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Soft Asphalt and Double Otta Seal—Self-Healing Sustainable Techniques for Low-Volume Gravel Road Rehabilitation

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Received: 8 January 2018; Accepted: 11 January 2018; Published: 15 January 2018

Abstract: Increased traffic flow on low-volume gravel roads and deficiencies of national road infrastructure, are increasingly apparent in Lithuania. Gravel roads do not comply with requirements, resulting in low driving comfort, longer travelling time, faster vehicle amortization, and dustiness. The control of dustiness is one of the most important road maintenance activities on gravel roads. Another important issue is the assurance of required driving comfort and safety. Soft asphalt and Otta Seal technologies were proposed as a sustainable solution for the improvement of low-volume roads in Lithuania. Five gravel roads were constructed with soft asphalt, and 13 gravel roads were sealed with double Otta Seal, in 2012. The main aim of this research was to check soft asphalt and double Otta Seal's ability to self-heal, on the basis of the results of the qualitative visual assessment of pavement defects and distress. The qualitative visual assessment was carried out twice a year following the opening of the rehabilitated road sections. The results confirmed soft asphalt and double Otta Seal's ability to self-heal. The healing effect was more than 13% and 19% on roads with soft asphalt and double Otta Seal, respectively. In addition, on some roads, all cracks observed in spring self-healed during summer.

Keywords: double Otta Seal; gravel roads; qualitative visual assessment of defects; soft (low viscosity) bitumen; soft asphalt; self-healing; sustainable technique

1. Introduction

According to the Lithuanian Road Administration under the Ministry of Transport and Communication (2015), in Lithuania, more than a third (33.9%) of state roads are gravel roads, and they cause low driving comfort, longer time of travel, faster vehicle amortization, and dustiness.

The control of dustiness is one of the most important maintenance activities on gravel roads. Vehicles travelling at a speed of 75 km/h on gravel roads with annual average daily traffic (AADT) equal to 100 vehicles per day (vpd), throw up about 25 tons of gravel wearing course aggregate annually, per kilometer [1]. This results in approximately 4 mm less thickness of the wearing course for a road 7 m in width [2]. Deficiency in the thickness of the wearing course leads to a corrugated road surface and faster pavement deterioration.

Furthermore, greater visibility is achieved when dustiness is controlled, thus increasing the safety of road users [3]. The less dustiness, the lower the rate of traffic accidents. It also results in lower costs related to vehicle repairs, medical expenses, and loss of life [4]. Dust particles penetrate into the engine and other mechanical components of vehicles, increasing vehicle wear, requiring more frequent maintenance, and hence resulting in higher vehicle operating costs [5,6]. Dust is also a health hazard because particles smaller than 10 μm accumulate in the human respiratory tract and cause allergies and asthma [7,8].

Typically, chemical dust suppressants, such as calcium or magnesium chloride and calcium lignosulphonate, are used to control dustiness. An analysis of the literature reveals that they might reduce dustiness by up to 80% and the total aggregate loss by up to 42–61% [9,10]. However, chemical dust suppressants usually enhance the corrosion of cars and often contain toxic ingredients that negatively influence vegetation and water life [11]. Moreover, their efficiency depends on the amount of precipitation. According to the Lithuanian Hydrometeorological Service under the Ministry of Environment (2013), in Lithuania, the average annual amount of precipitation varies from 600 mm to 900 mm. During the warm period, it varies from 400 mm to 500 mm. Hence, in Lithuania, using chemical dust suppressants to control dustiness is uneconomical, and control of dustiness remains a challenge [12].

Soft asphalt and Otta Seal technologies are a sustainable and economical solution to control dustiness on gravel roads [13–17]. Over the last decade, soft asphalt has been used on the low-volume roads of Nordic countries as it is less sensitive to frost heaves and fatigue, more flexible, and possesses self-healing abilities. Botswana, New Zealand, the United States (Minnesota), Norway, and Sweden, have already observed the benefits of Otta Seal, which can be constructed as a single layer or as double layers, and use it widely [18–22].

