

Article

The Influence of Synthetic Reinforcing Fibers on Selected Properties of Asphalt Mixtures for Surface and Binder Layers

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Abstract

Increasing traffic volumes, heavier axle loads, and the growing frequency of premature pavement distress pose major challenges for modern road infrastructure. In many regions, asphalt pavements experience early rutting, cracking, and moisture-induced damage, underscoring the need for improved material performance and longer service life. Reinforcing fibres are increasingly used to enhance asphalt mixture properties, with aramid fibres recognised for their superior mechanical and thermal stability. This study evaluates the effect of FlexForce (FF) fibres on the mechanical and fracture behaviour of two dense-graded asphalt concretes, AC 16 surf and AC 16 bin, produced with different binders and fibre dosages (0.02% and 0.04% by mixture weight). Laboratory tests, including indirect tensile strength ratio (ITSR), indirect tensile stiffness modulus (IT-CY), crack propagation resistance, and dynamic modulus measurements, were performed to assess moisture susceptibility, stiffness, and viscoelastic behaviour. The results showed that fibre addition had little effect on compactability and stiffness under standard conditions but improved temperature stability and stiffness at elevated temperatures, particularly when used with polymer-modified binders. Moisture resistance decreased slightly, while fracture performance improved moderately at intermediate temperatures. Overall, low fibre dosages (~0.02%) provided the most balanced performance, indicating that the mechanical benefits of aramid reinforcement depend strongly on binder rheology, temperature, and interfacial compatibility. These findings contribute to optimising fibre dosage and binder selection for aramid-reinforced asphalt layers in practice.

Keywords: pavement; asphalt concrete; reinforcement; synthetic fibre; aramid



Academic Editors: Baowen Lou, Agnar Johansen, Hannes Gräbe, Fernanda Bessa Ferreira and Bharadwaj R. K. Mantha

Received: 30 September 2025

Revised: 30 October 2025

Accepted: 5 November 2025

Published: 11 November 2025

Citation: Gallo, P.; Ben Ameer, A.; Valentin, J. The Influence of Synthetic Reinforcing Fibers on Selected Properties of Asphalt Mixtures for Surface and Binder Layers.

Infrastructures **2025**, *10*, 303.

<https://doi.org/10.3390/infrastructures10110303>

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1. Introduction

Bituminous mixtures remain the dominant paving material used in road infrastructure worldwide, with more than 90% of roads in Europe and the United States constructed using asphalt-based materials [1]. This widespread adoption is attributed to asphalt concrete's (AC) favourable properties, including surface smoothness, skid resistance, noise reduction, and structural flexibility. However, despite these advantages, asphalt pavements are increasingly susceptible to premature deterioration caused by growing traffic volumes, increased axle loads, environmental fluctuations (e.g., extreme temperatures and moisture), and the natural ageing of materials [2]. The long-term performance of asphalt pavements is closely linked to the quality of all structural layers, particularly the base course, which ensures overall stability, while the wearing and binder courses contribute to

surface durability and service life [3]. These layers must be resilient to various pavement distresses, including rutting, thermal and fatigue cracking, moisture damage, and freeze–thaw degradation. High-temperature conditions demand mixtures with high stiffness to minimise permanent deformation and to ensure the mixture’s stability by preventing binder drainage, while low-temperature conditions require sufficient flexibility to resist thermal induced cracking [3]. Moisture infiltration can accelerate damage in bituminous mixtures by weakening the adhesive bond at the aggregate–binder interface, reducing cohesion and promoting stripping, which is often reflected in lower indirect tensile strength ratios (ITSRs) [4–7]. In some cases, dissolved chemicals in the infiltrating water may react with susceptible aggregates, causing volumetric changes that further degrade the mixture. In parallel, oxidative ageing of bitumen reduces ductility and increases brittleness over time, further compromising performance [8].

To overcome these limitations, a broad range of modification strategies have been developed to enhance asphalt binder and mixture performance. These include the use of polymers [9,10], fibres [11,12], crumb rubber [13,14], plastics [15], nanomaterials [16], anti-stripping agents [17], and rejuvenators [18,19] introduced either via binder modification (wet method) or direct incorporation into the asphalt mixture (dry method). Among these, polymer modification is one of the most widely adopted strategies, particularly involving elastomers and plastomers. Plastomers improve binder stiffness at high temperatures but offer limited enhancement at low temperatures. In contrast, elastomers extend the binder’s viscoelastic range, significantly improving resistance to fatigue, permanent deformation, and low-temperature cracking [20–22]. The most used elastomer is styrene–butadiene–styrene (SBS), which has been shown to increase dynamic shear modulus and reduce phase angle, enhancing rutting resistance and thermal stability [23]. Other extensively studied additives include crumb rubber, obtained from recycled tyres, and natural asphalts, such as Trinidad Lake Asphalt and Gilsonite. These materials have been evaluated for their stiffening effects, environmental benefits, and compatibility with conventional bitumen [24–26]. In comparison, fibres have emerged as a particularly promising additive due to their multifunctional reinforcement potential.

Fibres can enhance the performance of hot mix asphalt (HMA) by creating a three-dimensional (3D) diffused structure which bridges microcracks, distributes tensile stresses, and improves structural integrity, particularly when synthetic or mineral fibres such as aramid, glass, or basalt are used [27]. Fibres’ size and level of interfacial adhesion between fibre and binder are crucial factors for sufficient stress transfer and effective operation. In contrast, cellulose fibres are primarily employed as stabilising additives to reduce binder draindown, especially in Stone Matrix Asphalt (SMA) and other mixtures with higher binder content but minimal contribution to mechanical reinforcement [12,28–30]. The effectiveness of fibre reinforcement depends on several factors, including fibre dosage, length, distribution, and the interaction with the bitumen matrix [31,32]. A wide variety of fibres have been used in asphalt reinforcement, including synthetic polymers (e.g., polypropylene, polyester), natural fibres (e.g., coconut, sisal, jute), and inorganic fibres such as glass, carbon, basalt, and steel [33–37]. Among these, aramid fibres have attracted significant attention for their exceptional tensile strength, thermal stability, fatigue resistance, and chemical inertness [3,38].

Aramid fibres are high-performance aromatic polyamides, composed of linear para-phenylene terephthalamide chains bonded by strong hydrogen bridges. This structure enables efficient stress transfer, resulting in high tensile strength, a high elastic modulus, and thermal stability. Compared to steel and glass fibres of the same weight, aramid fibres offer significantly better mechanical performance and are approximately 43% less dense than glass fibres. They retain their structural integrity under extreme conditions, with

a glass transition temperature (T_g) of up to 340 °C and thermal degradation beginning only at around 550 °C. They are also inherently non-flammable, with a limiting oxygen index (LOI) of 29, and exhibit low thermal expansion, abrasion resistance, and chemical inertness [39,40]. However, their relatively smooth surface morphology and low surface reactivity can limit bonding with bituminous binders. This challenge is often addressed through surface treatments, such as paraffin wax coatings, which improve fibre dispersion and binder adhesion during mixing [41]. When incorporated into asphalt mixtures, aramid fibres act as 3D micro-reinforcement, uniformly distributing stresses and enhancing resistance to deformation and cracking. Their addition has shown to improve indirect tensile strength, resilient and dynamic moduli, rutting resistance, and fatigue life, especially under high-strain and variable temperature conditions [42–46]. For example, Klinsky et al. demonstrated that incorporating only 0.05% aramid fibre increased the resilient modulus by 15% and the dynamic modulus by 30% [46]. Specialised variants such as aramid pulp fibres have demonstrated strong performance in low-temperature cracking resistance and freeze–thaw durability [47,48], while longer fibres (e.g., 38 mm) have been associated with lower failure temperatures in cold-climate applications [49]. Hybrid fibres, such as polyolefin–aramid blends, have also shown synergistic improvements in rutting and fatigue performance under sub-zero conditions [50]. Despite these advantages, some studies have noted a slight reduction in moisture and frost resistance, indicated by decreased indirect tensile strength ratio (ITSR) values relative to unmodified mixes [46].

A commercially available synthetic fibre product was selected for this study. It is a specifically engineered product for asphalt reinforcement which consists of 30% by weight of aramid fibres and 70% of polypropylene fibres. These short-cut 19 mm staple fibres are designed to improve tensile strength, cohesion, and crack resistance without negatively impacting workability. Despite promising experimental results, the overall performance of aramid fibres, especially at low dosages and across different mixture types, remains underexplored. There is a lack of comparative studies assessing their effects in both surface/wearing course asphalt mixtures (we selected an asphalt concrete mix type which is, in Czech standards, defined as ACO 16+, i.e., asphalt concrete for surface pavement layers with NMAS 16 mm and use on pavements with standard traffic loading) and binder course asphalt mixtures (we selected an asphalt concrete mix type which is, in Czech standards, defined as ACL 16S, i.e., superior asphalt concrete for binder pavement layers with NMAS 16 mm and use on pavements with very high traffic loading) under consistent laboratory conditions.

This study directly addresses that gap by providing a controlled comparison of aramid fibre reinforcement in surface and binder course asphalt concretes produced and tested under identical laboratory conditions. By analysing the influence of fibre dosage, binder type, and mixture function, it provides new insight into the mechanisms governing fibre performance and its practical applicability in multilayer pavement systems.

