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Future of Asphalt Development: A Review of Sustainable Additives and Advanced Technologies for Enhanced Asphalt Performance

Hussein Hatem Meteab*, University of Anbar, Iraq
Amal Shakir Abbood, University of Anbar, Iraq
Ghufran Hamed Nail, University of Anbar, Iraq.

ABSTRACT

The focus of this paper is the use of additives that improve bitumen and filler properties in asphalt mixes, which are analysed as advances in feature modification for performance enhancement. Novel fillers (calcite, quartz, soil types, liquid sulphur and Gil Sonite) as well as conventional ones and polymeric additions are considered. It also discusses the use of both natural and recycled rubber as well as cutting-edge materials such as graphene oxide, biochar, and phase-change materials.Techniques that support sustainable practices are given special attention, with waste-based materials such as used cooking oil waste, RA (reclaimed asphalt) mixtures with RAP (recycled asphalt pavement), ceramic fibers and waste motor oil. The report also considers potential modern approaches, such as microwave radiation and synthetic fibers, to make asphalt more durable and efficient. This paper provides an indepth review of these developments and a discussion on the impact they could have in changing the face of the asphalt industry is presented by profiling some of the R&D ongoing practices. Outlook is discussed including automated maintenance systems, digital devices for improving asphalt production, and self-healing asphalt. The description and analysis of the current state- of -the-art, and potential future directions for asphalt modification developed in the report are also intended to help researchers, engineers, and policy -makers design more durable, effective p avement systems. Al these parties may acquire knowledge of current and near future applied sciences with potential impact on construction and maintenance of the road infrastructure by this evaluation.

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***CORRESPONDENCE AUTHOR**

husenhatam86@uoanbar.edu.iq

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1. INTRODUCTION

Asphalt is critical to the world's infrastructure and is used to pave roads, which boosts transportation and encourages economic growth. But traditional asphalt from which the pitches are made, and which is derived mostly from petroleum has a litany of drawbacks given increasingly urgent demands for sturdier and more ecologically sensitive products. Common bitumen is susceptible to oxidation deterioration, high temperature variation, and deformation under the repetitive traffic load, which reduces pavement life cycle and increases maintenance cost.

Recent advancements in materials have offered an alternative to address these issues. These comprise: nanotechnology; microwave-assisted modification; self-healing asphalt systems; and eco-sensitive additives from biomass, recycled polymers, and industrial wastes.

The objective of this paper is to give an extensive account about the latest development in environmentally friendly modification of asphalt, highlighting possible benefits provided by new technologies with regard to technical performance, economy and ecology impact. This review is original as it compares the performances of additives and focuses on sustainable materials relevant to global decarbonization goals.

The word "asphalt" comes from the Greek word "asphaltos" which means "secure," and the Sanskrit word "bitumen," which means "pitch creating." In the past, it was initially applied to roofing and sealing ship hatches to stop water leaks. The Oxford English Dictionary and the American Society for Testing and Materials (ASTM) describe asphalt as a mixture of hydrocarbons derived from oil, either naturally or by distillation (Forbes, 2024).

The substance varies in color from dark black to brown, depending on the oil components. As stated in the American Heritage Dictionary, asphalt can be either solid or semi-solid. This brown-black material is produced either spontaneously from crude oil waste or as a byproduct of fractional oil distillation. The viscosity, or colloidal nature, of asphalt changes with temperature and time. The polymeric network of asphalt is temperature-dependent: it behaves as a viscous liquid at high temperatures, a flexible solid at low temperatures, and exhibits both viscous and elastic qualities at moderate temperatures. Asphalt can come from natural sources, such as lakes and asphalt springs, or artificial sources, such as crude oil refining towers (Yan et al., 2024). Asphalt is primarily composed of hydrocarbons, including paraffinic compounds, naphthenic compounds, and aromatic compounds. Paraffinic compounds are saturated straight chains with the general formula C_nH_{2n+2}. Naphthenic compounds are saturated cyclic compounds with the formula C_nH_{2n}. Aromatic compounds are closed unsaturated rings with the general formula C_nH_{2n-6}. Lighter crude oils contain more paraffinic compounds and may also include cyclic or non-cyclic compounds containing nitrogen, sulfur, and oxygen. In contrast, heavier crude oils tend to have higher concentrations of aromatic compounds (Boranbayeva et al., 2024). These elements are believed to contribute to some of the polar characteristics found in asphalt. Trace amounts of iron, vanadium, and nickel are also present. Organic solvents like dye and chloroform can disintegrate asphalt. Asphalt generally consists of the following components: Key Components of Asphalt: Maltenes: Maltenes are a mixture of saturated hydrocarbon compounds and aromatic compounds, which may additionally include heterocyclic aromatic compounds that dissolve in hexane. They possess a molecular weight of approximately 1000 g/mol and are significantly less solid than the asphalt from which they originate. Maltenes make up approximately 5-20% of asphalt's total weight.

