

## Article

# Comparison of the Bearing Capacity of Pavement Structures with Unbound and Cold Central-Plant Recycled Base Courses Based on FWD Data

Audrius Vaitkus, Judita Gražulytė , Igoris Kravcovas and Rafal Mickevič

Road Research Institute, Vilnius Gediminas Technical University, Linkmenų Str. 28, LT-08217 Vilnius, Lithuania; audrius.vaitkus@vilniustech.lt (A.V.); igoris.kravcovas@vilniustech.lt (I.K.); rafal.mickevic@vilniustech.lt (R.M.)

\* Correspondence: judita.grazulyte@vilniustech.lt



**Citation:** Vaitkus, A.; Gražulytė, J.; Kravcovas, I.; Mickevič, R. Comparison of the Bearing Capacity of Pavement Structures with Unbound and Cold Central-Plant Recycled Base Courses Based on FWD Data. *Sustainability* **2021**, *13*, 6310. <https://doi.org/10.3390/su13116310>

Academic Editor: Edoardo Bocci

Received: 26 April 2021

Accepted: 28 May 2021

Published: 2 June 2021

**Publisher's Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

**Abstract:** Bearing capacity changes over the year, depending on the water content in a pavement structure: the higher the water content, the lower the bearing capacity. As expected, the highest water content in a pavement structure is observed in the early spring as the ice lenses melt. Thus, spring is a critical period for pavement performance, because a decrease in bearing capacity results in faster pavement deterioration. The bearing capacity of pavement structures with an unbound base course and the negative effect of spring thawing on pavement performance have been analyzed by a considerable number of researchers. However, very little is known about the bearing capacity of pavement structures with a cold-recycled base course despite the significantly increasing usage of cold-recycled mixtures. This paper focuses on the bearing capacity of both unbound and cold central-plant recycled base courses at different seasons and their stability. A cold central-plant recycled (CCPR) base course was constructed from a mixture of 38.8% reclaimed asphalt pavement (RAP), 3.1% foamed bitumen and 2.3% cement. A virgin aggregate was added to achieve desirable aggregate gradation. The bearing capacity of the unbound and CCPR base layers, as well as the whole pavement structure, was evaluated by back-calculated E moduli from falling weight deflectometer (FWD) data. In addition to this, the residual pavement life was calculated using mechanistic-empirical pavement design principles. The results showed that the durability of pavement structures with a CCPR base course is more than seven times lower compared to that of pavement structures with an unbound base course, irrespective of season. Nevertheless, the bearing capacity (surface modulus  $E_0$ ) of the pavement structure with a CCPR base course gradually increases due to the curing processes of bituminous and hydraulic binders (in this study, within four years of operation, it increased by 28–47%, depending on the side of the road).

**Keywords:** bearing capacity; unbound base course; cold central-plant recycled base course; falling weight deflectometer (FWD); cold recycling in-plant

## 1. Introduction

Bearing capacity changes over the year depending on the water content in the pavement structure: the higher water content, the lower the bearing capacity [1–5]. As expected, the highest water content in the pavement structure is observed in the early spring [6,7]. The reason for that is the inability to drain water accumulated from melted ice and snow on the shoulders and embankment slopes within the pavement structure, because the bottom part of the pavement is still frozen. Consequently, the pavement part above the frost zone (typically subgrade and base courses) becomes soaked. This leads to a decrease in the bearing capacity of both individual layers and the whole pavement structure and afterward, results in faster pavement deterioration. This kind of phenomenon typically occurs in the regions where pavement structures are exposed to and affected by frost, ice, and snow and especially, where they periodically freeze and thaw.

The bearing capacity of pavement structures with an unbound base course and the negative effect of spring thawing on pavement performance have been analyzed by a considerable number of researchers [8–15]. Salour and Erlingsson [8] concluded that the back-calculated E modulus of the unbound base course in spring is 48% lower than in summer. Doré and Savard [12] found that pavement distresses, such as fatigue cracks, alligator cracks and permanent deformation, significantly increase during the spring thaw. Zhang and Macdonald [13] also confirmed that. Their study showed that about 60–75% of permanent deformation occurs during the spring thaw.

However, only a few studies have attempted to investigate the bearing capacity of pavement structures with a cold-recycled base course, despite the significantly increasing usage of cold-recycled mixtures. Vaitkus et al. [16] summarized the results from the plate load test on a cold-recycled base course in nine different road sections and concluded that mixtures bound with both a bituminous emulsion and cement have a higher bearing capacity than those with foamed bitumen and cement. Meocci et al. [17] analyzed measurements from a falling weight deflectometer (FWD) on the cold recycled base course after 29 days and 90 days of curing. They concluded that the bearing capacity increases within time and that their study confirms that the evolution of the curing process relates to the bituminous and hydraulic binders. A similar tendency was observed by [18]. However, they analyzed a much longer operation time (8 years), and measurements were done on the wearing course (the thickness of all asphalt layers was 19 cm). The back-calculated stiffness modulus based on the measured deflections revealed that the bearing capacity of the whole pavement structure increased within 3–5 years of construction and afterwards, decreased because of traffic. In addition to this, it was determined that the cold-recycled mixture with foamed bitumen and cement has 29% higher initial-bearing capacity than bituminous emulsion and cement, but after 3 years, both mixtures perform similarly.

Arimilli et al. [19] tried to mathematically assess the structural performance of pavement structures with a cold-recycled base course. In this case, cold-recycled mixtures were bound with either a bituminous emulsion or foamed bitumen. A stress-strain analysis showed that both mixtures were suitable for constructing the base course, but the use of the emulsion provided higher vertical compressive strain and deflection. Gu et al. [20] also used mathematical models to predict the performance of pavement structures with both cold central-plant and in-place recycled mixtures. In addition to this, they compared the predicted performance with the actual one and concluded that similar trends existed only in the first two years. Later, the rut depth was higher than predicted. It has to be noted that the prediction was performed using the Mechanistic-Empirical Pavement Design Guide, taking into account the viscoelasticity of cold-recycled mixtures with either bituminous emulsion or foamed bitumen.

Taking these studies together, there has been little discussion about the bearing capacity of pavement structures with a cold-recycled base course during different seasons and about the spring-thaw effect on pavement performance. Consequently, this paper analyzes the bearing capacity of pavement structures with both unbound and cold central-plant recycled (CCPR) base courses using a back-calculated surface modulus  $E_0$  from the FWD data measured at different seasons within four years of operation and directly measured surface deflections, as well as the calculated surface curvature index (SCI), base damage index (BDI) and base curvature index (BCI). In addition to this, the remaining pavement life was calculated to evaluate the effect of a CCPR base course on pavement durability in comparison with the unbound base course.

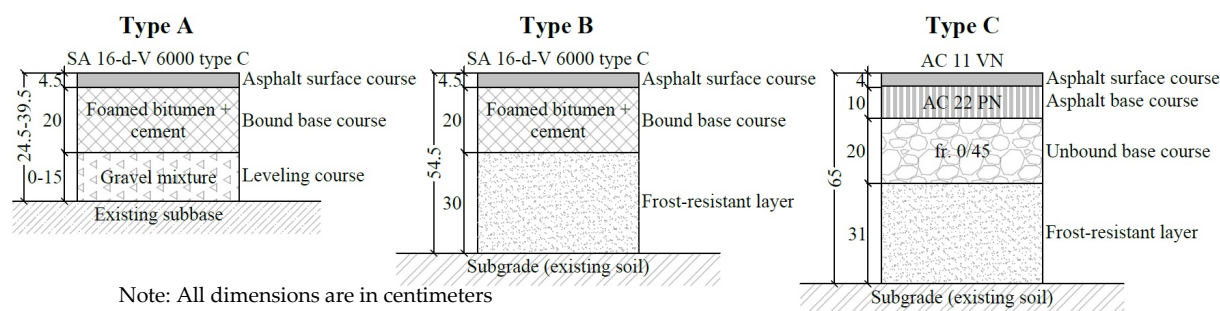
This study is very important for the further usage of a CCPR base course with a thin asphalt surface course on it, instead of the unbound base course with both asphalt base and surface courses, which is a typical pavement structure for newly constructed and reconstructed roads. The alternative solution to the typical one uses recycled asphalt from the existing old pavement and helps to save natural resources. In addition to this, a much thinner asphalt layer is constructed on the base course, which results in a lower cost for the pavement structure. It is worth highlighting that, according to Lithuanian normative

documents, both pavement structures are assumed equal and are used when the number of equivalent single-axle loads over a 20-year period is from 0.3 million to 1.0 million. However, as mentioned earlier, little is known about the bearing capacity of pavement structures with a CCPR base course at different seasons and the spring-thaw effect on that pavement performance. In addition to this, it is unknown if alternative pavement structures respond to load in the same manner as the typical structures and how this response changes depending on the season. This study will help to address this knowledge gap. Furthermore, the calculation of the remaining pavement life will show if there exist differences in durability.