The present study investigates the influence of FlexForce (FF) aramid and polypropylene (PP) fibres on the empirical and functional performance of two asphalt mixtures: ACO 16+ (AC 16 surf) and ACL 16S (AC 16 bin). Performance was evaluated using standard tests for air-void content, compaction behaviour, indirect tensile strength, moisture susceptibility, stiffness modulus, crack propagation resistance, and resistance to permanent deformation (by using a wheel tracking test). The aim is to determine whether synthetic fibre reinforcement enhances mixture performance and to evaluate how its effects vary by mixture type and binder characteristics. Aramid fibre reinforcement can contribute to pavement sustainability by improving mechanical performance and durability, which extends service life, reduces the frequency of maintenance interventions, and lowers the long-term consumption of materials and energy. Laboratory evaluations have shown that

asphalt mixtures reinforced with aramid synthetic fibres exhibit substantial gains in mechanical performance, with fatigue life improvements ranging from approximately 90% to 200%, depending on strain levels and mixture conditions [45,47]. Similar results have been reported for mixtures modified with short or pulp aramid fibres, which demonstrated enhanced durability and reduced cracking under fatigue and freeze–thaw loading [38,47]. Additional studies using hybrid fibres containing aramid combined with polyolefin or polypropylene also confirmed improved fatigue behaviour and overall mixture stability [46,49]. Comprehensive synthesis reports and selected field evaluations further indicate that fibre-modified pavements, including those reinforced with aramid-based fibres, tend to maintain surface integrity longer and require less frequent maintenance, thereby reducing rehabilitation demand over time [41,51]. From an environmental perspective, one cradle-to-grave life-cycle assessment (LCA) reported that assuming a 20% increase in time to first intervention due to aramid fibre inclusion resulted in about a 10% reduction in overall life-cycle greenhouse gas emissions [52]. These performance and durability improvements translate to extended pavement service life, reduced material and energy consumption, and lower maintenance expenditures, collectively supporting the economic and societal sustainability of road infrastructure. This work therefore adds to the growing body of research on high-performance, fibre-modified asphalt pavement technologies with potential life-cycle benefits.

2. Materials and Methods

2.1. Fibres

To enhance the mechanical performance of asphalt mixtures—particularly the ability to transfer tensile stresses effectively, reinforcing materials must exhibit the following characteristics:

- High tensile strength;
- High modulus of elasticity;
- Surface properties conducive to efficient stress transfer at the matrix–fibre interface.

Aramid fibres were the first organic (industrially manufactured) fibres used to reinforce advanced composites, offering both high tensile strength and elastic modulus. FlexForce fibres used in this study are a product of CIUR a.s., Brandýs nad Labem-Stará Boleslav, Czechia.

The values from Table 1 confirm the excellent strength, stiffness, and density-related advantages of aramid fibres.

Table 1. Selected physical and mechanical properties of synthetic fibres.

Trade Name	Polymer	Fibre Type	Density (g/cm ³)	Tensile Strength (GPa)	Elongation at Break (%)	Modulus of Elasticity (GPa)
Kevlar [40]	PPTA	K-29	1.44	2.90	3.60	71.00
Twaron [40]	PPTA	K-49	1.44	3.00	2.40	112.00
Technora [40]	ODA/PPTA	Standard	1.44	2.90	3.60	70.00
Nomex [40]	MPDI	Standard	1.39	3.40	4.60	72.00
FlexForce (aramid)	PPTA	Standard	1.44	3.15	3.65	86.00
FlexForce (polypropylene)	PP	Standard	0.91	0.2–0.5	-	-

Figure 1 shows a microscopic image of short staple para-aramid fibres. The fibre surfaces appear generally smooth, with fine longitudinal striations formed during the spinning process. Although structurally stable, this surface morphology may limit mechanical interlock and reduce the efficiency of stress transfer at the matrix–fibre interface. Chemically, aramid fibres are highly inert and possess few reactive functional groups, which may further hinder interfacial bonding unless suitable surface treatments are applied. The molecular architecture of aramid fibres is depicted in Figure 2. In this study, FlexForce aramid and polypropylene fibres were used to reinforce bituminous mixtures.

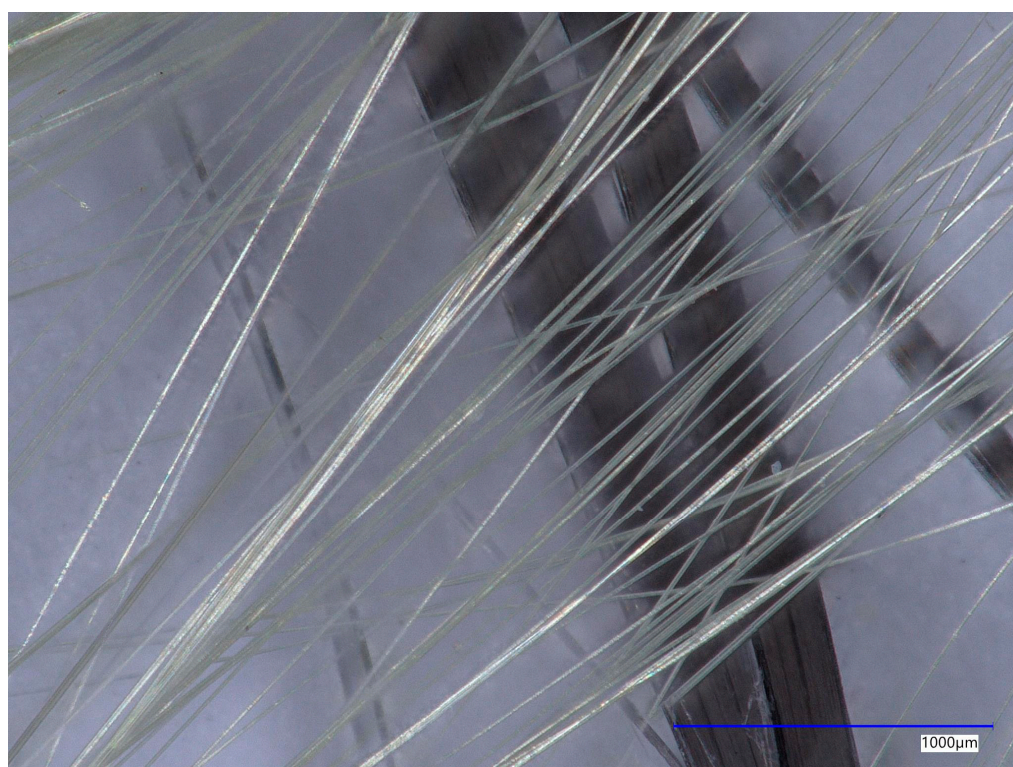


Figure 1. Microscopic image of staple FlexForce aramid fibres (white/silver) and polypropylene fibres (black).

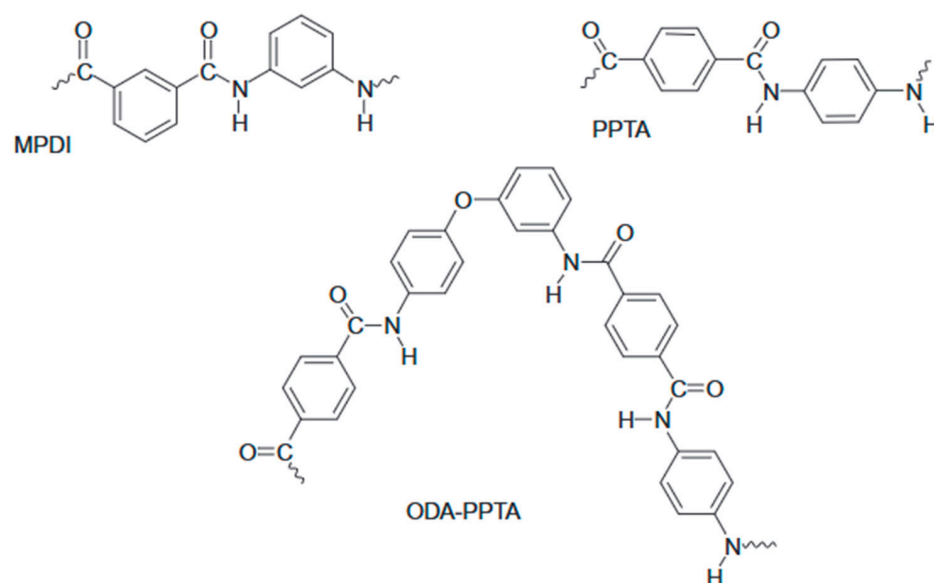


Figure 2. Representation of Aramid Polymer Molecules [40].

2.2. Bitumen Mixtures

The influence of FF fibres on asphalt performance was assessed on two dense-graded asphalt concrete mixtures with a nominal maximum aggregate size of 16 mm. According to Czech standard ČSN 73 6121:2023 [53], these correspond to AC 16 surf (ACO 16+), used for surface courses, and AC 16 bin (ACL 16S), used for binder courses. Each mixture type was produced in three variants, as summarised in Table 2. For mixtures containing polymer-modified bitumen (PMB), mixing and compaction were performed at 160 °C, while those with conventional 50/70 bitumen were processed at 150 °C. The bituminous binders used were 5.4% PMB 45/80-75 and conventional 50/70 for the surface mixture (AC 16 surf) and 4.7% PMB 25/55-60 for the binder mixture (AC 16 bin). Both polymer-modified binders were SBS-modified bitumen (styrene–butadiene–styrene) conforming to ČSN EN 14023 [54]. Binder selection was based on the functional role of each layer and its associated performance demands. Therefore, it was possible to evaluate the theoretical benefits of aramid fibre reinforcement with different types of bitumen and observe how much they could improve the mechanical properties of a mixture with conventional 50/70 bitumen. If the selected characteristics of mechanical properties would be close to a mixture with PMB, then it could be an economical option for some applications.

