

Warm Mix Asphalt: Natural Additives and Sustainable Technologies for Reducing Environmental Pollution

Prodhan Md Safiq Raihan¹, Robinson Vega Diaz², Lei Wan¹

¹Department of Transportation Engineering, Hohai University, Nanjing, China

²College of Environmental Science and Engineering, Hohai University, Nanjing, China

Email: safiq.sdut@outlook.com, robinsonvegadiaz@gmail.com, wl2664617855@163.com.com

How to cite this paper: Raihan, P.M.S., Diaz, R.V. and Wan, L. (2025) Warm Mix Asphalt: Natural Additives and Sustainable Technologies for Reducing Environmental Pollution. *World Journal of Engineering and Technology*, 13, 764-790.

<https://doi.org/10.4236/wjet.2025.134049>

Received: August 2, 2025

Accepted: September 12, 2025

Published: September 15, 2025

Copyright © 2025 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

Warm Mix Asphalt (WMA) has emerged as a promising sustainable alternative to traditional Hot Mix Asphalt (HMA), offering substantial environmental and performance advantages by enabling asphalt production and compaction at lower temperatures. This review paper explores the role of natural and renewable additives—such as bio-based waxes, vegetable oils, natural zeolites, and bio-binders—in enhancing the workability, compatibility, and durability of WMA while significantly reducing energy consumption, greenhouse gas emissions, and environmental pollution. Particular emphasis is placed on how these additives improve binder performance, enable higher incorporation of Reclaimed Asphalt Pavement (RAP), and contribute to circular economy principles by valorizing bio-waste and industrial by-products. The paper also discusses the limitations and challenges associated with variability of natural feedstocks, field performance uncertainties, and standardization needs. By synthesizing recent research and field applications, this study highlights the practical potential of bio-based WMA technologies to advance sustainable road construction and identifies critical areas for future research and large-scale implementation.

Keywords

Warm Mix Asphalt (WMA), Sustainable Pavement, Bio-Based Additives, Vegetable Oils, Natural Zeolites, Bio-Binders, Reclaimed Asphalt Pavement (RAP), Environmental Pollution Prevention, Circular Economy, Binder Aging

1. Introduction

Asphalt pavements are a fundamental component of modern transportation in-

frastructure worldwide. However, the traditional production and placement of Hot Mix Asphalt (HMA) involve heating aggregates and bitumen to high temperatures—typically between 150°C and 180°C—to ensure proper coating and workability. This high-temperature process is energy-intensive and results in significant environmental impacts, including elevated fuel consumption and the emission of greenhouse gases (GHGs) such as carbon dioxide (CO₂), as well as volatile organic compounds (VOCs) and particulate matter that contribute to air pollution and health risks for workers and nearby community [1].

In response to increasing environmental concerns and stricter regulatory requirements aimed at reducing the carbon footprint of road construction, Warm Mix Asphalt (WMA) technology has emerged as a sustainable alternative. WMA allows asphalt mixtures to be produced and placed at temperatures 20°C to 40°C lower than HMA, resulting in reduced energy consumption, decreased emissions, and improved working conditions [2]. Beyond these operational advantages, WMA has been shown to reduce oxidative aging of the asphalt binder during production, which can enhance pavement durability and extend service life, thereby lowering life-cycle environmental impacts.

An important recent development in WMA technology is the incorporation of natural and renewable additives—such as bio-based waxes, vegetable oils, natural zeolites, and bio-binders—that further enhance environmental benefits while maintaining or improving pavement performance. These additives can reduce the viscosity of the asphalt binder at lower temperatures, improve mix workability, rejuvenate aged binders, and promote higher usage of Reclaimed Asphalt Pavement (RAP), thus supporting circular economy principles [3].

This paper presents a comprehensive review of the current state of knowledge on the use of natural additives in WMA with a focus on their role in preventing environmental pollution. The review covers the environmental impact of conventional asphalt production, different WMA technologies, natural additives and their mechanisms, performance improvements, challenges faced in practical implementation, and future research directions. By synthesizing recent advances and identifying knowledge gaps, this work aims to guide researchers, practitioners, and policymakers toward more sustainable asphalt pavement solutions [4].