## 2. Experiment

### 2.1. Test Site

The experiment to evaluate the bearing capacity of pavement structures with unbound and cold central-plant recycled base courses was conducted on a two-lane Lithuanian national road, No. 209 Joniškis–Žeimelis–Pasvalys, from 16.836 km to 27.900 km, which was reconstructed in 2016 using three types of pavement structures (Figure 1). Types A and B were designed with 20 cm of a cold central-plant recycled base course. On top of the base course was laid an asphalt surface course with a thickness of 4.5 cm. The difference between these two pavement structures is that type A was constructed on top of the existing sub-base using a 0–15 cm thick regulating course with a frost-resistant layer only where the road was widened, while in type B, the existing pavement structure was entirely removed, and a new 30 cm thick frost-resistant layer was constructed. Type C was designed as a typical pavement structure for newly constructed and reconstructed roads. It consisted of a frost-resistant layer (31 cm), an unbound base course (20 cm) and asphalt pavement (14 cm). The asphalt pavement consisted of an asphalt base course (10 cm) and an asphalt surface course (4 cm). In all types, the subgrade was improved with lime.



**Figure 1.** Pavement structures used in the test site.

The sections, in which each type of pavement structure was used, are represented in Figure 2.

All pavement structures were constructed in an area where the average annual temperature in the 1990–2019 period was 7.2 °C. The average temperature in January was −3.7 °C, and the average temperature in July was 18.4 °C. The average annual precipitation during the same period was 669 mm; the average depth of snow was 17.6 cm, and the average frost line was 50 cm. During the measurement period 2016–2019, the annual parameters were as follows: average annual temperature—7.6 °C, average temperature in January—4.7 °C, average temperature in July—17.9 °C, average precipitation—638 mm, average snow depth—14.3 cm and average frost line—42.3 cm.

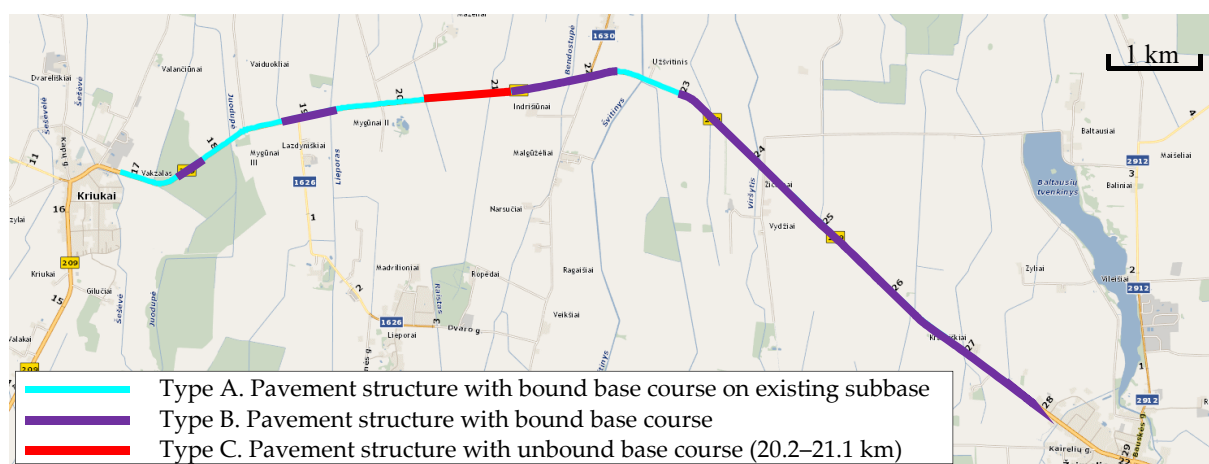


Figure 2. Test site location.

The annual average daily traffic (AADT) on road No. 209 for the period 2016–2019 is given in Figure 3. The numbers are derived from a stationary measurement post located at 8.181 km of this road, corresponding to the road section from 3.09 km to 29.14 km.

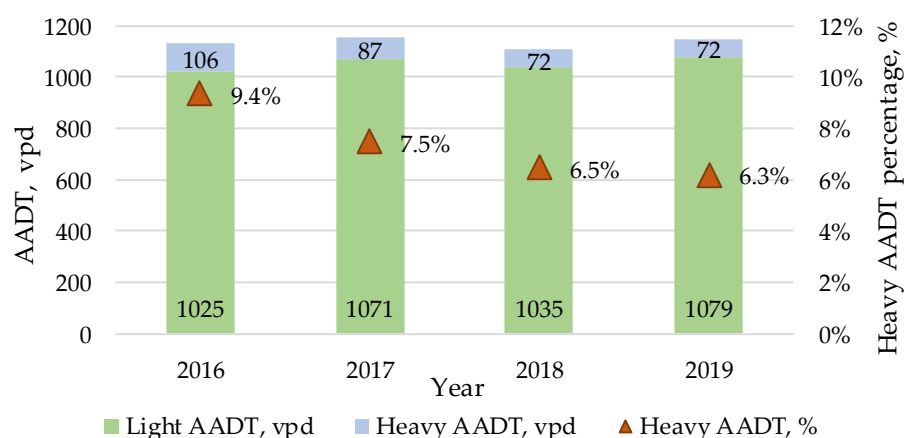


Figure 3. AADT on road No. 209 from 2016 to 2019.

## 2.2. Materials

The bound base course was constructed from a cold central-plant recycled mixture. For this purpose, the old pavement from the whole road section (16.836–21.200 km) was milled, broken, crushed and transported to a central plant, where 38.8% of it was mixed with 55.8% of crushed dolomite (0–32 mm) and bound with 2.3% of cement (CEM II/A-LL 42.5 N), as well as 3.1% of bitumen 50/70 (Figure 4). The properties of cold central-plant recycled mixture properties are represented in Table 1, and the gradation of the whole mixture, as well as its components, is depicted in Figure 5.

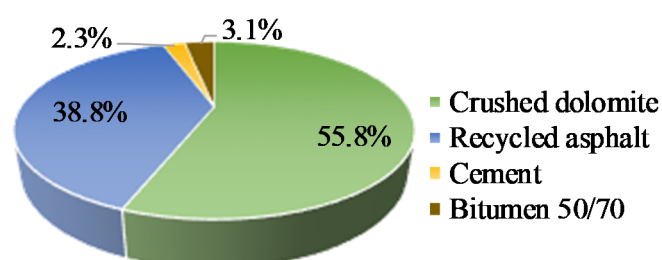
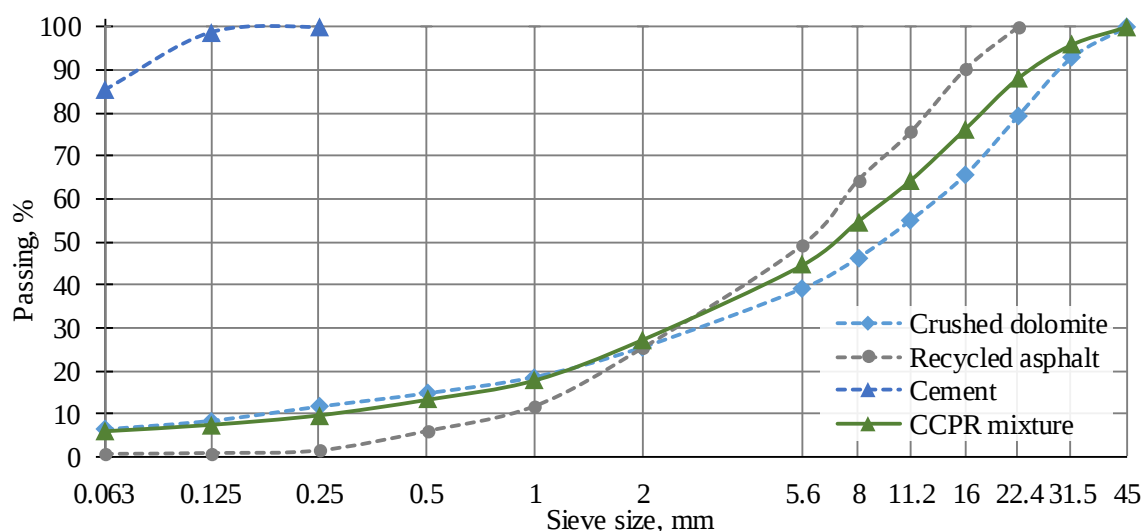


Figure 4. Cold-recycled mixture composition.