Laboratory specimens were prepared in accordance with ČSN EN 12697-30 [55]. For each mixture, six Marshall specimens were compacted as required by the product standard ČSN 73 6121:2023:

- AC 16 surf (ACO 16+): 2 × 50 blows at 150 °C for used paving grade bitumen and 160 °C for used PMB;
- AC 16 bin (ACL 16S): 2 × 75 blows at 160 °C, only PMB was used.

In addition, nine specimens per variant were compacted using 2 × 25 blows for moisture susceptibility testing (ITSR). For the wheel tracking and flexural strength tests, two slabs per mixture were prepared with a thickness of 60 mm and base dimensions of 320 × 260 mm. Beams were subsequently extracted and tested at 0 °C in accordance with ČSN 73 6120 [56]. All mixtures were designed to meet the requirements of ČSN 73 6121:2023.

Table 2. Composition and description of the asphalt mixtures tested. Mixture nomenclature follows EN 13108-1 [57] (Asphalt Concrete–AC), with Czech designations (ACO 16+ and ACL 16S) shown in parentheses for reference.

Mix ID	Mixture Type	Binder	Additive
Mix 1	AC 16 surf/ACO 16+	PMB 45/80-75	–
Mix 2			0.02% FlexForce (FF)
Mix 3		50/70	0.04% FlexForce (FF)
Mix 4	AC 16 bin/ACL 16S	PMB 25/55-60	–
Mix 5			0.02% FlexForce (FF)
Mix 6			0.04% FlexForce (FF)

The aggregate curves of both mixtures, AC 16 surf and AC 16 bin, are presented in Figures 3 and 4. The aggregate skeleton comprises coarse (8/11 mm), medium (4/8 mm), and fine (0/4 mm) crushed aggregates, selected to achieve optimal gradation, interlock, and load distribution. The aggregates were sourced at Bělice quarry (chert as a metamorphosed rock of the Central Bohemian Pluton). The mineral filler, consisting of finely ground lime-

stone (0/0.125 mm) from Velke Hydčice quarry, contributes to improved binder adhesion, mastic stiffening, and enhanced volumetric stability.

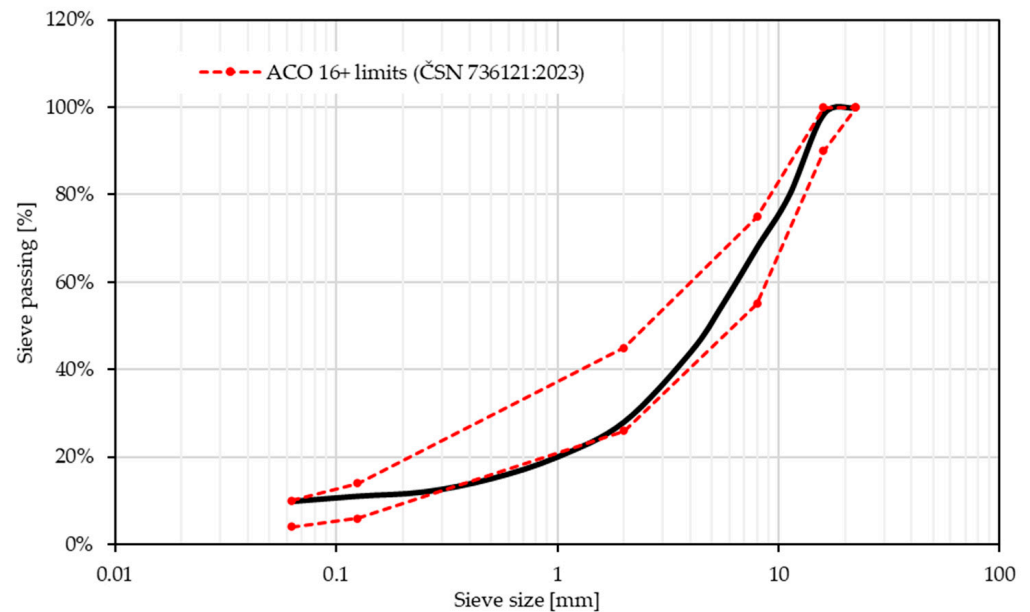


Figure 3. Gradation curve (black line) of the dense-graded asphalt concrete for the surface course (AC surf 16, standard's [53] designation ACO 16+)—Mix 1, 2 and 3.

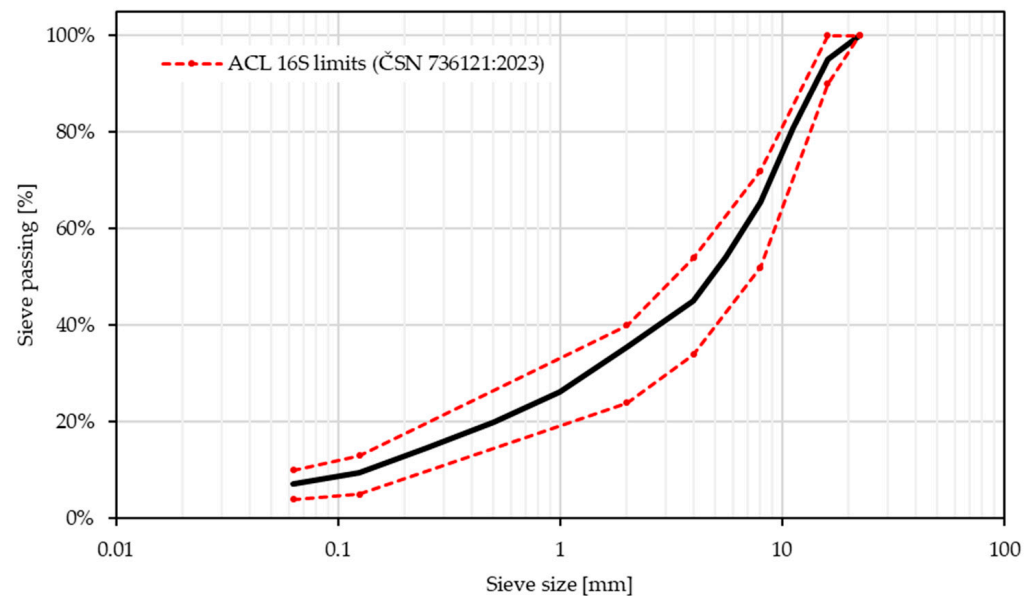


Figure 4. Gradation curve (black line) of the dense-graded asphalt concrete for the binder course (AC bin 16, standard's [53] designation ACL 16S)—Mix 4, 5 and 6.

FF fibres were incorporated at dosages of 0.02% or 0.04% by weight of the mixture. Dosage was recommended by a manufacturer. These high-strength, heat-resistant fibres act as micro-reinforcement elements within the mastic, enhancing tensile strength and distributing stresses more evenly across the aggregate skeleton. By bridging microcracks, they limit crack initiation and propagation under repeated loading. In addition, the fibres form a three-dimensional network within the mix, increasing binder viscosity locally and physically anchoring it to the aggregate surfaces. The fibres were added to the preheated aggregates during dry mixing to promote uniform dispersion, which was visually con-

firmed during mixing and specimen preparation All mixtures were designed to meet the volumetric and mechanical criteria specified in ČSN 73 6121:2023 [53].

2.3. Testing Methodology

2.3.1. Air Void and Compactability

The bulk density and air-void content of the Marshall specimens were determined according to the ČSN EN 12697-8 [58] and the ČSN EN 12697-6 [59] (Method B). Compactability was evaluated based on whether the air-void content of each mixture variant fell within the permissible limits specified in ČSN 73 6121:2023. This parameter provides valuable insight into the mixture's ability to achieve sufficient field compaction and internal stability.

2.3.2. Indirect Tensile Strength (ITS) and Moisture Susceptibility (ITSR)

The indirect tensile strength test was conducted in accordance with ČSN EN 12697-23 [60] to evaluate the tensile performance of the asphalt mixtures under quasi-static loading. The specimens were conditioned to a testing temperature of 15 °C and subjected to diametral loading at a constant deformation rate 50 mm/min. The ITS values were used to assess the reinforcing effect of synthetic fibres under dry and wet conditions. To determine the indirect tensile strength ratio (ITSR), which characterises the moisture susceptibility of the asphalt mixtures, testing followed the procedure specified in ČSN EN 12697-12 [61]. The specimens were divided into two groups: dry-conditioned and moisture-conditioned (via water bath at 40 °C for 72 h). Additionally, a modified procedure incorporating a single freeze–thaw cycle was applied, based on the AASHTO T283 protocol, as part of long-standing methodology used by FCE CTU in Prague. The combined use of both standards enabled evaluation under two levels of conditioning severity, ČSN EN 12697-12 for standard European conditions and AASHTO T283 for more demanding scenarios, ensuring broader comparability of results. The ITSR was determined by calculating the ratio of wet to dry ITS values and subsequently evaluating it against the minimum threshold of 80% as given by ČSN 73 6121:2023.

