Practical Application of Sustainable Road Structure: Mechanical and Environmental Approach

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Abstract: The principles of the circular economy are the basic determinants of the sustainable development of road construction. This paper presents a field study with a new concept of asphalt pavement structure with ecologically oriented attributes, significantly reducing the asphalt pavement carbon footprint while achieving a level of long-term performance comparable or greater than that of conventional pavement structures. The sustainable pavement consists of the introduction of a BIO-additive that allows for the integration of higher percentage of reclaimed asphalt pavement (RAP) as an alternative to the traditional asphalt mixtures. In the sub-base the use of construction and demolition waste was adopted. The results were obtained from a full-sized test section of the road structure divided for reference and eco-innovative cases. Mechanistic analyses were performed for materials and pavement structure based on laboratory tests and on-site assessment. The new eco-design solution was subjected to a comprehensive LCA and LCCA analysis and summarised by SWOT assessment.

Keywords: sustainable; road structure; RAP; BIO-additive; LCA; LCCA; SWOT

1. Introduction

Sustainable road construction is within the interest of both practitioners and researchers for past decades. The recently published NCHRP guidebook [1] summarizes current technical achievements and typical practices implemented in order to improve ecological footprint of road constructions. One should take into account that economic viability of innovative technical solutions has to be proved before they will be implemented in practice.

As stated by Huang et al. [2] in the paper dealing with greenhouse gas (GHG) emission monitored during road construction projects, several elements are found to contribute to the variation in CO₂: the technical standards of road (e.g., traffic, lane width), current structure condition (e.g., foundation, pavement), materials selection and construction technique as well as drainage and structures (type, number, etc.).

The construction of a road is an energy- and resource-intensive process, releasing large amounts of emissions to the environment and resulting in the depletion of natural resources. Therefore, road construction is a sector where measures need to be taken in order to reduce the energy demand and environmental impact, and, in particular, to reduce the use of raw materials with cost-effective measures. At present, potential measures with sound sustainability, including alternative binders, low temperature mixtures, the use of high rates of reclaimed asphalt (RAP) and a wide use of recycled materials, are not widely implemented, regulated, and harmonized within road construction and a wholesale shift to
use of these types of materials has yet to occur. A recent study by Manke [3] proved high performance in low, medium and high temperature of asphalt mixture with up to 50% or RAP and bio-origin binder.

Using waste materials in pavement construction will improve sustainability but one should take into account pavement durability, including moisture resistance. The long-term aging of asphalt will further reduce the moisture resistance of asphalt pavements. [4].

Another finding in the sustainable road technologies was presented by van de Ven [5] who proved that asphalt mixtures produced below 100 °C, the so-called half-warm foamed bitumen, are ecologically friendly and demonstrated high durability. According to the research presented by Iwański [6] optimization factors responsible for bitumen foaming process (pressure, bitumen temperature and water content) allow to reduce bitumen temperature retaining required foaming parameters. A rather untypical solution was presented by Zubaidy [7] where oil sludge was used to substitute part of the bituminous binder in the asphalt mixture incorporated up to 4% in asphalt mixture). A strengths, weaknesses, opportunities, and threats (SWOT) analysis was applied to assess asphalt mixture with crumb rubber [8]. The applied analysis underlined the environmental aspects of this technology, especially in the city areas.

In order to assess various technical solutions as more or less sustainable, the road life cycle should be taken into account. Moreover, not only construction but also maintenance techniques play a vital role in life cycle sustainability analysis. The sustainability of a developed road pavement can be assessed throughout the life cycle analysis (LCA) as well as life cycle cost analysis (LCCA). The LCA is an environmental assessment method, widely used in the construction and infrastructure projects, that allows to compare the environmental performance of the conventional (baseline) with alternatively developed scenario. The life cycle cost analysis allows to quantify the total costs occurred within the whole life cycle of a normalized 1 m² of road pavement. Although the LCA is a strong tool helping to increase the environmental effect of road construction, some highway agencies still do not take a full account of LCA implementation of road renovations projects [9].

Some researchers employed fuzzy logic expert systems for such assessment [10]. A complex study for assessing the sustainability of different types of asphalt mixtures and technologies was shown by Hamdar [11]. In this study performance, LCA and LCCA were combined for the assessment of warm mix asphalt (WMA) mixtures, with modified and unmodified binders. Another study assessing key sustainable parameters of asphalt mixtures was presented by Varma [12], where new and recycled materials used in road construction were assessed based on its performance and sustainability.

Complex mechanical and environmental approaches for the sustainable road structure are rarely visible in the literature. The main objective of this paper was to present a success story of practical application of sustainable road structure with in-depth field and laboratory verification.