**Table 1.** Properties of cold-recycled mixture.

| Parameter                                    | Value  |          |
|----------------------------------------------|--------|----------|
|                                              | Actual | Required |
| Indirect tensile strength after 7 days, MPa  | 0.6    | 0.6–0.8  |
| Indirect tensile strength after 28 days, MPa | 0.7    | 0.7–1.0  |
| Air voids content, %                         | 9.2    | 5–15     |
| Optimal water content, %                     | 6.4    | –        |
| Proctor density, Mg/m <sup>3</sup>           | 2.12   | –        |

**Figure 5.** Cold-recycled mixture gradation.

### 2.3. Field Testing

A falling weight deflectometer (FWD), which is one of the most popular nondestructive testing (NDT) devices, was used to evaluate the bearing capacity of the constructed pavement structures. A FWD transfers a 50 kN load to the road pavement through a 300 mm diameter circular plate, which results in 707 MPa pressure. The generated haversine pulse lasts about 30 ms. Dynamic deflections on the road surface due to applied loads are captured by sensors (geophones), which are positioned at different distances from the center of the loading plate (0, 200, 300, 450, 600, 900, 1200, 1500 and 1800 mm).

Measurements with a FWD enable the evaluation of the bearing capacity of the whole pavement structure (on the surface level), as well as at different depths (according to the position of the geophones). Over the years of using NDTs, many different parameters have been introduced to evaluate different layers or parts of pavement structures. Talvik and Aavik [21] compiled a table with a list of widely used deflection basin parameters. As a result, in addition to the surface deflection  $d_0$  and surface modulus  $E_0$ , this research also focuses on three basic deflection basin parameters:

- The surface curvature index (SCI) depicts the condition of top pavement layers;
- The base damage index (BDI) depicts the condition of base layers;
- The base curvature index (BCI) depicts the condition of the subgrade.

FWD measurements were carried out in October 2016 (immediately after the reconstruction of the road section), April 2017 and 2018 (as ice lenses melted), and May 2020. Each time, the same measurement procedure was applied, i.e., measurements were taken in the middle of the lane in 50 m intervals on the road section with an unbound base layer (20.2–21.2 km) and at 100 m intervals for the rest of the test road sections.

In addition to deflections, air, surface and asphalt-layer temperatures were recorded during FWD measurements. The asphalt layer temperature was measured in the middle of all asphalt layers. The lowest, highest and average asphalt surface and layer temperatures registered during all measurement periods are presented in Table 2.

**Table 2.** Asphalt surface and layer temperatures during all measurement periods.

| Measurement Period | Temperature of Asphalt Surface, °C |     |         | Temperature of Asphalt Layer, °C |     |         |
|--------------------|------------------------------------|-----|---------|----------------------------------|-----|---------|
|                    | Min                                | Max | Average | Min                              | Max | Average |
| Oct 2016           | 2                                  | 12  | 8.5     | 5                                | 8   | 5.9     |
| April 2017         | 11                                 | 29  | 23.4    | 13                               | 17  | 16.0    |
| April 2018         | 18                                 | 24  | 22.2    | 17                               | 19  | 18.2    |
| May 2020           | 18                                 | 31  | 25.9    | 11                               | 25  | 17.9    |

Since the measured deflections cannot be directly compared to each other due to the varying temperatures of the asphalt surface layer and loads, they were adjusted (normalized) to a reference (standard) load (50 kN) and temperature (20 °C). The adjustment (normalization) of the deflection was done by multiplying the measured deflection by the load and temperature correction factors. The load correction factor was derived by comparing the reference pressure, which is equal to 707,355 kPa and is caused by the 30 cm diameter plate and 50 kN load, with the measured one. The load correction factor was calculated by Equation (1):

$$k_L = \frac{P_{meas}}{P_{ref}} \quad (1)$$

where  $P_{meas}$  is the pressure under the pressure plate measured during the test, and  $P_{ref}$  is the reference pressure under the pressure plate.

The temperature correction factor was calculated by Equation (2) [22]:

$$k_T = 10^{-0.000221 \cdot h_{asf}^{1.0229} \cdot (T-20)} \quad (2)$$

where  $h_{asf}$  is the thickness of the asphalt layers, and  $T$  is the temperature of the asphalt layer measured during the test.

The surface modulus  $E_0$  was calculated from the normalized surface deflections using Boussinesq's equation [23]:

$$E_0 = \frac{f \cdot (1 - \nu^2) \cdot \sigma_0 \cdot a}{d_0} \quad (3)$$

where  $f$  is a stress distribution factor ( $f = 2$ , as the stress was distributed uniformly);  $\nu$  is Poisson's ratio;  $\sigma_0$  is the stress (pressure) at the surface under the plate;  $a$  is the plate radius, and  $d_0$  is the deflection at the center under the plate.

The surface curvature index (SCI) can be calculated at depths of 200 mm or 300 mm. The 200 mm depth was chosen to represent the condition of top bound layers because the top bound layer thickness is closer to this number (245 mm and 140 mm) than it is to 300 mm. The SCI is calculated by Equation (4). The base damage index (BDI) was calculated for the base layers using Equation (5). The base curvature index (BCI) was calculated for the subgrade by Equation (6). The lower values of these parameters mean the better condition of the layer.

$$SCI = d_0 - d_{200} \quad (4)$$

$$BDI = d_{300} - d_{600} \quad (5)$$

$$BCI = d_{600} - d_{900} \quad (6)$$

where  $d_0$  is the deflection at the center under the plate, and  $d_r$  is the deflection measured at  $r$  distance from the center of the plate

#### 2.4. Pavement Life Calculation

The pavement life calculation includes an estimation of the predicted number of ESALs using Equation (6) or Equation (7).

Pavement life was calculated by the mechanistic-empirical method using MN LAYER software [24] and accepting these assumptions (Yoder and Witczak, 1975 [25]):

- the thickness of the layers of the pavement structure is even;
- the layers are unrestricted in the horizontal direction;
- the properties of the materials in the layers are homogeneous, and isotropic asphalt layers and unbound layers have full adhesion, but there is partial adhesion between asphalt and the unbound layer;
- Poisson's ratio is constant, for asphalt layers—0.35 and for unbound layers—0.45;
- the reaction of the pavement structure calculated from a single wheel subjected to a force of 50 kN with a 15 cm radius of the contact area.

The fatigue function of asphalt was calculated using Equation (7) [26]:

$$N_{rib.} = \frac{k_1(T)}{F_{(\epsilon 6)}} \cdot \left( \frac{S_{mix}(T)}{\sigma_v \cdot \gamma_{AC}} \right)^{k_2(T)} \quad (7)$$

where  $S_{mix}(T)$  is the temperature-dependent modulus of asphalt  $E$ ;  $\sigma_v$  is the vertical stress due to load;  $\gamma_{AC}$  is the safety factor of the asphalt layer;  $F_{(\epsilon 6)}$  is the fatigue safety factor, and  $k_1(T)$  and  $k_2(T)$  are the temperature coefficients.

The limit number of loads of unbound base layers and earth bed was calculated according to Equation (8) [26]:

$$N_{rib.} = 10^{\frac{1}{0.7} \left( \frac{0.00875 \cdot E_{V2} \cdot 1.0}{\sigma_{ZZ} \cdot \gamma} \right)} \quad (8)$$

where  $\sigma_{zz}$  is the vertical stresses resulting from the effect of the load;  $\gamma$  is the safety factor of the hydraulically bound layer, and  $E_{V2}$  is deformation modulus.

Pavement structure Type C was selected as a reference for the calculation of theoretical surface deflection. Data for theoretical surface deflection calculations are represented in Table 3. Layers' modulus  $E$  values are, according to LST EN 12697-26:2018 [27], 4-point bending (4 PB) at 20 °C and 10 Hz.

**Table 3.** Data for theoretical surface deflection calculation.

| Pavement Structure                 | Thickness, cm | E modulus, MPa |
|------------------------------------|---------------|----------------|
| Asphalt surface course<br>AC 11 VN | 4             | 4000           |
| Asphalt base course<br>AC 22 PN    | 10            | 5600           |
| Unbound base course                | 20            | 350            |
| Frost-resistant layer              | 31            | 120            |
| Subgrade                           | —             | 45             |

In order to determine the remaining life of pavement structures Type B and Type C, calculations were made using MN LAYER software [24] and back-calculated  $E$  moduli. The  $E$  modulus of each layer was back-calculated with ELMOD software using the deflection basin fit method. A back-calculated  $E$  modulus shows the real time condition and the bearing capacity of pavement structural layers. After back-calculation, statistical indicators such as minimum, maximum, average and standard deviation values were calculated. One standard deviation below the average of back-calculated  $E$  modulus values was used in the calculations of the remaining pavement life. The use of one standard deviation below the average according to advisory circular 150/5320-6F, "Airport Pavement

Design and Evaluation" [28] allows a more accurate prediction of the remaining life of pavement structures.

The remaining pavement life was calculated by analyzing data from October 2016 and April 2018. That data were selected since measurements in October 2016 represent the performance of the pavement structure directly after construction, while data from April 2018 reveals pavement durability in the spring thaw.

