

A COMPREHENSIVE STUDY OF THE EFFECT OF BIOCHAR ON THE RHEOLOGICAL PROPERTIES AND DURABILITY OF ASPHALT CONCRETE MIXTURES

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Abstract. A comprehensive study of the effect of biochar on the rheological properties and durability of asphalt mixtures is particularly relevant given the need to improve the performance of road surfaces and implement environmentally friendly technologies. Biochar, obtained through the pyrolysis of plant materials, is considered a promising additive capable of improving the structural and mechanical properties of bitumen and mineral-bitumen composites. This study analyzed changes in the rheological parameters of bitumen binders at various biochar concentrations (from 2 to 10% by weight), including viscosity, complex shear modulus, and temperature sensitivity. It was found that the addition of bio-char improves the binder's structural stability by improving particle size distribution and increasing the amount of high-molecular-weight fractions. The impact of biochar on the durability of asphalt concrete was also assessed in terms of water resistance, crack resistance, and rutting. Test results indicate a reduction in bitumen aging, increased fatigue resistance, and improved thermal stability of the composite. Optimum biochar concentrations ensure the formation of a denser structure, preventing moisture penetration and the development of microcracks. The comprehensive analysis demonstrates that the use of biochar as a modifying additive not only improves the performance characteristics of asphalt mixtures but also enhances the environmental sustainability of road construction through the use of renewable materials and reduced CO₂ emissions. The results confirm the potential for further integration of biochar into asphalt concrete production processes.

Keywords: biochar, asphalt mixture, rheological parameters, modification.

1. Introduction

The most common type of pavement in Ukraine is asphalt concrete, which is characterized by high strength, deformability, good adhesion to vehicle tires, and other positive qualities. At the same time, the physical-mechanical and rheological characteristics of asphalt concrete mixtures deteriorate due to the increase in traffic flow and the overall load on asphalt pavements.

Domestic and international experience shows that, at present, replacing asphalt concrete with other materials for the construction of road pavements is quite problematic. Therefore, the main focus should be directed not only toward improving the technological process of laying asphalt concrete mixtures, but also toward their production, with the aim of enhancing their properties and quality (Zhou, 2024; Akhl et al., 2021; Mistry & Roy, 2021).

Statistical analysis shows that the service life of road pavements made of bitumen–mineral composites

amounts to only 50–70% of the standard (design) values. Low elasticity, insufficient crack resistance, and a limited operational temperature range restrict their use both during hot summer periods and in winter conditions.

Achieving high levels of reliability and durability of asphalt concrete pavements based on traditional materials and conventional types of asphalt concrete is not always possible. The most common methods for improving the quality of asphalt concrete and its components include the following:

- improvement of the quality characteristics of coarse and fine aggregates;
- modification of bitumen properties through the addition of modifying additives.

For regions that do not have a large number of deposits of stone materials, the latter approach is more promising (Zhang et al., 2022; Borzyak & Zhuravel, 2023; Ma et al., 2022; Yingying et al., 2020).

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2. Main part

At present, increased attention is being paid to bitumen modification, since the performance efficiency of asphalt concrete pavements largely depends on the properties of the binder. However, bitumen is a thermoplastic material; therefore, its softening at summer temperatures leads to plastic deformations, while brittleness at low winter temperatures results in low-temperature cracking. The properties of bitumen can be improved through modification with polymer additives, such as thermoplastic elastomers based on styrene-butadiene copolymers (SBS).

Nevertheless, the high cost of such additives necessitates the search for ways to reduce their content without deteriorating the operational performance of the materials. One effective approach to addressing this problem is the use of filled polymers, which are widely applied in various industries (Park et al., 2017; Amalina et al., 2022; Provatorova & Vikhrev, 2020).

Fillers have a significant influence on the technological, physical-mechanical, thermophysical, and other properties of polymer materials and generally contribute to a reduction in their cost, since in most cases they are more affordable than the polymer matrix. Among various types of fillers, carbon-based modifiers derived from sp^2 -hybridized carbon are of particular interest; these include graphene structures, carbon nanotubes, carbon nanofibers, and carbon black (Kim et al., 2011; Wu-ping et al., 2023).