2.3.3. Stiffness (IT-CY)

The stiffness modulus was determined using the indirect tensile test on cylindrical specimens (IT-CY) under repeated loading, in accordance with the ČSN EN 12697-26 [62] (Annex C). Testing was performed at three temperatures typical for the environmental conditions in Czechia (0 °C, 15 °C, and 27 °C) to assess the thermal sensitivity and viscoelastic behaviour of each mixture variant. The test involved cyclic diametral loading with rest intervals between pulses to simulate traffic-induced loading conditions.

2.3.4. Crack Propagation Resistance (SCB Test)

The Semi-Circular Bending (SCB) test was performed to assess the crack propagation resistance of the mixtures, following the principles of ČSN EN 12697-44 [63] with a modified protocol used at the FCE CTU Prague [64,65], expanding upon the standard EN 12697-44 procedure. Semi-circular specimens with a notch were loaded at 0 °C and 15 °C, and the resulting force–displacement data were used to calculate fracture energy (G_f) [53,56] and two derived indices:

- Flexibility Index ($FI = G_f/m$) [66]
- Crack Resistance Index ($CRI = G_f/F_{max}$) [67]

where m is the post-peak slope of the force–displacement curve and F_{max} is the peak load.

2.3.5. Resistance to Permanent Deformation (Wheel Tracking Test)

The resistance of asphalt mixtures to permanent deformation (rutting) was evaluated using a small-size wheel tracking device in accordance with ČSN EN 12697-22 [68]. Testing was performed at 50 °C for mixtures with conventional 50/70 binder and at 60 °C for those incorporating polymer-modified binders (PMBs) in the case of AC surf 16 mixtures, while AC bin 16 mixtures were tested at 50 °C as specified for the binder courses. Test slabs were prepared with a thickness of 60 mm.

2.3.6. Dynamic Modulus (4-Point Bending Test)

The dynamic modulus ($|E^*|$) of the asphalt mixtures was determined using the 4-point bending test on prismatic beams, in accordance with ČSN EN 12697-26 [62] (Annex B). This test provides detailed insight into the viscoelastic behaviour of asphalt mixtures under repeated flexural loading, simulating real traffic-induced conditions. The test was performed at four temperatures: 0 °C, 10 °C, 20 °C, and 30 °C, with a sinusoidal loading pattern applied at controlled frequencies. The resulting stress–strain data were used to calculate the complex modulus ($|E^*|$) at each temperature, offering a performance profile over a representative temperature range. This method complements the IT-CY test by capturing mixture response in beam configuration and under continuous cyclic loading.

The test was conducted at four temperatures, 0 °C, 10 °C, 20 °C, and 30 °C, and at eleven selected load frequencies: 50, 30, 20, 15, 10, 8, 5, 3, 2, 1, and 0.1 Hz. A haversine load waveform was used to induce the target strain amplitude of 50 microstrains. The measured values of the dynamic modulus ($|E^*|$) at each temperature were used to plot isothermal curves, which were then horizontally shifted using the time–temperature superposition principle. This procedure produced a single smooth control curve that represents the viscoelastic behaviour of the material over a wide range of loading times (frequencies) and temperatures. Master curves for all mixtures were constructed for a reference temperature of 20 °C using the time–temperature superposition principle. The dynamic modulus standard $|E^*|$ represents the stiffness of the material, which is a tool to better understand the load distribution on the pavement structure. In contrast, the phase angle (δ) indicates the relative balance between elastic and viscous response and reflects the resistance of the mixture to permanent deformation under cyclic loading.

The low-temperature (high-frequency) region is defined as above 1000 Hz on the horizontal axis, the medium temperature region is between 1 and 1000 Hz and the high-temperature (low-frequency) region starts below 1 Hz.

3. Results

To evaluate the empirical and functional performance of asphalt mixtures modified with FlexForce fibres, a comprehensive series of laboratory tests was conducted. All testing procedures were performed in accordance with European and Czech technical standards to ensure consistency, repeatability, and relevance to real-world pavement performance.

3.1. Air Void and Compactability

As shown in Figure 5, only one mix variant of AC bin 16 complied with the standard limits. Mixes 1 and 2 containing 0.02% FF fibres failed to meet the compactability requirement, with Mix 2 even exhibiting the air-void content at approximately 1.2% higher than Mix 1. In contrast, Mix 3, which contained 0.04% fibres and 50/70 binder, met the standard limits and demonstrated the best performance in terms of compactability.

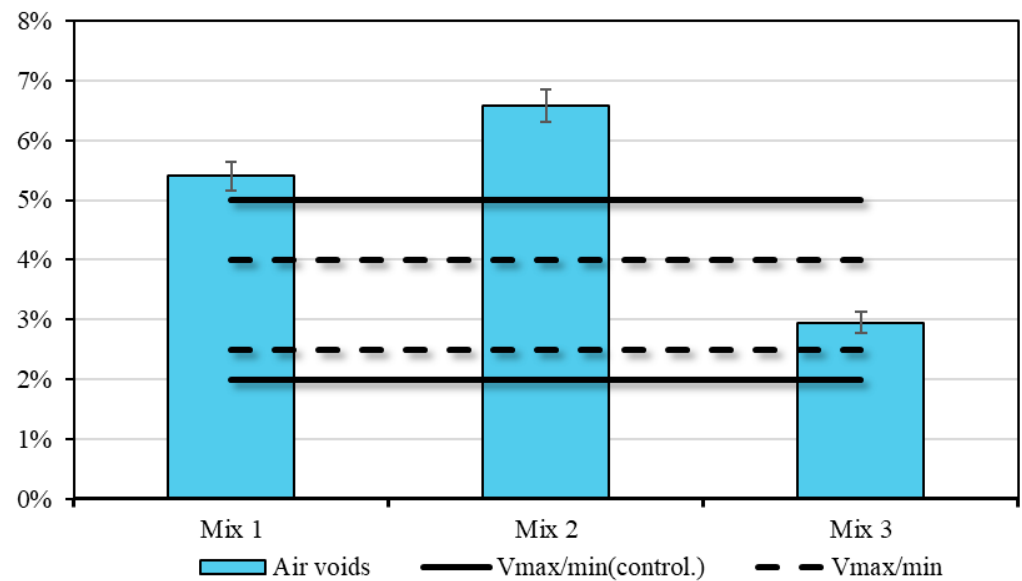


Figure 5. Air-void content of dense-graded asphalt concrete for the surface course (AC 16 surf). The dashed horizontal lines indicate the type-testing limit criteria, and the solid black lines indicate control limits according to ČSN 73 6121:2023 [53].

Figure 6 illustrates the air-void content of the AC 16 bin mixtures. All variants slightly exceeded the minimal limit defined in ČSN 73 6121:2023 [53]. Notably, the addition of FlexForce fibres did not affect the compactability of these base course mixtures. These findings highlight the importance of mixture composition and binder type when applying fibre reinforcement.

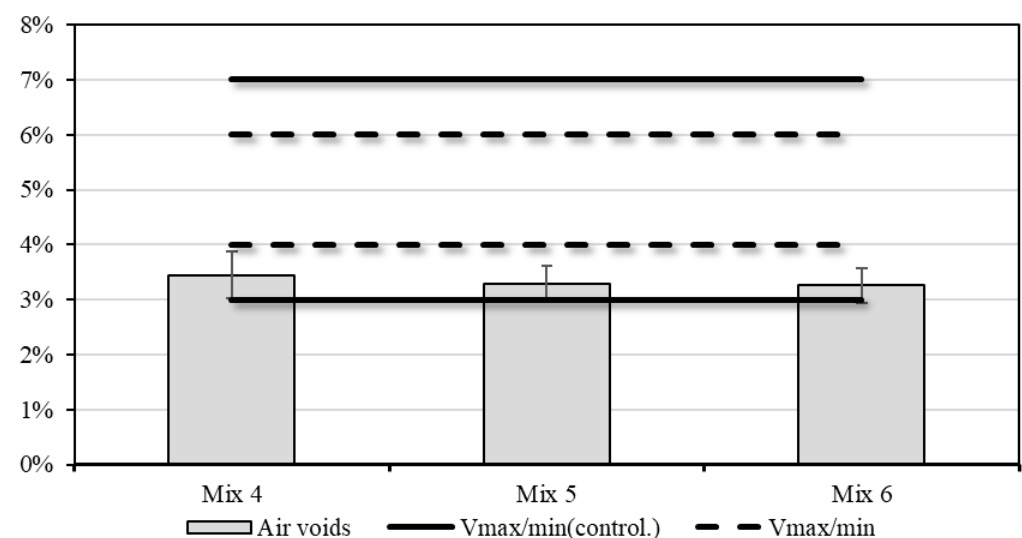


Figure 6. Air-void content of dense-graded asphalt concrete for the binder course (AC 16 bin). The dashed horizontal lines indicate the type-testing limit criteria, and the solid black lines indicate control limits according to ČSN 73 6121:2023 [53].