### 3. Results and Discussion

#### 3.1. Surface Deflection and Modulus

The normalized surface deflections ( $d_0$ ) measured with a FWD on each side are represented in Figure 6. The statistical analysis for this parameter is presented in Table 4. The directly correlating parameter with deflections is the surface modulus  $E_0$ , which is represented in Figure 7. The statistical analysis for this parameter is presented in Table 5.

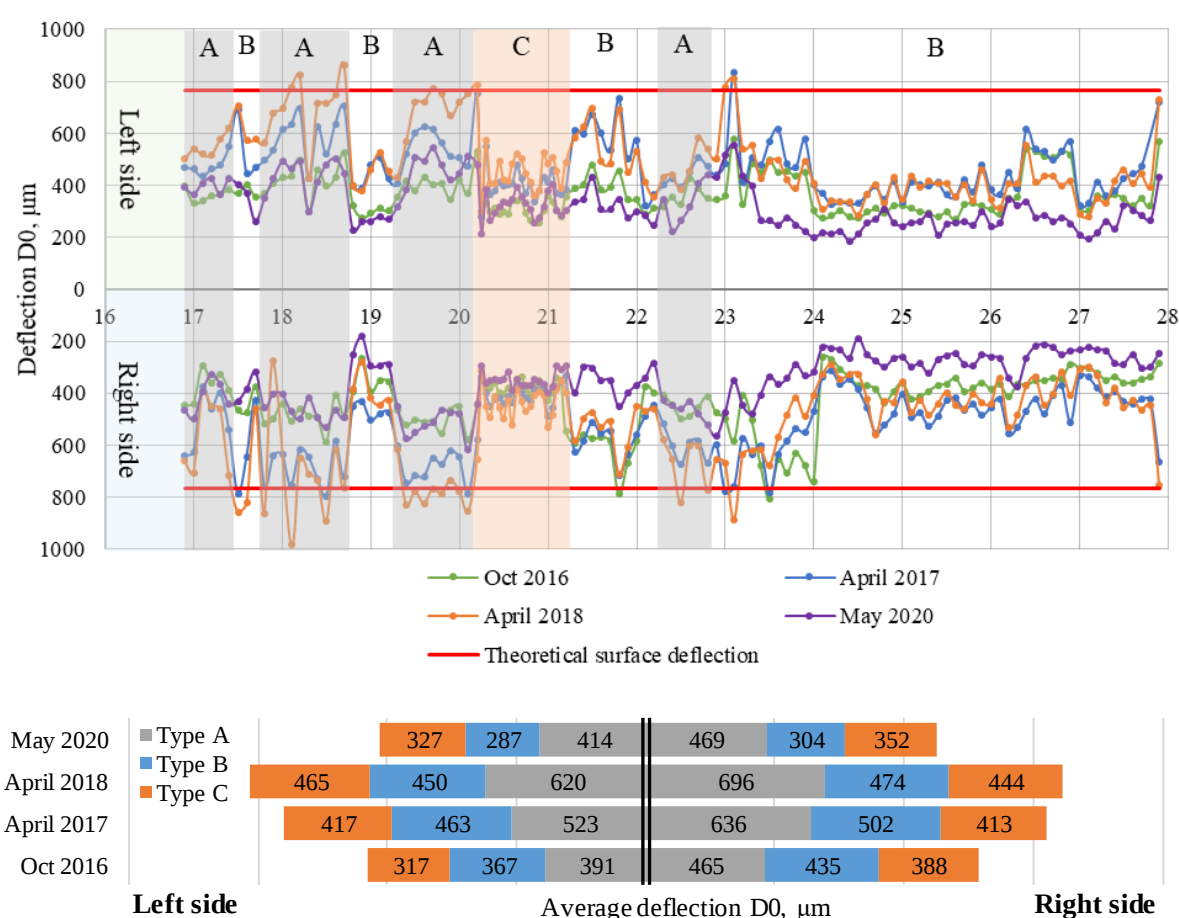


Figure 6. Deflection on each side of the road and their averages.

Table 4. Statistical analysis of deflections.

| Param.                    | Test Date  | Side  | Pavement Structure Type A |     |      |          |       | Pavement Structure Type B |     |      |          |       | Pavement Structure Type C |     |      |          |       |
|---------------------------|------------|-------|---------------------------|-----|------|----------|-------|---------------------------|-----|------|----------|-------|---------------------------|-----|------|----------|-------|
|                           |            |       | Min                       | Max | Avg. | St. dev. | CV, % | Min                       | Max | Avg. | St. dev. | CV, % | Min                       | Max | Avg. | St. dev. | CV, % |
| Deflection, $\mu\text{m}$ | Oct 2016   | Left  | 297                       | 526 | 391  | 50       | 12.8  | 268                       | 577 | 367  | 83       | 22.5  | 254                       | 530 | 317  | 57       | 17.9  |
|                           |            | Right | 295                       | 587 | 465  | 65       | 14.0  | 262                       | 807 | 435  | 133      | 30.5  | 338                       | 546 | 388  | 45       | 11.5  |
|                           | April 2017 | Left  | 395                       | 704 | 523  | 86       | 16.4  | 320                       | 833 | 463  | 112      | 24.2  | 281                       | 752 | 417  | 92       | 22.0  |
|                           |            | Right | 373                       | 798 | 636  | 101      | 15.9  | 312                       | 786 | 502  | 111      | 22.0  | 331                       | 579 | 413  | 54       | 13.0  |
|                           | April 2018 | Left  | 382                       | 863 | 620  | 132      | 21.4  | 281                       | 812 | 450  | 116      | 25.9  | 297                       | 787 | 465  | 96       | 20.7  |
|                           |            | Right | 278                       | 983 | 696  | 152      | 21.9  | 279                       | 889 | 474  | 132      | 27.8  | 312                       | 656 | 444  | 72       | 16.2  |
|                           | May 2020   | Left  | 223                       | 543 | 414  | 77       | 18.5  | 184                       | 556 | 287  | 73       | 25.3  | 213                       | 479 | 327  | 58       | 17.7  |
|                           |            | Right | 328                       | 618 | 469  | 59       | 12.6  | 183                       | 566 | 304  | 74       | 24.3  | 294                       | 441 | 352  | 35       | 10.1  |

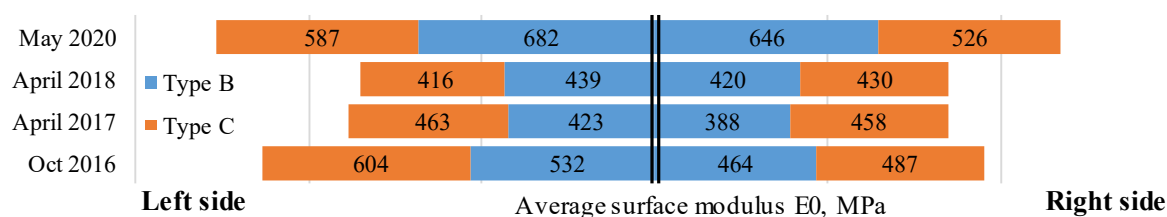


Figure 7. Surface moduli on each side of the road.

Table 5. Statistical analysis of surface moduli.

| Surface modulus, MPa Param. | Test date  | Side  | Pavement Structure Type B |      |      |          |       | Pavement Structure Type C |     |      |          |       |
|-----------------------------|------------|-------|---------------------------|------|------|----------|-------|---------------------------|-----|------|----------|-------|
|                             |            |       | Min                       | Max  | Avg. | St. dev. | CV, % | Min                       | Max | Avg. | St. dev. | CV, % |
|                             | Oct 2016   | Left  | 324                       | 698  | 532  | 103      | 19.4  | 354                       | 738 | 604  | 85       | 14.1  |
|                             |            | Right | 231                       | 716  | 464  | 117      | 25.3  | 342                       | 551 | 487  | 48       | 9.9   |
|                             | April 2017 | Left  | 222                       | 584  | 423  | 90       | 21.4  | 247                       | 661 | 463  | 79       | 17.1  |
|                             |            | Right | 237                       | 596  | 388  | 81       | 20.9  | 322                       | 564 | 458  | 55       | 11.9  |
|                             | April 2018 | Left  | 229                       | 664  | 439  | 99       | 22.5  | 236                       | 627 | 416  | 78       | 18.8  |
|                             |            | Right | 209                       | 666  | 420  | 103      | 24.5  | 283                       | 598 | 430  | 67       | 15.5  |
|                             | May 2020   | Left  | 334                       | 984  | 682  | 142      | 20.8  | 385                       | 858 | 587  | 104      | 17.7  |
|                             |            | Right | 327                       | 1025 | 646  | 142      | 22.0  | 408                       | 627 | 526  | 55       | 10.5  |

As seen from Figure 6, deflection varied from 183 to 983  $\mu\text{m}$  irrespective of the measurement time, while the surface moduli varied from 189 to 1025 MPa. The highest average deflection was determined on the pavement structure of Type A (with a bound base course on top of the existing sub-base) in April 2018 on the right side of the road—696  $\mu\text{m}$ , while Type B (with a bound base with a frost-resistant layer) and Type C (with an unbound base layer) performed quite similarly—474  $\mu\text{m}$  and 444  $\mu\text{m}$ , respectively. The surface moduli were 287, 420 and 430 MPa, respectively, for Type A, Type B and Type C. Thus, the pavement structure of Type A performed 31.7% and 33.3% worse than Types B and C, respectively, during these conditions. In fact, during each measurement on each side of the road, the pavement structure of Type B and C always outperformed Type A, with an improvement varying from 8.6% to 38.0%. One possible reason for this is that the FWD measurement point across the road could have been right above the edge of the existing sub-base, on top of which the rest of the pavement structure Type A was installed and that the existing sub-base could have been weak, which influenced the new pavement performance; thus, specific attention has to be paid to the construction in those places to ensure the desirable bearing capacity. This type of pavement structure (Type A) is unreliable in comparison with the other two structures and, as a result, it is omitted from further discussion about the results.