Soft asphalt and Otta Seal do not increase bearing capacity, but protect pavements from moisture infiltration and loss of aggregates, and improve driving conditions. Hence, soft asphalt and Otta Seal reduce the maintenance cost of gravel roads and ensure social satisfaction. From the viewpoint of dust minimization alone, these techniques reduce maintenance costs by more than 40% [21].

The suitability of soft asphalt and double Otta Seal for Lithuanian, low-volume gravel roads, was proven by Vaitkus et al. [23]. The main aim of this study is to show soft asphalt and double Otta Seal sustainability and ability to self-heal on the basis of the results of the qualitative visual assessment of pavement defects and distress. The novelty of this study is that these technologies are usually used in the construction of new pavement structures or the rehabilitation of old ones (the resistance of pavement structures to frost is ensured), but in this study, soft asphalt and double Otta Seal are used on the existing pavement structure and only a new unbound base course of crushed stones of 7–15 cm thickness is constructed (the pavement structure is susceptible to frost). Pavement structures that are not resistant to frost are prone to cracking and these cracks are instrumental in causing distress. Consequently, the pavement's ability to self-heal becomes a significant factor in ensuring the desirable performance of these types of pavement structures.

2. Test Road Sections

2.1. Soft Asphalt

In 2012, soft asphalt technology was used on five gravel road sections (Nos. 1716, 2430, 2518, 4028, and 5235; total length 7.39 km). On these road sections, AADT was less than 200 vpd, except on road no. 4028, where AADT was 640 vpd. The number of equivalent single axle loads (ESALs) was less than 0.1 million on all road sections.

The newly constructed pavement structure consisted of 4.5 cm of soft asphalt and a 15 cm unbound base layer of crushed stones. The bearing capacity of the base course had to be at least 120 MPa. If the thickness of the existing gravel pavement was lower than 35 cm, it was increased using unbound materials.

The soft asphalt SA 16-d-V6000 type C was used on the basis of the results of laboratory tests assessed by the Simple Additive Weighting (SAW) method [24,25]. The binder content varied from 4.6% (road No. 5235) to 5% (road No. 2430), air voids content varied from 5.5% (road No. 1716) to

6.9% (road No. 4028), and the indirect tensile strength ratio varied from 60% (road No. 1716) to 99.8% (road No. 2430). More information is given in [26].

2.2. Double Otta Seal

In 2012, double Otta Seal technology was used on the 13 gravel road sections (Nos. 1708, 1717, 4516(1), 4516(2), 3208, 4118, 1235, 2427, 3918, 4726, 5017, 2642, and 5123; total length 11.95 km). On these road sections, AADT was less than 300 vpd, except on road no. 3208, where AADT was 453 vpd. The number of ESALs was less than 0.1 million on all road sections.

Generally, Otta Seal consists of soft (low viscosity) binder sprayed on the surface, followed by the spreading and rolling of graded aggregates. The layer thickness is about 32 mm when double layers are constructed. On test road sections, double Otta Seal was constructed on the 7–10 cm newly constructed unbound base course of crushed stones. The bearing capacity of the base course had to be at least 120 MPa. If the thickness of the existing gravel pavement was lower than 30 cm, it was increased using unbound materials.

There were 0/16 fraction aggregates used, whose gradation limits are shown in Figure 1, and bitumen emulsion C60B1PA-V6000 or C60BF1-PA. The resistance to fragmentation, according to the impact resistance value (SZ), was ≤18, and the Los Angeles coefficient (LA) was ≤20. The recommended sprayed aggregate amount was 14 L/m^2, but it could be corrected according to the aggregate spread test results. Adhesive additives and primes were not used. More information is given in [23].