2. Study Approach

Innovations such as those proposed in the EU funded APSE project (Use of eco-friendly materials for a new concept of Asphalt Pavements for a Sustainable Environment) are fully aligned with the transition towards a circular economy model in the road sector. In this project a new concept of asphalt pavement structure with ecologically oriented attributes, significantly reducing the asphalt pavement carbon footprint while achieving a level of long-term performance comparable or greater than that of conventional pavement structures was established [13]. The proposed pavement consists of the introduction of a BIO-additive that allows for the integration of higher percentage of RAP in the binder and base course as an alternative to the traditional asphalt mixtures. In the sub-base the use of construction and demolition waste (CDW) was adopted as an equivalent for virgin aggregates in order to protect natural resources and to reduce haul transport.

As a result of the project, a full-scale validation of the eco-innovative pavement was implemented in Poland. This paper focuses on the analysis of the mechanical and
environmental performance of the pavement, based on data obtained from the Polish trial
section. The eco-pavement performance under real climate conditions was carried out by
supervising the plant production, laydown procedure, and quality control throughout the
construction process and finally to monitor the eco-pavement. The aim of the study was
to provide technologies that facilitate the asphalt recycling, the use of waste and novel
greener binders, all integrated appropriately into an optimal and eco-innovative design of
asphalt pavements. Furthermore, an economic and SWOT analysis has been conducted
to validate the commercial viability. It was assumed that, from the technical point of
view, the eco-pavement could give as good performance as the traditional one and remain
economically and ecologically effective. The successful results of the study indicate that
the eco-pavement can be adopted for widespread application in the right situations.

3. Materials, Testing Methods and Trial Sections
3.1. Materials Characteristics

Considering the structure of an eco-friendly flexible pavement, three different ma-
terials and technology solutions were investigated for each layer. For the surface course,
an asphalt mixture containing an alternative binder was examined. Lignin, as an energy
production waste by-product, was used to partially replace crude-derived bitumen and
polymers (due to intellectual property right (IPR) protection details regarding physical and
chemical properties cannot be presented). For the binder and base courses, higher (30%)
than the typical maximum observed in Polish road practice (20%, based on the internal
project survey with construction companies) amount of reclaimed asphalt pavement (RAP)
was applied for the production of new asphalt mixtures in regular asphalt mix plants. A
typical asphalt plant without an extra RAP heating, such as double barrel system, was used.
The entire production process was conducted without the need for major capital expendi-
ture thanks to the use of a BIO-additive as an aid in the homogenization of the mixture.
RAP was considered as a “black rock” in the asphalt mixture. Only surface activation by
the incorporation of the BIO-additive without deep rejuvenation effect was assumed. The
lower sub-base layer was composed of recycled aggregates derived from construction and
demolition waste (CDW). Considering the equivalent compaction and load capacity of the
CDW sub-base layer in relation to the reference solution (limestone subbase), CDW as the
material was not mechanically tested in this study, but elastic modulus of its layer was
calculated on the basis of FWD tests, as presented later in the paper.

The main parts of the asphalt pavement structure are binder and base layers. The
composition and properties of these layers are shown in Table 1.

Table 1. Composition and properties of base and binder courses layers.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Base Course AC 22</th>
<th>Binder Course AC 22</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reference Mixture</td>
<td>Standard Section</td>
</tr>
<tr>
<td>RAP content, %</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Bitumen type</td>
<td>35/50</td>
<td>35/50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+2.5% BIO</td>
</tr>
<tr>
<td>Extracted binder, %</td>
<td>3.9</td>
<td>3.6</td>
</tr>
<tr>
<td>Bulk density, $\rho_b$ (Mg/m$^3$)</td>
<td>2.478</td>
<td>2.473</td>
</tr>
<tr>
<td>Maximum density, $\rho_m$ (Mg/m$^3$)</td>
<td>2.591</td>
<td>2.612</td>
</tr>
<tr>
<td>Air voids, $V_m$ (%)</td>
<td>4.4</td>
<td>5.3</td>
</tr>
<tr>
<td>Core air voids, %</td>
<td>—</td>
<td>5.0</td>
</tr>
</tbody>
</table>
In relation to the BIO-additive, dual-function agent was used in accordance with the technology described in previous works [14,15]. In this technology, it is assumed that in the first process stage liquefied bitumen with BIO origin additive occurs, which helps in homogenizing RAP in the asphalt mixture. When RAP is directly incorporated to the mixer, BIO-additive provides mixing and homogenizing support. In order to not reduce the binder’s stiffness too much, in BIO-additive there are oxy-polymerization reactions that rebuild and restore bitumen stiffness over time. An oxy-polymerization reaction occurs in the binder as a result of the action of siccative that activates the polymerisation process [16,17]. The reaction is time-limited and does not over stiffen the binder. The point is that, in mixtures where RAP bitumen is not activated or is only surface-activated to a small extent, this additive only supports the production process and does not long-term change the properties of the material.