3.2. Indirect Tensile Strength (ITS) and Moisture Susceptibility (ITSR)

Figure 7 provides a detailed overview of the moisture susceptibility results. An increase in dry indirect tensile strength (ITS) was observed for nearly all mixtures containing FF fibres, except for Mix 2, which recorded a value comparable to its reference counterpart. The improvement in dry ITS was more pronounced in the AC 16 bin mixtures, indicating a reinforcing effect of the fibres under dry conditions. However, a reduction in the ITSR was

observed across all fibre-reinforced mixes. The reduction was minor in the case of AC 16 bin variants, suggesting that FF fibre addition had a limited adverse effect on their moisture susceptibility. This trend aligns with previous observations involving other fibre types (e.g., plant-based fibres [46,51]), indicating a consistent ITSR decreasing pattern regardless of fibre material. The reduction in ITSR may be attributed to weaker interfacial interactions between the fibre surface and the bituminous matrix. Similarly to aggregates, the effectiveness of reinforcement is influenced by chemical compatibility, surface energy, and interactions such as van der Waals forces or electrostatic effects. These factors should be carefully considered when selecting and modifying fibre reinforcements for asphalt applications.

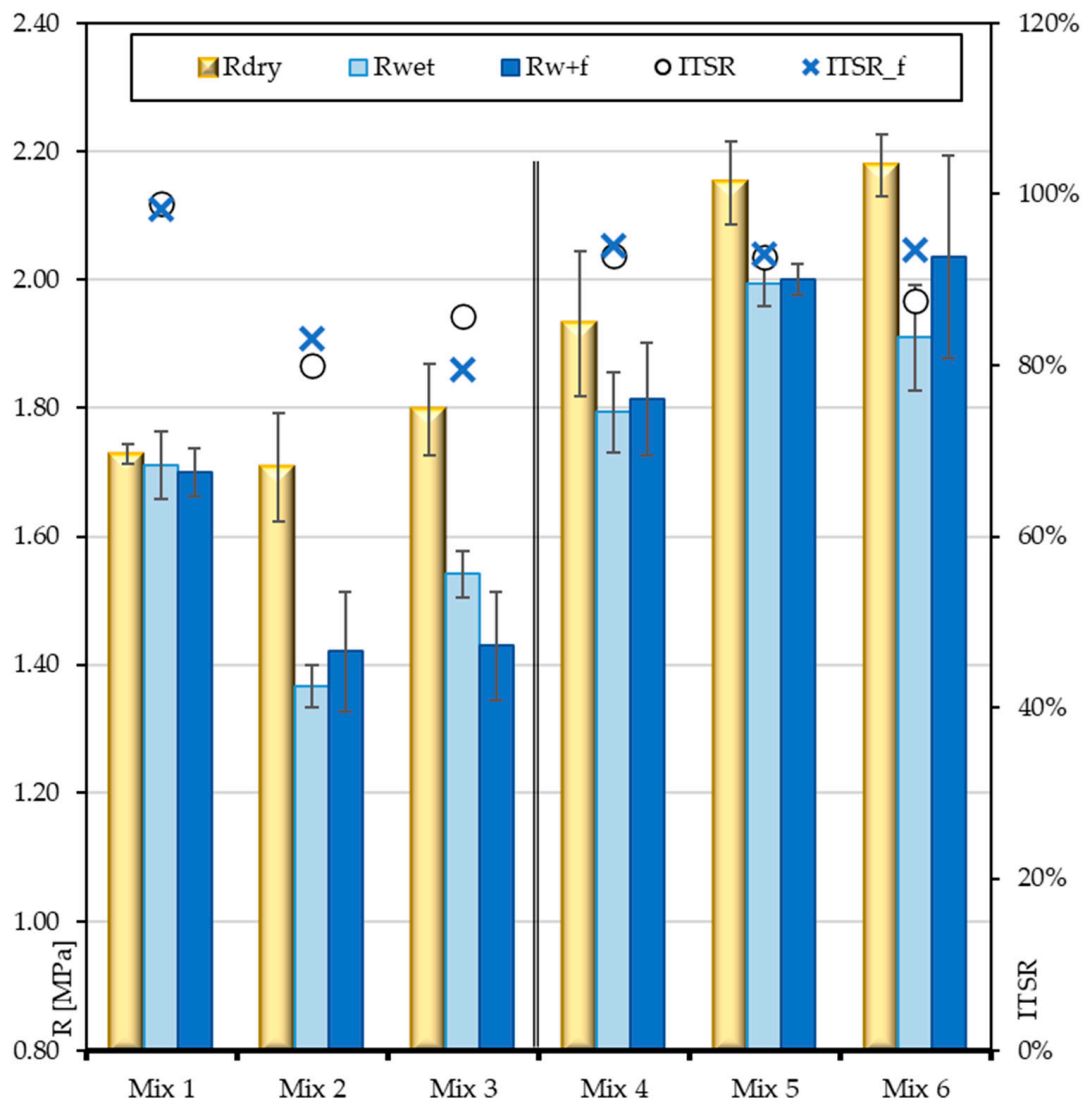


Figure 7. Moisture susceptibility results of asphalt mixtures. Columns represent indirect tensile strength (ITS [MPa], left axis); symbols indicate ITSR [%] determined according to EN 12697-12 [61] (white circles) and the modified AASHTO T283 procedure (blue crosses).

3.3. Stiffness (IT-CY)

The results are presented in Figure 8. As expected, Mix 3—containing conventional 50/70 bitumen—exhibited lower stiffness values compared to the other mixtures incorporating polymer-modified binders (PMBs). The remaining mixtures achieved comparable stiffness levels, with a slight increase observed in those containing FF fibres, particularly at 27 °C. Overall, mixtures with fibres and PMB exhibited reduced temperature sensitivity, in-

dicating improved resistance to thermal softening. This positive trend aligns with findings reported in previous studies involving other types of fibres [1,46].

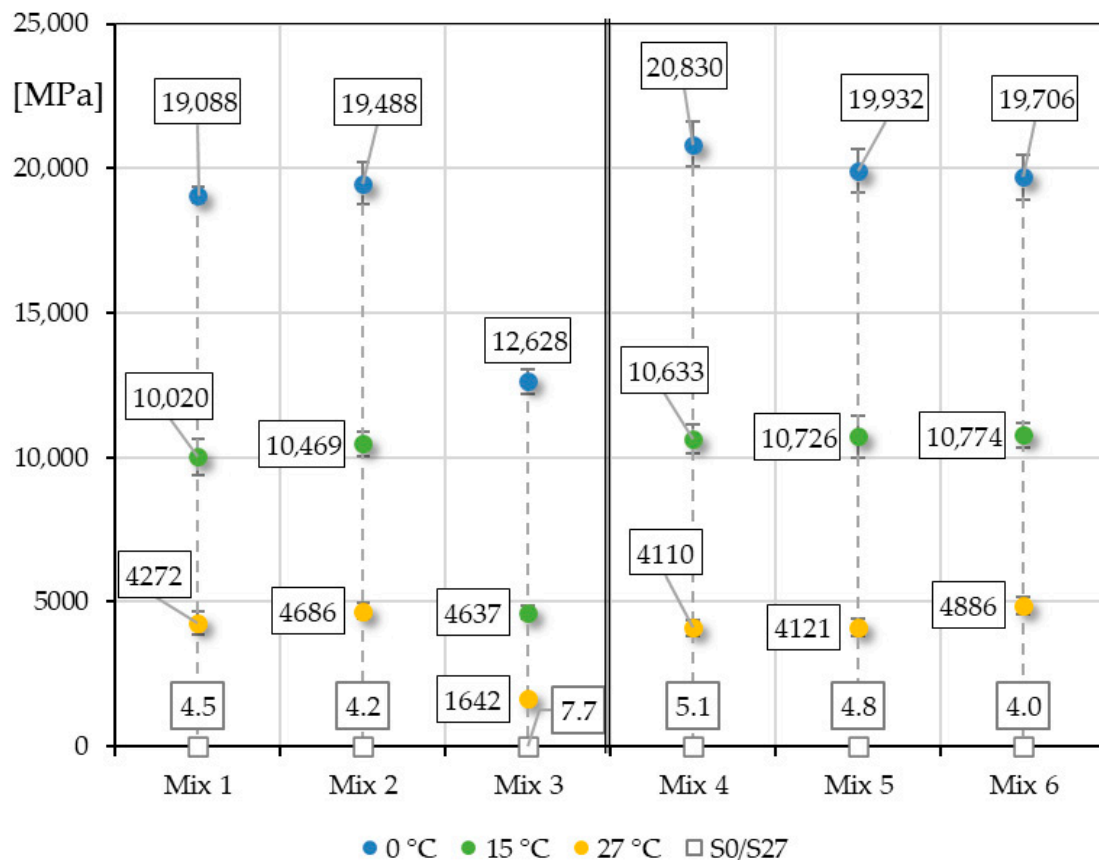


Figure 8. Indirect tensile stiffness modulus (IT-CY [MPa]) of asphalt mixtures at 0 °C, 15 °C, and 27 °C. Numbers above the horizontal axis indicate thermal susceptibility (ratio S_0/S_{27}).

Further insight can be drawn from the S_0/S_{27} ratios, which quantify the temperature sensitivity of the mixtures. Mix 3 displayed the highest stiffness ratio, indicating pronounced susceptibility to thermal softening. In contrast, Mix 6—containing 0.04% FF and PMB 25/55-60—exhibited the lowest ratio, confirming its enhanced thermal stability. These results emphasise the synergistic effect of polymer-modified binders and FF fibres in reducing temperature dependence. Moreover, Mixes 5 and 6 demonstrated nearly identical stiffness values at all temperatures, suggesting that 0.02% fibre content may already provide sufficient reinforcement for stiffness optimisation in AC 16 bin mixtures.