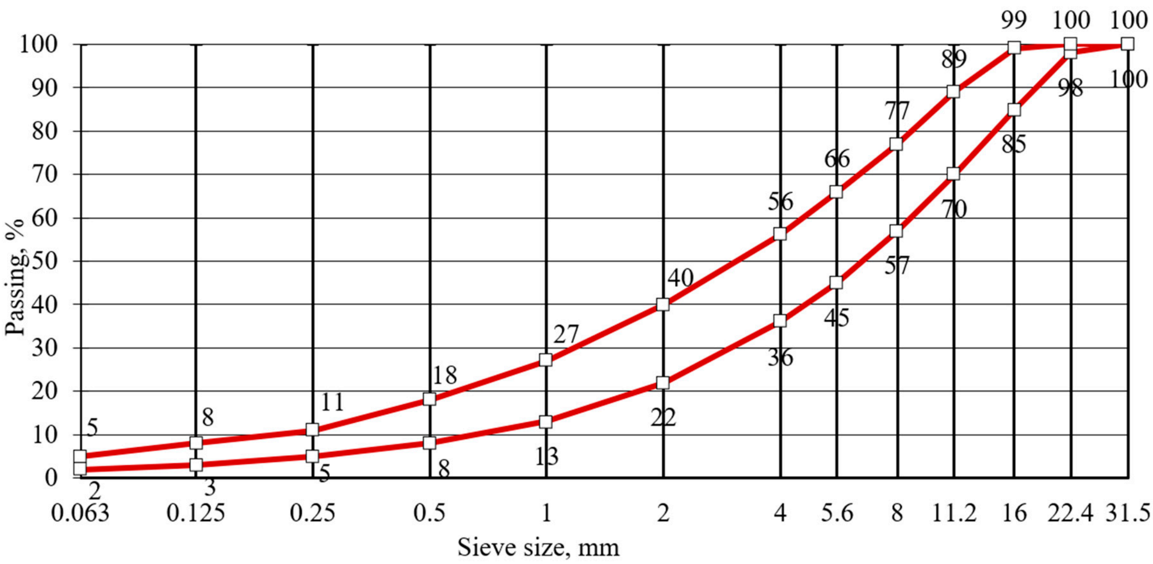

Figure 1. Aggregate gradation limits for double Otta Seal.

3. Research Methodology

In this study, the performance of soft asphalt and double Otta Seal was assessed on the basis of the results of the qualitative visual assessment of defects and distress. This assessment was carried out twice a year. The performance of the soft asphalt was determined in spring and summer. In summer, the qualitative visual assessment of defects and distress was carried out during the hottest period. The performance of double Otta Seal was determined in spring and autumn. In autumn 2016, the qualitative visual assessment of defects and distress on road sections covered with double Otta Seal, was not carried out.

In order to reveal soft asphalt and double Otta Seal's ability to self-heal, the focus was placed mainly on the length of longitudinal and transverse cracks, which are the main result of frost heaves and low temperatures during winter. The severity of longitudinal and transverse cracking was expressed in percentages, as the ratio of the length of the cracks to the length of the road section. The length of longitudinal and transverse cracks was measured with a distance wheel (Figure 2).

The severity of bleeding, potholes, raveling, and seals, was expressed in percentages and represents the distressed road section area.

Figure 2. Measurement of crack length with a distance wheel.

In order to show the sustainability of soft asphalt and double Otta Seal, a life cycle cost analysis was done. Gravel roads with chemical dust suppressants were not analyzed considering life cycle cost since they are less environmentally friendly and sustainable than bituminous materials. The reason is that gravel roads have a negative impact on the corrosion of cars, vegetation, and water life, and their effectiveness depends on the amount of precipitation [11,12]. All of these factors do not occur on roads with bituminous materials. Consequently, a life cycle analysis was conducted for soft asphalt, double Otta Seal, and asphalt concrete.

Dustiness was not directly measured on the test road sections since researchers have already shown that Otta Seal has similar dust emission levels to roads sealed with asphalt concrete (less than 5–10 g/m^2). Thus, bituminous materials on gravel roads reduce dustiness by 2–3 times or even more [21]. The exact soft asphalt and double Otta Seal effect on dustiness will be studied in future research.