2. Environmental Impact of Conventional Asphalt Production

The production and placement of Hot Mix Asphalt (HMA) have long been associated with significant environmental challenges. Conventional HMA requires mixing aggregate and bitumen at high temperatures, typically between 150°C and 180°C, to ensure proper coating, workability, and compaction. This high-temperature process consumes substantial amounts of fossil fuel, resulting in considerable greenhouse gas (GHG) emissions such as carbon dioxide (CO₂), sulfur dioxide (SO₂), and nitrogen oxides (NO_x).

In addition to direct emissions from combustion, asphalt plants generate significant amounts of volatile organic compounds (VOCs) and particulate matter,

which contribute to air pollution and pose health risks to workers and nearby communities. Studies estimate that traditional HMA can produce up to 30% more CO₂ emissions compared to Warm Mix Asphalt [2].

Furthermore, the high temperatures accelerate the oxidative aging of the asphalt binder during production and placement. This premature aging can reduce pavement flexibility and shorten its service life, leading to more frequent maintenance and rehabilitation cycles, which further increase energy consumption and environmental impacts throughout the pavement life cycle.

The health and safety of asphalt workers are also affected, as higher production temperatures generate dense fumes and aerosols, exposing workers to harmful chemicals. As governments and industries aim to meet stricter climate targets and occupational health standards, the need for sustainable alternatives like WMA becomes increasingly urgent.

3. Warm Mix Asphalt Technologies

Warm Mix Asphalt (WMA) has emerged as an innovative and sustainable solution to address the environmental drawbacks of conventional HMA. WMA technologies allow asphalt mixtures to be produced and compacted at temperatures 20°C to 40°C lower than traditional mixes, significantly reducing fuel consumption and emissions while maintaining or even improving pavement performance [5].

Three main categories of WMA technologies have been developed.

3.1. Chemical Additives

Chemical additives include surfactants, emulsifiers, and viscosity modifiers that improve the coating and workability of the asphalt binder at lower temperatures. Products like Evotherm and Rediset are well-known examples. These additives enhance the adhesion between binder and aggregates, allowing for effective mixing and compaction without compromising mechanical properties. Chemical WMA additives are widely used because they are easy to integrate into existing production processes [6].

3.2. Organic Additives

Organic additives, including synthetic and natural waxes, lower the viscosity of bitumen at mixing temperatures but solidify at service temperatures, providing stiffness and rutting resistance to the final pavement. Fischer-Tropsch (FT) waxes derived from coal or natural gas are commercially popular. However, there is growing interest in bio-based waxes, such as beeswax or rice bran wax, which are renewable and biodegradable. These natural waxes function similarly to synthetic waxes while offering additional sustainability benefits [7].

3.3. Foaming Techniques

Foaming methods reduce binder viscosity by introducing controlled amounts of

water into the hot binder, which rapidly vaporizes and expands, creating a foam that increases binder volume and improves aggregate coating [8]. Water can be introduced directly through mechanical foaming devices or indirectly using water-containing additives like zeolites. Natural zeolites, such as clinoptilolite, are especially attractive due to their abundance and low environmental impact [9].

Foamed WMA methods are popular because they require minimal changes to existing asphalt plants and equipment. They are also cost-effective and have been successfully used in many large-scale road projects worldwide [10].

4. Natural and Renewable Additives in Warm Mix Asphalt

While traditional WMA additives and foaming agents have already demonstrated significant environmental benefits over conventional HMA, further advances are focusing on replacing petroleum-derived or synthetic additives with natural, renewable, or waste-derived materials [11]. These natural additives not only reduce the carbon footprint of asphalt production but also often provide performance benefits such as improved workability, reduced binder aging, and increased durability. The following sub-sections review key types of natural additives currently researched and applied in Warm Mix Asphalt [12].