The lowest average deflection was measured on pavement structure Type B in May 2020—287 and 304  $\mu\text{m}$  (left and right side, respectively), with resulting surface moduli of 682 and 646 MPa, respectively. At that period, the average deflection on pavement structure Type C was 327 and 352  $\mu\text{m}$  (left and right side, respectively), and the surface moduli—587 and 526 MPa, respectively. This resulted in the average surface modulus for pavement structure Type B to be 16.3–22.8% higher than Type C, depending on the side of the road at that measurement period. When compared to the measurement period right after reconstruction (October 2016), the average surface modulus on pavement structure Type B improved by 28.3–39.3% (for the left and right side of the road, respectively) over the first 4.5 years, while on pavement structure Type C on the right side of the road, it increased by only 8.1%, and on the left side of the road, it actually decreased by 2.9%.

The theoretical deflection calculated for standard asphalt pavement with unbound base layers is 764  $\mu\text{m}$ . During all four measurement periods, the measured deflection on pavement Type C exceeded the theoretical deflection only at one point: the thaw period in April 2018 on the left side of the road at 20.2 km. This station is the first station on the border with pavement Type A, which is most likely the reason for the high deflections. The average deflection on this pavement type was 1.64–2.41 times lower than the theoretical deflection. During all four measurement periods, the deflection on pavement Type B exceeded the theoretical deflection only on several measurement points during thaw periods in 2017 and 2018 (up to three stations per measurement period per road side, which is up to 4.3% of all measurements). Most of the stations are also on a border with pavement structure Type A, which is the probable reason for the high deflections at those stations. The average deflection on this pavement type was 1.52–2.66 times lower than the theoretical deflection, which is similar to pavement structure Type C. The resulting numbers show a reserve for both pavement structures when comparing the measured deflections to the theoretical deflection of a standard pavement even during thaw periods. Based on an average deflection, the reserve ranges from 34.3% to 62.4% of the theoretical deflection.

In general, the average surface modulus on pavement structure Type B was 16.3–20.5% higher right after reconstruction in October 2016 when compared to the thaw period next year (April 2017) and 35.0–35.7% higher during the latest measurement period, May 2020, when compared to the thaw period in April 2018. For pavement structure Type C, the respective numbers are 5.9–23.3% (comparing 2016 to 2017) and 18.3–29.1% (comparing 2020 to 2018). The decrease in performance during thaw seasons is more substantial for pavement structure Type B than Type C, which could indicate that a pavement structure with a CCPR base course is more susceptible to hydrothermal conditions than the pavement structure with an unbound base course.

The surface modulus for the left side of the road was higher irrespective of different pavement structures and measurement time (period) than the right side of the road. For example, in October 2016, the average moduli of the left side for pavement structures Type B and Type C were, respectively, 14.6% and 24.1% higher than on the right side. The difference gradually decreased, and, in May 2020, the average moduli of the left side for pavement structures Type B and Type C were, respectively, only 5.6% and 11.5% higher than on the right side.

### 3.2. Deflection Basin Parameters (SCI, BDI, BCI)

The surface curvature indices (SCI) calculated for each side are represented in Figure 8. The statistical analysis for this parameter is presented in Table 6. The SCI varied from 31 to 251  $\mu\text{m}$  irrespective of the measurement time. The lowest average SCI was calculated on pavement structure Type C immediately after reconstruction in October 2016—41 and 51  $\mu\text{m}$  (left and right side of the road, respectively). The SCI on pavement structure Type B was two times higher than on Type C—83 and 108  $\mu\text{m}$ , respectively. In May 2020, the average SCI increased to 51 and 57  $\mu\text{m}$  for Type C and decreased to 60 and 71  $\mu\text{m}$  for Type B. Thus, from 2016 to 2020, CCPR-based pavement structures' disadvantage decreased from 100.4–109.7% to 18.3–25.2% compared to regular pavement regarding top layer performance. What is noticeable is that the average SCI on pavement structure Type B improved by 26.8–34.2% (depending on the road side) over the first 4.5 years, while on pavement structure Type C, the performance actually decreased by 10.2–24.0%.

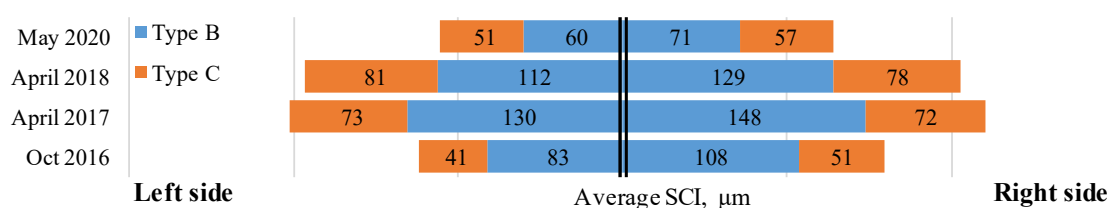


Figure 8. SCI on each side of the road.

Table 6. Statistical analysis of SCI.

| Param.             | Test Date  | Side  | Pavement Structure Type B |     |      |          |       | Pavement Structure Type C |     |      |          |       |
|--------------------|------------|-------|---------------------------|-----|------|----------|-------|---------------------------|-----|------|----------|-------|
|                    |            |       | Min                       | Max | Avg. | St. dev. | CV, % | Min                       | Max | Avg. | St. dev. | CV, % |
| SCI, $\mu\text{m}$ | Oct 2016   | Left  | 51                        | 168 | 83   | 28       | 34.1  | 31                        | 91  | 41   | 16       | 38.8  |
|                    |            | Right | 52                        | 247 | 108  | 48       | 44.8  | 38                        | 169 | 51   | 27       | 51.6  |
|                    | April 2017 | Left  | 79                        | 229 | 130  | 45       | 34.6  | 53                        | 151 | 73   | 20       | 26.9  |
|                    |            | Right | 85                        | 251 | 148  | 42       | 28.5  | 63                        | 83  | 72   | 6        | 7.7   |
|                    | April 2018 | Left  | 57                        | 209 | 112  | 34       | 30.7  | 57                        | 133 | 81   | 20       | 24.1  |
|                    |            | Right | 65                        | 246 | 129  | 44       | 33.8  | 63                        | 125 | 78   | 13       | 16.3  |
|                    | May 2020   | Left  | 39                        | 113 | 60   | 15       | 24.4  | 37                        | 72  | 51   | 7        | 14.6  |
|                    |            | Right | 42                        | 125 | 71   | 21       | 30.1  | 50                        | 63  | 57   | 4        | 6.6   |

The average SCI on pavement structure Type B was 37.6–57.8% higher during the thaw period in April 2017 when compared to the measurement period right after reconstruction in October 2016. The average SCI was 81.4–85.5% higher during the thaw period in April 2018 when compared to the latest measurement period, May 2020. For pavement structure Type C, the respective numbers are 40.9–76.4% (comparing 2017 to 2016) and 36.8–59.3% (comparing 2018 to 2020). This indicates that the top bound layer is almost equally susceptible to hydrothermal conditions irrespective of the pavement structure type.

As with the surface moduli, the condition on the left side of the road in regard of SCI was better than on the right side of the road. The average SCI for the left side of the road was lower than for the right side of the road irrespective of pavement structures and measurement time. For example, in October 2016, the average left side SCIs of the left sides of pavement structures Type B and Type C were, respectively, 23.4% and 19.9% lower than on the right side. The difference gradually decreased and, in May 2020, when the average SCIs of the left side of pavement structures Type B and Type C were, respectively, only 14.9% and 9.9% lower than on the right side. Although it is noticeable that, during thaw seasons, the SCI on the left side of the road was higher for pavement structure Type C (0.3% and 4.9%), while, for Type B, the left side condition was still better, lower by 12.2% and 13.0%, respectively.

