm or 100mm thick slabs for rutting test.

Prior to each tests, the void percentage of the specimens were measured with a gamma densimeter.

5.1.1 Complex modulus tests

All the materials produced in plant were characterised in lab using complex modulus tests (EN 12967-26) (2 point bending on trapezoidal specimens or parallelepiped specimens). The specimens were prepared from loose materials collected during the production. The materials were compacted using a slab compactor with rubber-tire wheels (EN 12697-33+A1, 2007), to produce 600 mm by 400 mm and 120 mm thick slabs or 500mm by 180mm and 100mm thick slab. After compaction, the slabs were sawn to produce trapezoidal specimens or parallelepiped specimens, which were tested in two-point bending mode, to measure their complex modulus norm ($|E^*|$) and phase angle (δ). Results at 15°C and 10Hz are presented in

Table 11.

All reference mixes exhibit high modulus, superior to the European criteria for this class of materials (> 7 GPa for BBSG mix, >3 GPa for porous asphalt and >9 GPa for GB3). The modulus of the innovative materials for Peri-Urban mixes (BB0/4 and BB0/8) are closed to the modulus of the BBTM. The modulus of the innovative Urban mix (BB0/4) is lower than the requirement for a BBTM.

Table 11. Experimental data obtained from complex modulus tests (15°C, 10Hz)

Mixes	Stiffness parameters (15°C and 10Hz)		Void (in %)
	E* (MPa)	φ (°)	
Requirements for a BBTM mix	≥ 3 000 MPa		
S2, Peri-urban, BB 0/4	2 502 MPa	22.2 °	19.4%
S2, Peri-urban, BB 0/8	2 654 MPa	23.0 °	18.2%
S3, Urban, BB 0/4	1 686 MPa	21.1°	26.3%
Requirements for a BBSG 3 mix	≥ 7 000 MPa		
S4, BBSG	10 368 MPa	17.5°	2.9%
Requirements for a Porous asphalt	≥ 3 000 MPa		
S1, Porous asphalt	4 260 MPa	20.2°	21.4%
Requirements for a GB 3	≥ 9000 MPa		
GB 3 (base layer)	12 711 MPa	11.4°	6.1%

5.1.2 Rutting test (French wheel tracking test)

The French wheel tracking tester (FWTT) is a piece of laboratory equipment designed to investigate the rutting resistance of bituminous mixtures under conditions of stress and temperature that aims simulating the conditions applied to pavement, in accordance to the standard EN 12697-22 (Figure 15). Parallelepipedic specimens of bituminous mixes are subjected to repeated passes of a wheel fitted with a type, mounted on a carriage that moves back and forth at a sinusoidal rhythm, inducing permanent deformation. Two specimens can be placed in the FWTT at a time, on two separate supports, for testing with the same parameters, under the same temperature conditions. The test is performed at the temperature of 60°C.

The void percentage of each specimen are measured with the gammadensimeter before the test.

Figure 15. Illustrations of the French wheel tracking tester

The obtained data is synthetized in Table 12.

The two innovative surface mixes (for urban and peri-urban conditions) are closed to a classical French surface layer: a BBTM (Béton Bitumineux Très Mince, or Very Thin Asphalt Layer). These two materials met the European specifications for resistance to rutting for a BBTM. However, high values of rut depth were obtained for these two mixes mainly due to an aggregates stripping (see Figure 17 and Figure 18). Stripping was also observed on the porous asphalt specimens (see Figure 16).

The reference BBSG meets the European specifications for resistance to rutting. Photographs of the BBSG specimens after the rutting test are presented on the Figure 19. No ravelling was observed with all the specimens. There is no specification for porous asphalt.

Table 12. Data obtained from French wheel tracking tests

Mixes	Rut depth EU method NF EN 12697-22+A1 xx cycles at 60 °C Rut Depth (%)	Void (in%)
Requirements for a BBTM mix	<20% at 3 000 cycles	
S2, Peri-urban, BB 0/4	13.1%±1.3%	20.4%±0.1%
S3, Urban, BB 0/4	15.2%±0.6%	23.1%±0.4%
Requirements for a BBSG mix	<10% at 30 000 cycles	
S4, BBSG	6.4%±0.4%	5.3%±0.5%
Requirements for a Porous asphalt	-	
S1, Porous asphalt	12.4%±0.4%	20.9%±0.8%

Figure 16. Porous asphalt specimens (S1) after the rutting test

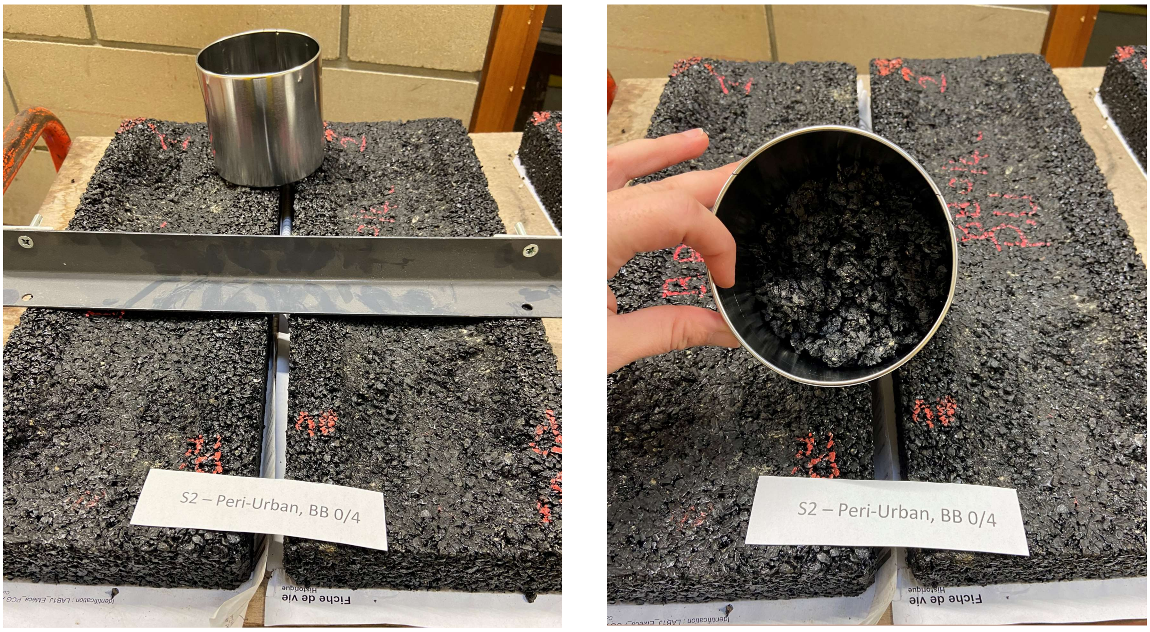


Figure 17. Peri-Urban specimens (S2) after the rutting test

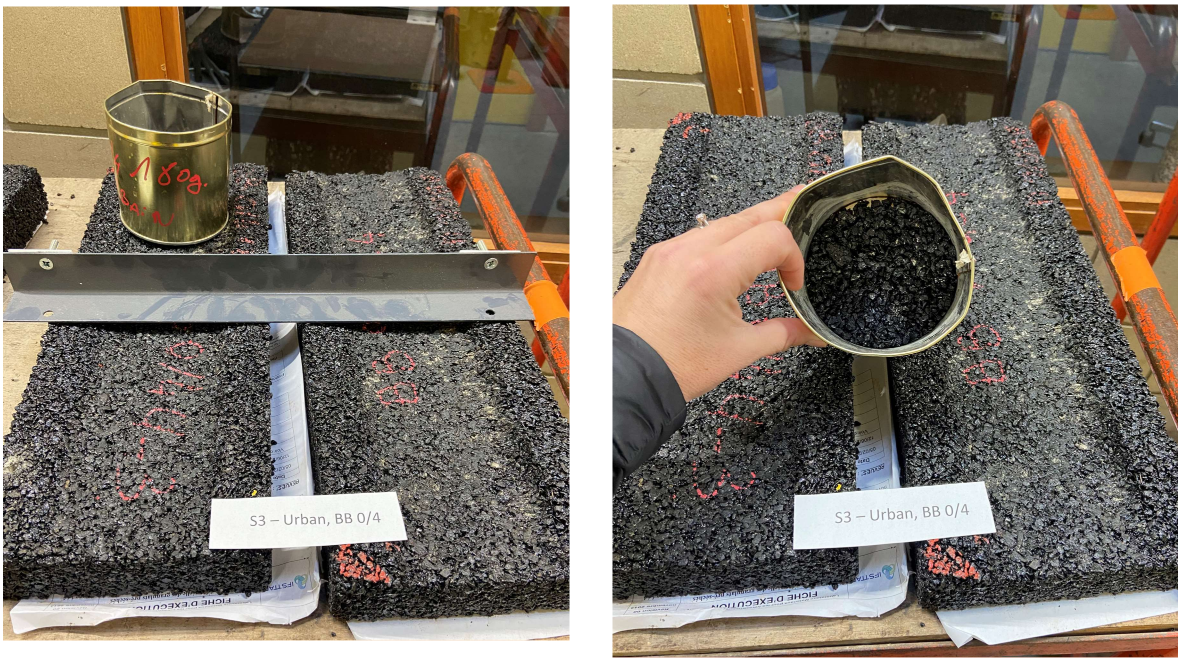


Figure 18. Urban specimens (S3) after the rutting test

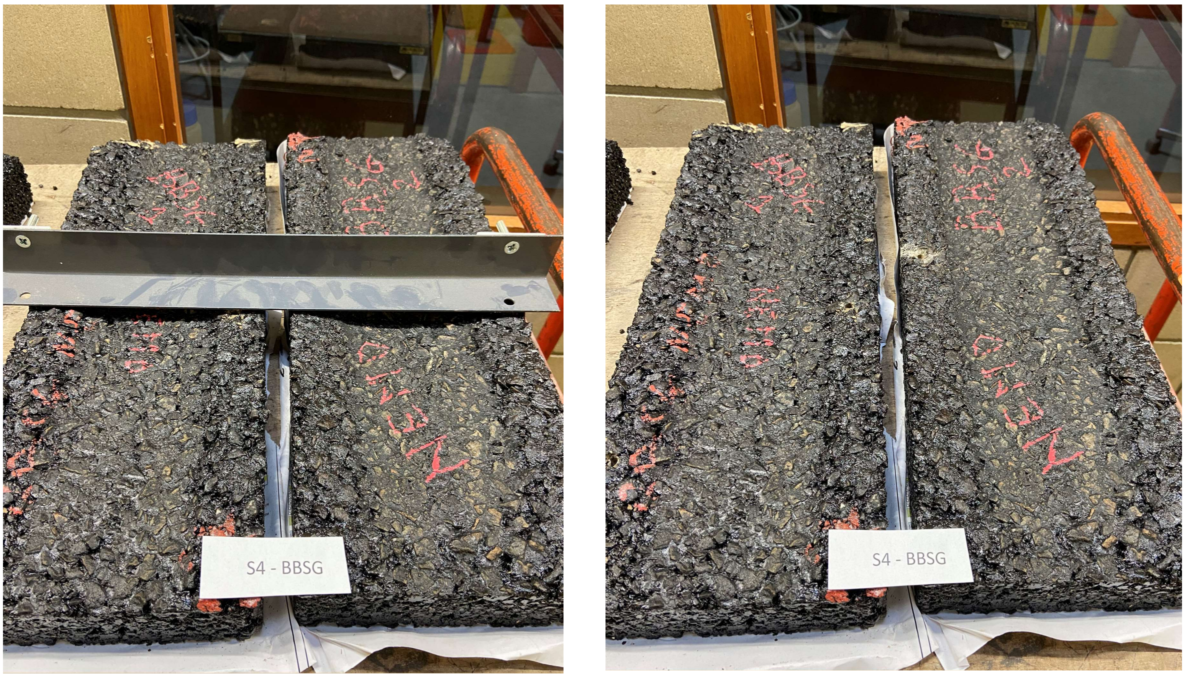


Figure 19. BBSG specimens (S4) after the rutting test

5.2 UC Laboratory tests on loose asphalt and prepared samples

In addition to the tests carried out by UGE, the experimental asphalt mixtures manufactured in the plant were collected during paving operation. This material was used to manufacture different slabs and specimens, which were characterised in the UC laboratory using different tests depending on the type of mixture:

- Urban mixture: Marshall (EN 12697-34), water sensitivity test (EN 12697-12) and wheel tracking test (EN 12697-22)

- Peri-urban mixture: Cantabro test at dry conditions (EN 12697-34), Cantabro test at wet conditions (NLT 362/92) and water sensitivity test (EN 12697-12).

The asphalt mixtures were collected as loose material, so they had to be reheated in order to compact the new specimens. The short aging process after production at the asphalt plant means the binder analysed at UC laboratory is slightly harder than the used at real scale in UGE facilities.

5.2.1. Urban mixture

The urban mixture was laid at real scale with a higher void percentage that the designed mixtures. The urban experimental mixture produced in Nantes had a 23.3% percentage of voids (Table 9), so this percentage was replicated at laboratory level in order to analyse its behaviour in the most similar conditions.
Conventional tests normally carried out on AC mixtures were carried out and compared with those obtained during the mixture design phase (more information is available in the deliverable D6.2). Table 13 shows the results of the tests carried out.

Table 13. Mechanical results of real and laboratory mixture (urban)

Results	Real mixture (asphalt plant)	Laboratory
Density (g/cm^3)	1.94 ± 0.00	2.14 ± 0.01
Voids in mixture (%)	23.9 ± 0.1	16.2 ± 0.3
Stability (kN)	6.5 ± 0.9	9.1 ± 0.2
Deformation (mm)	5.0 ± 1.8	3.3 ± 0.3
ITS^{Dry} (kPa)	966 ± 34	1,175 ± 21
ITS^{Wet} (kPa)	722 ± 28	981 ± 31
ITSR (%)	75	84
Slope (mm/1000 cycles)	1.08 ± 0.04	0.05 ± 0.02
Rut depth (mm)	10.4 ± 2.0	1.3 ± 0.14

As can be seen from the density and voids results, the real and laboratory mixtures exhibit significant differences. Due to the percentage of voids (23.9%), the real scale mixture resemble more to a porous asphalt mixture. Despite the bitumen was aged due to the binder was reheated, the resistances were lower mainly because of the higher percentage of voids, this is also clearly related with the higher slope obtained in the wheel tracking test. This is in line with the results achieved by UGE at real scale.