Asphaltenes are known as brittle, non-crystalline solids with a dark brownish-black color. They have a molecular weight ranging from 5000 to 20000 g/mol and make up about 5-25% of the asphalt's weight. Asphaltenes no longer dissolve in everyday pentane or heptane; however, they do dissolve in certain organic solvents. Their structure is composed of a multitude of different parts. There are thousands of different scented compounds, long chains of aliphatic compounds, heteroatoms (like Sulphur, nitrogen, and oxygen), and a lot of heavy metals (Primerano et al., 2024).

Asphaltenes do not soften in conventional pentane or heptane, although they do dissolve in several organic solvents. They have a very complex shape that comprises masses of aromatic compounds, lengthy aliphatic chains, heteroatoms (Sulphur, nitrogen, and oxygen), and massive amounts of heavy metals (vanadium and nickel). Asphaltenes also contain carbenes, which dissolve in carbon disapplied but no longer in carbon tetrachloride and are considered heavier than asphaltene. Typically, the concentration of carbenes in asphalt is zero. Normally, the concentration of carbenes in asphalt is 2% or less, but extreme oxidation situations can cause it to rise. The high carbon content of the material and its resistance to dissolution in carbon disulphide distinguish carbides, another element of asphalt. Certain types of asphalt with a high cracking tendency can contain up to 2% carbohydrate. Carbenes and carboids are heavier than asphaltenes, so they dissolve in carbon disulphide rather than carbon tetrachloride. The predominantly distinguishing features of carboids are their (i) highly carbon oriented nature and (ii) their resistance to being dissolved, when compared to other constituents of asphalt. The knowledge of the composition and properties of these constituents is important to enhance global performance and resistance of asphalt in some kind of packages as building floors, avenues construction, roofing (Paczuski, 2024; Satayeva et al., 2024).

2. RESEARCH-METHODOLOGY

2.1 Type of Research

This study uses a methodical approach to literature analysis based on peer-reviewed publications that were indexed in Scopus, ScienceDirect, and Google Scholar between 1973 and 2024. By categorizing the collected studies based on the kind of additive used mineral fillers, polymers, nanomaterials, recycled wastes, and bio-based modifiers mechanical, rheological, and environmental performance results were investigated.

2.2 Research Target

This study uses a methodical approach to literature analysis based on peer-reviewed publications that were indexed in Scopus, ScienceDirect, and Google Scholar between 1973 and 2024. By categorizing the collected studies based on the kind of additive used mineral fillers, polymers, nanomaterials, recycled wastes, and bio-based modifiers mechanical, rheological, and environmental performance results were investigated.

2.3 Procedure

This research procedure was carried out through several stages that were systematically arranged to ensure a comprehensive and unbiased literature analysis related to the use of sustainable additives in asphalt modification.

1. Data collection: Compiling research articles about sustainable additives and asphalt modification.
2. Comparative Evaluation: To find performance trends, studies are grouped by nation, additive kind, and test technique.
3. Trend Analysis: Showcasing the development of research from early mineral modifiers to contemporary nano-enhanced and self-healing materials.

4. This methodical methodology guarantees an unbiased evaluation of worldwide research advancements and their consequences for sustainable pavement engineering.

2.4 Data, Instruments, and Data Collection Techniques

We evaluate the properties of the asphalt and determine its quality through various methodologies and techniques. Several techniques are employed in these operations.

1. Marshall Test:

The Marshall test is used to evaluate the stability and flowability of asphalt mixes. In order to assess a cylindrical specimen's resistance to deformation and load-carrying capability, it is pulled at a particular temperature. The Marshall ratio, which is calculated by dividing the highest load by the specimen's weight unit, is one of the test's required characteristics. "Flow" refers to the density at which the specimen deforms under the applied stress, whereas "practical density" represents the interior density of the compacted specimen. To evaluate the quality and performance of pavement, this measurement is used, which allows us to know the stability, which represents the maximum load that the specimen can bear before it fails (Araz et al., 2023).

2. Softening Point:

Under constant conditions, the softening point is known as the onset of thermal shrinkage and softening. To make asphalt suitable for areas with high temperatures, it must have a high viscosity so that it can withstand high temperatures before it begins to cure. People often use the ring and ball method to determine the curing range. This method involves heating the asphalt sample until the steel ball reaches a predetermined penetration distance of approximately 8 inches (Weiwei et al., 2020).