4. Results and Discussion

4.1. Soft Asphalt

On road sections with soft asphalt, within five years of operation, longitudinal cracks, transverse cracks, bleeding, potholes, raveling, and seals, were observed. The extent of longitudinal cracks on each road section is shown in Figure 3. The most distressed road section was road no. 2430, where the average severity of longitudinal cracks was 10.00%. The maximum value of 24.10% and the lowest value of 2.16% on road no. 2430, were determined in summer 2016 and summer 2017, respectively. In summer 2013, the longitudinal cracks decreased by 62.98%. This reduction was a consequence of soft asphalt's ability to self-heal under high pavement temperatures. However, in summer 2014, longitudinal cracks showed lower self-healing than in the previous year (only 13.90%), and, in summer 2015, they did not change and even slightly increased (by 6.77%) in summer 2016. This happened because of a less warm summer in 2014, 2015, and 2016, than in 2013. In summer 2017, longitudinal cracks decreased by 87.23%, but the main reason was not soft-asphalt's ability to self-heal, since most of them were sealed during maintenance (Figure 4).

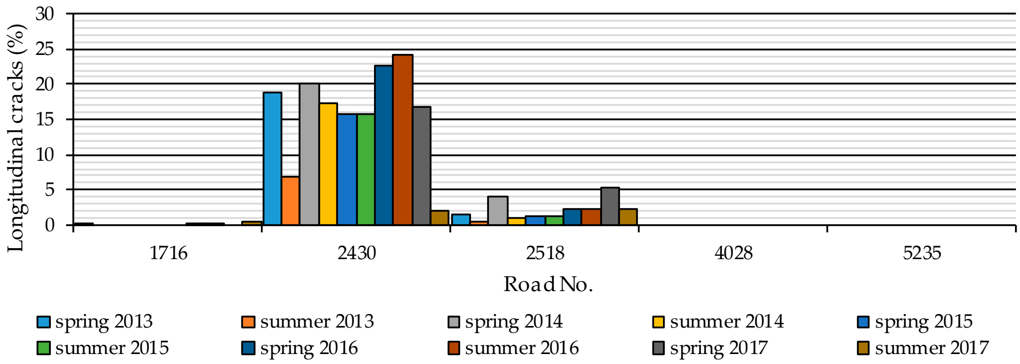

Figure 3. Longitudinal cracks on road sections covered with soft asphalt.

Figure 4. Sealed longitudinal cracks on road No. 2430 in summer 2017.

Similar tendencies for longitudinal crack development were observed on road No. 2518, where the maximum and the minimum values were 5.24% (spring 2017) and 0.39% (summer 2013), respectively. In summer 2013, 2014, and 2017, soft asphalt healed from 57% to 76% of longitudinal cracks. On road No. 1716, longitudinal cracks (0.07%) completely healed in summer 2013 and reappeared only in spring 2016 (0.35%). That summer, the length of longitudinal cracks neither increased nor decreased. However, it increased by 0.6% in summer 2017. On both roads (Nos. 4028 and 5235), longitudinal cracks had not yet formed.

The extent of transverse cracks on each road section is depicted in Figure 5. Transverse cracks appeared one year after soft asphalt construction (after winter 2013/2014). The most distressed road sections were roads No. 2430 and 2518 (Figure 6). The maximum value of 1.88% was determined on road No. 2518 in spring 2017. On this road, in 2014, 2016, and 2017, the length of transverse cracks decreased by 33–98% because of soft asphalt's ability to self-heal under high pavement temperatures. However, in summer 2015, twice as many transverse cracks were observed than in spring. This, as well as the tendency of longitudinal cracks to develop on road No. 2430, is strange because transverse cracks usually occur after winter and do not increase during summer. Sometimes, at high temperatures, they can disappear, but only if the wearing course has self-healing properties. On road No. 5235, transverse cracks (0.35%) completely healed in summer 2014 and reappeared only in spring 2016 (0.45%). That summer, the length of transverse cracks neither increased nor decreased. However, they almost doubled in length in spring 2017 and, in summer, decreased to their previous length (0.45%). On both roads (Nos. 1716 and 4028), transverse cracks had not yet formed.