5.2.2. Peri-Urban mixture

In the case of the peri-urban asphalt, two distinct mixtures were evaluated: one for the lower layer and the other for the upper layer. Both are porous asphalt (PA) mixtures and the results of the different tests are presented in Table 14.

Table 14. Mechanical results of real and laboratory mixtures of peri-urban asphalt

	Top layer		Bottom layer	
Results	Real mixture	Laboratory	Real mixture	Laboratory
Density (g/cm^3)	1.93 ± 0.00	1.95 ± 0.01	1.93 ± 0.00	1.94 ± 0.01
Voids in mixture (%)	21.9 ± 0.1	22.2 ± 0.3	22.6 ± 0.1	23.1 ± 0.4
Particle loss^{Dry} (%)	1.1 ± 0.4	0.8 ± 0.1	6.6 ± 0.6	5.5 ± 1.1
Particle loss^{Wet} (%)	4.5 ± 0.4	3.5 ± 0.7	10.9 ± 1.0	6.3 ± 1.0
ITS^{Dry} (kPa)	976 ± 15	1,142 ± 18	1011 ± 31	1,028 ± 60
ITS^{Wet} (kPa)	843 ± 24	983 ± 23	760 ± 20	860 ± 61
ITSR (%)	86	86	75	84

The difference in the voids content is small and could be due to the aging process of the mixture, as explained above. The particle losses of the mixtures remain at values similar to those obtained in the laboratory, being very low in the upper layer, which is the most important since it directly carries the exerted loads. In terms of resistance, the values are quite similar, and the differences are probably due to the different bitumen properties. The bottom layer is the only one that obtained a significantly lower ITSR score. However, as it is the bottom layer, it is less exposed, so it is not a major concern.

Therefore, in view of these results, the peri-urban mixtures spread on the carousel are very similar to those designed in the previous task, and they showed a good performance in general terms.

6 Carousel and methodology

6.1 Pavements structures

The fatigue experiment at the APT facility was carried out with a mean radius of 19.5 m and a total length of approximately 122.5 m, consisting of four asphalt sections, each 3 m wide. These sections were tested simultaneously and they correspond to the two experimental asphalt mixtures developed in task 6.2 and two reference mixtures. The positions of the different structures on the APT facility are showed in Figure 20. The peri-urban section (S2) is approximately 25 m long and the urban section (S3) is 35 m long. The two reference sections (S1, porous asphalt and S4, BBSG [Béton Bitumineux Semi-Grenu - Dense Graded Asphalt Mixture] are 25 m and 37.5 m long, respectively.

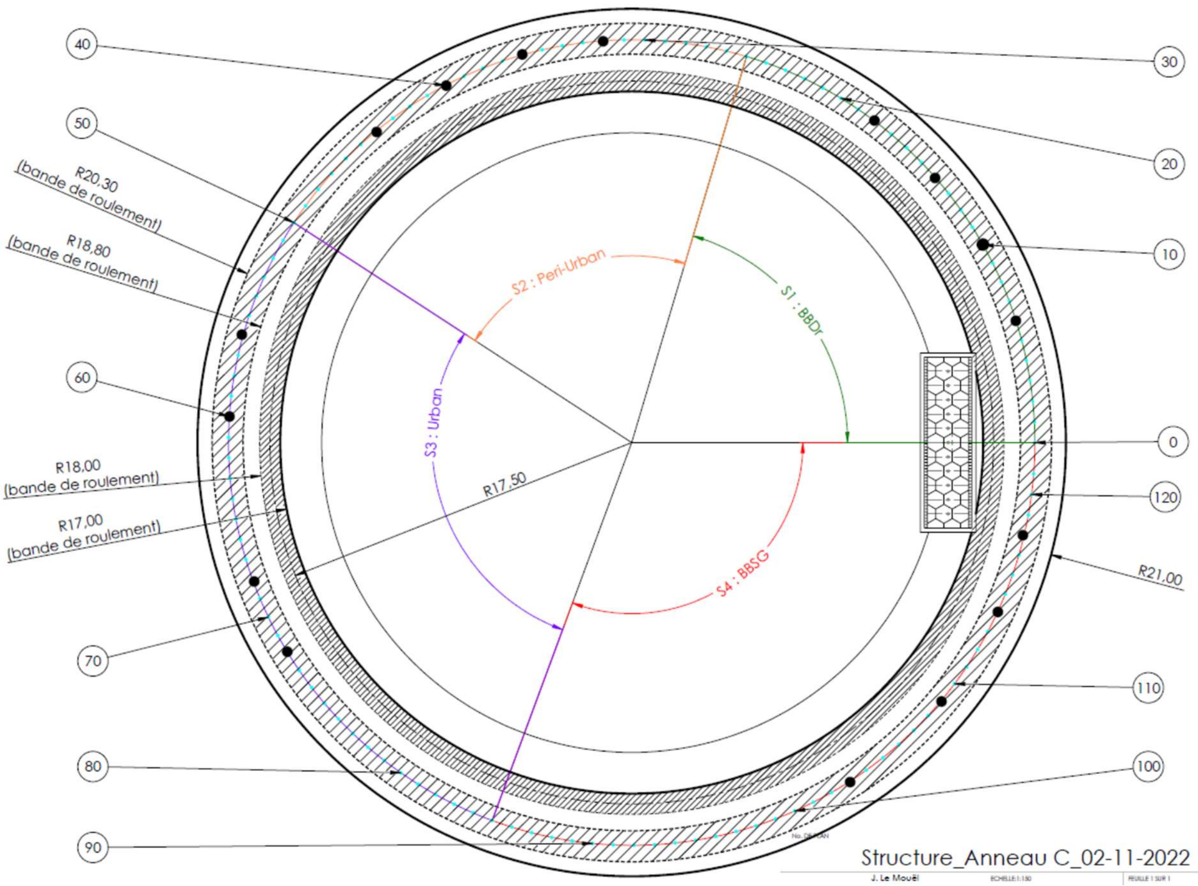


Figure 20. Sections of the project NEMO

6.2 Experimental conditions

Since there are two different asphalt mixtures to be evaluated, two fatigue test conditions are necessary as well. For that reason, the fatigue full scale test will be realized in two phases: the first one corresponds to the urban conditions and the second one to the peri-urban conditions. The major differences between them are the speed and the number of cycles applied for each one. Table 15 summarizes all the conditions for the two phases.

Prior to the pavement mechanical durability study, an inner ring of the carousel (17.5 m radius, see Figure 20) was subjected to 200,000 load cycles to test the degradation of the photocatalytic paint. The results of this study are presented in Deliverable 6.5.

Table 15. Loading conditions during each test phase

Conditions	Test for photocatalytic paint	Fatigue test	
		Urban	Peri-urban
Period	*15/11/2022 to 20/12/22*	*21/12/2022 to 24/02/2023*	*21/12/2022 to 28/08/2023*
Speed (rounds/min)	7 rounds/min	7 rounds/min	Between 7 and 10 rounds/min
Speed (km/h)	50 km/h	50 km/h	Between 50 and 72 km/h
Transverse wandering	± 26 cm	± 26 cm	± 52 cm
Length of wheel path	1 m	1 m	1.6 m
Load (dual wheels)	65 kN	65 kN	65 kN
Number of loads	200 000	200 000	850 000
Surface temperature (Min / Max)	-4.0°C / 21.6°C	-3.6°C / 29.4°C	-3.6°C / 60.4 °C
Mean temperature	7.2°C (+/- 4.2°C)	8.5°C (+/- 3.8°C)	15.7°C (+/- 9.5°C)

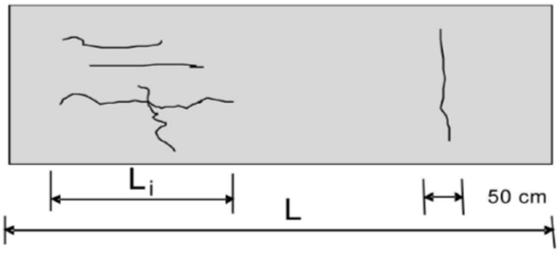
Furthermore, in order to perform measurements with a greater variety of wheel types, a tridem axle was installed on one arm of the carousel for 522,340 load cycles (June 20 to the end of the test) on one arm of the carousel.

6.3 Test program and monitoring procedures

Below are described a series of measurements carried out on the APT facility to monitor the mechanical behavior of the reference and experimental formulations over an increasing number of load cycles.

6.3.1 Visual crack monitoring

During the experiment, pavement cracking was assessed by visual inspection on all the sections, and cracks were marked with paint, to facilitate their identification. On the APT, the extent of cracking is conventionally defined as the percentage of the length of the pavement affected by cracks. For longitudinal cracks, the “cracked length” corresponds to the measured length of the cracks. For transversal cracks, a length of 50 cm is conventionally attributed to each crack (see Figure 21).



Extent of cracking (%) $=\sum_i L_i/L$
Li : lengths of zones with cracks

Figure 21. Evaluation of the extent of cracking

6.3.2 Falling weight deflectometer (FWD)

The FWD (Falling Weight Deflectometer) or Deflectometer with falling mass reproduces an impulse load close to that produced by the passing of a rolling load (Figure 22). The load is applied by means of a circular 30 cm diameter plate and this load of 65 kN at 30 Hz produces a deflection basin, which is measured at 9 points by geophones. FWD measurements were performed each meter at 0, 200 000, 500 000, 752 000 and 1 050 000 loads.

Figure 22. Falling weight deflectometer

6.3.3 Benkelman beam deflections

Deflections were also measured with a Benkelman Beam, the principle of which is similar to the FWD. A load of 65 kN is used to reproduce the passage of a rolling load but a low speed close to 3 km/h (at a frequency close to 1 Hz). During each series of measurements, 4 measurements were made on each pavement section. Benkelman beam measurements were performed at 0, 50 000, 100 000, 200 000, 500 000, 750 000, 1 000 000 and 1 050 000 loads.

6.3.4 Permanent deformation measurements

Rut depth measurements were made with a profilometer equipped with a laser sensor (Figure 23). The transversal profile of the pavement was measured on a width of about 1.4 m. The maximum rut depth value was then determined. Three measurements were performed on each section at the beginning of the test and then at 10 000, 20 000, 50 000, 100 000, 150 000, 200 000, 500 000, 750 000, 1 000 000 and 1 050 000 loads. From these measurements, average rut depths were determined for each section and each number of cycles. By dividing this average rut depth by the real layer thickness, the rutting percentage for each structure was determined as well as its evolution according to the number of cycles.

Figure 23. Illustration of the profilometer used for rut depth measurement

6.3.5 The instrumentation of pavement sections

Each section of the fatigue carousel was instrumented during its construction with the following sensors:

- 2 longitudinal strain gauges placed at the bottom of the base layer (Figure 24). The strain gauges are placed in the central part of the wheel path of the fatigue test track.
- Temperature sensors, placed at the surface, -2.5cm, -5cm, -7.5cm, -15cm and -30 cm, on two sections only.

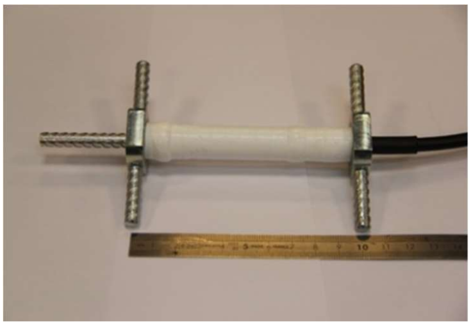


Figure 24. Strain gauge used for pavement instrumentation

7 Test with Urban conditions

The urban experiment was conducted between December 2022 and February 2023 to evaluate the mechanical behavior of the urban asphalt mixture. A total of 200,000 load cycles were performed under a load of 65 kN. The speed was set at 50 km/h. The loading conditions during the experiment are given in Table 15.

7.1 Environmental conditions

During this part of the test, the pavement surface temperature varied between -3.6°C and 29.4°C, with most values (86 %) comprised between 0 °C and 14°C. The mean surface temperature was 8.5°C (+/- 5.0°C), and the mean temperature in the central part of the bituminous layers was 8.5°C (+/-3.8°C). The histogram for the surface temperature distribution is presented in Figure 25. Temperature variations and load cycles during the test with urban conditions are presented in Figure 26.