3. Tensile Strength:

"Tensile strength" refers back to the functionality of asphalt concrete to face up to anxiety or pulling forces without breaking. This assets is crucial for pavement materials to withstand the burden of cars and environmental stresses efficaciously. Use tests consisting of the Semi-Circular Bending (SCB) test and the oblique tensile power (ITS) to check the tensile electricity of bituminous concrete, that is crucial for the durability and resilience of pavements (Sarsam, 2022).

4. Penetration Test:

The penetration test indicates the depth to which a standard needle penetrates an asphalt specimen under known conditions. Traditionally, it is possible to see penetration since 5s although not images are fully visible. Even if more sophisticated techniques have been applied to in depth study the penetration system (e.g., high-speed camera analyses, FEM modeling), they are performed on a complete scale and thus cannot be used for every kind of investigation since different components are involved to different extent to the overall asphalt deformation behavior (Ye et al., 2020).

5. Durability Test:

Durability tests are used to evaluate how well asphalt performs in harsh environments. Extreme environmental activity is simulated by subjecting asphalt samples to a few cycles of contaminated water, often rainfall and old car oil. This testing becomes essential for these asphalt materials' long-term stability (K. N. Kim & Le, 2023).

6. Viscosity Test:

Viscosity readings are essential to determine the asphalt tendency of flow or deformation. We also examine the effect of temperature and paving condition on viscosity-modified asphalt in our tests such as PI, PVN, VTS, GTS and CNI exclusive to us. These reviews offer great insights in regards to the general performance of this blanket over a wide range of temperatures (Zhou & Chen, 2023).

7. Indirect Tension Test:

In addition to preventing problems with direct tension testing, such as specimen separation and inner cracking, the indirect tension test evaluates the strength of the bonds between the layers of asphalt pavement. This analysis uses a mechanical model and stress superposition to compute oblique tensile strength using the elastic principle. Tensile stress is applied to the specimen, primarily at low temperatures, to verify the accuracy of the finished technique and test the resulting strength.(Q. Zhang et al., 2021).

8. Cracking Resistance:

Cracking resistance is the asphalt's potential to stand as much as the formation and propagation of cracks beneath various conditions. This belongings is essential for preserving asphalt surfaces tough and structurally sound. We compare the cloth's resistance to cracking through checks that simulate exclusive climatic and stress situations (P. Li et al., 2023).

9. Freeze-Thaw Test:

The ability of asphalt mixes to be repeatedly frozen and thawed is assessed using the freeze-thaw test. In a range of regions where temperatures fluctuate periodically, this kind of testing is essential for determining baseline fabric performance. Asphalt's resilience to multiple freeze-thaw cycles is tested over time (Yongchun et al., 2023)..

10. Rutting Resistance:

A high-traffic facility may also subject the asphalt surface to rutting (permanent deformation) by saturation; a resistance of the material to tackdown imparted thereby is called rutting resistance. A characteristic that must be preserved in order to guarantee the safety and performance of the pavement. We assess the rutting resistance at different loadings as a further proof that the asphalt is stable and can be used . Such testing technologies serve to develop & maintain high quality pavements through a thorough understanding of the performance and characteristics of asphalt. Additionally, through achieving high strength and high demand for the asphalts products, these processes assist in building a durable system (Rajan et al., 2023).

3. RESULTS AND DISCUSSION

3.1 Improving the applied properties of asphalt

Since natural asphalt cannot be used for paving in its original state, it is undergoing processes of upgrading. It is feasible to improve the specifications of asphalt in all of its forms, whether natural or blended, while looking at the techniques for developing and improving the applied qualities of asphalt. A review and comparison table of several researchers who have made different improvements to asphalt may be seen below.

Tabel 1: Comparison Table

Reference	Country	Year	Type of Additive	Tests Performed	Conclusion
(Anderson & Goetz, 1973)	USA	1973	Mineral fillers	Mechanical behavior and reinforcement	Enhanced mechanical properties of asphalt mixtures with mineral fillers
(Hoover, 1973)	USA	1973	Not specified	Surface improvement, dust palliation	Effective surface improvement and dust palliation for unpaved roads
(Saylak et al., 1975)	USA	1975	Sulfur	Mechanical behavior, performance analysis	Sulfur can be beneficially used in asphalt pavements to improve performance
(Verga et al., 1975)	Saudi Arabia	1975	Carboxylated SBR elastomer	Viscoelastic parameters	Carboxylated SBR elastomer enhances asphalt cement properties
(Majidzadeh, 1976)	USA	1976	Not specified	Fracture mechanics	Application of fracture mechanics improves the design of bituminous concrete
(Huff & Vallerga, 1979)	USA	1979	Reclaim and crumb rubber	Characteristics, performance analysis	Asphalt-rubber materials containing reclaim and crumb rubber show improved performance
(Gupta & Aggarwal, 1980)	USA	1980	Asphalt subsurface barrier	Productivity analysis	Asphalt subsurface barrier improves productivity of desert sandy soils
(Cheetham et al., 1980)	Canada	1980	Sulfur	Structural analysis	Improved characterization of sulfur asphalt materials for structural analysis
(Vallerga & Gridley, 1980)	USA	1980	Carbon black	Reinforcement properties	Carbon black reinforcement enhances asphalt paving mixtures