4.1. Bio-Based Waxes

Bio-based waxes are a promising category of natural organic additives that can be used to modify the rheological properties of asphalt binders in Warm Mix Asphalt (WMA). These waxes are derived from renewable biological resources such as plants, crops, or natural processes (e.g., beeswax from honey production). Unlike synthetic Fischer-Tropsch waxes produced from coal or natural gas, bio-waxes are biodegradable and have a lower environmental footprint, aligning with sustainability and circular economy goals [13].

Bio-based waxes primarily function by temporarily reducing the viscosity of the asphalt binder at mixing and compaction temperatures. When heated, the wax crystals melt, allowing the binder to flow more easily and coat the aggregates at lower temperatures (typically 20°C - 40°C below conventional HMA) [14]. Once the pavement cools to service temperatures, the wax recrystallizes, providing additional stiffness that can improve rutting resistance without significantly compromising low-temperature cracking performance [15].

Common types of bio-based waxes investigated for WMA applications include beeswax, rice bran wax, carnauba wax, and palm oil-derived waxes. These waxes differ in their melting points, chemical compositions, and effects on binder rheology. Beeswax, for example, is composed mainly of esters of fatty acids and long-chain alcohols and has a relatively moderate melting range (60°C - 65°C). Rice bran wax, a by-product of rice oil refining, contains high levels of wax esters and free fatty alcohols, making it suitable as a viscosity reducer and performance enhancer.

Recent laboratory studies have demonstrated that adding 1% - 4% by weight of

bio-wax to asphalt binder can reduce mixing temperatures by up to 30°C while maintaining or improving the stiffness modulus and rutting resistance of the final mix [16]. Moreover, bio-waxes can be blended with other renewable additives or reclaimed asphalt pavement (RAP) to further enhance sustainability performance [15].

However, the properties of natural waxes can vary due to climate, crop type, and processing methods, requiring careful quality control to ensure consistent performance (Table 1).

Table 1. Examples of bio-based waxes for warm mix asphalt.

Bio-Wax Type	Source	Typical Dosage (% binder)	Melting Point (°C)	Key Effects	Environmental Benefit
Beeswax	Beehive/honey industry	1% - 3%	60°C - 65°C	Lowers binder viscosity; moderate stiffening effect at service temperature	Renewable, biodegradable, supports local beekeeping
Rice Bran Wax	By-product of rice oil extraction	1% - 4%	77°C - 82°C	Good viscosity reduction, enhances rutting resistance	Adds value to agricultural waste, abundant in Asia
Carnauba Wax	Leaves of carnauba palm (<i>Copernicia prunifera</i>)	1% - 2%	80°C - 85°C	Strong stiffening at service temperature, good rutting control	Fully renewable, biodegradable
Palm Oil Wax	Fraction from palm oil refining	1% - 3%	50°C - 60°C	Softens binder for better workability; mild stiffening at ambient	Renewable, supports palm oil by-product utilization

4.2. Vegetable Oils

Vegetable oils represent another important class of natural and renewable additives for Warm Mix Asphalt (WMA) [17]. They are primarily used as **viscosity reducers, rejuvenators, or fluxing agents** that soften the asphalt binder, enhance workability at lower temperatures, and help rejuvenate aged bitumen—making them especially suitable for mixes with high Reclaimed Asphalt Pavement (RAP) content [17].

Unlike waxes, which solidify at ambient temperatures, vegetable oils remain liquid under typical service conditions. This allows them to effectively reduce binder stiffness and restore the balance of lighter fractions (maltenes) in aged asphalt, improving ductility and resistance to cracking [18].

Vegetable oils can be divided into two broad categories:

- **Virgin edible oils:** e.g., soybean oil, rapeseed (canola) oil, sunflower oil, palm oil [19].
- **Waste-derived oils:** e.g., waste cooking oil (WCO), which is recycled from restaurants and households [18].

Waste cooking oil (WCO) is especially attractive for WMA because it turns a

problematic waste stream—often improperly disposed of—into a valuable resource for sustainable pavements. Studies have shown that adding 2% - 6% WCO by weight of binder can reduce mixing and compaction temperatures by up to 30°C and restore the flexibility of RAP-heavy mixes [20].

