Aliya Suigenbayeva – Candidate of Technical Sciences, Associate Professor, Department of Chemistry and Pharmaceutical Engineering, of M. Auezov South Kazakhstan University, Shymkent, Republic of Kazakhstan; e-mail: syaljo@mail.ru. ORCID: https://orcid.org/0000-0002-9658-5001.

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A. Ualikhanov*, B. Nurzhan, A. Sabitova, Z. Sharipkhan, N. Mukhamediyarov
Shakarim University,
071412, Republic of Kazakhstan, Semey, 20 A Glinka Street
*e-mail: a.a.ualikhanov@gmail.com

HYBRID MODIFICATION OF BITUMEN FOR DURABLE AND SUSTAINABLE ASPHALT PAVEMENTS

Abstract: *Asphalt aging is a critical factor affecting the long-term performance and durability of pavement structures, as it induces complex chemical, rheological, and microstructural transformations in asphalt binders and mixtures. Environmental and mechanical stressors, including temperature, oxygen exposure, ultraviolet radiation, moisture ingress, and traffic loading, accelerate oxidation processes, leading to binder stiffening, embrittlement, and reduced resistance to cracking and moisture damage. In response to increasing environmental concerns and resource limitations, sustainable materials such as reclaimed asphalt pavement, bio-based binders, recycled polymers, and industrial by-products have been increasingly incorporated into asphalt mixtures; however, their influence on aging mechanisms and long-term durability remains insufficiently understood. This study presents a comprehensive literature-based review of asphalt aging mechanisms, sustainable material modification strategies, and durability prediction approaches. A structured multi-stage review methodology was applied to classify and evaluate modification technologies based on performance effectiveness, environmental sustainability, economic feasibility, and applicability under diverse climatic and operational conditions. The review synthesizes experimental and modelling findings on chemical aging processes, microstructural evolution, aggregate – binder interactions, and multiphysics ageing simulations. An integrated conceptual framework linking environmental exposure conditions, material aging mechanisms, microstructural parameters, and rheological performance indicators is proposed to support durability-based and sustainable pavement design. Key research gaps and future research directions are identified, including the need for advanced aging simulation protocols, multiscale characterization approaches, and long-term field validation of sustainable modifiers. The findings of this review provide a scientific basis for developing resilient and environmentally sustainable pavement infrastructure.*

Key words: *modified bitumen, hybrid modification systems, engineered bitumen, recycling, ecology*

Introduction

Asphalt pavements are a fundamental element of modern transportation infrastructure, and their long-term performance is strongly controlled by the aging behavior of asphalt binders and mixtures. Asphalt aging is a complex time-dependent process governed by coupled environmental and mechanical factors, including temperature, oxygen exposure, ultraviolet radiation, moisture ingress, and traffic loading. These factors induce chemical and rheological transformations in asphalt binders, leading to increased stiffness, embrittlement, and reduced resistance to cracking and moisture-related damage, which are among the primary causes of premature pavement deterioration and increased maintenance costs worldwide [1, 2]. Standard laboratory aging protocols, such as the Rolling Thin Film Oven Test (RTFOT) and Pressure Aging Vessel (PAV), are widely used to simulate short-term and long-term aging processes; however, numerous studies have reported significant discrepancies between laboratory-aged and field-aged binders, indicating that current accelerated aging methods do not fully reproduce real service conditions, particularly multiphysics phenomena such as thermal gradients, oxygen diffusion, ultraviolet exposure, and moisture transport through

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pavement layers [3-5]. In recent years, the pavement industry has increasingly adopted sustainable and circular material solutions to reduce greenhouse gas emissions, energy consumption, and reliance on virgin resources. Reclaimed asphalt pavement (RAP), bio-based binders, recycled polymers, and industrial by-products have been incorporated into asphalt mixtures to enhance sustainability and reduce construction costs [6-8]. Although these materials provide considerable environmental and economic benefits, their influence on aging mechanisms, microstructural evolution, and long-term durability remains insufficiently understood, and the interaction between sustainable modifiers and aging processes introduces additional complexity into pavement material behavior. Therefore, this study presents a comprehensive literature-based synthesis of asphalt aging mechanisms, sustainable material modification strategies, and predictive modelling approaches, with the objective of developing an integrated conceptual framework linking chemical aging, microstructural evolution, and rheological performance degradation to support durability-based and sustainable pavement design and to identify critical research gaps and future research directions in asphalt pavement engineering [9, 10].