The mechanism by which carbon fillers affect the properties of bituminous binders is associated with their influence on the dispersed structure of bitumen, its rheological characteristics, and the interfacial interactions between system components. The introduction of carbon modifiers promotes the formation of spatial network structures within the bitumen volume, which restricts the mobility of the maltene phase and stabilizes asphaltene aggregates.

Due to their high specific surface area and developed morphology, carbon fillers adsorb bitumen components—primarily aromatic and resinous fractions—thereby enhancing the structural stability of the binder and reducing its temperature sensitivity. The presence of π - π interactions between aromatic fragments of bitumen and the surface of sp^2 -hybridized carbon ensures enhanced interfacial adhesion and improved system homogeneity (Zhou et al., 2021; Jyoti Bora et al., 2020).

As a result of modification, an increase in high-temperature stiffness and resistance of bitumen to rutting is observed, along with improved thermo-oxidative stability and a reduced aging rate. The effectiveness of modification is significantly influenced by the degree of dispersion of carbon fillers, their concentration, and the nature of their surface properties, which determine the formation of a structural framework within the bituminous matrix.

One such material is biochar, obtained through high-temperature pyrolysis of various types of natural raw materials.

Authors who have investigated biochar (Tiza et al., 2022; Martinez-Toledo et al., 2024; Cruz et al., 2022; Fang et al., 2013) note that carbon as a modifier is highly promising due to the good compatibility of the carbonaceous component with the organic fraction of bitumen, as well as its specific structure (porous/fibrous in the case of biochar), which enables strong interactions with the bituminous matrix. The introduction of carbon into bituminous binders leads to increased stiffness at high temperatures, improved resistance to rutting, enhanced elasticity, and greater resistance to aging.

In the studies by Zhao et al. (2014) and Korniejenko et al. (2023), the reduced aging rate of bitumen modified with biochar derived from wood pyrolysis is attributed to its high carbon content, which enables a more uniform distribution within the bituminous matrix due to high compatibility with the chemical nature of bitumen and the establishment of more effective interactions. Improved adhesion of biochar-modified binders to mineral aggregates is also reported, which is explained by the presence of various functional groups (hydroxyl, carbonyl, etc.) on the surface of the carbon material.

One of the ideas developed in recent years is the healing of cracks in asphalt pavements (self-healing), achieved due to the susceptibility of bituminous binders containing electrically conductive carbon modifiers to microwave radiation.

In recent years, interest in natural materials has continued to grow and develop. According to a number of functional characteristics, certain natural carbon-containing materials can exhibit properties comparable to those of synthetic nanomaterials such as graphene, graphene oxide, and carbon nanotubes; however, they differ significantly in chemical composition and structural ordering (Zhang et al., 2022; Bandara et al., 2019; Zhu et al., 2020).

Biochar is a carbon-containing material formed as a result of the thermal decomposition of biomass under conditions of limited oxygen access and is characterized by a complex hierarchical structure. From a chemical perspective, biochar consists predominantly of amorphous and partially ordered carbon with the inclusion of aromatic fragments, as well as residual mineral components, ash elements, and surface functional groups. Among the most significant are hydroxyl, carboxyl, phenolic, and carbonyl groups, which form the active surface of the particles and determine their polarity. The physical structure of biochar is characterized by high porosity, the presence of micro-, meso-, and macropores, and a large specific surface area, which accounts for its high sorption capacity and well-developed interfacial contacts in composite materials.

When modifying bitumen, biochar interacts with its components at both physical and chemical levels. The

porous structure of biochar facilitates the penetration and retention of light bitumen fractions, resins, and oils, leading to a redistribution of the colloidal system and stabilization of the asphaltene phase. Chemical interactions are manifested through the adsorption of polar asphaltene and resin molecules on the surface of biochar via hydrogen bonding, π - π interactions between aromatic structures, and donor-acceptor interactions. This reduces the tendency of bitumen toward phase segregation, decreases temperature sensitivity, and enhances the viscoelastic properties of the binder (Park et al., 2017; Zhang et al., 2022; Amalina et al., 2022).