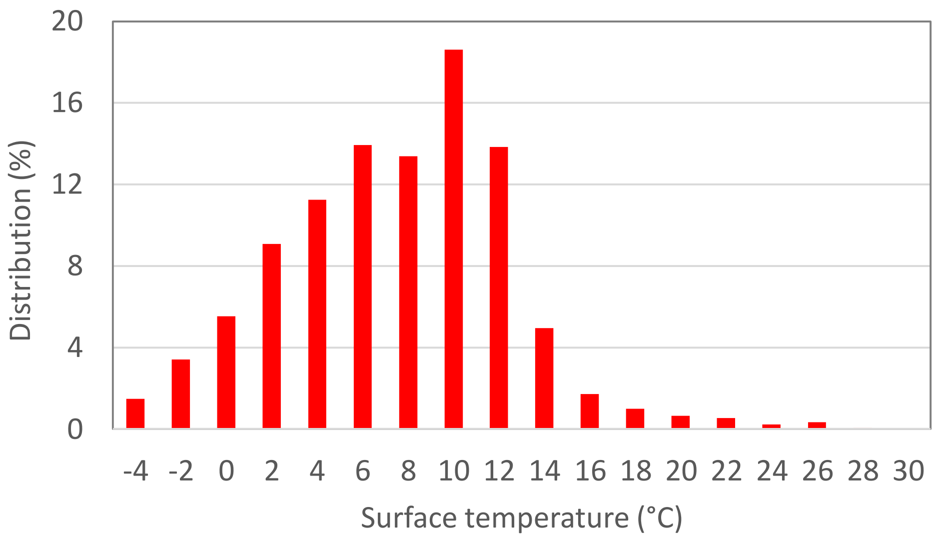


Figure 25. Histogram of the asphalt surface temperature distribution during the urban conditions experiment

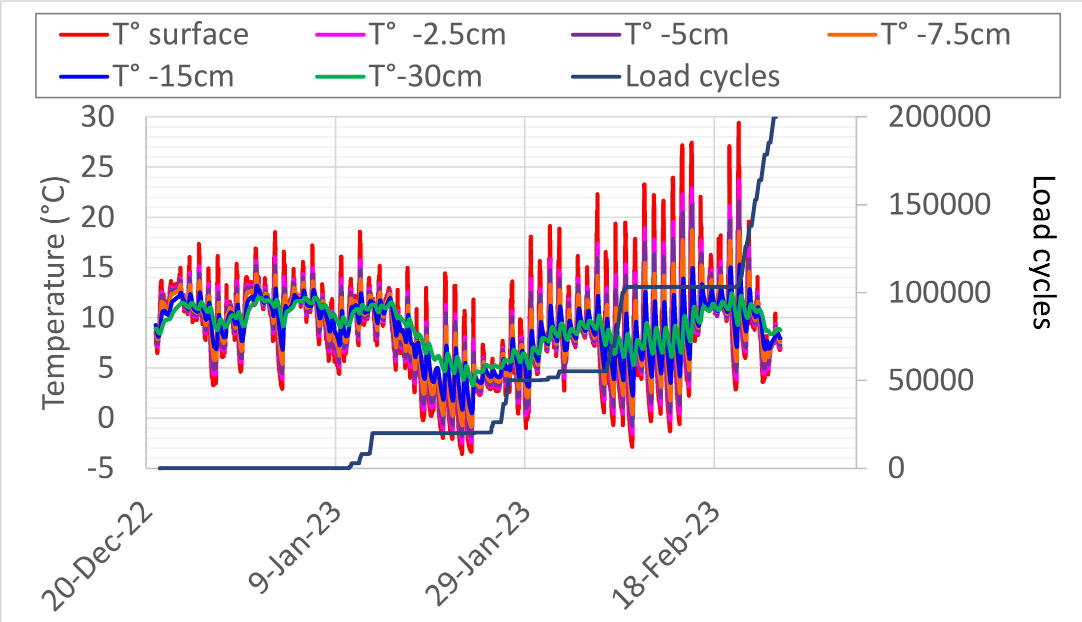


Figure 26. Temperature variations and load cycles during the urban conditions experiment

The histogram of the surface temperature distribution only during loading phases is presented on Figure 27. During the load cycle, 99% of the temperatures are between 0 and 20°C, and 96% between 0 and 16°C.

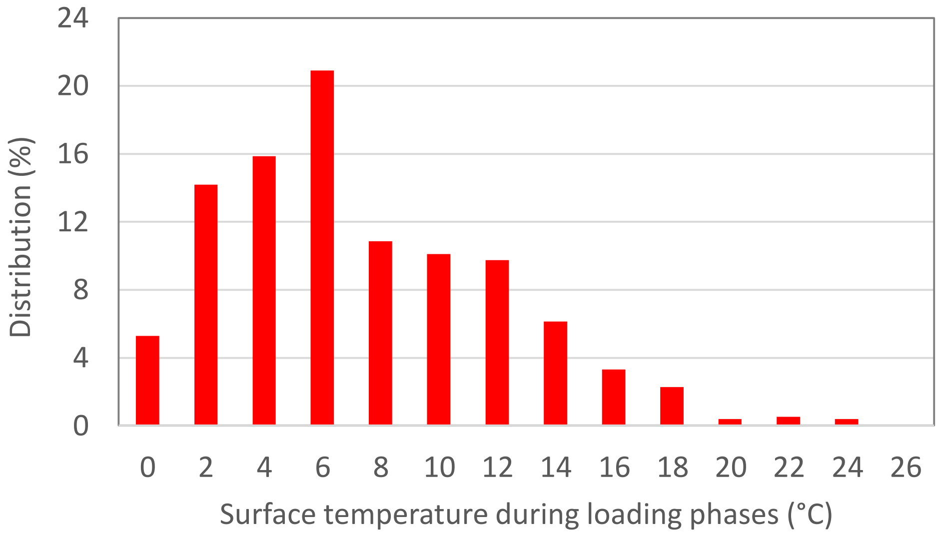


Figure 27. Histogram of the surface temperature distribution only during loading phases

The rainfall amounts on the test site is presented on Figure 28. The rainfall was moderate throughout the experiment.

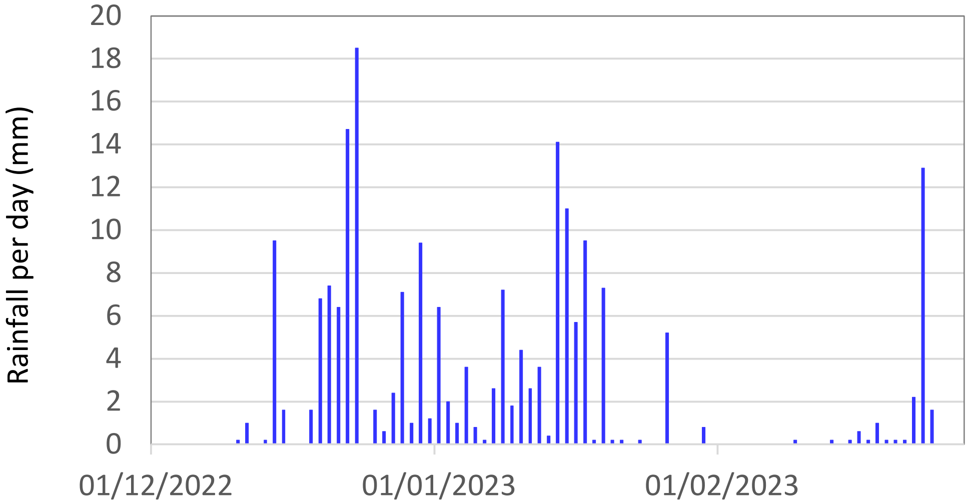


Figure 28. Rainfall amounts per day during the urban conditions experiment

7.2 Visual crack monitoring

Photographs of the different sections at the end of the first phase of the urban experiment (200,000 load cycles) are showed in Figure 29, Figure 30, Figure 31 and Figure 32. No crack or other surface damage was observed in any section at 200,000 load cycles.

Figure 29. Photograph of the reference porous asphalt at 200 000 load cycles

Figure 30. Photograph of the peri-urban mixture asphalt at 200 000 load cycles

Figure 31. Photograph of the urban mixture asphalt at 200 000 load cycles


Figure 32. Photograph of the BBSG reference mixture asphalt at 200 000 load cycles

7.3 Rut depth measurement

The accuracy of the measurements made with the profilometer is ~0.5 mm (enough to measure the texture of the pavement). The Figure 33 shows the raw transverse profile with increasing number of load cycles for the location of the urban section where the rut depth is maximum. The corresponding profiles for all constructed sections are presented in the “Rut depth measurements” appendix.

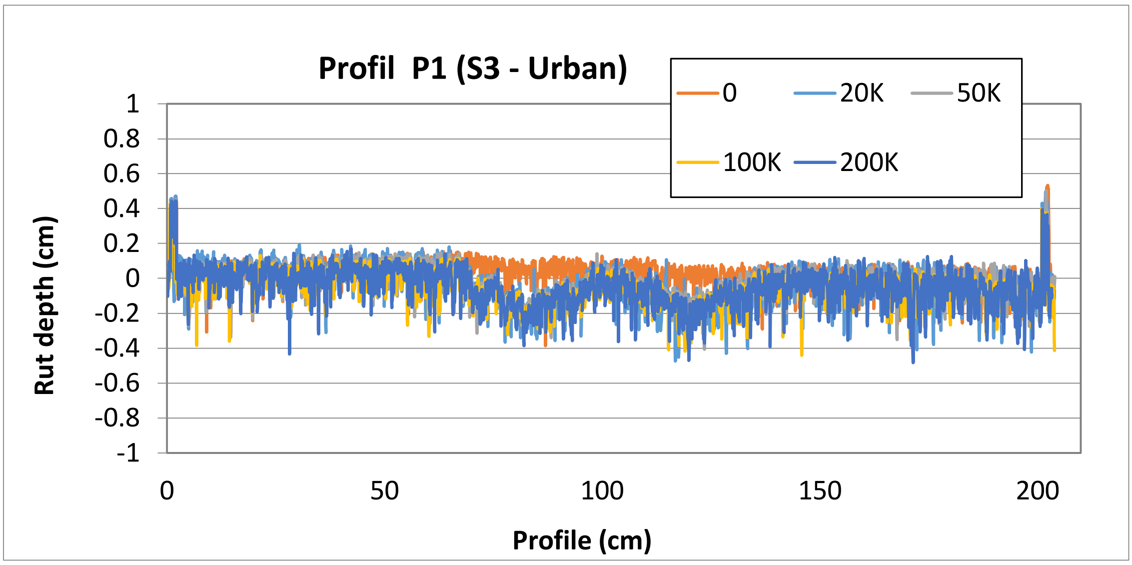


Figure 33. Rut depth profiles with increasing number of load cycles for the urban asphalt. The location of the profile is where the rut depth is maximum

In order to determine the maximum rut depth, for each measurement, an envelope curve is determined. This envelope curve is calculated using the maximum values of profile measurements, calculated by intervals of 10 mm. The maximum rut depth is then defined as the minimum value (lowest level) of the envelope curve. The evolution of rut depth (in mm) during the test is proposed in Figure 34.

It is worth noting that since the surface course thicknesses for the four sections are not the same, the evolution of relative rutting, expressed as a percentage of the surface course thickness, is also shown in Figure 35. For the peri-urban section, the thicknesses of the bottom and top layers are employed in calculations.

At the end of the urban conditions experiment, the rut depths (in %) are :

- 0.5% for porous asphalt
- 0.9% for peri-urban mix
- 1.7% for urban mix
- 0.4% for BBSG

Overall, no significant rutting was observed between the sections. However, the surface temperature was very low during this period of the experiment. In fact, rutting is generally accentuated by high temperatures and additional measurements are needed to evaluate rutting during hot periods.

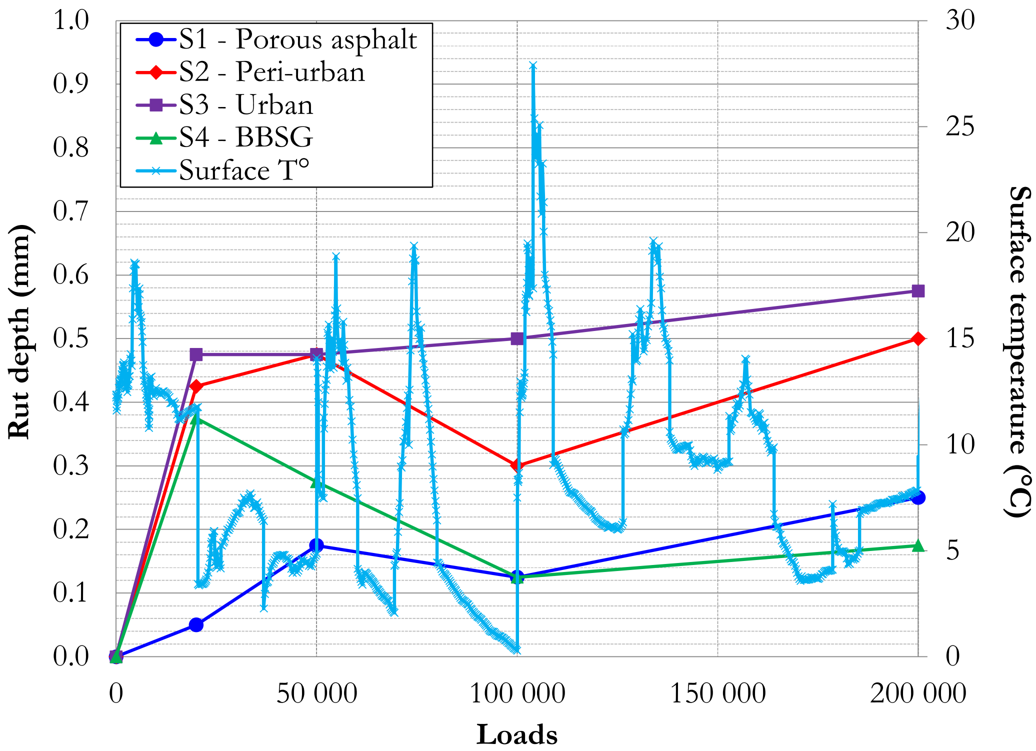


Figure 34. Evolution of maximum rut depth (in mm) during the urban condition experiment