Methods

The methodological framework of this study is based on a systematic and critical analysis of scientific literature on asphalt aging mechanisms, sustainable modification technologies, and durability prediction approaches. A comprehensive multi-stage review methodology was applied to ensure the completeness, objectivity, and scientific rigor of the analysis.

At the first stage, relevant modification and aging-related approaches were identified and classified according to predefined evaluation criteria. The primary criteria included performance effectiveness, environmental sustainability, economic feasibility, and applicability under diverse climatic and operational conditions. Performance effectiveness was defined as the ability of a modification strategy to improve key mechanical and durability-related properties of asphalt binders and mixtures, including stiffness, cracking resistance, rutting resistance, and fatigue performance. Environmental sustainability was assessed in terms of waste utilization, emission reduction potential, and the use of renewable or recycled materials. Economic feasibility reflected material availability, processing complexity, and scalability for practical implementation. Applicability was considered as the potential of the method to be used across different climatic regions and pavement structures. Based on this classification, the review focused on polymer and rubber modification, bio-based binders, recycled materials, mineral fillers, and studies related to laboratory and field aging of asphalt materials.

At the second stage, the selected approaches were evaluated based on experimental and modelling results reported in peer-reviewed publications. Key factors considered included testing conditions, reported performance indicators, and associated technological effects, such as mixing temperature, aging protocols, and material compatibility. Additionally, the selectivity of modification effects was analyzed, including aging resistance, phase stability, and retention of ductility, and potential trade-offs were documented. For instance, mineral fillers were reported to enhance stiffness but reduce fatigue resistance, rubber modification improved performance at low dosages but caused phase instability at higher contents, bio-based modifiers softened binders but reduced elasticity, while natural asphalt materials provided high residual strength and stability in warm mix technologies.

The final stage involved a comparative synthesis of the reviewed methods to identify advantages, limitations, and potential synergistic combinations. Strengths included improved durability and mechanical performance with polymer and nano-modifiers, environmental benefits associated with bio-based materials and recycled additives, and waste valorization through industrial by-product utilization. Identified limitations included reduced ductility in bio-modified binders, fatigue-related issues in mineral-filled systems, high costs of advanced modifiers, and phase instability at excessive rubber contents. Promising hybrid strategies were also identified, such as combining polymers with nanomaterials to achieve synergistic performance enhancement, integrating mineral and bio-based additives with polymer-modified binders to balance performance trade-offs, and using rejuvenators to mitigate aging and extend pavement service life.

Overall, the methodology adopts an interdisciplinary approach integrating knowledge from materials science, pavement engineering, environmental sustainability, and techno-economic analysis. The reviewed materials were obtained from peer-reviewed journals and international conference proceedings, ensuring the reliability and reproducibility of the synthesized findings. This methodological approach provides a robust basis for evaluating existing asphalt modification strategies and supports the development of conceptual frameworks for durable and sustainable pavement design.

Bitumen Aging and Sustainability Challenges

Asphalt pavements are subjected to continuous environmental and mechanical loading conditions that progressively alter binder properties and reduce the structural integrity and service life of pavement systems. Among various degradation mechanisms, oxidative aging is widely acknowledged as the primary factor responsible for binder hardening, embrittlement, and increased susceptibility to cracking and moisture-related damage. To simulate aging processes in the laboratory, standardized short-term and long-term aging procedures, including the Rolling Thin Film Oven Test (RTFOT) and Pressure Aging Vessel (PAV), have been widely implemented. However, numerous studies have reported that these laboratory protocols cannot fully reproduce the complex aging phenomena occurring in the field, particularly under multifactorial climatic conditions involving ultraviolet radiation, moisture penetration, and oxygen diffusion gradients through pavement layers. This discrepancy between laboratory and field aging highlights the need for improved aging simulation techniques and predictive frameworks that account for environmental exposure and in-service pavement conditions [1-3].