Reference	Country	Year	Type of Additive	Tests Performed	Conclusion
(Esch, 1982)	USA	1982	Rubber	Construction, benefits analysis	Rubber-modified asphalt pavements show significant benefits
(Mamlouk & Wood, 1983)	USA	1983	Emulsified asphalt mixtures	Properties analysis	Emulsified asphalt mixtures are suitable for low-volume roads
(Ruckel et al., 1983)	USA	1983	Foamed-asphalt	Preparation of design mixes, treatment analysis	Effective preparation and treatment of foamed-asphalt paving mixtures
(Kietzman & Rodier, 1984)	USA	1984	Diatomite filler	Performance analysis	Diatomite filler positively impacts the performance of asphalt pavements
(Nadkarni et al., 1985)	India	1985	Modified asphalts	Thermomechanical behavior analysis	Modified asphalts exhibit improved thermomechanical behavior
(Jew et al., 1986)	Canada	1986	Polyethylene	Application analysis	Polyethylene-modified bitumen is effective for paving applications
(Stroup-Gardiner & Epps, 1987)	USA	1987	Lime	Performance variables analysis	Four variables significantly affect the performance of lime in asphalt mixtures
(Shuler et al., 1987)	USA	1987	Polymer-modified asphalt	Properties, performance analysis	Polymer-modified asphalt properties are related to improved asphalt concrete performance
(McQuillen Jr et al., 1988)	USA	1988	Rubber	Economic analysis	Rubber-modified asphalt mixes offer economic advantages
(Al-Ohaly & Terrel, 1988)	USA	1988	Microwave heating	Adhesion, moisture damage analysis	Microwave heating improves adhesion and reduces moisture damage in asphalt mixtures
(Giavarini & Rinaldi, 1989)	Italy	1989	New adhesion agents	Development, performance analysis	Development of new adhesion agents enhances asphalt cement properties
(Al-Massaid et al., 1989)	Jordan	1989	Oil shale ash	Properties under normal and freeze-thaw conditions	Oil shale ash bituminous mixtures perform well under various conditions
(Sainton, 1990)	France	1990	Asphalt rubber binder	Advantages analysis	Asphalt rubber binder offers significant advantages for porous asphalt concrete
(Almudaiheem, 1990)	Saudi Arabia	1990	Crusher waste dust	Evaluation of sand-asphalt mixes	Crusher waste dust improves the performance of sand-asphalt mixes
(Torshizi, 1991)	USA	1990	Polymer-modified asphalt	Laboratory and field evaluation	Polymer-modified asphalt binders and mixtures show enhanced performance
(Oliveira et al., 2013)	Portugal	2013	Warm mix asphalt additive	Production temperatures, performance analysis	Warm mix asphalt additive reduces production temperatures and improves performance
(Mousavi et al., 2015)	Iran	2015	Styrene acrylonitrile copolymer	Rheological, mechanical properties analysis	Styrene acrylonitrile copolymer enhances bitumen properties
(Soleimanbeigi & Edil, 2015)	USA	2015	Recycled asphalt pavements	Geotechnical properties analysis	Thermal conditioning improves geotechnical properties of recycled asphalt pavements
(Abdul-Mawjoud & Thanoon, 2015)	Iraq	2015	SBR, PS-modified asphalt	Binder, HMA mixtures evaluation	SBR and PS-modified asphalt binders enhance HMA mixtures
(Shafabakhsh & Ani, 2015)	Iran	2015	Nano TiO_2/SiO_2	Rutting, fatigue performance analysis	Nano TiO_2/SiO_2 modified bitumen improves rutting and fatigue performance
(Bai et al., 2015)	South Korea	2015	Conductive fillers	Thermal properties analysis	Conductive fillers enhance the thermal properties of asphalt mixtures