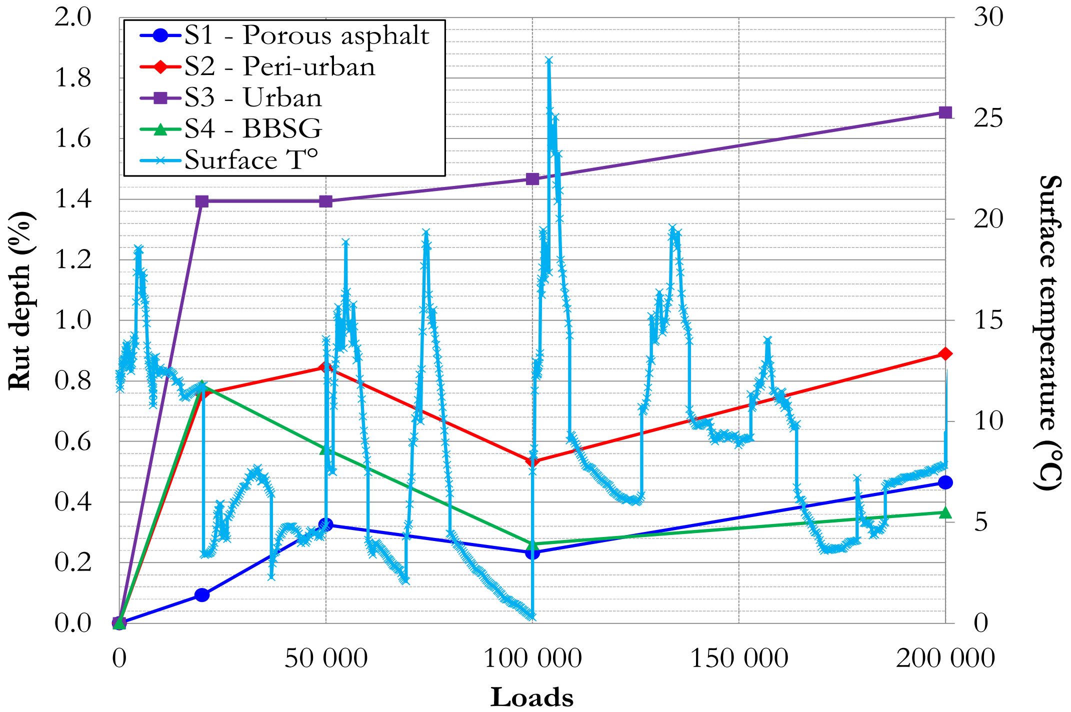


Figure 35. Evolution of maximum relative rut depth (in %) during the urban conditions experiment

7.4 Benkelman beam deflection measurements

Figure 36 shows the deflection values obtained on each section at different numbers of load cycles and the corresponding average temperatures in the bituminous layers. The following evolutions have been observed:

- The average temperatures range from 7 to 13°C.
- At the beginning of the test, the mean deflection levels are closed to 17 mm/100 on the four sections
- Prior to 50,000 load cycles and until the end of the urban experiment, deflections increased on all sections (even with decreasing temperatures), but with some significant differences. Prior to 200,000 cycles, the highest deflection was obtained on the BBSG section with 30.0 mm/100. Lower deflection values were obtained on the Peri-urban (i.e. 28.0 mm/100) and Porous Asphalt (i.e. 27.5 mm/100) sections. The lowest values were obtained on the urban section with 24.5 mm/100.

Overall, the final mean deflection value obtained on the urban innovative pavement is slightly lower than the mean deflection values obtained on the two reference sections (porous asphalt and BBSG sections) under urban conditions.

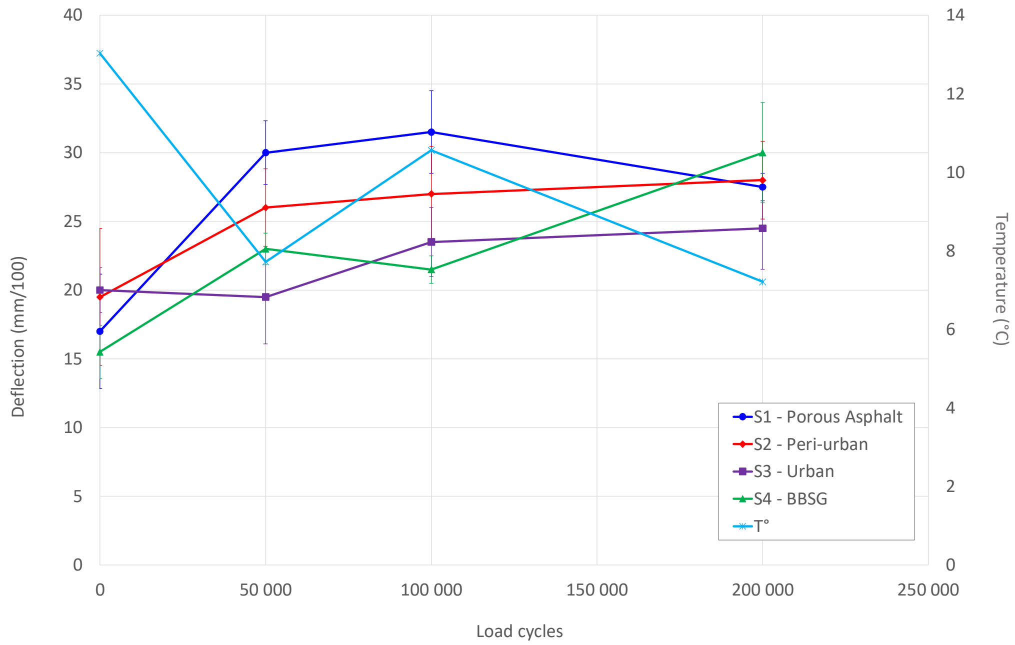


Figure 36. Measurements of the deflection using the Benkelman beam

7.5 FWD measurements

Figure 37 shows the evolution of the deflections under the first geophone (G1) as a function of the distance from the entrance of the carousel (see section 6.3.2). The temperature corresponding to each series of measurements was also monitored, but no temperature correction is applied to the data. The deflection measured under the first geophone with FWD is in the same order of magnitude as the deflection measured with the Benkelman beam.

Between 0 and 200 000 load cycles, the deflections decreased, probably due to a decrease in temperature. Deflections were similar for all sections. No deflection peak was observed, which means that there is no in-depth deterioration of the pavement structures.

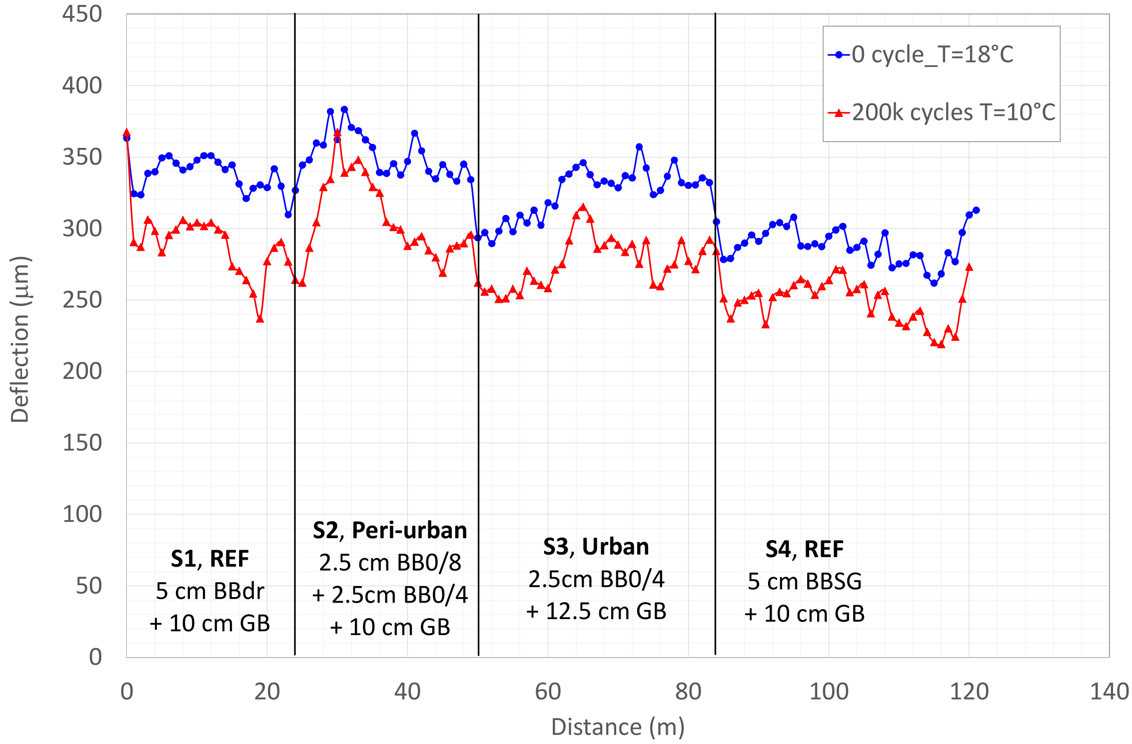


Figure 37. Initial and final deflection curves for the four sections tested under urban conditions (measurements were made with FWD at the level of geophone number one)

7.6 Strain gauges measurements

Two longitudinal strain gauges are installed at the bottom of the base layer in each section. Figure 38 shows the signal of the longitudinal strain gauges recorded under a passage of an arm of the carrousel. The maximum strains are in extension mode. Measurements are taken at:

- 2k load cycles (T=12.2°C)
- 26k load cycles (T=19.7°C)
- 211k load cycles (T=17.2°C)

These numbers of cycles were chosen because the measured temperatures are of the same order. Thus, for a given section, the longitudinal strain shows no significant evolution until 200 000 load cycles is reached.

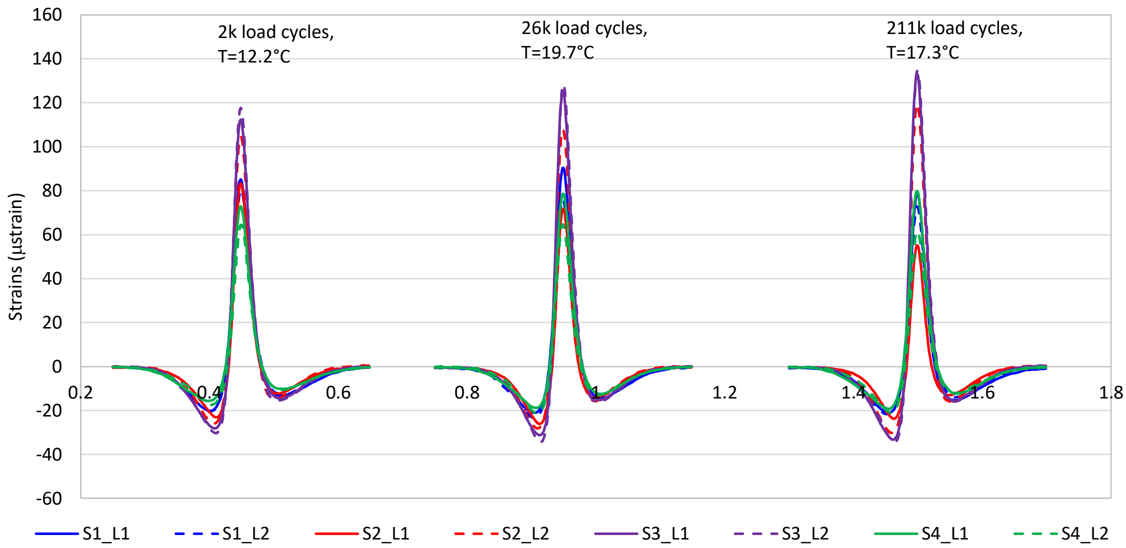


Figure 38. Longitudinal strain evolution at the bottom of the GB layer, speed 50 km/h

7.7 Representativeness of the first 200 000 load cycles

As a reminder, the test was carried out between December 2022 and February 2023. It aimed at evaluating the mechanical performance of wearing courses under urban traffic conditions: *i.e.,* 65 kN dual wheel load at a speed of approximately 50 km/h. A transverse wandering of ±50 cm was used and the number of load cycles reached 200,000.

According to the French design standard NF P98-086, the mechanical durability of the pavement is evaluated by taking into account the cumulative heavy vehicle traffic over the entire selected period, hereafter referred to as NPL. This parameter is determined from the number of heavy vehicles per day and the cumulative traffic factor for the selected period. It is also derived by dividing the equivalent number of reference axles (NE) by the average traffic aggressiveness coefficient (CAM): NE = NPL × CAM, where CAM = 0.1. Here , NE is equal to 200,000 load cycles, which corresponds to the total number of wheel passage on the APT facility. This results in an NPL of 2,000,000. The urban conditions experiment therefore accounts for:

- 2,000,000 passages of heavy vehicles on a urban area, or
- 10 years of road traffic with approximately 550 heavy goods vehicles per day (corresponding to a road traffic class T1 in France), or
- 20 years of traffic with approximately 275 heavy goods vehicles per day

7.8 Conclusion

During the urban experiment, the following measurements and/or observations were taken at the same number of load cycles on both reference and experimental section:

- Deflection measurement using a Benkelman beam
- FWD measurement
- Rut depth measurements
- Visual crack monitoring.

Overall, no cracking or significant surface damage was observed after 200,000 load cycles, or 20 years of traffic with approximately 275 trucks per day. In addition, and in contrast to laboratory tests on loose asphalt samples, no significant rutting was observed on any of the four sections. The deflections of the innovative urban and peri-urban pavements were close to those of the reference pavements. Taken together, under urban conditions and from a mechanical point of view, the two innovative sections behave the same as the two reference sections.

8 Test with Peri-Urban conditions

The peri-urban experiment was conducted between December 2022 and August 2023 to evaluate the mechanical behaviour of the peri-urban mixture. A total of 1,050,000 load cycles were applied under a load of 65 kN. The experiment starts with the urban conditions experiment up to 200,000 cycles and then continues with another 850,000 load cycles. The speed during this latter stage was between 50 and 70 km/h. The conditions used during this experiment are summarized in Table 15.

8.1 Environmental conditions

During the peri-urban experiment, the pavement surface temperature varied between -3.6°C and 60.4°C, with most values (68 %) comprised between 2°C and 24°C (93% of the temperatures are between 0 and 40°C). The mean surface temperature was 8.5°C (+/-5.0°C), and the mean temperature in the central part of the bituminous layers was 15.7°C (+/-9.5°C). The histogram of the pavement surface temperature distribution is displayed in Figure 39. Temperature variations and load cycles during the peri-urban conditions experiment are shown in Figure 40.