An analysis of longitudinal and transverse cracks revealed the road sections that performed the best and the worst. Roads No. 1716, 4028, and 5235, were the most resistant to cracking (Figure 7), while roads No. 2430 and 2518 suffered from longitudinal and transverse cracking (Figures 4 and 6) independently of both AADT and ESALs. It was noticed that longitudinal cracking was 10 to 13 times more severe than transverse cracking. Fortunately, soft asphalt's ability to self-heal contributed to the slower development of both longitudinal and transverse cracks and led to lower pavement susceptibility to the frost heaves, fatigue, and low temperatures that directly influence pavement cracking.

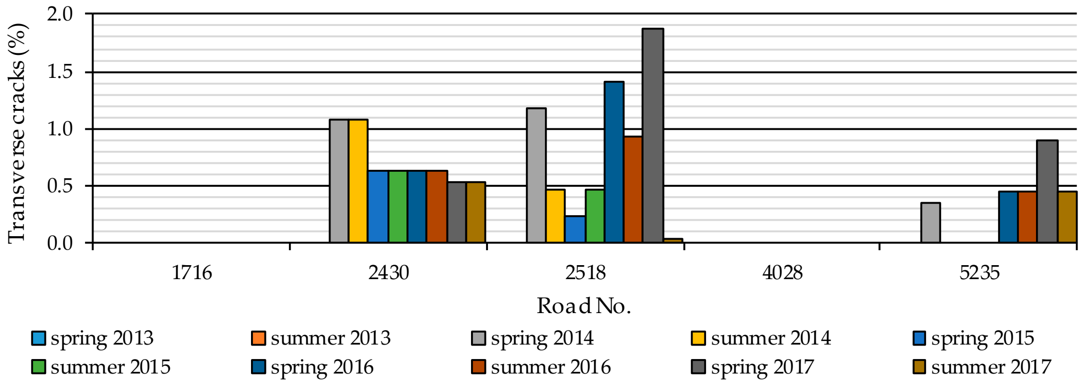

Figure 5. Transverse cracks on road sections covered with soft asphalt.

(**a**) (**b**) (**c**)

Figure 6. Transverse cracks on road sections covered with soft asphalt: (**a**) road No. 2430 in spring 2014; (**b**) road No. 2430 in spring 2016; (**c**) road No. 2518 in spring 2017.

(**a**) (**b**) (**c**)

Figure 7. Road sections that showed the best performance after 5 years of operation: (**a**) road No. 1716; (**b**) road No. 4028; (**c**) road No. 5235.

Bleeding, potholes, raveling, and seals are, at least, significant forms of distress. Only on road No. 1716 did bleeding reach up to 4%, while on all other roads it was less than 1%. Potholes, raveling, and seals on each road, at any season, were less than 0.5%.

4.2. Double Otta Seal

On road sections with double Otta Seal, within five years of operation, longitudinal cracks, transverse cracks, bleeding (especially in wheel paths), the loss of both binder and aggregates, and other small defects and distress, were observed. The extent of longitudinal cracks on each road section is shown in Figure 8. This distress was observed from spring 2014. The most distressed road sections were roads no. 1708, 4516(1), and 2642, where the average length of longitudinal cracks on each road, within five years of operation, was 24.62%, 11.83%, and 26.41%, respectively (Figure 9). The maximum value of 51.54% was determined in spring 2017 on road no. 1708. Such a huge development of longitudinal cracks occurred because of frost heaves and low bearing capacity during the spring thaw. On four roads (Nos. 4516(2), 3208, 1235, and 5123) the average length of longitudinal cracks within five years of operation varied from 1% to 7%. Other roads were not prone to the development of longitudinal cracks, because cracks appeared on less than 1% of road length. On some roads (e.g., Nos. 1708, 4516(1), 4516(2), 3208, 2427, 4726, and 5017), in autumn, fewer longitudinal cracks appeared than in spring because a soft bitumen was used for emulsion production, which resulted in pavement self-healing under high pavement temperatures, and thus some cracks healed during summer. However, some anomalies were observed on roads No. 1708, 3208, 2642, and 5123, in 2014 and 2015, since more longitudinal cracks were determined in autumn than in spring, which was unexpected.