Reference	Country	Year	Type of Additive	Tests Performed	Conclusion
(Hainin et al., 2015)	Malaysia	2015	Tire rubber powder	Performance evaluation	Tire rubber powder improves the performance of modified asphalt binder
(Pasandín et al., 2015)	Spain, Portugal	2015	Recycled concrete aggregates	Aging properties analysis	Aging affects the properties of bitumen with recycled concrete aggregates
(Oruç & Yılmaz, 2016)	Turkey	2016	Boron-containing additive	Performance properties analysis	Boron-containing additive improves asphalt performance properties
(Cong et al., 2022)	China	2016	Reclaimed SBS modified asphalt pavement	Properties analysis	Reclaimed SBS modified asphalt pavement shows improved properties
(Ragab et al., 2016)	Egypt	2016	Methyl methacrylate/ethylene glycol dimethacrylate	Thermo-mechanical properties analysis	The additives improve thermo-mechanical properties of asphalt binder
(Sun et al., 2016)	China	2016	Bio-oil from waste cooking oil	Properties analysis	Bio-oil derived from waste cooking oil improves asphalt binder properties
(Wan et al., 2016)	China	2016	Ceramic fiber	Characteristics analysis	Ceramic fiber modified asphalt mortar shows improved characteristics
(Al-Mufti & Fried, 2017)	Iraq	2017	Recycled asphalt aggregate	Strength properties analysis	Recycled asphalt aggregate concrete has improved strength properties
(Preciado et al., 2017)	Nepal	2017	Fibres, polymers	Mechanical properties analysis	Fibres and polymers improve the mechanical properties of hot mix asphalt
(Fernandes et al., 2017)	Portugal, USA	2017	Waste motor oil, elastomer modifiers	Performance improvement analysis	Replacing bitumen with waste motor oil and elastomer modifiers improves asphalt mixture performance
(Liang et al., 2017)	China	2017	SBR, polyphosphoric acid	Thermo-rheological behavior, compatibility analysis	SBR modified asphalt with polyphosphoric acid shows improved thermo-rheological behavior and compatibility
(M.-J. Kim et al., 2018)	South Korea	2018	Synthetic fibers	Mechanical properties analysis	Synthetic fibers enhance mechanical properties of asphalt concrete
(Q. Li et al., 2018)	China	2018	Steel slag powder	Low-temperature fracture properties analysis	Steel slag powder improves low-temperature fracture properties of asphalt mastic
(P. Li et al., 2023)	China	2018	Crumb rubber	Flexibility, anti-rutting performance analysis	Crumb rubber waste improves flexibility and anti-rutting performance of asphalt pavement
(Abd El-Rahman et al., 2018)	Egypt	2018	Waste EVA copolymer	Performance enhancement analysis	Waste EVA copolymer enhances the performance of blown asphalt binder
(Xiaoming & Eldouma, 2019)	Iraq	2019	Plastic wastes	Rheological tests, mechanical tests	Plastic waste improves the properties of natural asphalt, enhancing performance for paving applications
(H. Li et al., 2018)	China	2018	Polypropylene, crumb rubber, Tafpack Super	Asphalt performance improvement analysis	The additives improve asphalt performance in medium and high-temperature range
(Mousavinezhad et al., 2019)	China	2019	Waste engine oil, waste cooking oil	Performance improvement analysis	Waste oils improve the performance of aged asphalt
(Xu et al., 2019)	Iran	2019	Nano-clay, styrene-butadiene-styrene	Rutting performance analysis	The additives improve rutting performance in asphalt mixtures containing steel slag aggregates

Reference	Country	Year	Type of Additive	Tests Performed	Conclusion
(Ganjei & Aflaki, 2019)	China	2019	RET, polyurethane prepolymer	Performance improvement analysis	RET modified asphalt with polyurethane prepolymer shows improved performance
(Hainin et al., 2015)	Iran	2015	Nano-silica, styrene-butadiene-styrene	Self-healing properties analysis	The additives improve self-healing properties of asphalt mixtures
(Ahmed et al., 2020)	China	2020	Graphene-oxide	Mechanical behavior improvement analysis	Graphene-oxide improves mechanical behavior of hot mix asphalt
(Albayati & Abdulsattar, 2020)	Iraq	2020	Modified asphalt	Environmental resistance analysis	Modified asphalt enhances the resistance of porous asphalt mixture to environmental conditions
(E. A. A.-H. Mohammed et al., 2020)	Iraq	2020	Natural sand replacement	Performance evaluation analysis	Varying replacement percentages of natural sand impact performance of asphalt concrete mixes
(Lv et al., 2020)	Iraq	2020	Mineral filler	Mechanical properties analysis	Mineral filler affects the mechanical properties of hot mix asphalt
(F. Guo et al., 2020)(Mahmood et al., 2024)	China	2020	Waste crayfish shell powder	High-temperature stability, rheology, stiffness analysis	Waste crayfish shell powder improves high-temperature stability, rheology, and stiffness of asphalt binder
(Joni & Zghair, 2020)	Turkiye	2020	Fiber type, length, content	Asphalt properties, mixture performance analysis	Fiber type, length, and content significantly impact asphalt properties and mixture performance
(Adnan et al., 2020)	China	2020	Various fillers	Properties analysis	Different fillers enhance the properties of modified asphalt mixtures
(Amrani et al., 2020)	China	2020	Graphene-oxide	Mechanics behavior improvement analysis	Graphene-oxide improves the mechanics behavior of hot mix asphalt
(Pei et al., 2020)	Algeria	2020	Phosphate wastes	High-temperature rheological characteristics analysis	Phosphate wastes enhance high-temperature rheological characteristics of asphalt binder
(Ramadan et al., 2020)	jordan	2020	Oil sands de-oiled asphalt	Rheological properties, compatibility, stability analysis	Oil sands de-oiled asphalt shows improved rheological properties, compatibility, and stability
(Yu et al., 2021)	Iraq	2020	Engine Oil Waste	Rheological tests, mechanical tests	Engine oil waste improves the properties of asphalt binder, enhancing its performance and sustainability in paving applications
(Ismael et al., 2021)	Jordan	2020	Styrofoam	Mechanical properties analysis	Styrofoam-modified asphalt binders exhibit improved mechanical properties
(Alyousify & Taher, 2021)	Iraq	2021	Bamboo fibers	Mechanical properties analysis	Modified bamboo fibers reinforce asphalt mixtures and improve mechanical properties
(Salman & Abd Alwahab, 2021)	Iraq	2021	Carbon nanotubes	Rutting resistance analysis	Carbon nanotubes additive improves rutting resistance of asphalt pavement
(Abdalhameed & Abd, 2021)	Iraq	2021	Aggregate type	Hot mix asphalt properties evaluation	Different aggregate types affect the properties of hot mix asphalt
(Hameed et al., 2021)	Iraq	2021	Phase change material	Asphalt pavement behavior	Phase change material improves the behavior of asphalt pavement