Simultaneously, the pavement industry is experiencing increasing pressure to reduce greenhouse gas emissions, minimize energy consumption, and decrease dependence on virgin raw materials [4]. Consequently, sustainable pavement engineering strategies have increasingly focused on the utilization of reclaimed asphalt pavement (RAP), industrial by-products, bio-based binders, and recycled polymeric materials. RAP has been recognized as one of the most promising sustainable alternatives due to its significant economic and environmental advantages; however, the presence of highly aged binder in RAP can substantially influence mixture rheology and performance characteristics. In addition, bio-based binders, including bio-oils and lignin, along with waste-derived modifiers, have been proposed as renewable substitutes for conventional petroleum-based binders, offering potential reductions in carbon footprint and production energy requirements. Nevertheless, the incorporation of these sustainable materials introduces additional complexity in binder aging behavior, chemical interactions, and mechanical performance, thereby necessitating advanced characterization techniques, mechanistic design approaches, and performance-based evaluation frameworks [5, 6].

Chemical and Rheological Mechanisms of Asphalt Aging

Recent advances in asphalt research have substantially improved the understanding of aging mechanisms through the combined application of chemical, microstructural, and rheological characterization techniques [7]. Aging has been associated with significant compositional transformations within the SARA fractions, characterized by a gradual conversion of aromatic components into more polar resins and asphaltenes, leading to increased molecular weight and polarity of the binder system. Fourier transform infrared (FTIR) spectroscopy has been extensively employed to quantify oxidative aging through carbonyl and sulfoxide functional group indices, which have been shown to exhibit strong correlations with aging severity and degradation of mechanical performance properties [8, 9].

Microstructural studies using atomic force microscopy (AFM) and time-of-flight secondary ion mass spectrometry (TOF-SIMS) have revealed pronounced morphological changes in binder microstructure during aging, including the evolution of characteristic «bee-like» structures, phase separation, and heterogeneity development, particularly in wax-containing binders. These microstructural transformations are closely linked to changes in binder rheology and durability [10-12].

Rheological investigations have demonstrated that aging leads to an increase in complex shear modulus and a reduction in phase angle, indicating a shift toward more elastic and brittle material behavior [13]. To bridge the gap between chemical aging and mechanical performance, chemo-mechanical correlations linking oxidation indices with rheological parameters have been proposed as predictive tools for durability assessment and performance-based binder evaluation. Nevertheless, conventional laboratory aging protocols frequently produce comparable aging levels across different binders, which limits their ability to capture binder-specific aging susceptibility associated with crude oil source, molecular structure, and chemical composition. This limitation highlights the necessity for advanced aging simulation techniques capable of differentiating material-specific aging behavior and improving long-term performance prediction [14-16].

Field Aging versus Laboratory Aging

Comparative investigations of field-aged and laboratory-aged asphalt binders have consistently revealed pronounced differences in oxidation levels, rheological behavior, and mechanical performance characteristics. Binders extracted from in-service pavements typically exhibit substantially higher stiffness, oxidation indices, and molecular transformation levels than those aged using conventional Pressure Aging Vessel (PAV) procedures, even after extended aging cycles. These discrepancies are primarily attributed to the complex environmental exposure conditions experienced in the field, including ultraviolet radiation, moisture ingress, oxygen diffusion gradients, and temperature fluctuations across pavement layers, which are not fully replicated by standard laboratory aging protocols [17-19].

To better approximate field aging behavior, advanced laboratory simulation techniques have been proposed, including extended PAV conditioning, reactive oxygen species (ROS)-based aging, and diffusion-reaction ageing models that incorporate oxygen transport and reaction kinetics. Although these approaches improve the representation of oxidative aging mechanisms, achieving quantitative equivalence between laboratory-aged and field-aged binders remains challenging due to the inherently multiphysics nature of pavement aging processes [20, 21].

Recent multiphysics modelling frameworks integrating heat transfer, oxygen diffusion, and oxidation kinetics have demonstrated enhanced capability in predicting aging gradients, oxidation profiles, and durability evolution throughout pavement depth. These models provide a mechanistic understanding of coupled environmental and material interactions and highlight the limitations of simplified single-physics aging simulations. Consequently, the development of next-generation aging protocols and predictive frameworks that incorporate environmental exposure, pavement structural characteristics, and binder material properties is essential for accurate long-term performance prediction and durability-based pavement design [22-24].