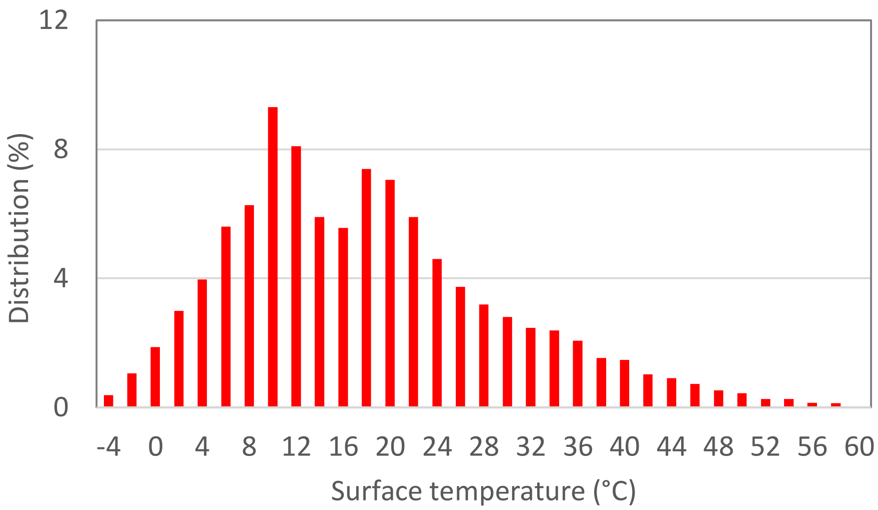


Figure 39. Histogram of the pavement surface temperature distribution during the peri-urban conditions experiment

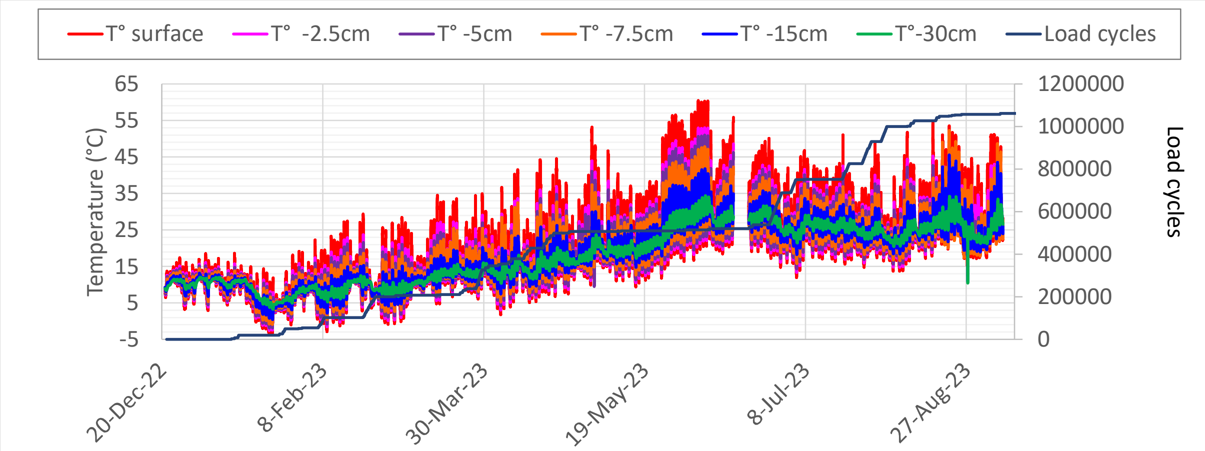


Figure 40. Pavement temperature and number of load cycles during the peri-urban conditions experiment

The histogram of the pavement surface temperature distribution only during the loading phases is presented on Figure 41. During the loading phases, 98% of the temperatures are between 0 and 40°C, and 95% are between 0 and 36°C.

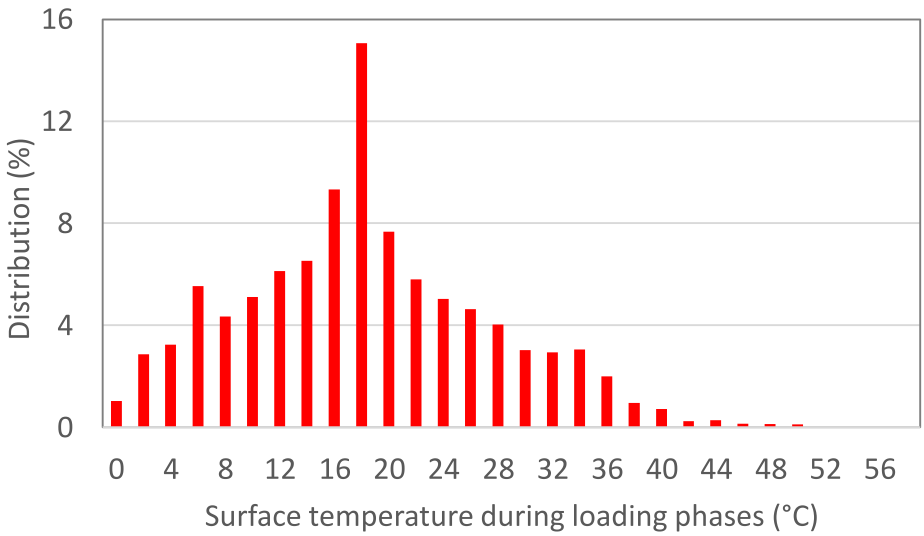


Figure 41. Histogram of the surface temperature distribution during loading phases only

The rainfall amounts at the level of the carousel is presented in Figure 42. The rainfall was moderate throughout the experiment with some rainy days with more than 16 mm of rain.

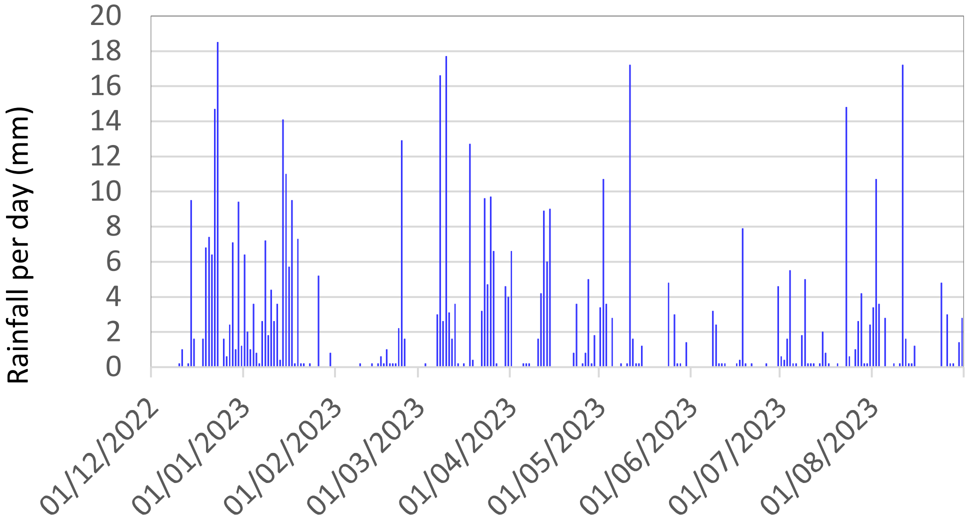


Figure 42. Daily rainfall amounts during the peri-urban conditions experiment

8.2 Visual crack monitoring

Photographs of the various sections at 1 million load cycles are presented in Figure 43, Figure 44, Figure 45, and Figure 46. No cracking was observed. Some areas with aggregates stripping were observed on peri-urban and urban sections.

Figure 43. Photographs of the reference porous asphalt after 1 million load cycles

Figure 44. Photographs of the experimental peri-urban mixture asphalt after 1 million load cycles

Figure 45. Photographs of the experimental urban mixture asphalt after 1 million load cycles

Figure 46. Photographs of the reference BBSG asphalt after 1 million load cycles

8.3 Rut depth measurement

The change in rut depth (in mm) during the peri-urban experiment is presented in Figure 47. As with the urban data, the relative rut depth is expressed as percentage of the surface course thickness in Figure 48. For the peri-urban section, the thicknesses of the bottom and top courses have been considered individually.

Rut depth increased progressively on the four sections up to 500,000 load cycles. During this period, the ambient temperatures were low. After 500,000 load cycles, rutting increased rapidly, presumably due to the related higher temperatures. In fact, rutting is generally accentuated by high temperatures.

After 1 050 000 load cycles under peri-urban conditions, rut depths are:

- 8.4% (4.5 mm) for porous asphalt
- 8.9% (5 mm) for peri-urban mix
- 11.7% (4 mm) for urban mix
- 11.5% (5.5 mm) for BBSG

It is important to note that, in France, for a pavement with medium traffic (150 trucks per day), rutting is considered as a serious damage if its depth exceeds 25 or 30mm (Blanc et al., 2019).

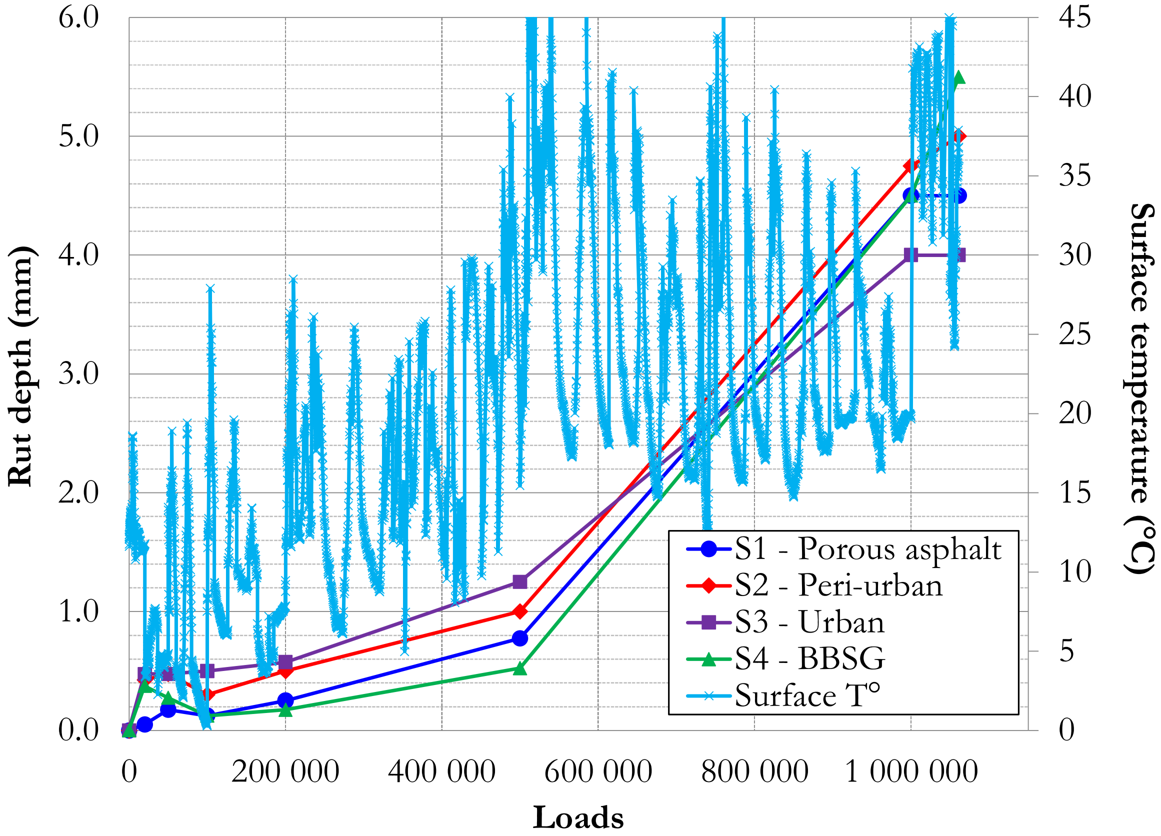


Figure 47. Rut depth (in mm) evolution during the peri-urban conditions experiment

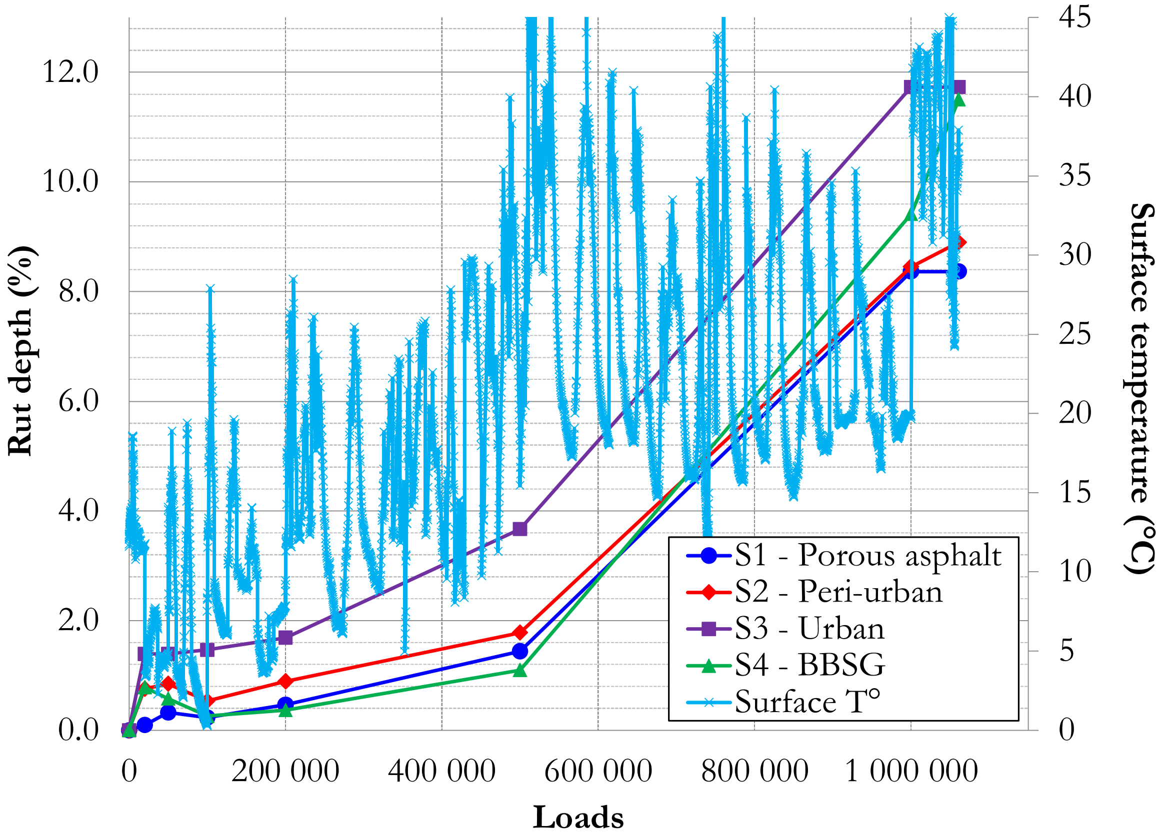


Figure 48. Rut depth (in %) evolution during the peri-urban conditions experiment

The raw transverse profile with increasing number of load cycles for the location where the rut depth is maximum is shown in Figure 49, Figure 50, Figure 51 and Figure 52 for the four sections.