3.2. Road Structure Trial Sections

The test section was located in the east-central part of Poland, 50 km south-west of Warsaw on a local city road. It consisted of two parts: the experimental section developed in the APSE project, located on the west part, and reference one, located on the east part of the road. This road has a medium traffic level (KR3), which means that the expected traffic during the service life period will be between 500,000 and 2,500,000 ESALs (equivalent standard axles loads)—KR is a Polish equivalent of ESALs traffic load-seven KR classes are observed in Poland.

The reference road section has the following structure, from surface to base layers: 5 cm of surface course (AC11—asphalt concrete 11), 6 cm of binder course (AC22), 7 cm of base course (AC22) and 20 cm of subbase with mechanically stabilized aggregates 0/31.5 mm (Figure 1). The APSE experimental road section has the same asphalt layers thickness as reference but exhibits some differences in materials composition (Figure 1b).

![Figure 1](image_url)

**Figure 1.** Structure of trial sections: (a) reference section and (b) APSE experimental section.

Both sections were only different in terms of the asphalt binder and base layers (30% RAP and BIO-additive used in the experimental section while only 20% RAP in the reference section) and subbase (CDW in the experimental section substituting virgin aggregates in the reference section). During the construction process, no technological differences between the experimental and the reference section were observed. Only visual differences could be seen on the sub-base layers (Figure 2a,b), however comparable compaction and load capacity of 160 MPa at the top of the layer were obtained. Upper layers e.g., base, binder, and wearing courses were visually the same (Figure 2c,d).
compaction and load capacity of 160 MPa at the top of the layer were obtained. Upper layers e.g., base, binder, and wearing courses were visually the same (Figure 2c,d).

Figure 2. Construction process: (a) APSE sub-base using CDW, (b) Reference sub-base using virgin aggregates, (c) compaction of reference binder course layer with 30% RAP, (d) paved APSE trial section.

During the project duration, the effectiveness of the asphalt was evaluated through all the phases, from early laboratory assessment to plant production, handling, application and post-trial evaluation. A direct comparison was made versus the reference asphalt mixes.

This validation will provide an opportunity to observe construction from start to finish and to record material property data, take samples, record observations through the construction, and monitor early-life performance. All analysis presented in this study lead to some recommendations for future applications, and to discuss whether new sustainable pavement concept is suitable for industry and asset managers.

3.3. Testing Methods

Fatigue and complex modulus tests were carried out by a four-point bending beam method (4PB) to estimate properties of asphalt concrete mixes used for base course layers. Beams were sawn from the bigger plates taken from constructed test sections. In the first step the base course layer was cut off from the rest of the structure and then a precise cut was made to the dimensions of $50 \times 63 \times 380$ mm. The complex modulus has been tested in accordance with the standard procedure (EN 12697-6, Annex B) at four temperature values ($0, 10, 20$ and $30$ °C) and at seven load frequency values ($0.5, 1, 2, 5, 8, 10$ and $15$ Hz).

The fatigue life was determined using the 4 PB test according to EN 12697-24 standard. Tests were performed at a constant strain mode (and different strain levels), at a frequency of 10 Hz and a temperature of 10 °C (typical testing conditions used in Poland).

Bearing capacity testing on the APSE section and the reference section was carried out using the Falling Weight Deflectometer (FWD) method. The test used a loading plate with a diameter of 300 mm and 9 sensors to measure the deflection bowl. A load of 50 kN was used, which caused a contact stress of 700 kPa. The measuring points were located every 25 m, on both sides of the carriageway. The FWD testing was conducted in September.
2017 and September 2018. Both the tests were carried out with the same measuring device. In terms of temperature, the differences were insignificant, however tests in 2017 were conducted at 14 °C, and in 2018 at 18 °C. Unfortunately, larger differences during this period were noted in terms of precipitation, which were at the multi-year average level in September 2018, and almost three times greater in 2017. The overall annual rainfall in 2017 was also 60% higher than in 2018. Such a large difference in precipitation could have had a significant impact on the results of the FWD tests. A higher water table and high sub-grade moisture lead to higher deflections of the pavement. According to the assumptions of the so-called deflection methods for the design of pavement reinforcements, it is related to lower fatigue life of the pavement structure. Higher deflections also mean lower stiffness of the layers, which results in higher values of strains in the structure and lower fatigue life assessed in the mechanistic pavement design. This assumption is verified later in this study.

Based on the pavement deflection curve developed with FWD and structural characteristics, stiffness modulus were calculated for road structural layers. Calculations were conducted with ELMOD6 software.