Within asphalt concrete, biochar exerts a comprehensive influence not only on the bituminous binder but also on the "bitumen-mineral aggregate" system. Biochar particles, when distributed within the bitumen film, contribute to increased structural strength and improved adhesion to the surface of mineral grains. Owing to its developed surface area and chemical activity, biochar enhances the bonding between bitumen and aggregates, reduces the moisture susceptibility of asphalt concrete, and increases its resistance to moisture-induced damage. Physically, biochar can act as a micro-reinforcing element, promoting stress redistribution in contact zones and reducing the concentration of local deformations.

In addition, biochar is capable of partially interacting with the mineral component of asphalt concrete by adsorbing moisture and reducing its negative effect on adhesive bonds. The combined chemical and physical mechanisms of interaction between biochar, bitumen, and the mineral components of asphalt concrete lead to increased resistance to rutting, improved crack resistance at low temperatures, and enhanced durability of road pavements, which confirms the promising potential of its application in modern asphalt concrete compositions (Zhang et al., 2022; Mistry & Roy, 2021).

Taking all of the above into account, the distinctive features of biochar composition are expected to have a positive effect on the structuring of the bituminous matrix in the presence of a polymer when biochar is used as a modifier of polymer-bitumen binders, thereby improving their properties, as demonstrated in previously conducted studies (Mistry & Roy, 2021; Zhang et al., 2022; Amalina et al., 2022; Korniejenko et al., 2023). Since carbon is the key structural component of the material, the objective of the present work was to study the effect of biochar on the structure formation of bituminous binders.

3. Materials and methods

The aim of this study is to investigate the effect of fine-fraction biochar on the properties of bitumen. In the study, the properties of bitumen were determined using standard test methods. Bitumen of grade BND 70/100 was used as the base material. Prior to modification, the bitumen was tested for compliance with the requirements

of DSTU 9116:2021 Bitumen and bituminous binders. Polymer-modified road bitumens. Technical specifications (UkrNDNC, 2021). The test results are presented in Table 1.

Table 1. Properties of the base bitumen

Parameter	Value	Standarts
Needle penetration depth, 0.1 mm, at 25 °C	92	DSTU EN 1426 (UkrNDNC, 2018h)
Needle penetration depth, 0.1 mm, at 0 °C	52	
Ductility, cm, at 25 °C	80.5	DSTU EN 13398 (UkrNDNC, 2018g)
Softening point, °C (Ring-and-Ball method)	50	DSTU EN 1427 (UkrNDNC, 2018i)
Brittleness temperature, °C	-22	DSTU EN 12593 (UkrNDNC, 2018a)
Change in softening point after aging, °C	1.6	DSTU EN 12607-1 (UkrNDNC, 2015)

Wood-derived biochar obtained at a pyrolysis temperature of 650 °C was used as a modifier. Prior to incorporation into the bitumen, the biochar was dried to constant weight and sieved through a 0.063 mm mesh. Its physicochemical properties were determined using standard laboratory methods (specific surface area by the BET method, elemental analysis, and proximate analysis). The characteristics of the biochar are presented in Table 2.

Table 2. Physicochemical characteristics of wood biochar

Parameter	Value
Specific surface area, m ² /g	450
Density, g/cm ³	0.45
Ash content, %	5
Moisture content, %	4
Carbon (C), %	80
Hydrogen (H), %	3
Nitrogen (N), %	0.5
Oxygen (O), %	12
Volatile matter content, %	10
pH value	8

The bitumen was heated to a temperature of 120–140 °C. Biochar was introduced in amounts of 2%, 5%, and 10% by weight of the binder and mixed using a mechanical stirrer at a speed of 1000–1500 rpm for 40 minutes under controlled temperature conditions. The modification process is shown in Figure 1.