The base damage index is presented in Figure 9. The statistical analysis for this parameter is presented in Table 7. The BDI varied from 32 to 236  $\mu\text{m}$  irrespective of the measurement time. The lowest average BDI was determined to be on pavement structure Type B during the latest filed test, on May 2020—69 and 70  $\mu\text{m}$  (left and right side of the road, respectively). In October 2016, the average BDIs were 85 and 100  $\mu\text{m}$ . This means that, over 4.5 years on average, the base condition improved by 18.4–30.2% for Type B, depending on the side of the road. At the same time, the base condition on pavement structure Type C improved only on the right side of the road (by 5.6%) and decreased by 8.4% on the left side of the road. During the latest measurement period in May 2020, the average BDI for pavement structure Type B was 15.1–20.9% lower than for Type C, depending on the side of the road.

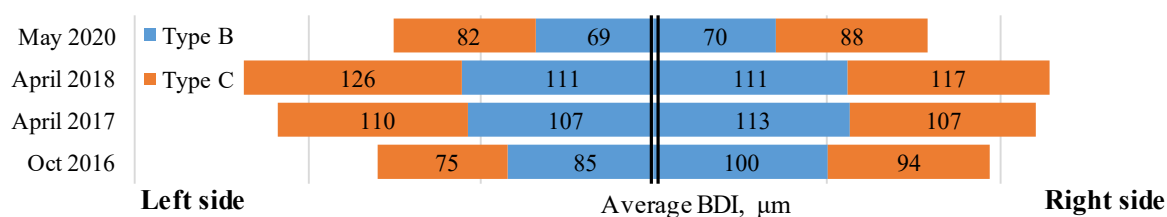


Figure 9. BDI on each side of the road.

Table 7. Statistical analysis of BDI.

| Param.             | Test Date  | Side  | Pavement Structure Type B |     |      |          |       | Pavement Structure Type C |     |      |          |       |
|--------------------|------------|-------|---------------------------|-----|------|----------|-------|---------------------------|-----|------|----------|-------|
|                    |            |       | Min                       | Max | Avg. | St. dev. | CV, % | Min                       | Max | Avg. | St. dev. | CV, % |
| BDI, $\mu\text{m}$ | Oct 2016   | Left  | 60                        | 164 | 85   | 20       | 23.6  | 61                        | 122 | 75   | 12       | 16.3  |
|                    |            | Right | 58                        | 200 | 100  | 32       | 31.5  | 79                        | 129 | 94   | 10       | 10.2  |
|                    | April 2017 | Left  | 73                        | 196 | 107  | 26       | 24.5  | 72                        | 195 | 110  | 23       | 20.7  |
|                    |            | Right | 73                        | 204 | 113  | 26       | 23.3  | 80                        | 130 | 107  | 11       | 9.9   |
|                    | April 2018 | Left  | 67                        | 215 | 111  | 32       | 28.9  | 86                        | 210 | 126  | 24       | 19.2  |
|                    |            | Right | 59                        | 229 | 111  | 35       | 31.5  | 86                        | 155 | 117  | 16       | 14.1  |
|                    | May 2020   | Left  | 44                        | 138 | 69   | 19       | 28.1  | 58                        | 102 | 82   | 12       | 14.5  |
|                    |            | Right | 32                        | 149 | 70   | 19       | 27.1  | 78                        | 102 | 88   | 7        | 8.1   |

The average BDI on pavement structure Type B was 13.1–26.9% higher during the thaw period in April 2017 when compared to the measurement period right after reconstruction in October 2016. The average BDI was 59.0–60.3% higher during the thaw period in April 2018 when compared to the latest measurement period, in May 2020. For pavement structure Type C, the respective numbers are 14.5–46.8% (comparing 2017 to 2016) and 32.1–54.9% (comparing 2018 to 2020). The results are inconsistent, as the first comparison shows a more substantial decrease in base performance for pavement structure Type C, while the second comparison shows a more substantial decrease in base performance for pavement structure Type B. This could be the result of an ongoing decrease of the average BDI for pavement structure Type B.

The average BDI for the left side of the road was lower than for the right side, irrespective of the measurement period, for pavement structure Type B, ranging from 0.2% to 15.4%. For pavement structure Type C, on the other hand, the left side of the road performed better than the right side only during the measurement periods October 2016 and May 2020 (by 7.8–19.8%), while, during the thaw seasons, the condition on the left side was worse than the right side (by 2.8–3.1%).

The base curvature index is presented in Figure 10. The statistical analysis for this parameter is presented in Table 8. The BCI varied from 25 to 134  $\mu\text{m}$  irrespective of the measurement time. The lowest average BCI was determined on pavement structure Type B during the latest filed test, in May 2020—43 and 44  $\mu\text{m}$  (left and right side of the road, respectively). In October 2016, the average BCI was 49 and 54  $\mu\text{m}$ . This means that, over 4.5 years on average, the subgrade condition improved by 12.5–18.3% for Type B, depending on the side of the road. At the same time, the subgrade condition on pavement structure Type C improved only on the right side of the road (by 14.7%) and decreased by 0.5% on the left side of the road. During the latest measurement period of May 2020, the average BCI for pavement structure Type B was 15.9–19.0% lower than Type C depending on the side of the road.

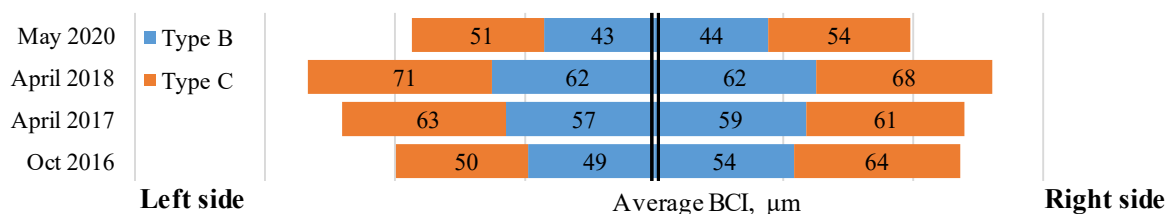


Figure 10. BCI on each side of the road.

**Table 8.** Statistical analysis of all relevant parameters.

| Param.             | Test Date  | Side  | Pavement Structure Type B |     |      |          |       | Pavement Structure Type C |     |      |          |       |
|--------------------|------------|-------|---------------------------|-----|------|----------|-------|---------------------------|-----|------|----------|-------|
|                    |            |       | Min                       | Max | Avg. | St. dev. | CV, % | Min                       | Max | Avg. | St. dev. | CV, % |
| BCI, $\mu\text{m}$ | Oct 2016   | Left  | 36                        | 88  | 49   | 10       | 19.8  | 41                        | 71  | 50   | 7        | 14.7  |
|                    |            | Right | 36                        | 86  | 54   | 11       | 19.8  | 56                        | 74  | 64   | 4        | 5.9   |
|                    | April 2017 | Left  | 36                        | 117 | 57   | 14       | 25.0  | 38                        | 110 | 63   | 15       | 23.7  |
|                    |            | Right | 38                        | 107 | 59   | 13       | 22.6  | 46                        | 87  | 61   | 9        | 14.8  |
|                    | April 2018 | Left  | 36                        | 109 | 62   | 17       | 27.0  | 43                        | 118 | 71   | 15       | 21.5  |
|                    |            | Right | 38                        | 118 | 62   | 15       | 24.8  | 44                        | 111 | 68   | 14       | 21.1  |
|                    | May 2020   | Left  | 25                        | 87  | 43   | 12       | 27.9  | 30                        | 76  | 51   | 10       | 20.3  |
|                    |            | Right | 25                        | 88  | 44   | 11       | 24.7  | 43                        | 69  | 54   | 7        | 12.6  |

The average BCI on pavement structure Type B was 9.1–17.5% higher during the thaw period in April 2017 when compared to the measurement period right after reconstruction in October 2016. The average BCI was 41.0–45.8% higher during the thaw period in April 2018 when compared to the latest measurement period, May 2020. For pavement structure Type C, an anomaly was detected, as the average BCI on the right side of the road was lower during the thaw period in April 2017 when compared to October 2016. While, on the right side during the thaw period, the subgrade performed 24.2% worse than right after reconstruction. The average BCI on pavement structure Type C was 26.0–39.9% higher during the thaw period in April 2018 when compared to the latest measurement period, May 2020.

The average BCI for the left side of the road was lower right after reconstruction for both pavement structures—Type B and Type C during the measurement period of October 2016 by 9.4% and 20.7%, respectively. During both thaw measurement periods, the difference was not significant, ranging from 3.7% lower performance on the left side to 2.4% higher performance on the left side when compared to the right side, irrespective of the pavement structure. The average BCI again improved for the left side for both pavement structures—Type B and Type C during the latest measurement period, May 2020, by 2.9% and 6.6% respectively.