4. Mechanical Analysis
4.1. Laboratory Tests of the Complex Modulus and Fatigue Life

The results of the tests are presented in Figure 3 in the form of the master curves of the stiffness module E, the components of the complex modulus—the elastic part E1 and the viscous part E2, and the phase shift angle. The graphs shown indicate that both mixtures have similar rheological characteristics. The greatest differences in the stiffness modulus and the components of the complex modulus occur at low and medium reduced frequencies, which corresponds to high temperature conditions and/or long loading times. The reference mixture has a higher stiffness under such conditions, with very similar phase shift angle values. As a result, both the component of the elastic part and the viscous part of the complex modulus are greater than for the APSE mixture. As the temperature decreases and the frequency increases, the differences disappear, especially in the range of the values of the stiffness modulus and the elastic phase. The phase shift angle values are slightly higher under these conditions, which also results in a higher share of the viscous phase. According to the results of the complex modulus of the tested mixtures, it can be concluded that the APSE mixtures show lower stiffness, despite the higher reclaimed asphalt content which potentially stiffens the mixture. This is the result of a refreshing effect of the BIO-additive. Differences in the rheological properties of mixtures can affect their functional properties, such as resistance to permanent strains, cracking or fatigue life.

The analysis of fatigue life most often evaluates the $\epsilon_6$ parameter (eps6), which determines the strain under the fatigue test, during which the life of 1 million load cycles is obtained. A higher value means potentially better fatigue properties. Additional information is provided by the fatigue characteristic, which is described by the equation:

$$N = A \cdot \epsilon^b$$  \hspace{1cm} (1)

where: $N$—fatigue life, $\epsilon$—strain during fatigue test; $A$, $b$—linear regression parameters, and $b$ is the slope of the fatigue line. Moreover, the fatigue law was extrapolated to obtain fatigue endurance limit (FEL), which is defined as strain value in the fatigue test leading to 50 million cycles [18].
The use of refreshers, such as BIO-additive in the APSE mixture, is intended to reduce the risk of stiffening of the mixture. In this context, it can be assessed that the effect of the use of BIO-additive in the mixture is visible. Despite the higher reclaimed asphalt content, the APSE mixture is less stiff than the reference mixture and the fatigue resistance is slightly weaker despite the higher RAP content. The fatigue life test is not a testing method commonly used in Poland for asphalt concrete but is taken into account in scientific and research work. In the study presented by Sybilski & Bąkowski [22], the values of parameter $\varepsilon_6$ for AC 25 bituminous mixtures with 35/50 asphalt binder of various manufacturers and with different binder content ranged from 96 to 130 $\mu$m/m. In a recent study [23], the AC 22 35/50 achieved a score of 117 $\mu$m/m, while AC 22 P 50/70 the score of 108 $\mu$m/m, respectively. Taking the above into account, it can be concluded that the results

Figure 3. Master curves of the complex modulus and reference modulus of the APSE mixture.

The results of the fatigue tests are presented in Figures 4 and 5 in the form of graphs of fatigue characteristics and a comparison of the values of parameters $\varepsilon_6$ and FEL. In general, it can be concluded that the characteristics of the APSE and reference mixture are similar, showing a slightly better fatigue resistance for the reference mixture. Its fatigue characteristic line is shifted towards higher values. This results in differences in strain values $\varepsilon_6$ and FEL, where differences reach 10–20%, respectively. The fatigue life depends on many factors. In particular, considering the properties and composition of the bituminous mixture, the type of asphalt binder and its properties, as well as the content in the bituminous mixture and voids [19] are the main influencing factors. For the analysed mixtures, differences in their fatigue resistance may be due to at least two factors. The first is the use of the BIO-additive, which affects the properties of the asphalt binder. The second, probably the decisive factor, is the use of reclaimed asphalt pavement in a larger amount in the APSE mixture than in the reference mixture. Higher reclaimed asphalt content means more than all a larger amount of the “old” asphalt binder, which may have inferior properties associated with possible stiffening due to aging and fatigue processes. The increase in the share of reclaimed asphalt can affect the functional properties of the mixture. Fatigue life and crack resistance may deteriorate if stiffness is increased, while resistance to permanent strains may increase [20]. Naturally, the effect of the use of reclaimed asphalt can vary. It does not necessarily have to mean significant differences in functional properties [21]. It all depends on the properties of the reclaimed asphalt and other constituent materials. The use of refreshers, such as BIO-additive in the APSE mixture, is intended to reduce the risk of stiffening of the mixture. In this context, it can be assessed that the effect of the use of BIO-additive in the mixture is visible. Despite the higher reclaimed asphalt content, the APSE mixture is less stiff than the reference mixture and the fatigue resistance is slightly weaker despite the higher RAP content. The fatigue life test is not a testing method commonly used in Poland for asphalt concrete but is taken into account in scientific and research work. In the study presented by Sybilski & Bąkowski [22], the values of parameter $\varepsilon_6$ for AC 25 bituminous mixtures with 35/50 asphalt binder of various manufacturers and with different binder content ranged from 96 to 130 $\mu$m/m. In a recent study [23], the AC 22 35/50 achieved a score of 117 $\mu$m/m, while AC 22 P 50/70 the score of 108 $\mu$m/m, respectively. Taking the above into account, it can be concluded that the results
of fatigue life tested for the APSE mixture and the reference mixture remain at the level for the asphalt concrete for sub-bases using unmodified asphalt binder. This is extremely important because the fatigue life of the sub-base layer is crucial for the fatigue life of the entire structure. Therefore, it should be concluded that, on the one hand, the APSE mix is objectively characterized by a slightly weaker fatigue life. However, the obtained result allows to classify it at the level of typical mixtures for the base layers, which should be assessed positively in the context of the application of an increased amount of RAP.