Virgin vegetable oils, such as soybean or rapeseed oil, offer similar performance but raise sustainability concerns if they compete with food supplies. Thus, many researchers recommend prioritizing waste or non-food-grade vegetable oils to align with circular economy goals [21].

Vegetable oils can also be blended with other WMA additives, such as waxes or polymers, to create hybrid modifiers that combine the benefits of viscosity reduction, rejuvenation, and performance enhancement [17] (Table 2).

Table 2. Examples of vegetable oils for warm mix asphalt.

Oil Type	Source	Typical Dosage (% binder)	Key Functions	Benefits	Sustainability Impact
Waste Cooking Oil (WCO)	Recycled from households, restaurants	2% - 6%	Viscosity reducer, rejuvenator for RAP	Lowers mixing temperature, restores aged binder, improves ductility	Diverts waste oil from improper disposal
Soybean Oil	Virgin or non-edible grades from soy crops	2% - 5%	Softens binder, improves workability	Effective for viscosity reduction, improves cracking resistance	Renewable but may compete with food crops
Rapeseed (Canola) Oil	Virgin or industrial grades	2% - 5%	Binder softening, mild rejuvenator	Similar to soybean oil, good low-temperature performance	Widely available in Europe; potential food supply impact
Palm Oil	Fraction from palm oil refining	2% - 4%	Softens binder, mild rejuvenation	Enhances workability at low temps	Renewable but linked to land use concerns if unsustainable sources used

4.3. Natural Zeolites

Natural zeolites are one of the most widely adopted mineral-based additives for Warm Mix Asphalt (WMA) due to their simple, effective foaming mechanism and environmentally friendly characteristics. Zeolites are crystalline hydrated aluminosilicate minerals with a unique porous structure that can trap and gradually release water molecules when heated [22].

In WMA production, natural zeolites—particularly **clinoptilolite**, one of the most abundant natural zeolite types—are added to the hot binder during mixing. The released water vapor creates micro-foaming within the asphalt binder, expanding its volume and temporarily reducing its viscosity. This improves aggregate coating and mixture workability at temperatures 20°C - 30°C lower than conventional Hot Mix Asphalt (HMA) [23].

Unlike organic chemical additives, zeolites are inert, non-toxic, and do not chemically react with the bitumen [24]. They provide a purely physical foaming effect, which makes them especially suitable for plants looking for a low-cost, easy-to-implement WMA method with minimal equipment modifications [25].

Zeolites are naturally occurring in volcanic tuff deposits and are abundant in many countries, including Türkiye, China, India, Italy, and the United States. The use of natural zeolites also supports sustainable resource utilization and can provide economic benefits for regions with significant mineral reserves [26].

Commonly, natural zeolites are added at rates of 0.3% to 0.5% by weight of the total asphalt mix (approximately 3 - 6 kg per tonne of mix). Care must be taken to control moisture content and ensure proper dispersion to achieve consistent foaming performance [27] (Table 3).

Table 3. Examples of natural zeolites for warm mix asphalt.

Zeolite Type	Main Mineral	Typical Dosage (% of mix)	Foaming Mechanism	Benefits	Sustainability Impact
Clinoptilolite	Hydrated aluminosilicate	0.3% - 0.5%	Releases water vapor when heated, creating micro-foam in binder	Reduces mixing temp by 20°C - 30°C, improves workability, simple to apply	Naturally abundant, non-toxic, minimal processing required
Mordenite	Hydrated aluminosilicate	0.3% - 0.5%	Similar physical water-release foaming	Good thermal stability, low cost	Available in volcanic regions, supports local mining economies
Chabazite	Hydrated aluminosilicate	0.3% - 0.5%	Physical water-release foaming	Effective foaming at moderate temps	Low environmental impact, widely available

4.4. Bio-Binders and Waste-Derived Additives

Bio-binders and waste-derived additives are gaining significant attention as sustainable alternatives to conventional petroleum-based asphalt binders and chemical modifiers. These materials are obtained from renewable biological sources or recycled industrial/agricultural waste, contributing directly to resource conservation, waste valorization, and circular economy principles in pavement construction.