The extent of transverse cracks on each road section is shown in Figure 10. This distress was observed from spring 2014. The most distressed road section was road no. 1235, where the average length of transverse cracks within five years of operation was 1.75% (Figure 11). It was emphasized that, on this road section, more than 85% less transverse cracks were determined in autumn than in spring. A similar tendency, of a decrease in transverse cracks, was also observed on other roads (e.g., Nos. 4516(1), 4516(2), 3208, 4726, and 5017). Hence, on the roads covered with double Otta Seal, transverse cracks self-healed under high pavement temperatures. The maximum value of 4.19% of transverse cracks was determined in spring 2014 on road No. 5017. Four roads (Nos. 1708, 1717, 2642, and 5123) were resistant to the development of transverse cracks, since within five years of operation no transverse cracks appeared. On other roads, the average of transverse cracks within five years of operation was less than 1%.

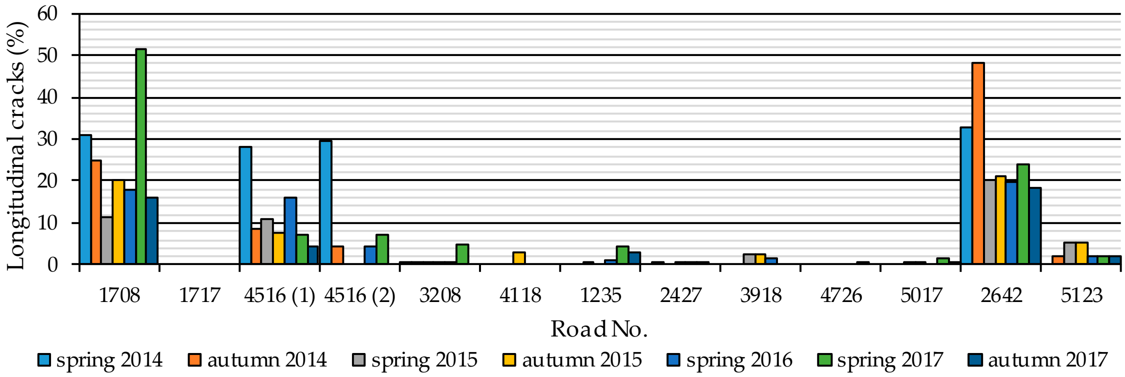

Figure 8. Longitudinal cracks on road sections covered with double Otta Seal.

(**a**) (**b**) (**c**)

Figure 9. Longitudinal cracks on road sections covered with double Otta Seal: (**a**) road No. 1708 in spring 2017; (**b**) road No. 4516(1) in spring 2014; (**c**) road No. 2642 in spring 2016.

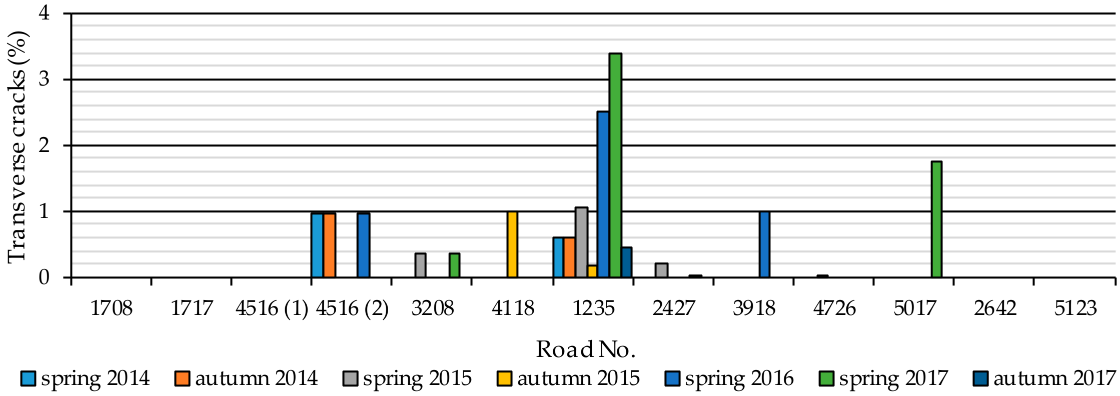

Figure 10. Transverse cracks on road sections covered with double Otta Seal.