Reference	Country	Year	Type of Additive	Tests Performed	Conclusion
				improvement analysis	
(Aliaa & Salman, 2021)	Iraq	2021	Reclaimed asphalt pavement (RAP)	Rutting performance analysis	Inclusion of RAP materials enhances rutting performance of asphalt layers
(K. A. Mohammed et al., 2021)	Iraq	2021	Waste paper fiber, recycled low-density polyethylene	Modified asphalt binder evaluation	Waste paper fiber and recycled polyethylene improve modified asphalt binder
(Huang et al., 2021)	Pakistan	2021	Iron filling wastes	Asphalt concrete mixtures properties improvement	Iron filling wastes improve the properties of asphalt concrete mixtures
(Y. Guo et al., 2021)	China	2021	Waste cork, thinner	Rheological properties analysis	Waste cork with thinner enhances rheological properties of asphalt
(Ma et al., 2022)	China	2021	Waste toner	Workability, mechanical properties evaluation	Waste toner improves workability and mechanical properties of asphalt binder and mixture
(Wang et al., 2022)	Iraq	2021	Natural Rock Asphalt	Rheological tests, mechanical tests	Natural rock asphalt significantly enhances the performance of asphalt binders, improving their durability and suitability for paving applications
(Z. Li et al., 2022)	China	2021	Recycled shell waste	High- and low-temperature rheological properties analysis	Recycled shell waste improves rheological properties of asphalt at high and low temperatures
(Du et al., 2022)	China	2022	Biochar	High-temperature properties improvement analysis	Biochar improves high-temperature properties of asphalt binder
(Martinho et al., 2022)	Portugal	2022	Microcapsules, graphene	Rheological, self-healing properties analysis	Microcapsules with graphene enhance rheological and self-healing properties of asphalt
(Hussain et al., 2022)	iraq	2022	Plant fibers	Asphalt binders properties analysis	Plant fibers improve the properties of asphalt binders
(Deng et al., 2022)	China	2022	Zinc oxide, expanded vermiculite	Aging resistance, performance evaluation	Zinc oxide and expanded vermiculite composite improves aging resistance and performance of asphalt binder
(S. Liu et al., 2023)	China	2022	Plastic waste	Bituminous binders properties improvement	Plastic waste in a circular economy approach improves the properties of bituminous binders
(Y. Liu et al., 2023)	China	2022	Nanoclay, hydrophilic bentonite	Mechanical properties enhancement analysis	Nanoclay and hydrophilic bentonite as filler enhance mechanical properties of asphalt
(Adnan & Wang, 2023)	China	2022	Manganese dioxide	Chemical modification, healing improvement analysis	Manganese dioxide plays dual roles in chemical modification and healing improvement
(Lan et al., 2023)	China	2023	Coal gangue	Performance enhancement, microstructure control	Coal gangue enhances performance and allows for microstructure control of modified asphalt
(Niu et al., 2023)	China	2023	Anhydrous calcium sulfate whiskers	Preparation, characterization, properties analysis	Anhydrous calcium sulfate whiskers improve properties of asphalt
(J. Zhang et al., 2023)	China	2023	Tire rubber, graphene	Rheological performance, compatibility enhancement	Tire rubber with graphene enhances rheological performance and compatibility of asphalt binder