Sustainable Modifiers and Recycled Materials in Asphalt Systems

The literature widely documents the integration of recycled and bio-based materials in asphalt pavements as an effective strategy to enhance environmental sustainability and mechanical performance. Reclaimed asphalt pavement (RAP) has been extensively implemented in hot mix asphalt due to its significant economic and ecological advantages, including reduced consumption of virgin materials and lower production costs. However, high RAP contents have been reported to increase mixture stiffness and susceptibility to cracking, which necessitates the use of rejuvenators and careful binder selection to restore aged binder properties and achieve balanced mixture performance [25, 26].

In addition, bio-based modifiers, such as bio-oils and lignin, have been proposed as renewable alternatives or supplements to petroleum-based binders [27]. These materials have demonstrated the ability to improve binder workability, reduce mixing and compaction temperatures, and influence aging resistance depending on their dosage, molecular structure, and chemical composition. Despite their sustainability benefits, the performance of bio-based materials remains highly formulation-dependent, and their long-term durability under field conditions is still insufficiently understood [28-31].

Waste plastics, crumb rubber, and industrial by-products have also been incorporated into asphalt mixtures to enhance high-temperature performance and promote circular economy practices. Plastomeric and elastomeric modifiers have been shown to increase hybrid resistance, dynamic modulus, and mixture stiffness, thereby improving performance under heavy traffic and elevated temperatures. However, excessive polymer content may adversely affect low-temperature cracking resistance, highlighting the need for optimized formulation and performance-based mixture design [32].

Furthermore, industrial waste materials, including blast furnace slag, fly ash, and recycled glass, have demonstrated potential to improve mechanical performance while reducing environmental impacts. Nevertheless, variability in material properties, potential leaching of hazardous constituents, and uncertainties in long-term performance necessitate systematic characterization, environmental risk assessment, and life-cycle assessment (LCA) methodologies prior to large-scale implementation. Overall, these findings confirm that recycled and bio-based materials offer significant opportunities for sustainable pavement engineering, but their successful application requires integrated material design frameworks and rigorous performance evaluation strategies [33-35].

Aggregate Structure and Microstructural Performance Mechanisms

Aggregate structure has been widely recognized as a governing factor in asphalt mixture performance, as aggregates represent approximately 90-95% of the total mixture mass and form the primary load-bearing skeleton of pavement layers. Consequently, the mechanical response of asphalt mixtures is strongly controlled by aggregate characteristics, including mineralogical composition, particle size distribution, and packing structure [36, 37]. Rheology-based methodologies have been increasingly applied to quantify asphalt-aggregate interactions, demonstrating that aggregate mineral composition significantly affects adhesive bonding, interfacial chemistry, and viscoelastic behavior of asphalt mastics. For instance, calcium-rich fillers have been reported to exhibit stronger physico-chemical interactions with asphalt binders compared to silica-based fillers, resulting in enhanced stiffness, adhesion, and overall mechanical performance of asphalt mixtures [38, 39].

Recent advances in microstructural characterization have provided deeper insights into the internal structure of asphalt mixtures and its role in deformation and cracking mechanisms. Image-based techniques and discrete element modelling (DEM) have revealed that aggregate contact orientation, coordination number, and spatial distribution of mortar film thickness are critical microstructural parameters governing rutting and cracking behavior. Furthermore, the internal structural evolution of asphalt mixtures under repeated traffic loading has been shown to significantly influence load transfer mechanisms and damage accumulation processes. Analytical frameworks describing aggregate packing states, such as coarse pack, dense pack, and fine pack structures, offer quantitative tools for optimizing mixture gradation, predicting mechanical performance, and enhancing durability [40, 41].

These findings underscore the necessity of adopting multi-scale characterization approaches that integrate microstructural analysis with macroscopic mechanical testing. Linking aggregate-scale structural parameters to mixture-level rheological and fracture properties is essential for developing performance-based mixture design methodologies and improving the predictive capability of pavement durability models [42-44].