### 3.3. Backcalculation E Modulus and Remaining Pavement Life

The back-calculated E moduli with ELMOD software for pavement structures of Type B and Type C are represented in Table 9. During the measurement period October 2016, the average E modulus of the bound layer of pavement structure Type B was 1.88 times greater on the left side of the road (1.32 times greater on the right side of the road) than in the thaw season in April 2018. The average E modulus of the frost-resistant layer in October 2016 was 1.57 times greater on the left side of the road (1.29 times greater on the right side of the road) than in the thaw season in April 2018. The average E modulus of the subgrade in October 2016 was 1.23 times greater on the left side of the road (1.18 times greater on the right side of the road) than in the thaw season in April 2018.

The average back-calculated E modulus of the bound layer of pavement structures of Type C during the measurement period October 2016 was 1.91 times greater on the left side of the road (2.42 times greater on the right side of the road) than during the thaw season in April 2018. The average E modulus of the unbound layer in October 2016 was 1.37 times greater on the left side of the road (1.75 times greater on the right side of the road) than in the thaw season in April 2018. The average E modulus of the frost-resistant layer in October 2016 was 1.10 times greater on the left side of the road (1.45 times greater on the right side of the road) than in the thaw season in April 2018. The average E modulus of the subgrade in October 2016 was 1.08 times greater on the left side of the road (1.29 times greater on the right side of the road) than in the thaw season in April 2018.

**Table 9.** Statistical indicators of back-calculated E moduli.

| Parameter      | Test Date  | Side  | Layer           | Pavement Structure Type B |      |      |          | Pavement Structure Type C |      |      |          |
|----------------|------------|-------|-----------------|---------------------------|------|------|----------|---------------------------|------|------|----------|
|                |            |       |                 | Min                       | Max  | Avg. | St. dev. | Min                       | Max  | Avg. | St. dev. |
| E modulus, MPa | Oct 2016   | Left  | Bound           | 836                       | 6385 | 1895 | 643      | 5190                      | 8029 | 6599 | 836      |
|                |            | Right |                 | 616                       | 7488 | 1602 | 716      | 2864                      | 9546 | 8128 | 1537     |
|                |            | Left  | Unbound         | –                         | –    | –    | –        | 276                       | 579  | 448  | 79       |
|                |            | Right |                 | –                         | –    | –    | –        | 250                       | 673  | 528  | 104      |
|                |            | Left  | Frost-resistant | 12                        | 730  | 394  | 121      | 149                       | 321  | 225  | 37       |
|                |            | Right |                 | 10                        | 753  | 310  | 161      | 213                       | 504  | 346  | 90       |
|                |            | Left  | Subgrade        | 28                        | 158  | 92   | 23       | 58                        | 82   | 68   | 7        |
|                |            | Right |                 | 18                        | 184  | 86   | 31       | 53                        | 114  | 80   | 13       |
|                | April 2018 | Left  | Bound           | 490                       | 2015 | 1007 | 368      | 2897                      | 4555 | 3457 | 416      |
|                |            | Right |                 | 621                       | 2403 | 1217 | 360      | 1773                      | 4335 | 3356 | 641      |
|                |            | Left  | Unbound         | –                         | –    | –    | –        | 244                       | 426  | 327  | 45       |
|                |            | Right |                 | –                         | –    | –    | –        | 138                       | 420  | 301  | 58       |
|                |            | Left  | Frost-resistant | 30                        | 558  | 251  | 110      | 86                        | 429  | 247  | 86       |
|                |            | Right |                 | 91                        | 541  | 241  | 98       | 113                       | 397  | 239  | 75       |
|                |            | Left  | Subgrade        | 25                        | 167  | 75   | 27       | 37                        | 106  | 63   | 14       |
|                |            | Right |                 | 30                        | 138  | 73   | 26       | 26                        | 101  | 62   | 16       |

The average back-calculated E modulus of the bound layer during the measurement period October 2016 of pavement structures Type C was 3.48 times greater on the left side of the road (5.07 times greater on the right side of the road) than pavement structure Type B. The average E modulus of the frost-resistant layer of pavement structure Type B was 1.75 times greater on the left side of the road (0.90 times smaller on the right side of the road) than pavement structure Type C. The average E modulus of the subgrade of pavement structure Type B was 1.35 times greater on the left side of the road (1.08 times greater on the right side of the road) than pavement structure Type C.

The average back-calculated E modulus of the bound layer during the measurement period of April 2018 of pavement structures Type C was 3.44 times greater on the left side of the road (2.76 times greater on the right side of the road) than pavement structure Type B. The average E modulus of the frost-resistant layer of pavement structure Type B was 1.02 times greater on the left side of the road (1.01 times greater on the right side of the road) than pavement structure Type C. The average E modulus of the subgrade of pavement structure Type B was 1.19 times greater on the left side of the road (1.18 times greater on the right side of the road) than pavement structure Type C.

Calculated pavement surface deflection,  $E_0$  and the predicted number of ESALs are represented in Table 10. Calculated pavement surface deflection of October 2016 for pavement structure Type B is 0.90 times smaller than the thaw season in April 2018 and, for pavement structure Type C—0.60 times smaller than the thaw season in 2018.  $E_0$  modulus calculated for October 2016 for pavement structure Type B is 1.11 times greater than in the thaw season in April 2018 and, for pavement structure Type C, it is 1.65 times greater than the thaw season of April 2018. The predicted number of ESALs calculated of October 2016 for pavement structures B is 3 times greater than the thaw season of April 2018, for pavement structures C—45.43 times greater than the thaw season of April 2018.

**Table 10.** Results of pavement life calculations.

| Test Date  | Side  | Pavement Structure Type | Parameter                 |             |                              |
|------------|-------|-------------------------|---------------------------|-------------|------------------------------|
|            |       |                         | Deflection, $\mu\text{m}$ | $E_0$ , MPa | Predicted Number ESALs, mln. |
| Oct 2016   | Right | B                       | 886                       | 210         | 0.03                         |
| April 2018 | Right | B                       | 983                       | 190         | 0.01                         |
| Oct 2016   | Right | C                       | 505                       | 369         | 3.18                         |
| April 2018 | Right | C                       | 839                       | 222         | 0.07                         |

Calculated pavement surface deflection of October 2016 for pavement structure Type B is 1.75 times greater than for pavement structure Type C, for the thaw season in April 2018 is 1.17 times greater.  $E_0$ -modulus-calculated pavement surface deflection in October 2016 for pavement structure Type B is 0.57 times smaller than pavement structure Type C, for the thaw season of April 2018—0.86 times smaller. The predicted number of ESALs in October 2016 on pavement structure Type C is 106 times greater than pavement structure Type B and, for the thaw season of April 2018, 7 times greater.

#### 4. Conclusions

The analysis of FWD data and calculated deflection basin parameters (SCI, BDI, BCI), as well as a comparison of measured and theoretically calculated deflection, in addition to the predicted pavement life on the basis of back-calculated E moduli, led to the following conclusions:

- In all cases, the pavement with a CCPR base course constructed on the existing sub-base (Type A) performs 9–38% worse than fully reconstructed pavements (Types B and C) in terms of surface modulus  $E_0$ , irrespective of the base course type (CCPR or unbound). The reason for this may be that the measurements' position on pavement structure Type A coincided with the edge of the existing sub-base, since the road was widened in those sections. Thus, to ensure a desirable bearing capacity, specific attention has to be paid to the construction in such conditions.
- The theoretical deflection on the pavement surface calculated using mechanistic-empirical pavement design principles is exceeded only in some individual measurement points in the spring thaw (Type B and C). The average deflection on the pavement surface was lower than the theoretical value even in the thaw of 2017 and 2018 when it increased by 9–26% (Type B) and by 6–47% (Type C), respectively, compared to in October. The same tendency was determined regarding SCI (increased by 35–57% in Type B and by 41–98% in Type C) and BDI (increased by 13–31 in Type B and by 14–68% in Type C).
- The use of a CCPR base course (Type B) leads to much more scattered FWD data (the coefficient of variation varied from 22% to 31%) than from the pavement structure with the unbound base course (Type C, the coefficient of variation varied from 10% to 22%). The reason for this may be related to the inhomogeneity of the CCPR base course (38.8% reclaimed asphalt). Therefore, for the determination of the residual life of pavement structures with a CCPR base course, we recommend the use of input data that reflects the pavement performance with a deflection value equal to the average deflection calculated based on the measured FWD data and decreased by one standard deviation (average deflection minus one standard deviation). Such an approach will prevent the pavement structure from premature failures.
- Based on the pavement design with back-calculated E moduli, the durability of the pavement structure with a CCPR base course (Type B) is more than seven times lower compared to that of the pavement structure with an unbound base course (Type C), irrespective of season. This result may be explained by the fact that soft asphalt with a very thin layer (4.5 cm) was constructed on the CCPR base course, and its E modulus is more than five times lower than that of asphalt concrete mixtures used in typical pavement structures with an unbound base course. Nevertheless, it must be emphasized that it has already been proven by a number of researchers that the bearing capacity of pavement structures with a CCPR base course gradually increases over time due to the curing processes of bituminous and hydraulic binders (in this study, the surface modulus  $E_0$  increased by 28–47%, depending on the side of the road) and significantly prolongs pavement life. Unfortunately, this increase in bearing capacity cannot be assessed by typical mechanistic-empirical pavement design principles.
- Seeking to design a pavement structure based on the back-calculated E moduli from FWD data, it is vital to adjust (normalize) all measured data to a reference (standard)

load and climate conditions. However, in this study, an applied temperature correction factor is determined based on the FWD measurements on the test road in the summer when hydrothermal conditions did not affect the stiffness of unbound layers. While in practice, measurements are done irrespective of the season, for example, in spring when the bearing capacity (E modulus) of unbound layers are affected by water content. Thus, this effect should be also incorporated in the correction factor. Further studies, which take this into account, will be undertaken.