Regarding the causes of rutting, the profiles obtained at the end of the rutting test show only downward deformation for the porous asphalt section. For the other three sections, the shape of the two wheel tracks of the dual wheel axle can be observed. This suggests a post-compaction mechanism (of the bituminous or granular layers) for the porous asphalt section and a light shear flow mechanism for the other three sections.

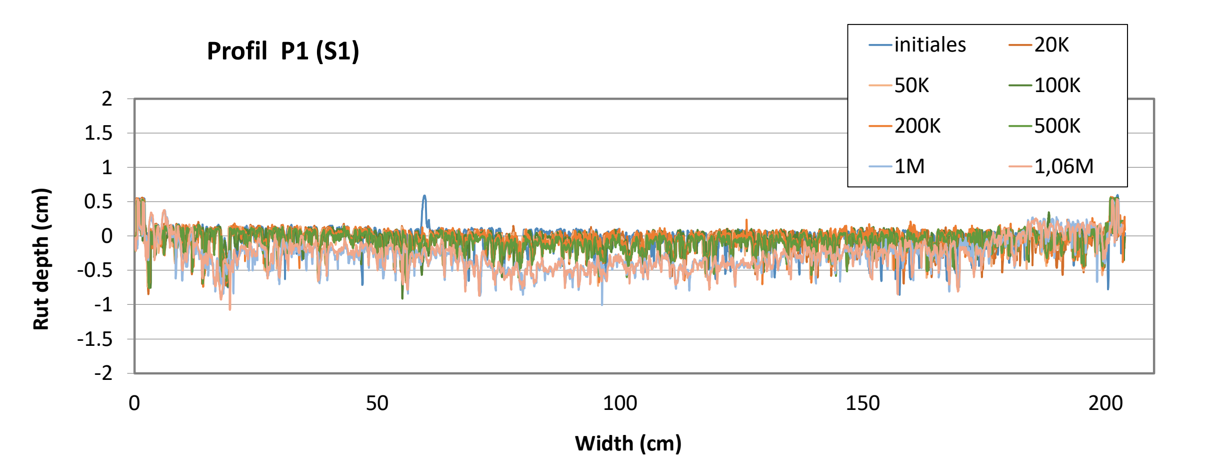


Figure 49. Rut depth profile for section 1 (Porous asphalt) under peri-urban conditions

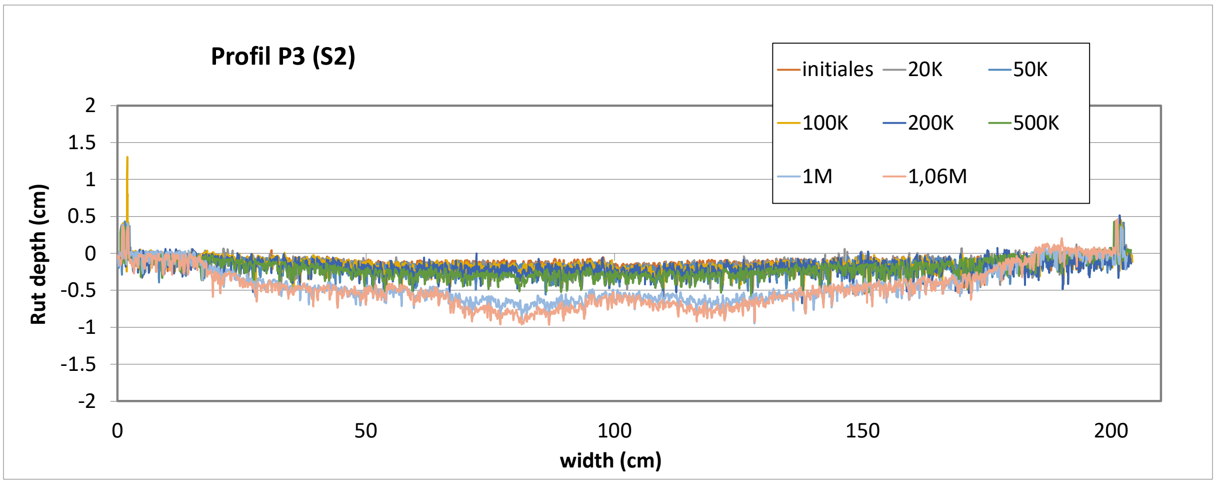


Figure 50. Rut depth profile for section 2 (peri-urban mixture asphalt) under peri-urban conditions

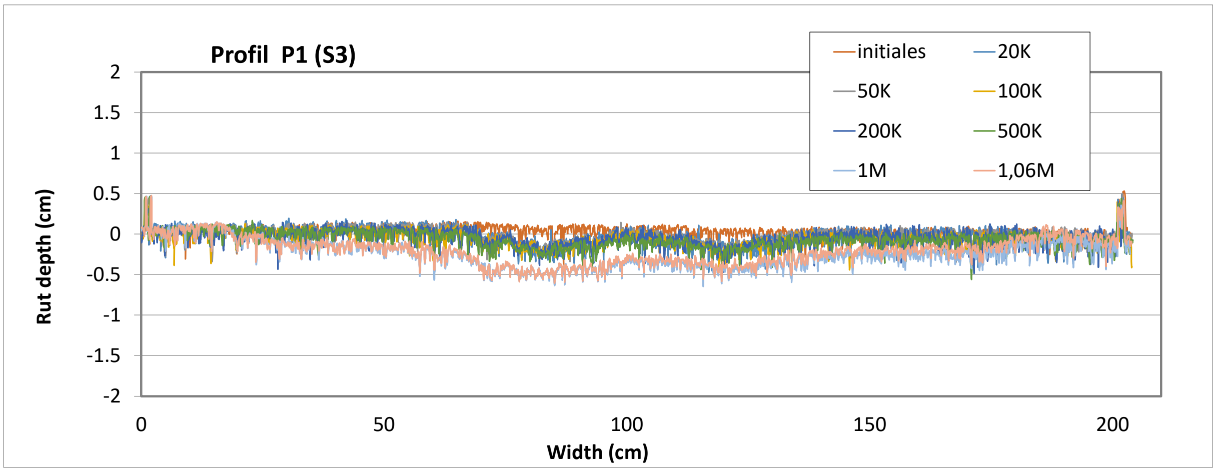


Figure 51. Rut depth profile for section 3 (urban mixture asphalt) under peri-urban conditions

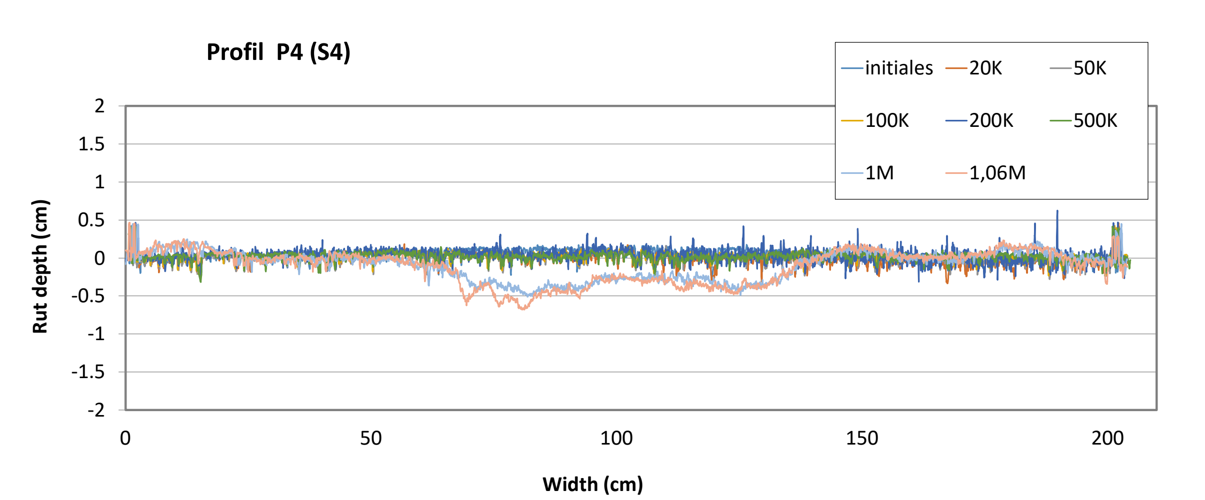


Figure 52. Rut depth profile for section 3 (BBSG asphalt) under peri-urban conditions

Figure 53 illustrates the typical rut profiles obtained on the four sections. It can be seen that the rut depth is very limited on all the sections. In addition,

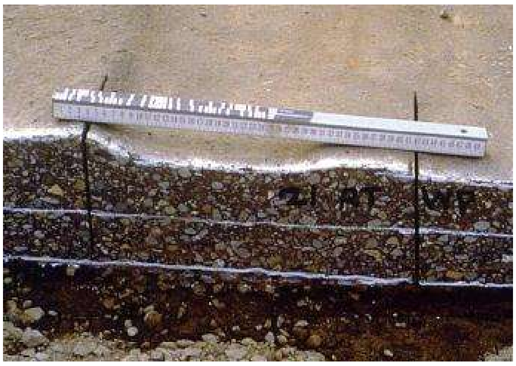


Figure 54 shows a trench cut in a pavement tested at WesTrack (Federal Highway Administration, 1999, “Pavement performance of coarse graded mixes at WesTrack – premature rutting”, FHWA report RD-99-134, 19). The latter demonstrates a case of significant rutting due to shear flow within the pavement surface course. Clearly, such major lateral flow of the bituminous material was not observed in all the sections of the NEMO peri-urban experiment.

However, it is not possible to determine from the surface observations whether the rutting affects only the bituminous layers, or also the granular base. It is only during the deconstruction of the pavement that it will be possible to cut trenches into the pavements and, thus, to evaluate the deformations of the different pavement layers.

Porous asphalt (P1)

Peri-urban mixture (P3)

Urban mixture (P1)

BBSG mixture (P4)

Figure 53. Typical rut profiles obtained on the four sections

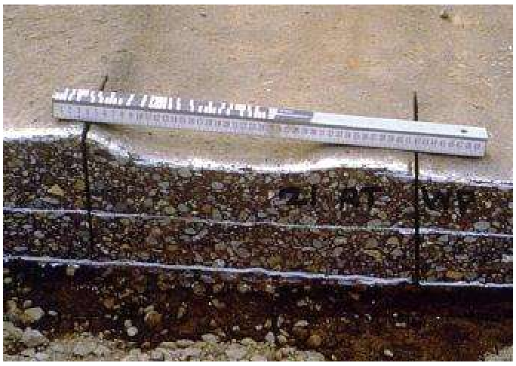


Figure 54. Example of rutting due to shear flow (Wes Track experiment)

8.4 Benkelman beam measurement

Figure 55 shows mean deflection values (with 4 measurements per section) obtained on each section, at different numbers of load cycles. The corresponding mean temperatures in the bituminous layers are also displayed. The following observations are made:

- At the beginning of the experiment, the mean deflection levels are closed to 17 mm/100 on all sections
- Then, until the end of the experiment, the deflections increased on all sections (probably in part due to the increased temperatures), but with some differences. At 1,050000 load cycles, the highest deflection was obtained on the reference porous asphalt section with 38.5 mm/100. Slightly lower deflection was obtained on the reference BBSG section (34 mm/100). The lowest values were obtained on the peri-urban and urban sections with 32.5 mm/100 and 30.5 mm/100, respectively.

Therefore, the mean deflection values obtained on the two innovative sections (peri-urban and urban sections) are slightly lower than the mean deflection obtained on the two reference sections. It is important to note that the urban section was initially not originally designed for 1 million load cycles.