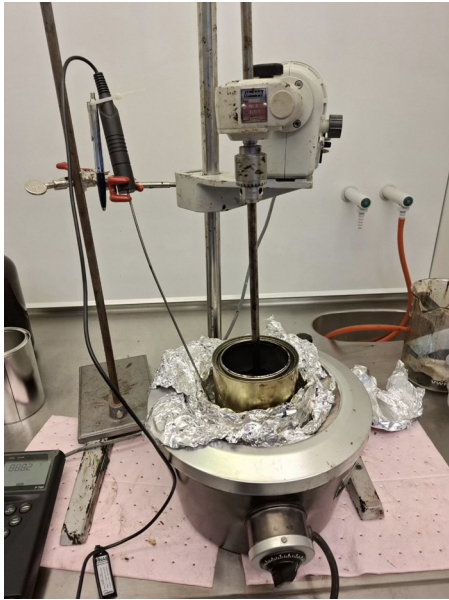


Figure 1. Bitumen modification process with biochar

The properties of modified binders were determined according to the same standards as for the original bitumen. All tests were carried out in at least three replicates. Dense asphalt concrete mixtures were prepared in accordance with DSTU B V.2.7-119 (UkrNDNC, 2011) and DSTU EN 13108-1 (UkrNDNC, 2019b). The samples were compacted using the Marshall method in accordance with DSTU EN 12697-30 (UkrNDNC, 2020).

The following tests were carried out: average density (DSTU EN 12697-6 (UkrNDNC, 2019a)); maximum density (DSTU EN 12697-5 (UkrNDNC, 2018b)); air voids and water saturation (DSTU EN 12697-8 (UkrNDNC, 2018c)); compressive strength (20 °C, 50 °C) (DSTU EN 12697-23 (UkrNDNC, 2024)); splitting strength (DSTU EN 12697-23 (UkrNDNC, 2024)); water resistance (DSTU EN 12697-12 (UkrNDNC, 2018d)); Shear resistance (DSTU EN 12697-24 (UkrNDNC, 2018f)); rutting resistance (DSTU EN 12697-22 (UkrNDNC, 2018e)). Each test was conducted on at least three samples. Average values were used for analysis.

4. Biobitumen testing

The dependence of the rheological properties of the resulting modified bitumen on the amount of modifier (2, 5, 10%) – biochar – is shown in Figures 2–5.

According to Figure 2, the softening point decreases with increasing biochar content. At first glance, this trend appears contradictory, as a decrease in penetration indicates an increase in binder stiffness, which is usually accompanied by an increase in softening point.

Quantitative analysis shows that the decrease in softening point does not exceed 3–6% over the studied concentration range. Thus, the decrease in this parameter is

moderate compared to the more pronounced decrease in penetration (12–25%).