![Fatigue Test Results](image1)

**Figure 4. Fatigue Test Results.**

![Comparison of fatigue strains (ε6 and FEL)](image2)

**Figure 5. Comparison of fatigue strains (ε6 and FEL).**
4.2. Loading Testing on Test Sections

On the basis of the FWD deflections and knowing the thickness of the structural layers, calculations of elastic modulus of layers with the back-calculation method were conducted using the ELMOD 6 software [24]. The structure was divided into a packet of bituminous layers, the sub-base and the sub-grade and the elastic moduli were marked as E1, E2 and E3, respectively. The modulus of the bituminous layers packet has been designed at 13 °C, which is the equivalent temperature used in the design of the pavements in Poland [25]. The results of the calculations are shown in Figure 6. A common feature of all pairs of measurements from the two years is the increase in stiffness after a year of service life of the road. This dependence can be justified by the extremely different rain conditions discussed above. While the increase in the sub-grade elastic modulus or mineral sub-base can be associated with differences in the moisture content of the layers, this is no longer so obvious in terms of the stiffness of the asphalt binder packet. This may be due to some shortcomings in the back-calculation method for determination of moduli. It is also worth noting that in the case of the APSE structure, the increase in stiffness is much greater, at about 40%, which can proof the longevity of the processes occurring in the mixture with the BIO-additive. The measurement in 2017 showed significantly higher stiffness of the asphalt binder packet in the reference section, while in 2018, the results remained at the same level. The comparison of the stiffness of the individual layers of the APSE structure and the reference structure does not allow for the indication of an unambiguous relationship. Taking into account the scattering of the results, it can be concluded that the differences are generally not statistically significant and thus the structures are comparable in terms of the stiffness of the layers.

Further parts of the study included an analysis of the fatigue life of the structure using mechanistic method. Mechanistic method of pavement designing stands on the evaluation of the pavement fatigue life on the basis of stress and strain field analysis. Pavement is considered as an elastic multilayer structure with defined thicknesses laying on an infinite half space. Each layer is described by: thickness, stiffness modulus and Poisson ratio. Horizontal elastic tensile strain in the bottom of asphalt layers and vertical compressive elastic strain at the top layer of the soil base were calculated. Evaluations of the strain field in pavement structure were conducted with NOAH 2.0 software with the following assumptions: single wheel load of 50 kN, contact pressure: \( q = 850 \text{ kPa} \) and equivalent temperature: 13 °C. Evaluations of asphalt layers fatigue life (\( N \)) were conducted using the AASHTO 2004 law:

\[
N_{asf} = 7.3557 \times 10^{-6} \times C \times k_1' \times (\varepsilon_t^{-3.9492}) \times E^{-1.281}
\]

where:

\[
C = 10^M
\]

\[
M = 4.84 + \left( \frac{V_b}{V_a + V_b} - 0.69 \right)
\]

\( N_{asf} \)—fatigue life, (number of equivalent standard axles),
\( \varepsilon_t \)—tensile strain, (\( \mu \)m/m),
\( E \)—stiffness modulus, (MPa),
\( V_b \)—asphalt content by volume, (\%v/v),
\( V_a \)—air voids, (\%v/v),
\( h_{ac} \)—total thickness of bituminous layers, (cm)
\( k_1' \)—parameter according to the formula:
Figure 6. Elastic modulus of pavement structure layers at the years 2017 and 2018: (a) $E_1$—Asphalt layers, (b) $E_2$—Sub-base, (c) $E_3$—Sub-grade.
\[ k_1' = \frac{1}{0.000398 + \frac{\varepsilon(11.02 - 1.374 \cdot hac)}{0.003602}} \]  

(5)

The criterion of subgrade strain according to the equation of the Asphalt Institute:

\[ \varepsilon_p = 0.0105 \cdot N_{gr}^{-0.223} \]  

(6)

where:

- \( N_{gr} \) — life, (number of equivalent standard axles),
- \( \varepsilon_p \) — subgrade strain, (\( \mu \text{m/m} \)).