(**a**) (**b**) (**c**)

Figure 11. Transverse cracks on road No. 1235: (**a**) in spring 2017; (**b**) in spring 2017; (**c**) in autumn 2017.

An analysis of longitudinal and transverse cracks revealed the road sections that performed the best and the worst. Roads No. 1717, 4118, 2427, 3918, 4726, and 5017, were the most resistant to cracking (Figure 12), since the average of both longitudinal and transverse cracks within five years of operation was less than 1%, while roads No. 1708, 4516(1), 1235, and 2642, suffered from longitudinal or transverse cracking (Figures 9 and 11). The severity of cracking did not depend on AADT and ESALs on test roads. It was noticed that longitudinal cracking was 12 to 25 times more severe than transverse cracking. Fortunately, double Otta Seal's ability to self-heal contributed to the slower development of both longitudinal and transverse cracks and led to lower pavement susceptibility to frost heaves, fatigue, and low temperatures.

(**a**) (**b**) (**c**)

Figure 12. Road sections that showed the best performance after 5 years of operation: (**a**) road No. 4118; (**b**) road No. 4726; (**c**) road No. 5017.

Qualitative visual assessments of defects and distress revealed that road sections covered with double Otta Seal tended to undergo bleeding (especially in wheel paths). The bleeding, loss of both binder and aggregates, and other small defects and distress, on each road section within three years of operation, are given in [23] and this tendency has not changed significantly.

4.3. Life Cycle Cost

Life cycle analysis for soft asphalt, double Otta Seal, and asphalt concrete, is given in [24]. This revealed that soft asphalt construction was up to 29% cheaper than asphalt concrete, while double Otta Seal saved 44% of asphalt concrete construction cost [24]. It should be noted that maintenance cost was not included in that analysis. However, the expected service life and the actual maintenance needs of the test road sections with soft asphalt and double Otta Seal showed positive results, especially for soft asphalt.

5. Conclusions

Soft asphalt and double Otta Seal can be termed as self-healing, sustainable techniques for low road rehabilitation. These technologies perform as standard asphalt pavements providing smooth, durable, and flexible surfaces, and greatly prolonging maintenance periods. The analysis of the qualitative visual assessments of pavement defects and distress during five years of road operation revealed the following:

- Longitudinal cracking was 10 to 25 times more severe than transverse cracking, depending on the technology (soft asphalt or double Otta Seal) and existing pavement structure composition. An adequate frost resistance of the whole pavement structure and bearing capacity of the base and subgrade (especially during the spring thaw), were vital for satisfactory pavement performance.
- Both technologies were able to self-heal during spring–summer. The healing effect was more than 13% and 19% on roads with soft asphalt and double Otta Seal, respectively. In addition, on some roads, all cracks observed in spring self-healed during summer.
- Three of five roads with soft asphalt (Nos. 1716, 4028, and 5235) and six of 13 roads with double Otta Seal (Nos. 1717, 4118, 2427, 3918, 4726, and 5017) were resistant to both longitudinal and transverse cracking (the average of cracking was less than 1%) independent of both AADT and ESALs. This might be related to the existing pavement structure composition and thickness, since during the design process, neither structure composition nor thickness were considered. Further evaluation and analysis of these factors will be conducted in future research.

The pavement condition of rehabilitated low-volume gravel roads after five years' operation confirmed the suitability of soft asphalt and double Otta Seal technologies for the improvement of gravel roads with annual average daily traffic of less than 300 vpd (except roads No. 3208 and 4028) and 0.1 million ESALs over a 20-year period.

Author Contributions: Audrius Vaitkus initiated the research, set objectives and led the study. Faustina Tuminienė and Judita Gražulytė carried out qualitative visual assessments of defects and distress on these roads. Donatas Čygas, Viktoras Vorobjovas, and Judita Gražulytė analyzed the results and wrote the manuscript. All of the authors contributed to the discussion, refined the final manuscript, and approved it.

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

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