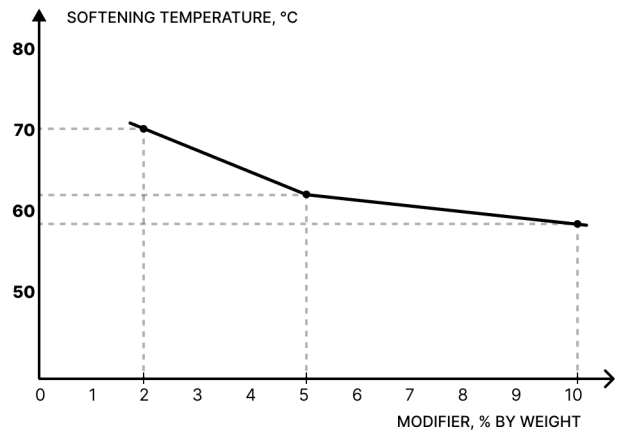


Figure 2. Dependence of softening point on biochar content

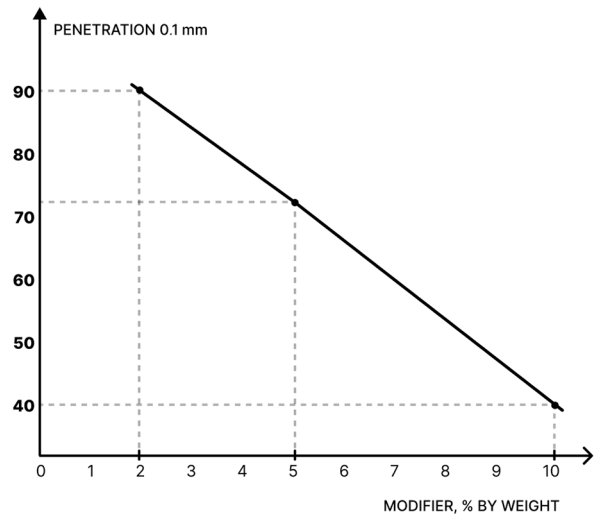


Figure 3. Dependence of penetration on biochar content

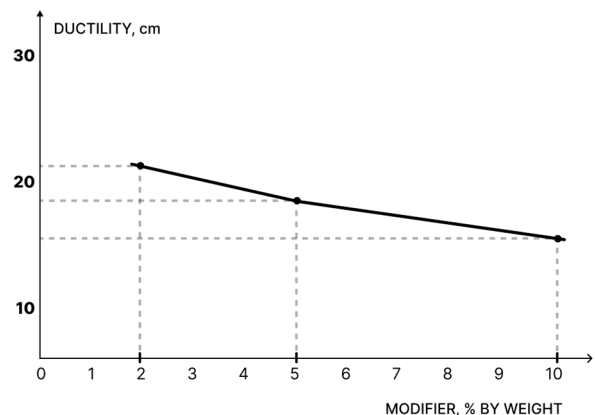


Figure 4. Dependence of ductility on biochar content

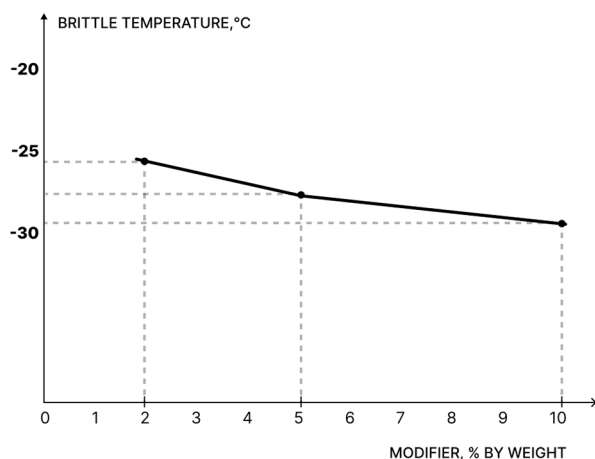


Figure 5. Dependence of brittle temperature on biochar content

The observed discrepancy can be explained by the following factors:

The penetration test characterizes resistance to localized deformation under short-term loading, while the ring and ball method reflects the behavior of the material under prolonged heating and the transition to a viscous flow state. The addition of biochar increases structural rigidity at moderate temperatures due to the reinforcing effect of the particles. However, it can also partially disrupt the continuity of the bitumen matrix, which slightly reduces the onset temperature of macroscopic flow.

At high concentrations (10%), biochar particles can agglomerate, reducing the efficiency of stress transfer and potentially affecting the thermal stability of the system.

Therefore, a decrease in softening point cannot be interpreted as a deterioration in high-temperature properties without a comprehensive analysis of strength and rutting parameters, which generally demonstrate positive trends.

Figure 3 shows a steady decrease in penetration with increasing biochar content. The decrease reaches 25% at 10% modifier, confirming a significant increase in binder rigidity.

This trend is expected, as biochar particles act as a rigid microdispersed filler, limiting the mobility of maltene fractions and strengthening the asphaltene network. However, excessive stiffness can negatively impact the relaxation properties of the material, which must be taken into account when designing the pavement.

Figure 4 shows a gradual decrease in extensibility (by approximately 8–15%) with increasing biochar content. The absence of a sharp drop indicates that acceptable deformability is maintained within the studied concentration range.

However, a decrease in extensibility combined with a decrease in penetration indicates an increase in brittleness at higher modifier dosages. This effect can become critical at low operating temperatures if not compensated for by improved crack resistance.

Figure 5 shows a decrease in the brittleness temperature by 2–4 °C with increasing biochar content, indicating improved low-temperature properties.

The simultaneous increase in stiffness (decreased penetration) and improved frost resistance appears contradictory at first glance. However, this can be explained by the redistribution of internal stresses within the bitumen structure. Biochar is capable of stabilizing the asphaltene network and promoting more uniform dissipation of thermal stress at the microscale.

Thus, the increase in frost resistance is associated not so much with increased flexibility as with the structural stabilization of the system.