The structure fatigue life \( N_{\text{min}} \) is the lowest of the \( N_{\text{asf}} \) and \( N_{gr} \) values. The volumetric properties of the sub-base were based on the results of the verification tests carried out during the construction of the sections. The obtained results of the elastic moduli are also characterized by quite large dispersions, so their statistical variability was taken into account in the mechanistic analysis. The calculation of the condition of strains in the road pavement structure in a probabilistic approach is a complex issue. The NOAH software uses the Rosenbluth method \([26]\). It consists of an approximation of the continuous distribution of probability by a discrete (three-point) distribution characterized by statistical moments such as, for example, the average, variance, etc. The result is a continuous beta distribution of the strain values of the structure. For the analysis, layer strains were used for the 95% probability level, which is typically used in calculations for the pavement structure designs. The results of the calculations are presented in Table 2. Differences in strain values based on FWD measurements in 2017 and 2018 are a consequence of the different elastic modulus values. The fatigue life of the reference structure is generally higher in all cases than the APSE structure. In the case of APSE structure, fatigue life is determined by the sub-grade criterion. The results obtained on the basis of tests in 2017 are much lower than in 2018, which is due to the previously discussed extremely unfavourable conditions in that period. Nevertheless, they are suitable for the traffic load category KR3 on this road. The results of measurements in 2018 allow classifying the load capacity of the structure in the higher traffic class KR4, which means the range of the number of axes of 100 kN over a period of 20 years from 2.5 to 7.3 million. It is also worth noting that the APSE structure is 2 cm thinner than the standard structure for the KR4 class according to the Polish catalogue for the design of asphalt pavements \([25]\). When assessing the APSE structure, it should be objectively stated that, on the one hand, the fatigue life of this structure is lower than that of the reference structure, but at the same time it successfully meets the requirement for desired traffic category.

Table 2. Strains and calculated life criteria for reference and experimental pavements.

<table>
<thead>
<tr>
<th>Strain, ( \mu \text{m/m} )</th>
<th>Pavement Structure and Year</th>
<th>Reference 2017</th>
<th>Reference 2018</th>
<th>Experimental 2017</th>
<th>Experimental 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon_a )</td>
<td></td>
<td>118.0</td>
<td>103.7</td>
<td>156.6</td>
<td>116.2</td>
</tr>
<tr>
<td>( \varepsilon_g )</td>
<td></td>
<td>385.0</td>
<td>333.5</td>
<td>484.2</td>
<td>376.3</td>
</tr>
<tr>
<td>Life criteria</td>
<td>Design life, mln of 100 kN Esals</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( N_a )</td>
<td></td>
<td>3.2</td>
<td>4.6</td>
<td>1.8</td>
<td>3.9</td>
</tr>
<tr>
<td>( N_g )</td>
<td></td>
<td>2.7</td>
<td>5.2</td>
<td>1.0</td>
<td>3.0</td>
</tr>
<tr>
<td>( N_{\text{min}} )</td>
<td></td>
<td>2.7</td>
<td>4.6</td>
<td>1.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>
5. Economic and Environmental Analysis

5.1. Environmental Approach

The environmental assessment of APSE pavement was performed using LCA approach. This study utilises the ReCiPe Midpoint characterisation method [27], developed by the University of Leiden, Netherlands and uses a combination of primary and secondary data sources. Whilst some primary data were readily available (e.g., mixtures design and their production) other data proved to be unobtainable due to concerns around confidentiality and loss of competitive advantage from the industry. Other sources of secondary data used include data sets from e.g., GaBi Databases [28], Eurobitume Report [29], ICE Carbon & Price book [30] and other peer reviewed sources. All data used for the purposes of analysis are representative for the European case, with minor exceptions due to lack of comprehensive data. The following nine stages of life cycle were considered for the purpose of this study: 1—material acquisition, 2—processing, 3—transport and storage, 4—asphalt production, 5—material transport to site, 6—construction, 7—service, 8—maintenance and 9—end of life.

Within the LCA, a normalized 1 m² of road pavement was assessed, comparing reference pavement with APSE alternative. The conventional pavement design included raw aggregates and 0% RAP content, as well as use of SBS polymers in the surface layer. The analysis was performed for “cradle to gate” and “cradle to grave” stages of pavement’s life cycle, considering 60 years of pavements life and under assumption of surface layer rehabilitation in years 15 and 45, as well as surface and binder layer replacement in year 30. The results of life cycle impact assessment (LCIA) are summarised in Figure 7.