3.4. Crack Propagation Resistance (SCB Test)

In the case of AC 16 surf mixes (Figure 9) and apart from the fracture toughness at 15 °C, Mix 3 with paving grade bitumen 50/70 had the highest values of the monitored parameters. Here, the combined effect of the binder with the higher proportion of FF fibres provided better resistance to crack propagation. The effect did not manifest itself in this way for the fracture toughness (FT) at 15 °C. This finding shows the dominant effect of softer binder on FT at elevated temperature. Furthermore, Mix 3 showed an increase in the total fracture energy of the test and in the two indexes. At 0 °C, there was a clear increase in FT and both fracture energies and a slight increase in both indexes. Comparison of Mix 1 and Mix 2 yields the finding that for the mixture with PMB and addition of FF fibres (Mix 2), the fracture toughness and fracture energy decreased up to F_{max} for both test temperatures. The overall fracture energy and both indexes were lower at 0 °C and slightly higher at 15 °C

than for Mix 1. The results are ambiguous in terms of interpreting the fracture behaviour in relation to the effect of the type of binder used or the combination with fibre dispersed reinforcement. This means that no logical dependencies could be traced between Mix 1 and Mix 2. In terms of the individual properties determined, the fracture energy of the crack, which is the difference between the total fracture energy and the fracture energy up to the maximum force F_{max} , can be a decisive parameter for the design. This was only significantly increased in Mix 3, where the increase in parameters is influenced using a softer road binder. The dispersed reinforcement naturally increases the viscosity of the bitumen, which may explain the increase in fracture energy for Mix 3 at 15 °C. On the other hand, the fibres seem to not bring any advantages at 0 °C, when the bitumen composite is stiff.

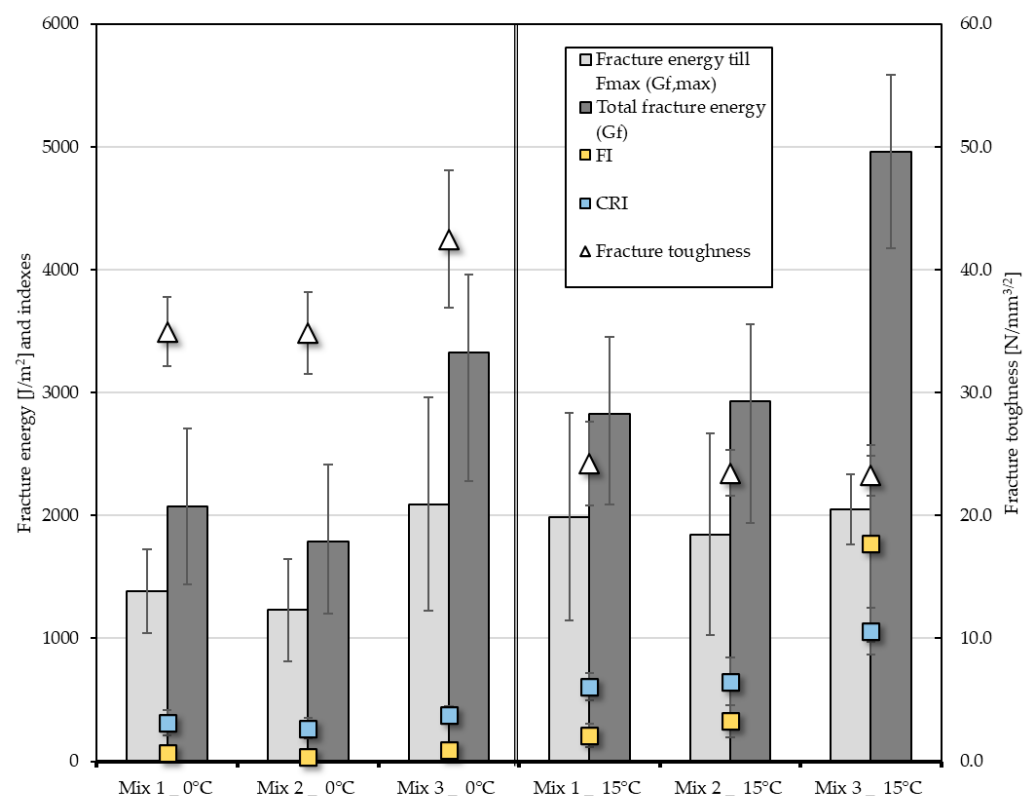


Figure 9. Crack propagation results of AC 16 surf mixtures.

Testing of AC 16 bin mixes produced similar findings (Figure 10). The mixes with the addition of FF fibres (Mix 5 and 6) and at 0 °C showed a reduction in fracture toughness and achieved similar G_f and CRI. It was not possible to calculate the flexibility index of Mix 6. This mixture was prone to a brittle behaviour, with lowest fracture toughness recorded. It is contrary to the assumption since, in this case, it is generally expected that the presence of a higher proportion of fibres in combination with a polymer-modified binder will increase the resistance to crack propagation. At 15 °C, Mix 6 had the highest values of all parameters monitored, which may be the strongest evidence of the functionality of FF fibres to increase resistance to crack propagation. However, the fracture energy of the crack remained practically the same as that of the mix without fibres.

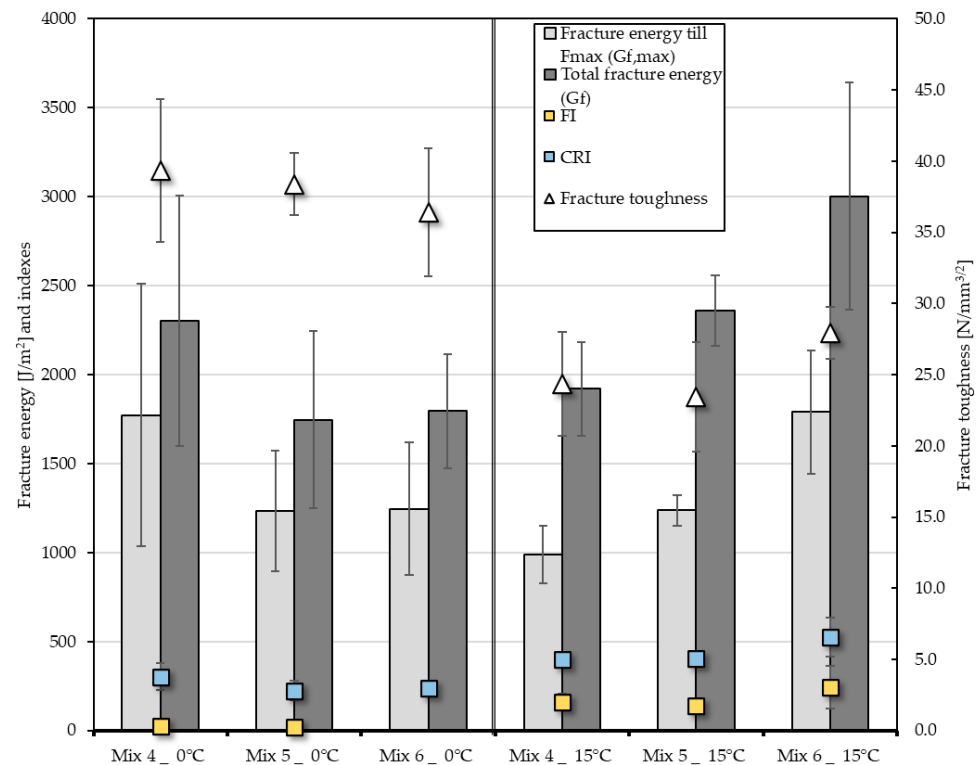


Figure 10. Crack propagation results of AC 16 bin mixtures.

3.5. Resistance to Permanent Deformation (Wheel Tracking Test)

The performance of each mixture was assessed against the threshold values defined in ČSN 73 6121:2023 [53]. For AC 16 surf mixtures, the standard limits are maximum relative track depth $PRD_{AIR} \leq 6.0\%$ and maximum track depth increment $WTS_{AIR} \leq 0.08 \text{ mm}/10^3 \text{ cycles}$. For AC 16 bin mixtures, the corresponding limits are $PRD_{AIR} \leq 3.0\%$ and $WTS_{AIR} \leq 0.05 \text{ mm}/10^3 \text{ cycles}$.

As shown in Table 3, Mix 2 (AC 16 surf with PMB and 0.02% FF fibres) exhibited improved rutting resistance, with reductions in PRD_{AIR} , WTS_{AIR} , and total rut depth after 10,000 cycles. In contrast, Mix 3 (AC 16 surf with 50/70 binder and 0.04% FF) showed the poorest performance, with the highest values of all monitored deformation parameters—consistent with expectations for unmodified binders under high-temperature loading. The addition of fibres should have helped to mitigate this issue. However, properties of the binder seem to be the major determinant and even higher fibre dosage was not a sufficient solution.

Table 3. Results of permanent deformation resistance testing for AC 16 bin and AC 16 surf asphalt mixtures.