In the range of 2–5%, the dependence of properties on biochar content is close to linear; however, at 10%, deviations begin to appear, which may indicate structural saturation or particle agglomeration.

A comprehensive analysis shows that:

- 2% biochar provides a significant increase in stiffness without excessive loss of ductility;
- 5% provides an additional increase, but with less effectiveness;
- 10% approaches the limit at which structural homogeneity can decrease.

Based on this, concentrations of 2% and 5% were selected for further asphalt concrete research.

5. Bioasphalt testing

As part of this study, a series of laboratory tests were conducted to evaluate the physical and mechanical properties of asphalt concrete mixtures with biomodified and polymer-modified bitumen:

- Sample 1 – bitumen with 2% biochar;
- Sample 2 – bitumen with 5% biochar;
- Sample 3 – polymer-modified bitumen.

Primary attention was paid to water resistance and strength, as these parameters largely determine the operational reliability and durability of road surfaces. The obtained experimental data allow for a comparative assessment of the effectiveness of polymer and biomodifiers, as well as an evaluation of their impact on the performance of asphalt concrete under operational loads. The results are presented in Figures 6–9.

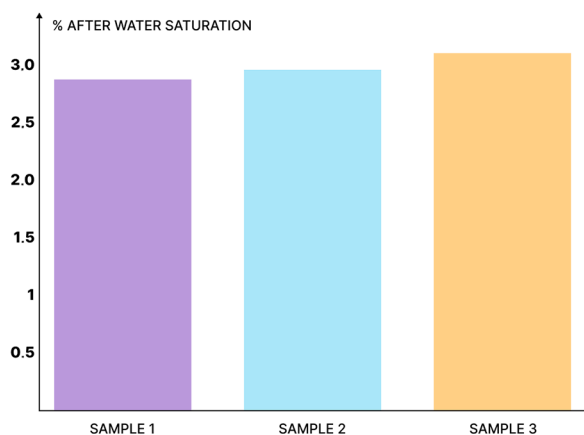


Figure 6. Water saturation values of asphalt concrete samples

Water saturation (Figure 6) is an important parameter, as it affects the strength and durability of road surfaces, especially in conditions of high humidity and adverse climatic factors.

A quantitative analysis of the results shows that, compared to asphalt concrete with polymer-modified bitumen (sample 3), water saturation:

- decreased by approximately 9–11% for sample 1 (2% biochar);
- decreased by 14–17% for sample 2 (5% biochar).

Thus, increasing the biochar content from 2% to 5% provided an additional reduction in water saturation by approximately 4–6%, indicating improved adhesion and reduced porosity of the asphalt concrete structure.

Compressive strength (Figure 7) is an important indicator of the mechanical properties of asphalt concrete pavements and their ability to withstand traffic loads and temperature effects.

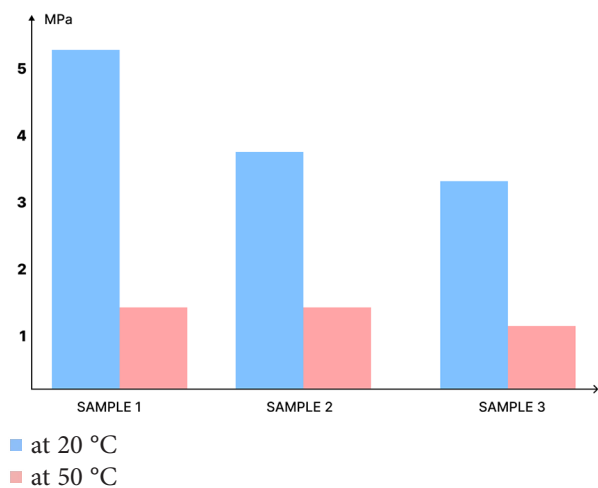


Figure 7. Compressive strength values

At 20 °C, the compressive strength of asphalt concrete with biomodified bitumen increased:

- by approximately 7–10% for Sample 1;
- by 11–14% for Sample 2

compared to polymer-modified asphalt concrete.