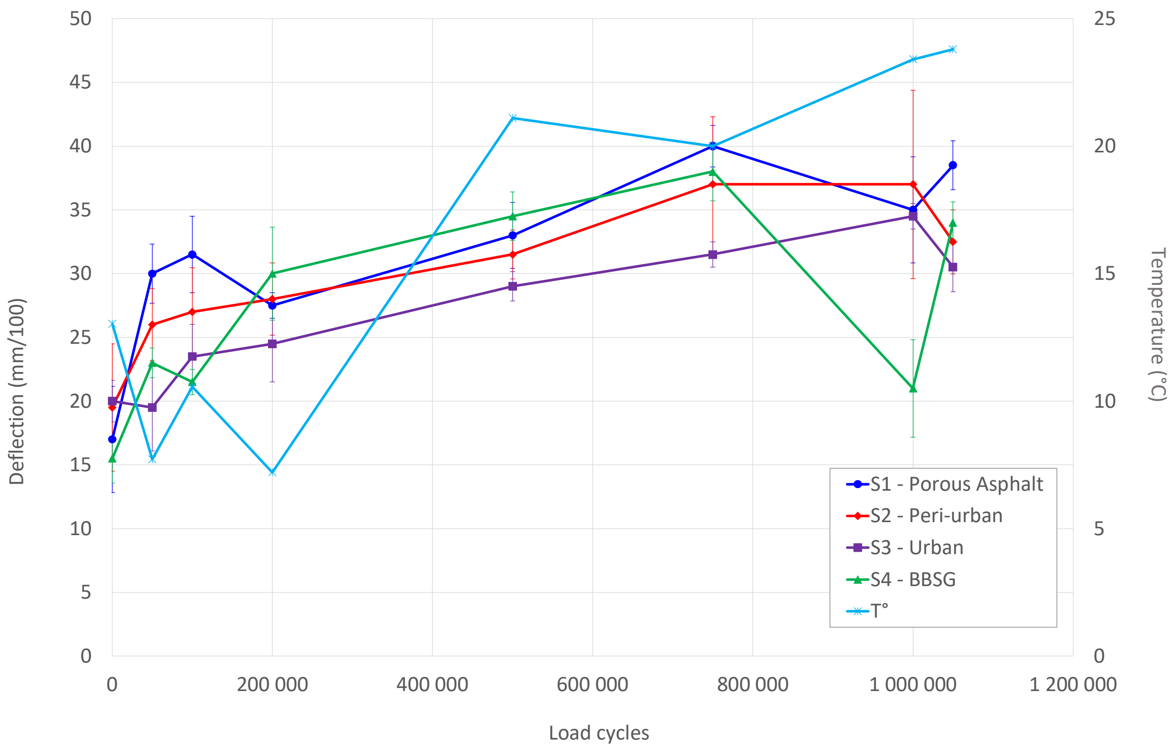


Figure 55. Measurements of the deflection with the Benkelman beam

8.5 FWD measurement

Figure 56 shows the evolution of the maximum deflections, as a function of distance on the test track, for the successive FWD campaigns at 0, 200 000, 500 000, 752 000 and 1 000 000 load cycles. The temperature corresponding to each series of measurements is also measured, but no temperature correction is applied to the data.

The following trends are observed:

For all the sections, between 0 and 500,000 cycles, the deflections are almost identical and no significant differences are detected. Thus, subsequent measurements were carried out at higher temperatures. On the peri-urban section there appear to be localised deflection peaks, probably indicating the onset of localised damage to the structure. For the other sections, despite higher temperatures, there was no substantial change in deflection values.

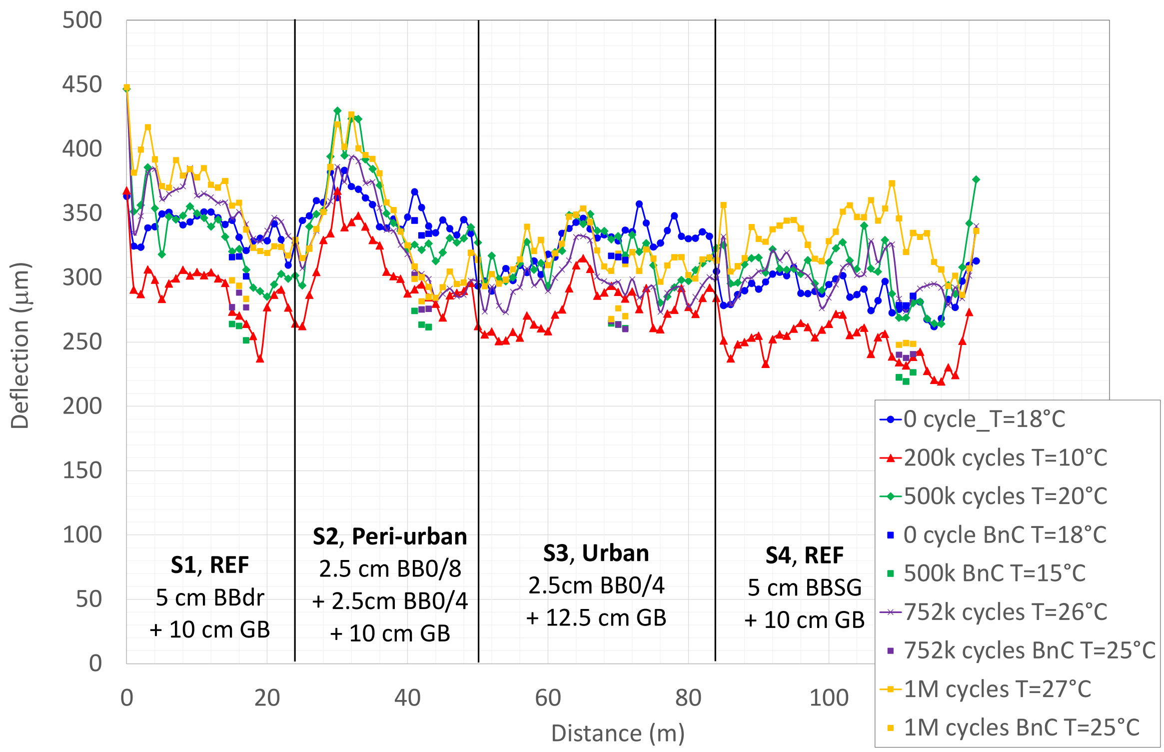


Figure 56. FWD values obtained during the peri-urban conditions experiment

8.6 Strain gauges measurement

The evolution of the longitudinal strain signals, for each section, is presented on Figure 57. At the beginning of the peri-urban fatigue experiment, the longitudinal strains at the bottom of the GB layer were between 70 and 110 µstrains. During the experiment, the longitudinal strain level is quite the same for the two reference section (S1 – Porous asphalt and S4 – BBSG), with some slight variations depending of the temperature.

For the urban section (S3), the longitudinal strain level is the same for the two gauges during all the experiment, and the strain level increases progressively (from 110 to 150 µstrains). This may indicate localised damage beginning to occur closed to the gauges.

For the peri-urban section (S2), the level of one gauge (S2-L2) increases (from 80 to 200 µstrains) and the level of the other gauge (S2-L1) decreases (from 80 to 20 µstrains). There is no obvious explanation yet for the decrease in deformation, except perhaps that the gauge is not properly gripped in the asphalt.

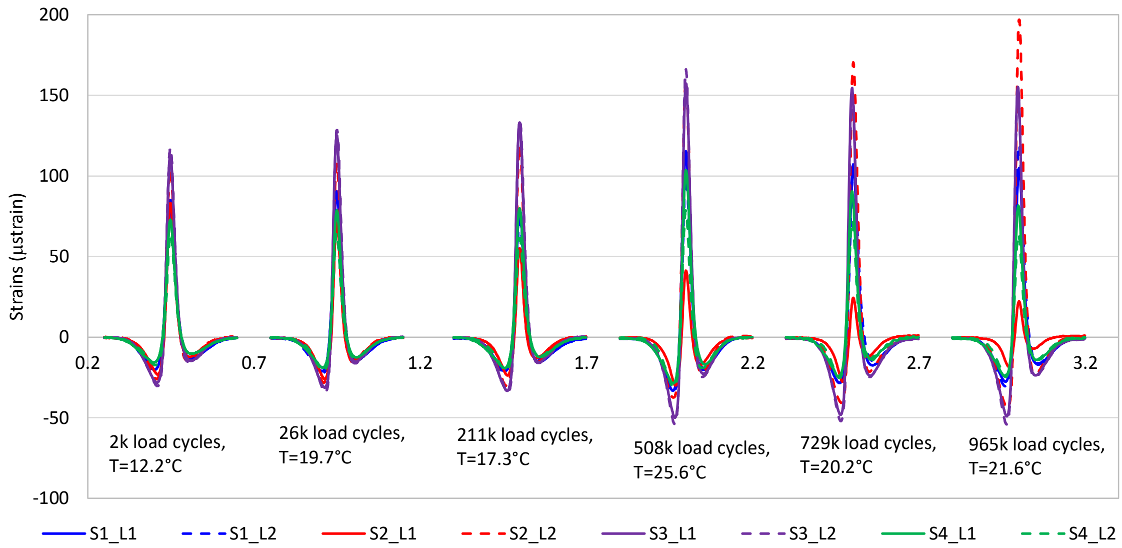


Figure 57. Longitudinal strain evolution at the bottom of the GB layer, speed 50 km/h

8.7 Representativeness of the 1 million load cycles

According to the French design standard NF P98-086, the mechanical design of the pavement is carried out by considering the cumulative heavy goods vehicle traffic over the entire design period selected, designated by NPL. This parameter is determined from the number of daily heavy goods vehicles and the traffic cumulative factor for the design period.

In the peri-urban case, NPL can also be determined from the Equivalent Number of reference axles (NE) using the average aggressiveness coefficient of traffic, CAM , via NE = NPL × CAM,
Where:

- CAM = 0.8 for highway or 2*2 lanes (through road)
- For access road (these pavements correspond to the local road network, as opposed to the through roads. This network has multiple functions: peri-urban roads, links between towns, rural roads, tourist routes, etc.)
  - CAM = 0.3 if NPL < 50 heavy goods vehicles per day
  - CAM = 0.4 if 50 heavy goods vehicles per day < NPL < 85 heavy goods vehicles per day
  - CAM = 0.5 if NPL > 85 heavy goods vehicles per day

according to the French design standard for bituminous materials.

Here, NE is equal to 1 050 000 cycles, corresponding to the total number of load cycles on the APT facility. Hence, this experiment on the APT facility represents:

- *1 312 000 passages of heavy vehicles on a highway*
  - *7 years of traffic with approximately 500 heavy goods vehicles per day (corresponding to a road traffic class T1 in France) or*
  - *18 years of traffic with approximately 200 heavy goods vehicles per day (corresponding to a road traffic class T2 in France) or*
- *More than 2 million passages of heavy vehicles on an access road*
  - *More than 20 years of traffic*

8.8 Conclusions for peri-urban experimentation

The experiment was conducted between December 2022 and August 2023, assessing the peri-urban mixture's mechanical durability over a wide range of temperatures and meteorological conditions. Unlike in the urban experiment, the speed was between 50 and 70 km/h and a lateral displacement of ±80 cm (instead of ±50 cm) was applied. The number of load cycles achieved exceeded 1,000,000, reproducing more than 20 years of peri-urban traffic.

During the experiment, the following measurements were performed on each section:

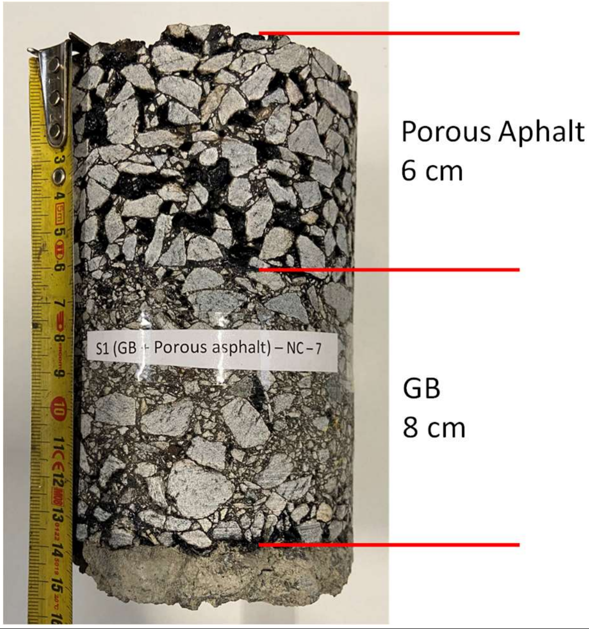
- Deflection measurement using a Benkelman beam
- FWD measurement
- Rut depth measurements
- Visual crack monitoring.

No cracking was observed at the end of the 1,050,000 cycles. However, some localized areas of aggregate stripping were observed on both the peri-urban and urban sections. An important finding is the absence of significant rutting and the fact that deflection was quite similar on the reference and innovative sections.

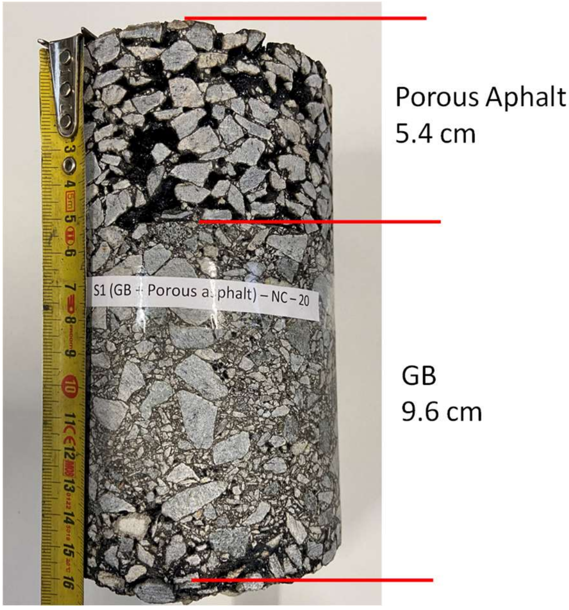
Overall, the durability monitoring during accelerated testing shows that the two innovative mixtures develop comparable mechanical properties to the reference ones.