Modelling and Performance Prediction of Pavement Aging

Multiphysics modelling frameworks have been developed to simulate the progression of asphalt aging across pavement depth and over service time by integrating coupled thermal transport, oxygen diffusion, and oxidation reaction kinetics. These advanced models have demonstrated the capability to predict temperature distributions, oxygen concentration gradients, and the formation of oxidation products within pavement layers, and have been validated using field measurements and FTIR-based oxidation indices. Such frameworks confirm that asphalt aging is governed by interacting environmental and material processes, including heat transfer, oxygen ingress, and chemical reaction kinetics, which cannot be adequately captured by simplified single-physics ageing simulations. Consequently, multiphysics approaches provide a mechanistic basis for understanding aging gradients and for improving the reliability of long-term pavement performance prediction models [45, 46]

In parallel, mixture-based rheological evaluation methods have been proposed to assess cracking resistance and aging susceptibility at the mixture scale. Approaches such as Black space analysis and the Glover – Rowe parameter incorporate both stiffness and stress relaxation characteristics, enabling a more comprehensive representation of viscoelastic behavior compared to conventional binder-based indices [47]. Previous studies reported strong correlations between mixture-based rheological parameters and fracture-based performance indicators, demonstrating their potential for predicting cracking initiation and damage evolution. Furthermore, the integration of rheological master curves into performance-based mixture design frameworks has been recognized as a promising strategy for quantifying durability and supporting mechanistic-empirical pavement design [48]. Nevertheless, the application of these rheological indicators in routine design practice remains limited, and further research is required to establish standardized thresholds and field-validated performance criteria [49, 50].

Future Directions

Despite substantial progress in asphalt materials research, several critical knowledge gaps remain that limit the accuracy of durability prediction and the implementation of sustainable pavement technologies. Existing laboratory aging protocols, including RTFOT and PAV, do not adequately reproduce the combined effects of ultraviolet radiation, moisture ingress, and oxygen diffusion gradients that occur under real field conditions. As a result, laboratory-aged binders often fail to capture the complex multiphysics aging mechanisms and spatial aging gradients observed in in-service pavements.

In addition, the long-term field performance of bio-based and waste-derived modifiers remains insufficiently documented. Although numerous laboratory studies have demonstrated promising mechanical and environmental benefits, the lack of long-term field validation and standardized performance evaluation frameworks hinders their widespread implementation. Moreover, the interactions among aggregate microstructure, binder aging processes, and mixture-level mechanical performance are not fully incorporated into current mechanistic-empirical pavement design methodologies. This limitation restricts the ability to predict performance based on microstructural and chemo-mechanical parameters.

Future research should prioritize the development of integrated aging simulation protocols that combine thermal, oxidative, ultraviolet, and moisture-related mechanisms. Multiscale characterization approaches linking molecular-scale transformations, microstructural evolution, and macroscopic mechanical performance are required to establish mechanistic durability models. Furthermore, multiphysics predictive frameworks that incorporate environmental, structural, and material properties should be integrated into performance-based pavement design methodologies. The establishment of unified durability frameworks that couple environmental exposure, material aging, and mechanical response represents a critical step toward next-generation resilient and sustainable pavement infrastructure.

Conceptual Framework

Based on the reviewed literature, an integrated conceptual framework is proposed to describe the coupled mechanisms governing asphalt aging and pavement durability under sustainable material scenarios. The framework links environmental exposure conditions, binder chemical aging processes, microstructural evolution of asphalt mixtures, and mechanical performance degradation across multiple spatial and temporal scales.

The conceptual model integrates key environmental drivers, including temperature, oxygen diffusion, ultraviolet radiation, and moisture ingress, with material-level aging mechanisms such as oxidation, molecular restructuring, and phase separation. At the microstructural level, aggregate packing structure, mortar film thickness distribution, and binder-aggregate interfacial interactions are incorporated as controlling parameters influencing stress distribution, crack initiation, and deformation mechanisms.

Furthermore, the framework incorporates rheological indicators (e.g., complex modulus, phase angle, Glover-Rowe parameter) and multiphysics modelling outputs (e.g., temperature gradients, oxygen concentration profiles, oxidation kinetics) to predict aging progression and durability evolution across pavement depth. Sustainable modifiers, including bio-based binders, recycled polymers, and industrial by-products, are embedded into the framework to evaluate their effects on aging resistance and long-term performance.