The LCIA results indicate that on average APSE pavement can lead to savings in carbon emissions of 7.9 kg CO₂ eq/m² (14%), considering cradle to grave system boundaries, while in the context of cradle to gate, the savings can reach 8.8 kg CO₂ eq/m², while inclusion of RAP and BIO-additive in binder and base layers lead to 6% and 7.6% CO₂ eq. emissions reduction in binder and sub-base layers. The greatest savings were attributable to sub-base layer, where CDW substituted 100% of virgin aggregates.
5.2. Economic Analysis

The economic feasibility of developed APSE pavement has been assessed at a material level, as well as considering the environmental costs (costs of externalities), comparing the conventional flexible pavement structure with APSE pavement. As mentioned above, the APSE test sections were performed in Poland on a local medium-traffic level road. Given the exact geographical locations of this case study, the costs of the input materials, as well as national standards for pavement structures, the total costs of 1 m² of road pavement can slightly varies across other European countries. The economic feasibility of APSE pavement has been assessed following the methodology described in ISO standard [31]. The cost-effectiveness of innovative materials has been evaluated, comparing APSE pavement with conventional pavement. According to the international guidelines, the following four phases of pavement life cycle are investigated within the life cycle costing analysis (LCCA): 1—Construction, 2—Operation, 3—Maintenance & Rehabilitation and 4—End-of-life. Additionally, the environmental costs throughout the life cycle stages of pavement are quantified. As a functional unit in the study is chosen 1 m² of road structure. Therefore, the costs of 1 m² of road are compared across the pavement alternatives. The estimated costs throughout the life cycle of the pavement are discounted to the base year of the analysis to determine the Net Present Value (NPV) for the pavement alternatives. Based on the recommendations of European Commission [32], the discount rate selected within the scope of this analysis is 4%. The model developed in Excel by authors allows to quantify the construction costs of APSE and conventional road pavements and identify the cost-effective alternatives.

Based on the LCCA calculations performed, it was found that using 30% RAP with BIO-additive in binder- and base- layers implies up to 18% and 20% reduction in the costs of these layers. Moreover, the substitution of virgin aggregates with CDW reduces the cost of this layer by 67% (Figure 8).

![Figure 8. Materials costs of flexible pavement in Poland, total costs of 1 m² of conventional and apse road pavement.](image)

The total material costs during road production stage were approximately 30% lower, compared to baseline in Poland.

As part of the LCCA, the environmental costs of pavement structures were estimated by allocating shadow price on the environmental impacts quantified within the LCA. The
environmental costs of 1 m² of APSE pavement was estimated to be EUR 68.14, or 27% lower than of conventional pavement (with 0% RAP and virgin aggregates (Figure 9).

![Figure 9. Environmental costs of 1 m² of pavement structure.](image)

Considering the costs of materials, as well as environmental costs of externalities (based on the life cycle impact assessment results), it can be estimated that over 60 years of pavement’s life cycle, APSE concept can lead to 25% reduction in total costs, applying 4% discount rate (Figure 10).

![Figure 10. Total life cycle costs (in NPV) of pavement structures, considering costs of materials and costs of externalities.](image)
Nowadays, application of up to 20% of RAP directly to the mixer, in binder and base layers and use of CDW in sub-base becomes a common practice. The use of BIO-additive allows to increase the RAP content to 30% (without extra heating), thereby achieving approximately 4% reduction in the total costs of pavement structure.

5.3. SWOT Analysis and Market Outlook

The SWOT analysis (results presented in Table 3) summarised the strengths and weaknesses of the APSE products compared to conventional asphalt, while the Opportunities and Threats summarised the market prospects and competitive situation among the market players.

Table 3. SWOT analysis for sustainable road structure produced by using APSE products.

<table>
<thead>
<tr>
<th>INTERNAL</th>
<th>STRENGTHS</th>
<th>WEAKNESSES</th>
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<tbody>
<tr>
<td>BIO-additive</td>
<td>allowing for a higher RAP utilisation.</td>
<td>Relatively high price of BIO-additive due to the use of</td>
</tr>
<tr>
<td>APSE concept</td>
<td>a remarkable improved LCA profile compared to the conventional paving.</td>
<td>relatively high raw materials prices and processing costs.</td>
</tr>
<tr>
<td></td>
<td>APSE solution up to 25% cheaper than the conventional paving concept.</td>
<td>Market readiness of the green APSE road paving concept.</td>
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<td></td>
<td>The use of CDW supports implementation of the Waste Directive.</td>
<td>Agreement and availability of resources to go full in for the</td>
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<td></td>
<td></td>
<td>commercialisation of the APSE concept and/or individual KER (e.g., BIO-additive, CDW</td>
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<td></td>
<td></td>
<td>aggregates).</td>
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<tr>
<td></td>
<td></td>
<td>Very positive legislative drivers concerning the use of waste</td>
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<td></td>
<td></td>
<td>for secondary raw material, circular economy, etc.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(in Europe and US).</td>
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<tr>
<td></td>
<td></td>
<td>Market focus on LCA performance, high use of RAP and</td>
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<tr>
<td></td>
<td></td>
<td>recycling or aggregates (in Europe and US).</td>
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<td></td>
<td></td>
<td>High market demand for bitumen in Asian markets, where price could</td>
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<tr>
<td></td>
<td></td>
<td>become an issue which will benefit RAP usage.</td>
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<tr>
<td>EXTERNAL</td>
<td></td>
<td>Competing environmentally friendly road paving concepts,</td>
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<td></td>
<td></td>
<td>e.g., warm mix asphalt, noise reduction, other bitumen substitution solutions.</td>
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<td></td>
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<td>Continuation of the economic crisis in Europe, combined with declining demand for road</td>
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<td>transport due to swift between transport modes, e.g., freight to trails,</td>
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<td></td>
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<td>passengers to public transport. Green</td>
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<td>demands become less politically interesting.</td>
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<tr>
<td></td>
<td></td>
<td>Global recession slowing new infrastructure investments.</td>
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</tbody>
</table>