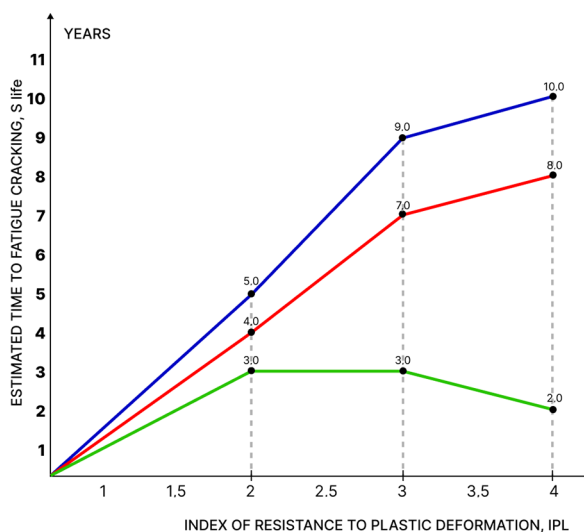
At 50 °C, the strengthening effect was more pronounced:

- Sample 1 showed an increase of 12–16%;
- Sample 2 showed an increase of 16–20%.

This confirms that the introduction of biochar significantly improves deformation resistance at high temperatures. However, the increase in performance between 2% and 5% biochar did not exceed 4–6%, indicating a decrease in the rate of increase in the effect with increasing modifier concentration.

The change in the service life of the pavement before plastic deformation occurs characterizes the period of maintaining performance properties without rutting or plastic flow.

Quantitative evaluation of the rutting test results (Figure 8) showed that:



- asphalt concrete with 2% bio-modified binder
- asphalt concrete with 5% bio-modified binder
- asphalt concrete with polymer-modified binder

Figure 8. Change in pavement service life

Asphalt concrete with 2% biochar demonstrated a service life increase of approximately 22–28% compared to polymer-modified asphalt concrete;

Asphalt concrete with 5% biochar demonstrated a service life increase of 27–34%.

The additional increase between 2% and 5% biochar was only 5–7%, which allows the 2% content to be considered close to optimal in terms of rutting resistance.

The conducted studies revealed a direct correlation between the improvement of physical and mechanical properties and increased resistance to plastic deformation.

The obtained data on splitting strength (Figure 9) are used to evaluate the quality of the asphalt concrete mixture and its crack resistance.

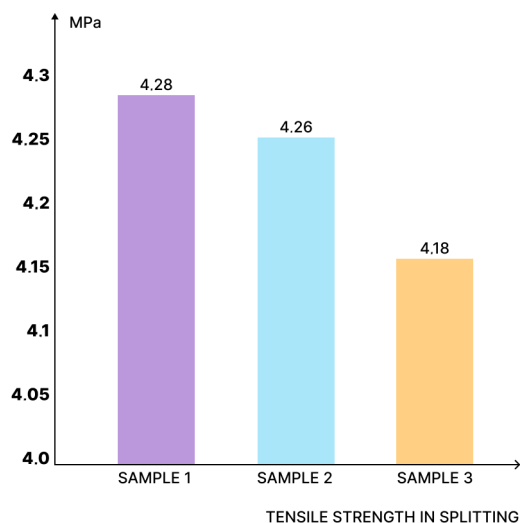


Figure 9. Splitting strength data of the samples

Compared to polymer-modified asphalt concrete:

- Sample 1 showed an increase of 8–11%;
- Sample 2 showed an increase of 10–13%.

The difference between 2% and 5% biochar did not exceed 2–3%, indicating that the main effect was achieved at a lower modifier concentration.

Shear tests were conducted to assess the ability of asphalt concrete to maintain its structure under dynamic loads.