Bio-binders are partially or fully renewable materials that can replace a portion of the bitumen or act as modifiers to adjust the rheological and aging properties of asphalt binders. They can be derived from lignin, tall oil, algae, pyrolysis bio-oils, or residues from the paper, forestry, or food industries [28].

- **Lignin**, the second most abundant natural polymer on Earth (after cellulose), is extracted as a by-product of the pulp and paper industry. It has shown promise as a partial bitumen substitute due to its aromatic structure and high carbon content, which provides compatibility with the bitumen matrix and contributes to binder stiffness [29].

- **Pyrolysis bio-oils**, produced from fast pyrolysis of biomass such as wood chips or agricultural residues, contain complex mixtures of phenols and organic acids that can soften aged binders, reduce viscosity, and rejuvenate RAP-heavy mixtures. However, issues such as high oxygen content and long-term stability need to be carefully addressed [30].
- **Waste-derived oils and residues**, such as waste engine oil residue or used motor oil, have been explored to restore the maltene fraction of oxidized binders and improve the workability of recycled mixes. However, their use must be managed carefully to prevent contamination with heavy metals or other hazardous substances.

The main advantage of using bio-binders and waste-derived additives in WMA is their dual role: lowering mixing and compaction temperatures while partially replacing virgin bitumen—a petroleum-based, non-renewable material. This significantly reduces the carbon footprint and total energy demand of asphalt pavements [31] (Table 4).

Table 4. Examples of bio-binders and waste-derived additives for warm mix asphalt.

Material	Source	Typical Application	Key Functions	Benefits	Sustainability Impact
Lignin	By-product of pulp & paper, lignocellulosic biomass	Partial bitumen replacement (5% - 20%)	Increases binder stiffness, reduces binder demand	Improves high-temp rutting resistance, renewable	Utilizes forestry waste, reduces bitumen dependency
Pyrolysis Bio-Oil	Fast pyrolysis of wood, straw, or agri-residues	Modifier/rejuvenator (5% - 10%)	Softens aged binder, reduces viscosity	Enhances RAP mix performance, reduces temp	Adds value to biomass waste streams
Waste Engine Oil Residue	Recovered used motor oil	Rejuvenator (2% - 6%)	Restores maltene fraction, improves workability	Enables higher RAP %, lowers mixing temp	Diverts hazardous oil waste, reduces landfill disposal
Tall Oil	By-product of wood pulping	Partial binder extender (5% - 10%)	Improves workability, mild rejuvenation	Maintains workability at lower temps	Fully renewable, common in forestry regions

5. Performance Benefits of Natural Additives in Warm Mix Asphalt

The use of natural and renewable additives in Warm Mix Asphalt (WMA) not only reduces the environmental footprint of pavement construction but also offers multiple performance-related advantages. These benefits can help address common challenges associated with low-temperature mixing and ensure that the durability and structural integrity of pavements are maintained or even enhanced compared to conventional Hot Mix Asphalt (HMA).

This section highlights how bio-based waxes, vegetable oils, natural zeolites, and bio-binders contribute to the mechanical performance, durability, and sus-

tainability of WMA mixtures [32].

5.1. Improved Workability and Compactability

One of the most significant performance benefits of Warm Mix Asphalt (WMA) technologies—particularly when using natural and renewable additives—is the substantial improvement in mix workability and compactability at reduced temperatures. These enhancements directly contribute to better pavement quality, longer service life, and reduced construction risks [33].

Workability Improvement Mechanism

Workability refers to the ease with which the asphalt mix can be handled, placed, and spread during paving operations. In conventional Hot Mix Asphalt (HMA), high production temperatures (typically 150°C - 180°C) are necessary to lower the binder viscosity enough to ensure complete coating of aggregates and smooth flow of the mix. Lowering production temperatures without an additive can result in a stiffer mix, poor coating, and difficulties during compaction [34].