This integrated conceptual framework provides a holistic basis for performance-based pavement design and durability prediction, bridging the gap between material science, pavement engineering, and sustainability assessment.

Limitations of the Review

This review is subject to several limitations that should be acknowledged. First, the study is based exclusively on previously published laboratory, field, and modelling investigations and does not include original experimental validation. Consequently, the conclusions rely on the accuracy and consistency of reported data, which may vary due to differences in materials, testing protocols, and environmental conditions across studies.

Second, variations in binder source, aggregate properties, aging procedures, and characterization techniques may affect the comparability of reported results and introduce uncertainty in the synthesis. In particular, discrepancies between laboratory and field aging conditions and the lack of standardized evaluation protocols for sustainable modifiers limit the ability to derive universal conclusions.

Third, the review primarily focuses on technical and mechanistic aspects of asphalt aging and does not comprehensively address economic, social, and policy dimensions of sustainable pavement implementation. Nevertheless, the synthesized findings provide a comprehensive state-of-the-art overview of asphalt aging mechanisms, sustainable material modification strategies, and predictive modelling approaches, and identify critical research gaps for future experimental and field investigations.

Conclusion

This study provides a comprehensive literature-based synthesis of asphalt aging mechanisms, sustainable material modification strategies, and durability prediction approaches for modern pavement engineering. The review demonstrates that asphalt aging is governed by coupled chemical, rheological, and microstructural processes, which are strongly influenced by environmental exposure conditions, material composition, and pavement structural characteristics. Significant discrepancies between laboratory and field aging highlight the limitations of conventional accelerated aging protocols and the necessity for advanced simulation frameworks that incorporate multiphysics environmental interactions.

The analysis confirms that sustainable materials, including reclaimed asphalt pavement, bio-based binders, recycled polymers, and industrial by-products, offer substantial environmental and economic benefits but introduce additional complexity in aging behavior and long-term performance. While polymer and nanomaterial modifiers enhance stiffness and durability, bio-based and recycled materials present trade-offs between sustainability, ductility, and fatigue resistance, requiring optimized hybrid modification strategies. Aggregate structure and microstructural parameters, such as packing characteristics and mortar film thickness, were identified as critical factors governing mechanical performance and cracking susceptibility.

Furthermore, multiphysics modelling and mixture-based rheological indicators were shown to provide promising tools for predicting aging gradients and pavement durability. Based on the synthesized findings, an integrated conceptual framework linking environmental drivers, material aging mechanisms, microstructural evolution, and mechanical performance was proposed to support performance-based and sustainable pavement design.

Future research should focus on developing standardized aging protocols that better replicate field conditions, long-term field validation of sustainable modifiers, and multiscale characterization approaches integrating microstructural and mechanical performance indicators. The integration of mechanistic durability models with sustainability assessment frameworks represents a critical step toward the development of resilient and environmentally sustainable pavement infrastructure.

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А. Уалиханов*, Б. Нұржан, А. Сабитова, Ж. Шәріпхан, Н. Мухамедияров
Шәкәрім университет,
071412, Республика Казахстан, г. Семей, ул. Глинки, 20 А
*e-mail: a.a.ualikhanov@gmail.com