The potential market for the APSE exploitable results can be viewed from different angles. Firstly, we can regard the entire APSE green road pavement concept consisting of all layers from base layer, binder and surface layer. However, given the different lifecycles of the different layers, we could also regard the market potential for individual APSE components, e.g., lignin polymer modified bitumen (not applied in trial case), RAP + BIO-additive and CDW sub-base. Each of the APSE components would require very different market entrance strategies.

Another important dimension is the geographical scope. If we take the consumption of bitumen as an indicator for the overall demand for road construction globally, the European market constitutes around 10% of the global market, while large growth potential comes from Asian countries.

As far as RAP + BIO-additive and CDW are concerned for green solutions related to the binder layer, and base layer the individual solutions are less interesting as these are not unique to the market, only as part of the overall APSE concept these green solutions add value to the overall green profile of the asphalt concept.

The timing of the APSE road construction concept is optimal as there are strong “green” drivers supported by several EU directives, e.g., pressure to lower carbon footprint in both construction and maintenance, higher use of RAP, resource efficiency and lower energy use.

6. Conclusions

Reducing the negative impact of road construction to the environment should go hand in hand with ensuring a comparable fatigue life of new solutions compared to those currently used. Prior to the analysis it was hypothesised that the inclusion of recycled and novel materials, as those used in the APSE design, would result in a pavement with an
enhanced environmental profile. The results, both in terms of cradle to grave and cradle to site system boundaries, overwhelmingly indicate that recycling RAP and CDW in the bound and unbound courses, alongside using a BIO-additive to accommodate higher proportions of rejuvenated RAP, is environmentally advantageous across all mid-point impact categories. The environmental benefits associated with the additional processes of recycling, producing novel materials and their transportation, far outweigh the negative impacts they generate. It was confirmed in the study that addition of the BIO-additive allows for higher RAP content, those reducing virgin binder and aggregate without temperature increase, what influenced high sustainability to the highest extent.

Considering the fatigue life of the APSE and reference mixtures, it can be concluded that they exhibit characteristic level for the asphalt concrete for the sub-base with unmodified asphalt binder. This is important because the fatigue life of the sub-base layer is crucial for the fatigue life of the entire structure. In addition, it can be stated that the fatigue resistance of the APSE mixture remains at an appropriate level despite the use of 30% of RAP compared to the 20% of RAP in the reference mixture, which exhibits a little better fatigue characteristic. The fatigue life of the reference structure, measured on-site by the FWD, is generally higher than the APSE structure in all the scenarios. In the APSE structure, fatigue life is determined by the sub-grade criterion. The results of measurements in 2018 allow classifying the bearing capacity of the structure in the medium traffic category, which means the range of the number of axes of 100 kN over a period of 20 years from 2.5 to 7.3 million. It is also worth noting that the APSE structure is 2 cm thinner than the typical flexible structure recommended for this traffic category. This successfully proves the appropriate bearing capacity of this structure.

The APSE eco-pavement can be considered valid based on the results presented in this paper and confirms that this concept is suitable to reduce the environmental impact associated to the construction of roads, reduce the consumption of raw materials and energy and create a new model of pavement construction.

Author Contributions: Conceptualization, K.J.K. and J.B.K.; Methodology, K.J.K. and W.B.; Formal analysis, J.B.K.; Investigation, J.B.K. and B.H.A.; Data curation, W.B. and A.K.; Writing—original draft, K.J.K. and J.B.K.; Project administration, R.C.B.; Funding acquisition, R.C.B. All authors have read and agreed to the published version of the manuscript.

Funding: The research leading to these results received funding from the European Union’s Seventh Program for research, technological development, and demonstration under grant agreement No. 603862. This work was also supported by funds for science for years 2017–2021 granted by the Polish Ministry of Science and Higher Education to support international projects. This article reflects only the author’s views, and the European Union is not liable for any use that may be made of the information contained. The authors wish to express their gratitude to other partners of the consortium to make feasible the results presented in this paper.

Data Availability Statement: No extra information.

Acknowledgments: The authors would like to acknowledge Piotr Radziszewski and Michał Sarnowski for involvement and in-depth discussion.

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

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