Natural additives such as **bio-based waxes, vegetable oils, natural zeolites, and bio-binders** modify the binder's rheology by either physically reducing its viscosity (organic additives) or creating foaming effects (zeolites). Bio-waxes melt when heated, temporarily lubricating the binder and allowing it to flow more freely around aggregates at temperatures 20°C - 40°C lower than HMA. Vegetable oils act as internal lubricants and rejuvenators, softening the binder and restoring workability, especially in RAP-rich mixes. Natural zeolites, on the other hand, release water vapor under heat, generating micro-foaming that expands the binder volume and reduces internal friction within the mix [35].

Enhanced Compactability

Compactability refers to the mix's ability to be effectively densified under the action of rollers during construction. Proper compaction is critical to minimize air voids, achieve design density, and ensure long-term pavement durability by reducing moisture damage and oxidation susceptibility [36].

The reduced viscosity and internal friction achieved through WMA additives allow the mix to be compacted more easily, even at lower temperatures. This results in faster achievement of target density, reduced risk of cold spots or incomplete densification, and extended paving windows in colder climates or remote sites where maintaining high temperatures is challenging [37].

Several field studies have shown that using WMA with natural additives can:

- Improve density by up to 2% compared to conventional HMA at the same or lower compaction temperatures.
- Reduce required compaction effort (roller passes) by 10% - 30%, saving fuel and equipment wear [38].
- Enable successful compaction at ambient temperatures as low as 5°C - 10°C lower than would be feasible for HMA, extending paving seasons in cold regions.

Practical and Environmental Implications

Better workability and compactability not only improve the immediate quality of the pavement but also reduce energy consumption at the asphalt plant, lower fuel use for compaction equipment, and decrease construction time. In remote or urban projects where haul distances are long, improved workability allows longer haul times without risking premature cooling of the mix, further improving logistical flexibility.

These benefits make WMA with natural additives an attractive option for agencies and contractors aiming to balance environmental sustainability with high-performance pavements.

5.2. Reduced Binder Aging

Another notable performance advantage of Warm Mix Asphalt (WMA) technologies, especially when incorporating natural additives, is the **reduction in asphalt binder aging** during both production and laying processes. Binder aging is a critical factor that affects pavement durability, cracking resistance, and long-term maintenance needs.

Understanding Binder Aging

Asphalt binder is a complex blend of hydrocarbons and heteroatoms that gradually hardens due to oxidation and volatilization of lighter fractions during mixing, transport, and placement. In conventional Hot Mix Asphalt (HMA) production, the binder is exposed to high temperatures (often 150°C - 180°C) for extended periods. This prolonged thermal exposure accelerates oxidation, leading to increased stiffness and brittleness. Over time, this contributes to reduced flexibility, increased susceptibility to fatigue cracking, and premature pavement distress, especially in cold climates.

How WMA Lowers Binder Aging

WMA technologies lower the production and compaction temperatures by 20°C - 40°C compared to HMA. This temperature reduction significantly decreases thermal oxidation and the volatilization of lighter binder components. By minimizing heat-induced aging at the mixing plant and during haulage, WMA helps preserve the binder's viscoelastic balance and ductility.

Natural additives further enhance this benefit. For instance:

- **Bio-based waxes** melt and temporarily lower binder viscosity without requiring extreme heat, so less oxidation occurs [39].
- **Vegetable oils and bio-oils** act as softening agents or rejuvenators, compensating for any loss of lighter fractions by restoring maltene content, which counteracts binder hardening [40].
- **Bio-binders** such as lignin or pyrolysis oils can partially replace virgin bitumen with renewable fractions that offer additional resistance to aging when properly blended [41].

Field and Laboratory Evidence

Studies have demonstrated that WMA binders typically exhibit lower levels of oxidation indicators—such as carbonyl and sulfoxide functional groups—than

HMA binders prepared under equivalent conditions. Rheological analyses (e.g., Dynamic Shear Rheometer tests) show that WMA binders often retain higher phase angles, indicating better flexibility and lower risk of thermal cracking over time [42].