Annexes

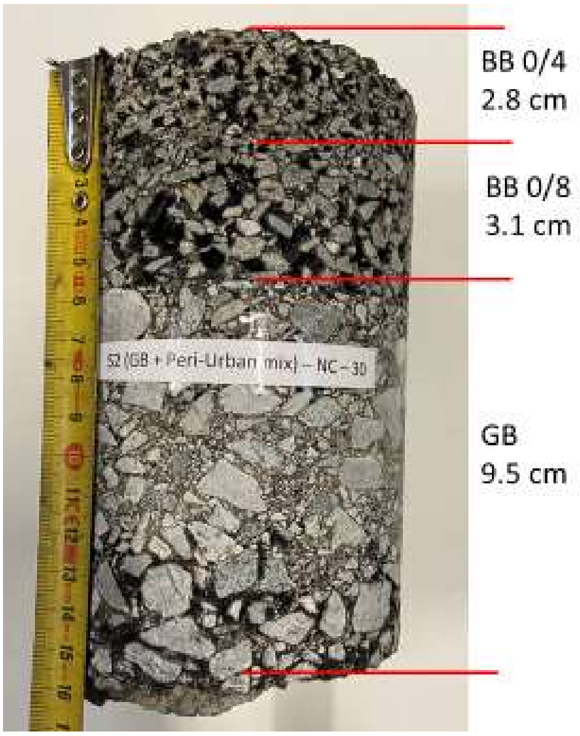
9 Reference and innovative pavement cores



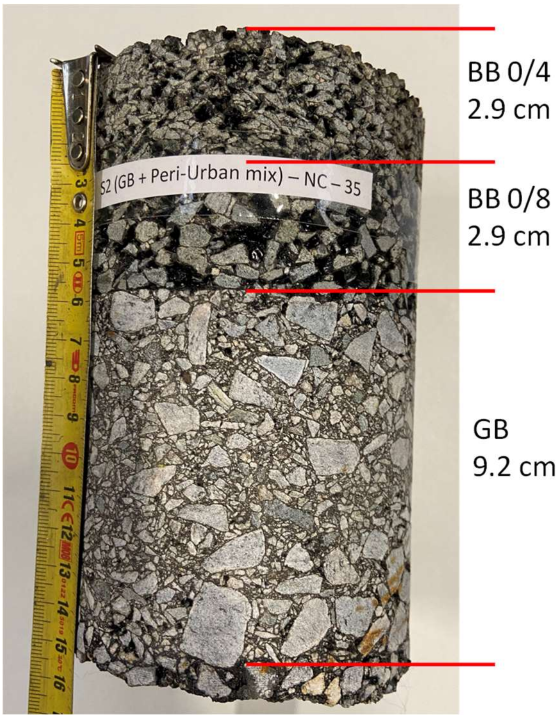
Section 1 (Porous asphalt + GB)



Section 1 (Porous asphalt + GB)

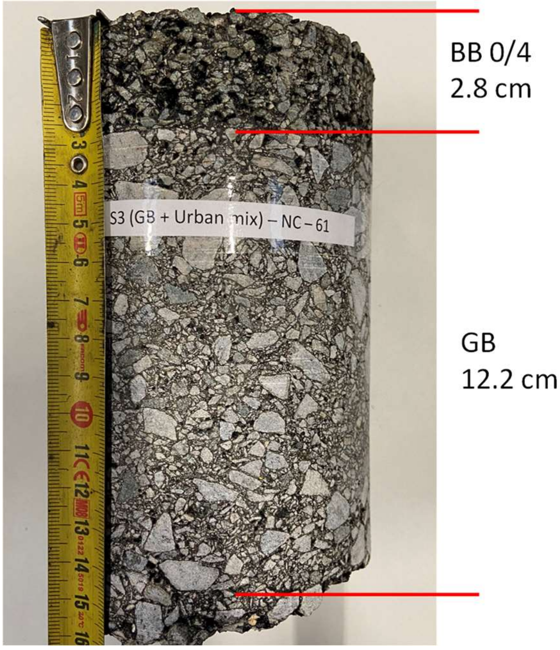


Section 2 (Peri-Urban : BB0/4 + BB 0/8 + GB)

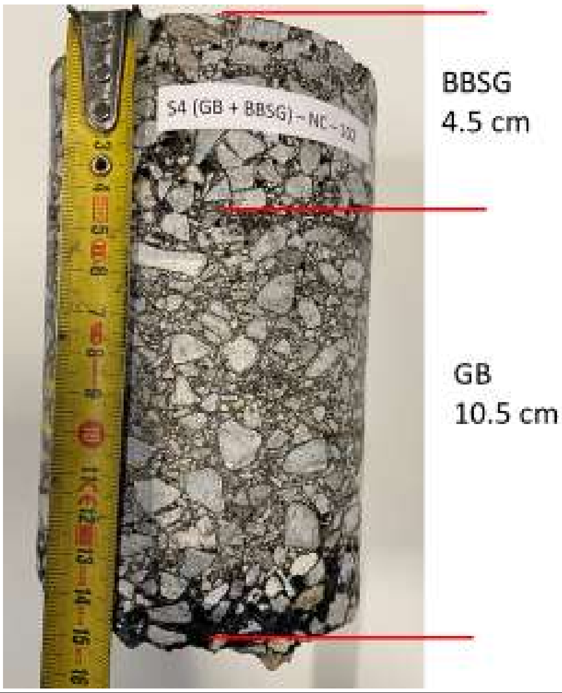


Section 2 (Peri-Urban : BB0/4 + BB 0/8 + GB)

Section 3 (Urban : BB 0/4 + GB)



Section 3 (Urban : BB 0/4 + GB)



Section 4 (BBSG + GB)

Section 4 (BBSG + GB)

10 Raw rut depth profiles

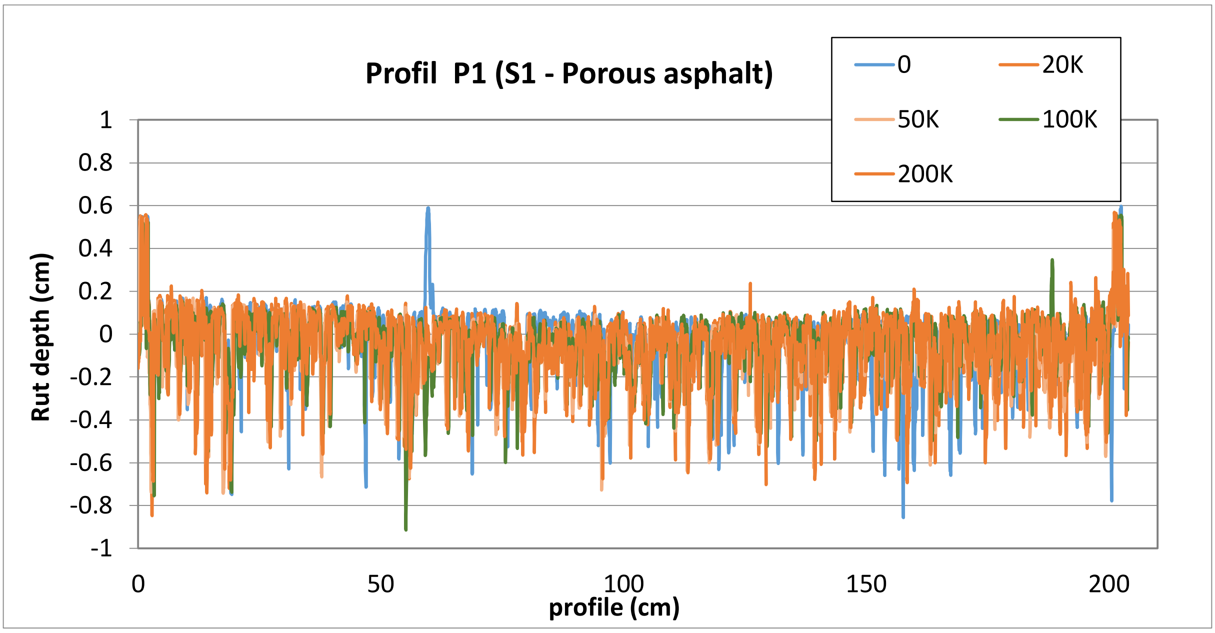


Figure 58. Rut depth measurement for section 1, Porous asphalt

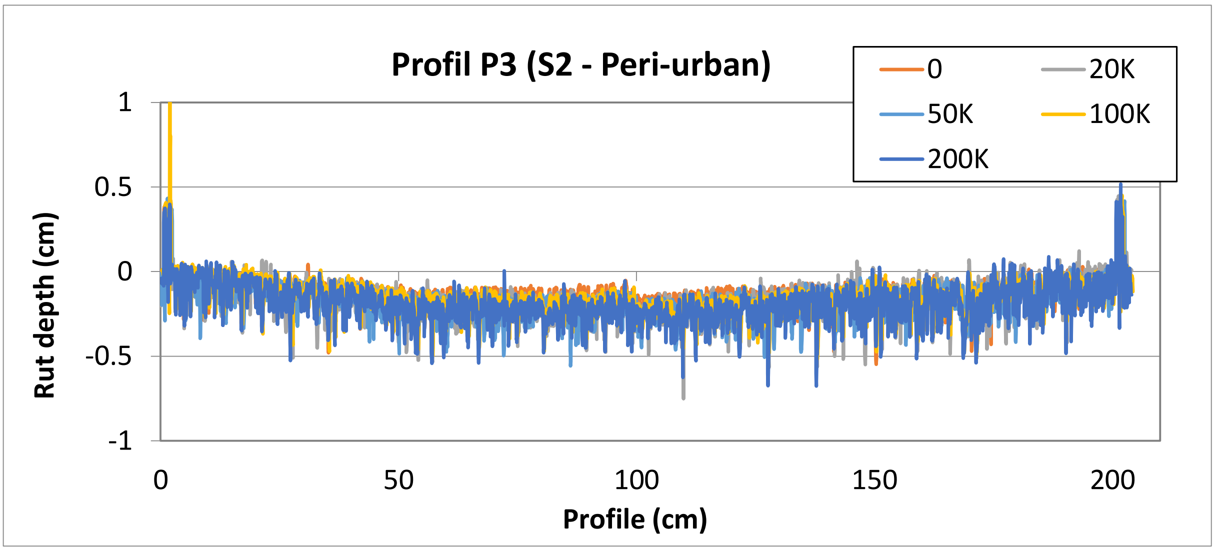


Figure 59. Rut depth measurement for section 2, Peri-urban mix

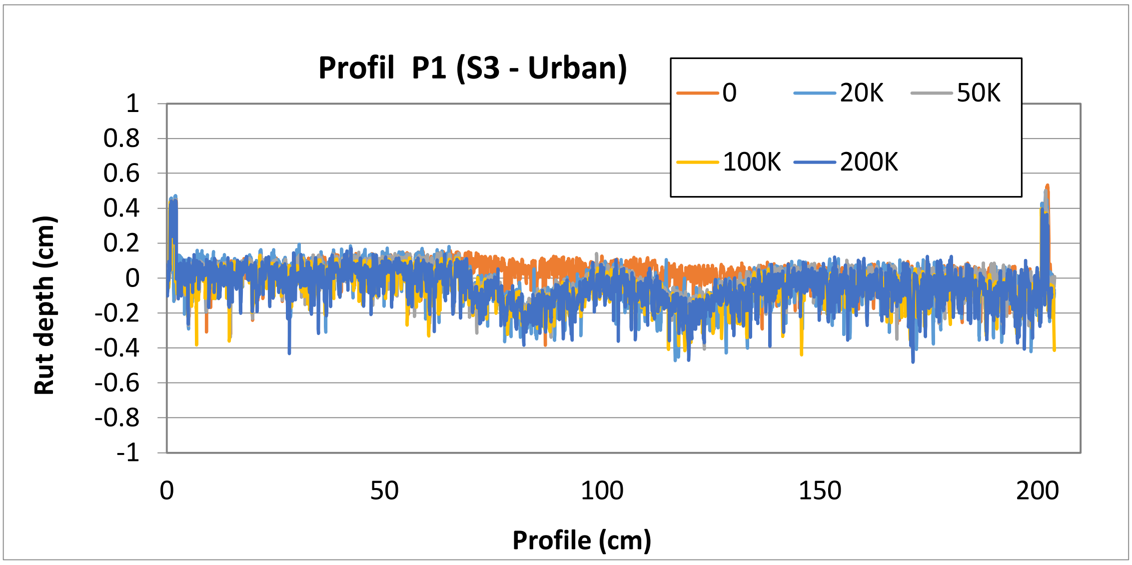


Figure 60. Rut depth measurement for section 3, Urban mix

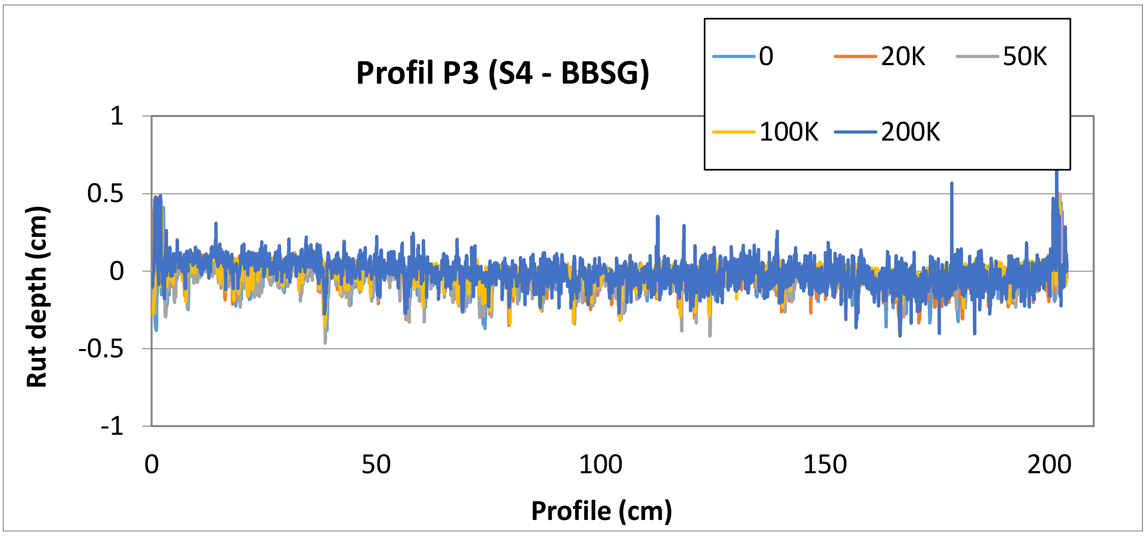


Figure 61. Rut depth measurement for section 4, BBSG

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