Mixture	Thickness (mm)	Bulk Density (g.cm ⁻³)	Compaction Degree (%)	Rut Depth After 10,000 Cycles (mm)	WTS _{AIR} [mm/10 ³ Cycles]	PRD _{AIR} [%]
Mix 1	60.33	2416	100.8%	1.58	0.021	2.4
Mix 2	61.26	2371	99.9%	0.91	0.014	1.4
Mix 3	60.68	2444	100.4%	2.23	0.034	3.4
Mix 4	62.18	2431	99.2%	0.95	0.015	1.4
Mix 5	60.71	2439	99.2%	1.56	0.022	2.4
Mix 6	61.1	2437	100.0%	2.26	0.032	3.4

For AC 16 bin mixtures, the trend was reversed. Mix 6, containing 0.04% FF fibres, recorded the highest deformation values and even exceeded the maximum PRD_{AIR} specified in the standard. This behaviour suggests that, unlike in the surface course mixtures, the higher fibre dosage in binder course mixtures may have altered the mastic rheology, increasing local viscosity and restricting aggregate mobility during compaction. Although Mix 6 exhibited a similar or slightly lower air-void content compared with Mix 4 and Mix 5, the reduced rutting resistance cannot be solely attributed to volumetric parameters. The smooth, chemically inert surface of aramid fibres may have limited interfacial bonding with the bituminous matrix, resulting in less efficient stress transfer and local slippage under repeated loading. This weak fibre–binder interaction likely impeded energy dissipation and contributed to higher permanent deformation. Similar findings were reported [69–71], who observed that insufficient fibre–binder compatibility diminishes the reinforcing efficiency under high-temperature conditions. Nevertheless, the fibres still enhanced structural integrity by stabilising the aggregate skeleton, indicating that improved surface treatment or hybridisation with polymers could further optimise their performance in high-stress pavement layers.

This suggests that, unlike in surface course mixtures, the higher FF fibre content in binder course mixtures may hinder aggregate rearrangement during compaction, possibly due to increased mastic viscosity and reduced binder mobility, resulting in higher air voids and, consequently, lower resistance to permanent deformation.

3.6. Dynamic Modulus (4-Point Bending Test)

Looking at Figure 11, we see the scatter of the dynamic modulus of the AC surf 16 mixtures in the high and medium temperature region (to the left of the grey dashed line). To indicate the limitation of permanent deformation formation, it is desirable (as in the IT-CY method) that the mixture has the highest stiffness in the high-temperature region. A low stiffness of the mixture at low temperatures is then advantageous in terms of minimising the risk of low-temperature cracking. In other words, the asphalt mix should have the lowest possible temperature sensitivity. This behaviour is shown by Mix 2 combining PMB and FF fibre admixture. For the reference mix (Mix 1), there was a clear decrease in stiffness in the medium and higher temperature range. Then, in the low-temperature region, the modulus of all asphalt mixes levelled off, while the modulus of Mix 3 with 50/70 binder continued its upward trend. In addition to this finding, a correlation with the stiffness measurements by the IT-CY method can be observed. It is evident that the change in binder type is the main factor affecting the stiffness of the mix, and even a twofold increase in FF fibre content did not have a significant effect on the results.

Only one type of binder was used for the AC bin mix type shown in Figure 12. Mix 4 and Mix 5 drew similar master curves. Surprisingly, Mix 5 with 0.02% FF fibres had a lower dynamic modulus over the entire temperature/frequency range than the mix without fibres. A twofold increase in fibre content for Mix 6 then led to the desired master curve waveform. The results correlate with the stiffness measured by the IT-CY method, but for which the differences between the mixes were not significant.

The black space diagram (Figure 13) further clarifies the relationship between stiffness and viscoelasticity for the surface course mixtures. All three mixtures follow a consistent downward trend, with dynamic modulus decreasing as the phase angle increases. While the differences among the mixtures are relatively small, Mix 2 maintains a slightly more stable distribution of data points across the mid-phase angle range (approximately 5–20°), indicating a balanced viscoelastic response. Mix 3 shows slightly greater variability, particularly at higher phase angles, which may reflect reduced consistency under prolonged or high-temperature loading. Overall, these patterns support the conclusion that the combina-

tion of a polymer-modified binder with low-dosage FF fibres (Mix 2) offers a well-balanced stiffness–elasticity profile, suitable for surface course applications.

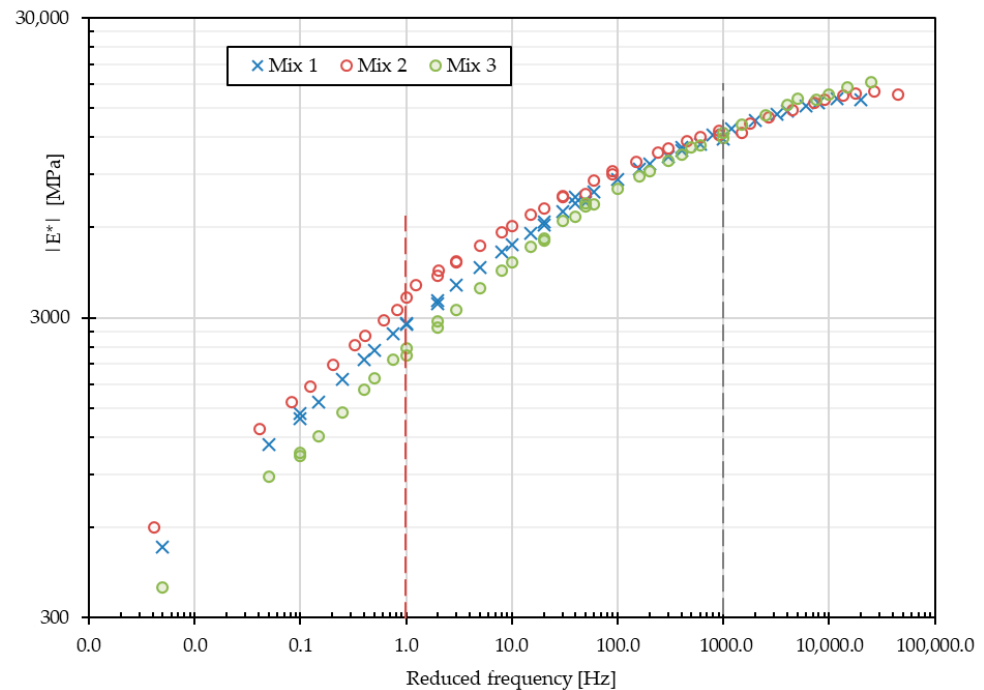


Figure 11. Master curves of the dynamic stiffness modulus of AC surf 16 mixtures; the vertical dashed lines define the boundaries of the individual temperature regions. Left from the red dashed line is the region of high temperatures. Region between the dashed lines is devoted to medium temperatures and right to the grey line is the low temperature region.

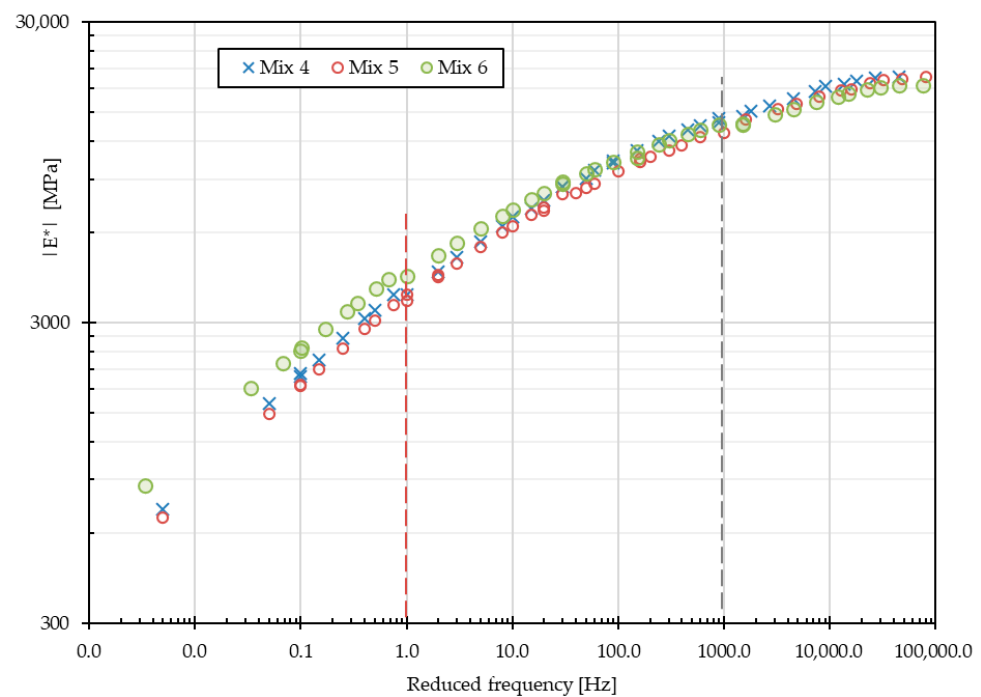


Figure 12. Master curves of the dynamic stiffness modulus of AC 16 bin mixtures; the vertical dashed lines define the boundaries of the individual temperature regions. Left from the red dashed line is the region of high temperatures. Region between the dashed lines is devoted to medium temperatures and right to the grey line is the low temperature region.