Reference	Country	Year	Type of Additive	Tests Performed	Conclusion
(Zhou & Chen, 2023)	China	2023	Waste wind turbine blades	Performance improvement analysis	Waste wind turbine blades utilization improves performance of asphalt mixture
(A. M. Mohammed & Abed, 2023)	Iraq	2023	Cow dung fiber	Rheological, fatigue properties analysis	Pretreated cow dung fiber improves rheological and fatigue properties of asphalt binder
(Al-Hadidy, 2024)	Iraq	2023	Waste dry battery powder	Physicochemical properties enhancement analysis	Waste dry battery powder enhances physicochemical properties of asphalt binder
(Abd Ali et al., 2024)	Iraq	2024	Fumed silica nanoparticles	High viscosity modified asphalt enhancement analysis	Low-cost fumed silica nanoparticles enhance high viscosity modified asphalt
(Khaled et al., 2024)	Iraq	2023	Nano-$CaCO_3$	Local asphalt pavement improvement analysis	Nano-CaCO3 improves local asphalt pavement
(Mahmood et al., 2024)	Iraq	2023	Waste materials	Performance investigation analysis	Waste materials enhance performance of asphalt mixtures
(Farraj Muslim et al., 2024)	Iraq	2024	Waste engine oil	Rutting deformation resistance evaluation	Waste engine oil rejuvenates reclaimed asphalt mixtures to resist rutting deformation
(Khedaywi et al., 2024)	Iraq	2024	Glass fiber	Modified asphalt mixtures performance evaluation	Different lengths of glass fiber enhance performance of modified asphalt mixtures
(Abdelmagid & Qiu, 2024)	Iraq	2024	Sulfur waste	Mechanical performance evaluation	Sulfur waste as an alternative filler improves mechanical performance of hot and warm asphalt mixtures
(Abdukadir et al., 2024)	Iraq	2024	Poly vinyl chloride, glass, tires	Rheological specification improvement analysis	Wastes of poly vinyl chloride, glass, and tires improve the organic chemical and physical rheological
(Sienkiewicz et al., 2024)	Jordan	2024	Waste glass	Feasibility study, binder and asphalt mixture analysis	Waste glass is feasible for use in binder and asphalt mixture, improving properties

4. DISCUSSION

An analysis of experiments conducted between 1973 and 2024 shows a distinct shift in asphalt modification techniques, from sulfur-based additives and mineral fillers in earlier research to sophisticated nanomaterials and waste-derived chemicals in more recent times. Large-scale experiments with polymer-modified binders and nanocomposites have been spearheaded by nations like the United States and China, but Iraq has made a substantial contribution to the development of affordable, environmentally friendly solutions using locally accessible resources like sulfur waste, nano-$CaCO_3$, and recycled oils.

The general pattern shows that using discarded and recyclable materials improves rutting resistance and mechanical strength while also lessening the impact on the environment. Additionally, the most promising potential for long-lasting and self-healing pavements in the future lies in hybrid systems that include nanoparticles, fibers, and phase-change materials.

4.1 Future Directions in Asphalt Enhancement:

Future generations of asphalt technology will probably be driven primarily by new inventions and eco-friendly methods. The following are a few keygen zones with significant potential:

1. Advanced Self-Healing Technologies:

Self-repairing roads Smart road surfaces—those that can heal themselves after damage in addition to being intelligent enough to adapt to weather and traffic patterns—are now becoming a reality. Further advancements in microencapsulation technology and the creation of adequate, low-cost recovery agents may be necessary before further widespread acceptance and commercial use.

2. Digital Transformation in Asphalt Production:

Users in the asphalt industry can significantly improve scheduling, stock management, and productivity with the introduction of virtual tools and software. Real-time monitoring and predictive reconfiguration are made possible by these improvements in operation performance.

3. Autonomous and Robotic Systems:

In the construction industry, drones and driverless vehicles can potentially be used for asphalt making as well as maintenance to enhance safety and decrease labor expenses. Such technologies would contribute to improved pavement life and customer satisfaction through a more accurate laydown, controlling, and checking of the asphalt mat.

4. Sustainable asphalt solutions:

To lessen environmental issues, more research will be done on eco-friendly asphalt mixtures. In order to lower carbon emissions, it also includes hot-mix asphalt technologies and the use of waste materials like tires, waste plastic, and industrial byproducts..

5. Innovative additive materials:

This knowledge and capacity to alter asphalt performance is enormous thanks to additional research on the aforementioned additives, including biochar, graphene, phase-exchange materials (PCM), and specialty clays. These materials are very flexible, heat resistant, and long-lasting, and they will improve pavement curing.