ГИБРИДНАЯ МОДИФИКАЦИЯ БИТУМА ДЛЯ ДОЛГОВЕЧНЫХ И УСТОЙЧИВЫХ АСФАЛЬТОБЕТОННЫХ ПОКРЫТИЙ

Старение асфальта является критическим фактором, влияющим на долговременные эксплуатационные характеристики и долговечность дорожных покрытий, поскольку оно вызывает сложные химические, реологические и микроструктурные преобразования в битумных вяжущих и асфальтобетонных смесях. Экологические и механические воздействия, включая температуру, воздействие кислорода, ультрафиолетовое излучение, проникновение влаги и транспортные нагрузки, ускоряют процессы окисления, что приводит к увеличению жесткости вяжущего, его охрупчиванию и снижению сопротивления растрескиванию и влагоразрушению. В ответ на возрастающие экологические ограничения и дефицит ресурсов устойчивые материалы, такие как регенерированный асфальтобетон (RAP), био-вяжущие, переработанные полимеры и промышленные побочные продукты, все чаще внедряются в асфальтобетонные смеси; однако их влияние на механизмы старения и долговременную долговечность остается недостаточно изученным. В данном исследовании представлен комплексный обзор литературы, посвященный механизмам старения асфальта, стратегиям модификации с использованием устойчивых материалов и подходам к прогнозированию долговечности. Для классификации и оценки технологий модификации была применена структурированная многоэтапная методология обзора, основанная на критериях эксплуатационной эффективности, экологической устойчивости, экономической целесообразности и применимости в различных климатических и эксплуатационных условиях. В обзоре синтезированы экспериментальные и моделирующие результаты, касающиеся химических процессов старения, эволюции микроструктуры, взаимодействия заполнителя и вяжущего, а также многофизических моделей старения. Предложена интегрированная концептуальная модель, связывающая условия внешнего воздействия, механизмы старения материала, микроструктурные параметры и реологические показатели для поддержки проектирования долговечных и устойчивых дорожных покрытий. Выявлены ключевые научные пробелы и направления дальнейших исследований, включая необходимость разработки усовершенствованных протоколов моделирования старения, многоуровневых методов характеризации и долгосрочной полевой валидации устойчивых модификаторов. Результаты данного обзора создают научную основу для разработки устойчивой и долговечной дорожной инфраструктуры.

Ключевые слова: *модифицированный битум, гибридные системы модификации, инженерный битум, переработка, экология№*

А. Уалиханов*, Б. Нұржан, А. Сабитова, Ж. Шәріпхан, Н. Мухамедияров
Шәкәрім университеті,
071412, Қазақстан Республикасы, Семей қ., Глинки к-сі, 20 А
*e-mail: a.a.ualikhanov@gmail.com

БИТУМДЫ ГИБРИДТІ МОДИФИКАЦИЯЛАУ: ҰЗАҚ МЕРЗІМДІ ЖӘНЕ ТҰРАҚТЫ АСФАЛЬТБЕТОН ЖАБЫНДАРЫ ҮШІН

Асфальттың қартаюы жол жабынының ұзақ мерзімді пайдалану сипаттамалары мен беріктігіне әсер ететін негізгі фактор болып табылады, өйткені ол битумды байланыстырғыштар мен асфальтобетон қоспаларында күрделі химиялық, реологиялық және микроструктуралық өзгерістерге әкеледі. Температура, оттегінің әсері, ультракүлгін сәулелену, ылғалдың енуі және көлік жүктемелері сияқты экологиялық және механикалық факторлар тотығу процестерін жеделдетіп, байланыстырғыштың қаттылығының артуына, морттанып кетуіне және жарықшақтарға және ылғал әсерінен бұзылуға төзімділіктің төмендеуіне әкеледі. Қоршаған ортаға қойылатын талаптардың күшеюіне және ресурстардың шектелуіне байланысты регенерацияланған асфальтобетон (RAP), био-негізді байланыстырғыштар, қайта өңделген полимерлер және өнеркәсіптік қалдық өнімдер сияқты тұрақты материалдар асфальтобетон қоспаларына кеңінен енгізілуде; алайда олардың қартаю механизмдеріне және ұзақ мерзімді беріктікке әсері әлі толық зерттелмеген.Бұл зерттеуде асфальттың қартаю механизмдері, тұрақты материалдармен модификациялау стратегиялары және беріктікті болжау тәсілдері бойынша әдебиеттерге кешенді шолу ұсынылған. Модификациялау технологияларын жіктеу және бағалау үшін пайдалану тиімділігі, экологиялық тұрақтылық, экономикалық тиімділік және әртүрлі климаттық және пайдалану жағдайларында қолдану мүмкіндігі критерийлеріне негізделген құрылымдалған көпсатылы шолу әдістемесі қолданылды. Шолуда химиялық қартаю процестері, микроструктураның эволюциясы, толтырғыш пен байланыстырғыштың өзара әрекеттесуі және көпфизикалық қартаю модельдері бойынша эксперименттік және модельдеу нәтижелері синтезделді. Қоршаған орта әсері жағдайларын, материалдың қартаю механизмдерін, микроструктуралық параметрлерді және реологиялық көрсеткіштерді байланыстыратын интеграцияланған тұжырымдамалық модель ұсынылды, ол берік және тұрақты жол жабындарын жобалауды қолдауға арналған. Қартаюды модельдеудің жетілдірілген протоколдарын әзірлеу, көпдеңгейлі сипаттау әдістері және тұрақты модификаторларды ұзақ мерзімді далалық валидациялау қажеттілігі сияқты негізгі ғылыми олқылықтар мен болашақ зерттеу бағыттары анықталды. Осы шолудың нәтижелері тұрақты және ұзақ мерзімді жол инфрақұрылымын дамыту үшін ғылыми негіз болып табылады.