Quantitative analysis of shear parameters (Figure 10) showed that:

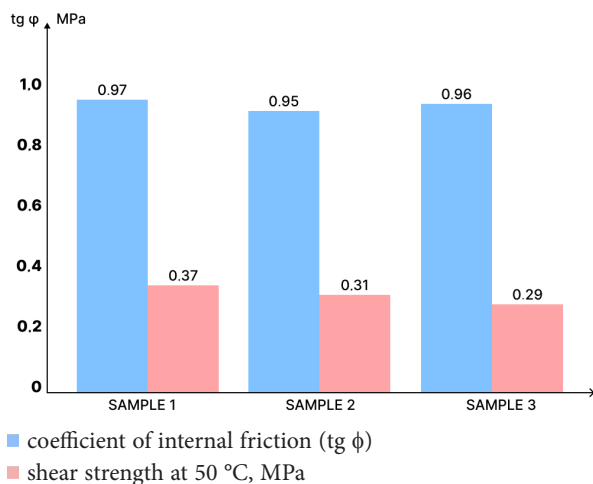


Figure 10. Shear resistance values of asphalt concrete samples

The coefficient of internal friction increased by 5–8% for Sample 1 and by 4–6% for Sample 2 compared to the polymer-modified mixture;

Shear adhesion increased by 12–18% for Sample 1 and by 8–14% for Sample 2.

It should be noted that the mixture with 2% biochar demonstrated slightly higher adhesion values than the mixture with 5%, which may be due to possible particle agglomeration at a higher modifier content.

Testing asphalt concrete for water saturation, compressive and splitting strength, shear resistance, and durability are key methods for assessing the quality and performance characteristics of the material. The studies showed that increasing the biochar content from 2% to 5% leads to improved performance, but the greatest effect is achieved at 2%, allowing this concentration to be considered optimal from a mechanical and technological standpoint.

Improvements in water resistance (up to 17%) and compressive strength (up to 20% at 50 °C) are consistent with increased binder stiffness and improved adhesion.

However, the fact that a mixture with 2% biochar in some cases demonstrates higher shear adhesion than a mixture with 5% biochar indicates that increasing the filler content does not provide a proportional increase in strength. This may be due to:

- incomplete dispersion of biochar at higher concentrations;

- formation of microvoids due to particle agglomeration;
- excessive increase in stiffness, limiting stress redistribution.

Similarly, the additional increase in service life between 2% and 5% does not exceed 5–7%, indicating a decrease in effectiveness as the optimal modifier content is exceeded. Thus, biochar modification improves mechanical properties; however, the relationship is not linear, and a “higher is better” effect is not confirmed.

1. The experimental results confirm the effectiveness of biochar as a modifier; however, the behavior of individual parameters (in particular, softening temperature) indicates the complex nature of the interactions within the system.

2. The data obtained suggest that biochar acts not only as a rigid filler but also as a structural stabilizer of the bitumen colloidal system. However, excessive biochar content may lead to decreased homogeneity and a reduction in performance gains.

3. The optimal concentration for practical use should be considered to be approximately 2%, as it provides a balanced combination of rheological properties and durability of asphalt concrete without any negative effects.

6. Conclusions

The addition of 2–5% biochar to bitumen significantly impacts its rheological properties. Specifically, penetration decreased by 12–25%, indicating increased stiffness; softening point increased by 4–8%; brittleness temperature decreased by 2–4 °C, indicating improved low-temperature properties; and extensibility decreased moderately (by 8–15%), remaining within acceptable regulatory limits. These results quantitatively confirm the structuring effect of biochar on the bitumen matrix.

- Asphalt concrete mixtures with biomodified bitumen demonstrated improved physical and mechanical properties compared to polymer-modified mixtures. Water saturation decreased to 17%, compressive strength increased by 7–14% at 20 °C and by 12–20% at 50 °C, and splitting strength increased by 8–13%. These improvements indicate increased water resistance and load-bearing capacity of the pavement.
- Biochar modification increased resistance to residual (plastic) deformation. Service life before reaching critical rut depth increased by 22–34%, and shear adhesion by 8–18%, confirming increased structural stability of asphalt concrete under high temperatures and dynamic loads.
- Although increasing the biochar content from 2% to 5% provided additional improvements (typically within 3–7% depending on the parameter), the greatest effect was achieved at 2%. This concentration provides an optimal balance between increasing rigidity and maintaining sufficient deformability

of the material.

- Overall, the study quantitatively confirms that biochar is an effective bitumen modifier. The improvements recorded-up to a 20% increase in strength, a 17% reduction in water saturation, and a more than 30% increase in rutting resistance-indicate the potential of using biochar to increase the durability and operational reliability of asphalt concrete pavements.

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