**Author Contributions:** Conceptualization, A.V.; methodology, J.G.; software, R.M.; formal analysis, I.K. and R.M.; writing—original draft preparation, I.K. and R.M.; writing—review and editing, J.G.; supervision, A.V. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Simonsen, E.; Isacsson, U. Thaw weakening of pavement structures in cold regions. *Cold Reg. Sci. Technol.* **1999**, *29*, 135–151. [CrossRef]
2. Yi, J.; Doré, G.; Bilodeau, J.-P.; Prophète, F. Monitoring the structural behaviour variation of a flexible pavement structure during freeze and thaw. In Proceedings of the 2014 Conference of the Transportation Association of Canada, Montreal, QC, Canada, 28 September–1 October 2014; pp. 1–12.
3. Ishikawa, T.; Lin, T.; Kawabata, S.; Kameyama, S.; Tokoro, T. Effect evaluation of freeze-thaw on resilient modulus of unsaturated granular base course material in pavement. *Transp. Geotech.* **2019**, *21*, 100284. [CrossRef]
4. Saevardottir, T.; Erlingsson, S. Effect of moisture content on pavement behaviour in a heavy vehicle simulator test. *Road Mater. Pavement Des.* **2013**, *14*, 274–286. [CrossRef]
5. Saevardottir, T.; Erlingsson, S. Water Impact on the Behaviour of Flexible Pavement Structures in an Accelerated Test. *Road Mater. Pavement Des.* **2013**, *14*, 256–277. [CrossRef]
6. Charlier, R.; Horny, P.; Srsen, M.; Hermansson, A.; Bjarnason, G.; Erlingsson, S.; Pavsic, P. Water Influence on Bearing Capacity and Pavement Performance. In *Water in Road Structures*; Dawson, A., Ed.; Springer: Dordrecht, The Netherlands, 2009; pp. 175–192.
7. Wen, Z.; Zhang, M.; Ma, W.; Wu, Q.; Niu, F.; Yu, Q.; Fan, Z.; Sun, Z. Thermal-moisture dynamics of embankments with asphalt pavement in permafrost regions of central Tibetan Plateau. *Eur. J. Environ. Civ. Eng.* **2015**, *19*, 387–399. [CrossRef]
8. Salour, F.; Erlingsson, S. Investigation of a pavement structural behaviour during spring thaw using falling weight deflectometer. *Road Mater. Pavement Des.* **2013**, *14*, 141–158. [CrossRef]
9. Vaitkus, A.; Laurinavičius, A.; Oginskas, R.; Motiejūnas, A.; Paliukaitė, M.; Barvidienė, O. The road of experimental pavement structures: Experience of five years operation. *Balt. J. Road Bridg. Eng.* **2012**, *7*, 220–227. [CrossRef]
10. White, T.D.; Coree, B.J. Threshold Pavement Thickness to Survive Spring Thaw. In *Proceedings of the Third International Conference on Bearing Capacity of Roads and Airfields*; Norwegian University of Science and Technology, Ed.; Tapir Publishers: Trondheim, Norway, 1990; pp. 41–51.
11. St-Laurent, D.; Roy, M. Évaluation Structurale des Chaussées Souples dans un Contexte Climatique Nordique: Une Étude Avec le FWD (Structural Evaluation of Flexible Pavements in a Northern Context: A Study Using the FWD.). In Proceedings of the 30th Annual Conference of AQTR, Association Québécoise du Transport et des Routes, Quebec, QC, Canada, 1995. Available online: <https://corpus.ulaval.ca/jspui/handle/20.500.11794/45150> (accessed on 20 May 2021).
12. Doré, G.; Savard, Y. Analysis of Seasonal Pavement Deterioration. In Proceedings of the Transportation Research Board; Preprint no. 981046, Transportation Research Board of the National Academies, Washington, DC, USA, 1998.
13. Zhang, W.; Macdonald, R.A. Response and Performance of a Test Pavement to Freeze-Thaw Cycles in the Danish Road Testing Machine. In Proceedings of the Fifth International Conference on Unbound Aggregates in Roads, Nottingham, UK, 21–23 June 2000; pp. 77–86.
14. Lekarp, F.; Isacsson, U.; Dawson, A. State of the Art. I: Resilient Response of Unbound Aggregates. *J. Transp. Eng.* **2000**, *126*, 66–75. [CrossRef]
15. Lekarp, F.; Isacsson, U.; Dawson, A. State of the Art. II: Permanent Strain Response of Unbound Aggregates. *J. Transp. Eng.* **2000**, *126*, 76–83. [CrossRef]

16. Vaitkus, A.; Gražulytė, J.; Juknevičiūtė-Žilinskienė, L.; Andrejevas, V. Review of Lithuanian Experience in Asphalt Pavements Cold Recycling. In Proceedings of the 10th International Conference “Environmental Engineering”, VGTU Technika, Vilnius, Lithuania, 27–28 April 2017.
17. Meocci, M.; Grilli, A.; La Torre, F.; Bocci, M. Evaluation of mechanical performance of cement-bitumen-treated materials through laboratory and in-situ testing. *Road Mater. Pavement Des.* **2017**, *18*, 376–389. [CrossRef]
18. Godenzoni, C.; Graziani, A.; Bocci, E.; Bocci, M. The evolution of the mechanical behaviour of cold recycled mixtures stabilised with cement and bitumen: Field and laboratory study. *Road Mater. Pavement Des.* **2018**, *19*, 856–877. [CrossRef]
19. Arimilli, S.; Nagabhushana, M.N.; Jain, P.K. Comparative mechanistic-empirical analysis for design of alternative cold recycled asphalt technologies with conventional pavement. *Road Mater. Pavement Des.* **2018**, *19*, 1595–1616. [CrossRef]
20. Gu, F.; Ma, W.; West, R.C.; Taylor, A.J.; Zhang, Y. Structural performance and sustainability assessment of cold central-plant and in-place recycled asphalt pavements: A case study. *J. Clean. Prod.* **2019**, *208*, 1513–1523. [CrossRef]
21. Talvik, O.; Aavik, A. Use of FWD Deflection Basin Parameters (SCI, BDI, BCI) for Pavement Condition Assessment. *Balt. J. Road Bridg. Eng.* **2009**, *4*, 196–202. [CrossRef]
22. Motiejūnas, A.; Paliukaitė, M.; Vaitkus, A.; Čygas, D.; Laurinavičius, A. Research on the Dependence of Asphalt Pavement Stiffness Upon the Temperature of Pavement Layers. *Balt. J. Road Bridg. Eng.* **2010**, *5*, 50–54. [CrossRef]
23. Ullidtz, P. *Pavement Analysis*; Elsevier: New York, NY, USA, 1987.
24. Khazanovich, L.; Wang, Q. MnLayer: High-performance layered elastic analysis program. *Transp. Res. Rec.* **2008**, *2038*, 63–75. [CrossRef]
25. Yoder, E.J.; Witczak, M.W. *Principles of Pavement Design*, 2nd ed.; Wiley: New York, NY, USA, 1975.
26. FGSV. *Richtlinien für die Rechnerische Dimensionierung des Oberbaus von Verkehrsflächen mit Asphaltdeckschicht*. RDO—Asphalt 09; FGSV: Köln, Germany, 2009.
27. LST EN 12697-26:2018 Bituminous Mixtures—Test Methods—Part 26: Stiffness (Bituminiai Mišiniai Bandymo Metodai. 26 Dalis. Standis). 2018. Available online: <https://standards.iteh.ai/catalog/standards/cen/99e7a977-c432-4028-b14d-4e1cb9f84ddc/en-12697-26-2018> (accessed on 20 May 2021).
28. FAA. Airport Pavement Design and Evaluation. AC No. 150/5320-6F. 2016. Available online: [https://www.faa.gov/documentlibrary/media/advisory\\_circular/150-5320-6f.pdf](https://www.faa.gov/documentlibrary/media/advisory_circular/150-5320-6f.pdf) (accessed on 20 May 2021).