Түйін сөздер: *модификацияланған битум, гибридті модификациялау жүйелері, инженерлік битум, қайта өңдеу, экология№*

Сведение об авторах

Асылан Айдинович Уалиханов* – докторант кафедры «Химия и экология», Шәкәрім университет, город Семей, Республика Казахстан; e-mail: icetea3221337@gmail.com. ORCID: https://orcid.org/0009-0002-0405-1027.

Нұржан Бекарыс – студент ОП 6В05301 кафедры «Химия и экология», Шәкәрім университет, город Семей, Республика Казахстан; e-mail: nurzanbekarys2007@gmail.com.

Альфира Нуржановна Сабитова – Шәкәрім университет, PhD, заведующий кафедрой «Химия и экология», Семей, Казахстан. ORCID: https://orcid.org/0000-0002-3360-7998.

Жанна Шәріпханқызы Шәріпхан – докторант кафедры «Химия и экология», Шәкәрім университет, город Семей, Республика Казахстан. ORCID: https://orcid.org/0000-0002-2484-7287.

Нурлан Мухамедияров – докторант кафедры «Химия и экология», Шәкәрім университет, город Семей, Республика Казахстан. ORCID https://orcid.org/0000-0001-5073-5978.

Авторлар туралы мәліметтер

Асылан Айдинович Уалиханов* – «Химия және экология» кафедрасының докторанты, Шәкәрім университеті, Қазақстан Республикасы; e-mail: icetea3221337@gmail.com. ORCID: https://orcid.org/0009-0002-0405-1027.

Нұржан Бекарыс – «Химия және экология» кафедрасының 6В05301 ОБ студенті, Шәкәрім университеті, Қазақстан Республикасы; e-mail: nurzanbekarys2007@gmail.com.

Альфира Нұржанқызы Сабитова – Шәкәрім университет, PhD, «Химия және экология» кафедрасының меңгерушісі, Семей, Қазақстан; e-mail: alfa-1983@mail.ru. ORCID: https://orcid.org/0000-0002-3360-7998.

Жанна Шәріпханқызы Шәріпхан – «Химия және экология» кафедрасының докторанты, Шәкәрім университеті, Қазақстан Республикасы. ORCID: https://orcid.org/0000-0002-2484-7287.

Нурлан Мухамедияров – «Химия және экология» кафедрасының докторанты, Шәкәрім университеті, Қазақстан Республикасы. ORCID https://orcid.org/0000-0001-5073-5978.

Information about the authors

Asylan Ualikhanov* – PhD student at the Department of «Chemistry and Ecology», Shakarim University, Republic of Kazakhstan; e-mail: icetea3221337@gmail.com. ORCID: https://orcid.org/0009-0002-0405-1027.

Nurzhan Bekarys – student of the EP 6B05301, Department of «Chemistry and Ecology», Shakarim University, Republic of Kazakhstan; e-mail: nurzanbekarys2007@gmail.com.

Alfira Sabitova – Shakarim University, PhD, head of the department «Chemistry and ecology», Semey, Kazakhstan; e-mail: alfa-1983@mail.ru. ORCID: https://orcid.org/0000-0002-3360-7998.

Zhanna Sharipkhan – PhD student at the Department of «Chemistry and Ecology», Shakarim University, Republic of Kazakhstan. ORCID: https://orcid.org/0000-0002-2484-7287.

Nurlan Mukhamediarov – PhD student at the Department of «Chemistry and Ecology», Shakarim University, Republic of Kazakhstan. ORCID https://orcid.org/0000-0001-5073-5978.

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