6. Enhanced testing and quality assurance:

New test protocols must be created in order to guarantee accurate and consistent data. Real-time monitoring and non-negative testing will improve the accuracy of asphalts' quality and performance monitoring.

7. Circular Economy Practices:

By recycling and reusing old paving materials and other assets with eco-friendly qualities, the software, which is based on the circular economy in financial systems, has the potential to reduce waste and unlock value from valuable resources. This method will assist us in developing sustainable and environmentally friendly infrastructure.

8. Utilization of Novel Clays:

The Use of Kaolin and Flint Homes, and Auspices Clays, Which are not Exploited will improve Physical Asphalt Properties, Durability And Water Proofing.

9. Hybrid Material Additives:

By combining different kinds of clay with cutting-edge materials like biochar, graphene, or block-alternative materials, asphalt performance may be greatly increased. Multiple types of concurrent demand are supported by this composite method. The asphalt industry can create durable pavement designs for future requirements because to thermal stability and weather resistance. Road performance will be greatly enhanced by combining different clays with cutting-edge ingredients like biochar, graphene, or block replacements while creating asphalts. Multiple kinds of concurrent demand can be handled by such integrated dynamics. It is possible to achieve heat and weather resistance with contemporary road planning and construction that adheres to long-term design requirements.

11. Summary of Asphalt Improvements:

Enhancing performance and sustainability has been a common focus of development in the asphalt era in recent years. Specific findings from various studies include the following:

12. Key Insights:

Materials and Additives: Various Additives: Studies have greatly improved the mechanical, thermal, and environmental properties of asphalt. These additives, which improve the strength and quality of asphalt materials, include fibers, polymers, nanoparticles, and spent oils.

Emerging Materials:It has been found that phase transition materials such as graphene and biochar have better environmental protection effect and long term using time.

13. Sustainability:

Recycled Products: Turning trash into trendy products that lessen the ecological footprint. RAPs, recycled asphalt pavements, are a great example of how the impact on our environment can be minimized because we chose to minimize it. Warm Mix Technology : Rubberized rubber modified and warm mix asphalt are two technologies that lower emissions, conserve energy and benefit the environment as well as the economy.

14. Cost-Effectiveness and Balancing Performance and Cost:

It can provide substantial financial savings without sacrifice in quality by taking advantage of the latest additives and a high volume of recycled content. Regional Focus:

Iraq: Research focus is on upgrading infrastructure in a cost-efficient manner, using the rich local resources of sulfur waste and nano calcium carbonate. To enhance asphalt performance, Chinese researchers are concentrating on nanotechnology and renewable resources. The improvement of mechanical and thermal characteristics using polymers and industrial waste has been the subject of several studies conducted in Western nations. Conclusions, both general and specific:

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

The reviewed research consistently shows that adding sustainable additives like polymers, nanoclays, biochar, and recycled waste materials can greatly improve the mechanical and rheological properties of asphalt binders. Material science developments have made it possible to create asphalt formulations that are more economical and ecologically friendly without sacrificing long-term performance or durability. Improvements in rheological, mechanical, and thermal properties have been noted in most studies, indicating that the use of different additives is essential to maximizing asphalt performance. In particular, the reuse of waste and recycled materials has emerged as a major research focus due to its contribution to environmental sustainability, while the application of nanotechnology is becoming increasingly popular as a means of further enhancing asphalt performance at the micro and nanoscale.

The role of using local resources is also reflected through the trends of regional researches. Researches conducted in Iraq have mentioned that using local materials may help enhance the performance of asphalt, reducing the cost and negative impacts. Similar to this, the studies conducted in Western countries have mainly focused on experimenting using polymers and industrial waste to upgrade the mechanical and thermal performance of asphalt, and also, the studies conducted in China have mainly focused on using innovative technologies and renewable resources on developing environment-friendly asphalt with superior performance. Based on these results, it is advised that future research focus on long-term field performance evaluation of modified asphalt under actual traffic loads and different climatic conditions; carry out thorough life cycle assessments (LCA) to ascertain the economic and environmental viability of large-scale application of waste-based additives; and investigate smart asphalt systems that incorporate sensors and artificial intelligence for real-time condition monitoring, defect detection, and predictive maintenance. To support sustainable development, it is also important to encourage the use of region-specific additives made from local agricultural and industrial waste. When combined, these tactics can promote sustainable asphalt technologies and help create a built environment that is more resilient, efficient, and ecologically conscious.

5.2 Recommendations

It is an absolute requirement that scientists, engineers, and politicians should join hands in order to move the asphalt technology development field forward. Innovations are happening continuously in terms of material and sustainable technology development, which leads to long-lasting and environment-friendly infrastructure development. This eventually leads to even greater environmental advantages.

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