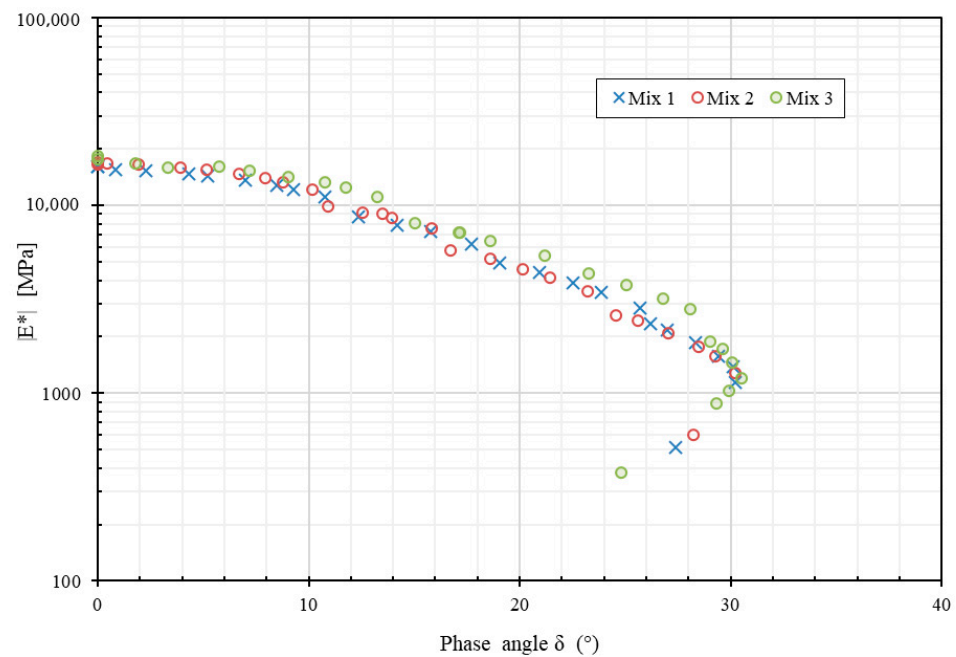


Figure 13. Black space diagram for Mix 1–3 (AC 16 surf).

All three binder course asphalt mixtures (Figure 14) follow a consistent decreasing trend in stiffness with increasing phase angle, showing similar viscoelastic profiles. While the differences among the mixtures are relatively minor, Mix 4 and Mix 5 tend to retain slightly higher dynamic modulus values at higher phase angles (above 25°), suggesting marginally better stiffness retention under conditions of thermal or long-duration loading. In contrast, Mix 6 shows a slightly earlier drop in modulus as the phase angle increases, which may reflect a more viscous response under such conditions. Overall, although all three mixes perform comparably, the black space diagram indicates that increasing fibre content to 0.04% (Mix 6) does not lead to a significant improvement in stiffness–elasticity balance for the binder course. Instead, the use of 0.02% fibres (Mix 5) appears to achieve a similar performance to the reference (Mix 4), with no clear trade-offs.

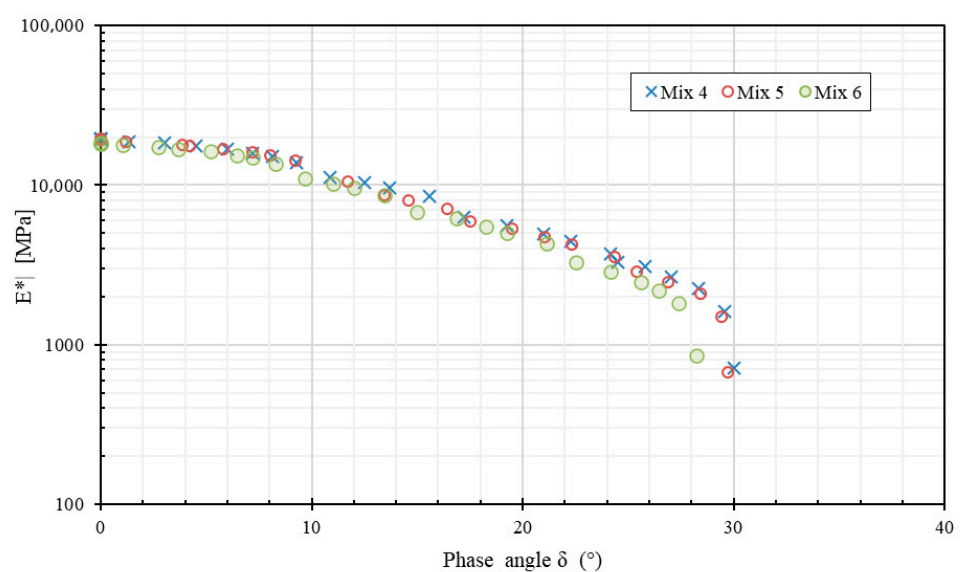


Figure 14. Black space diagram for Mix 4–6 (AC 16 bin).

The analysis of dynamic modulus behaviour and black space diagrams confirms that binder type plays a dominant role in determining the stiffness and viscoelastic response of asphalt mixtures. For the surface course mixtures, the combination of polymer-modified binder and low-dosage FF fibres (Mix 2) demonstrated the most favourable performance, offering enhanced stiffness at high temperatures and a balanced viscoelastic profile, while minimising temperature sensitivity. In contrast, increasing fibre content in case of using a conventional paving grade bitumen (Mix 3) yielded limited benefits and greater variability under thermal stress. For the binder course mixtures, the addition of 0.02% FF fibres (Mix 5) did not significantly alter performance compared to the reference (Mix 4), while a higher fibre content (Mix 6) resulted in a more viscous response without substantial gains in stiffness. Overall, the results suggest that the optimal performance is achieved through the synergistic use of polymer modification and a moderate fibre dosage, rather than relying on fibre content alone.

4. Conclusions

This study evaluated the influence of FlexForce fibres on the mechanical and functional performance of two dense-graded asphalt concrete mixtures: AC 16 surf (surface course) and AC 16 bin (binder course), prepared with polymer-modified and conventional binders. The findings highlight that the effects of aramid and polypropylene fibres depend strongly on binder type, fibre dosage, and temperature.

- **Compactability and Air-Void Content:** The addition of FF fibres had no consistent influence on compactability. In surface-course mixtures, one fibre-reinforced variant showed slightly higher air-void content, whereas binder course mixtures exhibited comparable values across all variants. Overall, the fibres did not impair workability or mixture density.
- **Moisture Susceptibility:** A slight increase in dry ITS was observed in most fibre-reinforced mixtures, confirming a moderate reinforcing effect under dry conditions. Conversely, all fibre-modified mixtures showed lower ITSR values, suggesting that limited bonding at the fibre–binder interface reduces moisture resistance.
- **Stiffness and Thermal Sensitivity:** Fibre incorporation generally resulted in similar or marginally higher stiffness (IT-CY) compared with the reference mixtures, particularly at elevated temperatures (27 °C). This demonstrates that fibre reinforcement enhances stiffness without increasing thermal susceptibility, especially when combined with polymer-modified binders.
- **Crack Propagation Resistance:** Fracture behaviour exhibited temperature-dependent trends. At 0 °C, fibres did not improve fracture resistance and occasionally induced brittleness, whereas at 15 °C, a partial improvement in fracture energy and flexibility indices was achieved. This confirms that the beneficial fibre effect becomes most pronounced at intermediate temperatures, where the binder–fibre system maintains sufficient ductility.
- **Resistance to Permanent Deformation:** For AC 16 surf mixtures, adding 0.02% FF fibres (Mix 2) improved rutting resistance, while higher fibre dosage or the use of unmodified binder (Mix 3) reduced this benefit. In contrast, AC 16 bin mixtures with 0.04% fibres (Mix 6) showed greater deformation despite similar air voids, likely due to increased mastic viscosity and weak fibre–binder adhesion caused by the smooth, inert fibre surface. This limited bonding reduced stress transfer and energy dissipation under repeated loading. Nevertheless, the fibres helped to stabilise the aggregate skeleton, indicating potential for improved performance through enhanced surface treatment or polymer coupling.

- **Dynamic Modulus and Viscoelastic Behaviour:** Dynamic modulus testing confirmed that FF fibres can improve stiffness and viscoelastic balance. For both mixture types, fibre addition resulted in smoother master curves and reduced temperature susceptibility, indicating enhanced temperature stability.

In summary, aramid fibres at low dosages ($\approx 0.02\%$) can improve selected mechanical properties, particularly stiffness and high-temperature stability, when used with polymer-modified binders. Their effectiveness is governed by the interaction between fibre content, binder rheology, and temperature. Future research should focus on elucidating fibre–binder interfacial mechanisms, optimising fibre dosage for different gradations, and evaluating long-term durability to establish design guidelines for aramid-reinforced asphalt layers.

Author Contributions: Conceptualisation, J.V.; methodology, J.V.; validation, P.G. and J.V.; formal analysis, P.G. and J.V.; investigation, P.G. and A.B.A.; resources, J.V.; data curation, P.G. and A.B.A.; writing—original draft preparation, P.G. and A.B.A.; writing—review and editing, P.G., A.B.A. and J.V.; visualisation, P.G.; supervision, J.V.; project administration, J.V.; funding acquisition, J.V. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Ministry of Environment of the Czech Republic as part of research project CirkArena, project No. CZ.10.03.01/00/22_003/0000045.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: We would like to thank our colleague Pavla Vacková for partial funding acquisition.

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

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