Moreover, when WMA is combined with high RAP content, the rejuvenating effect of vegetable oils or bio-oils helps soften the aged binder within the RAP, improving blend homogeneity and delaying age-related brittleness [43].

Practical Implications

Reducing binder aging at the production stage extends the service life of pavements by maintaining a more favorable balance between stiffness and ductility. This lowers the likelihood of premature fatigue cracking and thermal cracking, especially in regions with significant temperature variations. As a result, agencies can expect reduced maintenance costs and improved sustainability of road assets [44].

5.3. Enhanced Moisture Resistance

One of the persistent challenges in asphalt pavement performance is moisture damage, also known as stripping—a phenomenon where the bond between the asphalt binder and aggregates weakens under the combined effect of water infiltration and repeated traffic loading. Stripping leads to loss of cohesion, raveling, potholes, and reduced pavement service life [45].

While lowering production temperatures is the core benefit of Warm Mix Asphalt (WMA) technologies, early concerns were raised that reduced mixing temperatures might impair aggregate coating and bonding, potentially making WMA more vulnerable to moisture-induced damage compared to conventional Hot Mix Asphalt (HMA). However, numerous studies and practical applications have shown that, when used with appropriate natural additives, WMA can maintain or even improve moisture resistance [46].

Mechanisms for Improved Moisture Resistance

Natural and renewable additives play a critical role in protecting WMA from stripping by modifying the binder's physical and chemical properties to promote stronger adhesion to aggregate surfaces:

- **Bio-based waxes** improve aggregate coating by temporarily reducing binder viscosity, ensuring thorough and uniform coverage even at lower temperatures. This better coverage reduces the likelihood of water infiltrating and disrupting the bond.
- **Vegetable oils and bio-oils** often contain naturally occurring polar functional groups (e.g., carboxylic acids) that can enhance binder-aggregate adhesion through stronger physico-chemical interactions.
- **Natural zeolites**, though primarily used for their foaming effect, have been shown to help maintain good coating because the micro-foam improves binder distribution over aggregate surfaces.
- **Some bio-binders**, such as lignin, contain aromatic structures and hydroxyl

groups that can act as natural anti-stripping agents, improving binder wettability and adhesion.

Additionally, many WMA additives allow for higher Reclaimed Asphalt Pavement (RAP) content. The fine mineral particles in RAP can improve binder film thickness, creating an extra barrier to moisture infiltration [47].

Evidence from Research and Field Practice

Experimental studies often use the **Tensile Strength Ratio (TSR)** or **AASHTO T283 test** to assess moisture susceptibility. Research comparing HMA and WMA mixes has found that when bio-based or zeolite additives are used, the TSR values of WMA mixes typically meet or exceed standard moisture resistance thresholds (typically $\geq 80\%$). Some studies even report better retained strength than comparable HMA, especially when natural anti-stripping agents are blended with the binder.

Field trials have confirmed that pavements built with WMA and natural additives perform comparably to HMA in wet climates, provided that proper mix design and quality control are observed.

Practical Considerations

To fully realize enhanced moisture resistance:

- Proper mixing time and additive dosage must be ensured to achieve complete coating.
- Aggregate type and cleanliness are crucial—natural additives are not a substitute for good aggregate selection.
- When required by specifications, additional anti-stripping agents can be used alongside natural WMA additives to meet stringent durability standards.

5.4. Higher Potential for Recycling

One of the major sustainability benefits of Warm Mix Asphalt (WMA) technologies is their ability to enable **greater incorporation of Reclaimed Asphalt Pavement (RAP)** into new mixes without compromising performance. RAP consists of milled or removed asphalt pavement that contains both aggregates and aged binder. Recycling RAP conserves natural resources, reduces landfill disposal, and cuts the demand for virgin aggregates and bitumen—all of which are important for sustainable road construction [48].

Recycling Challenges in Conventional HMA

In traditional Hot Mix Asphalt (HMA), incorporating high RAP content often presents performance and production challenges. The aged binder in RAP is stiffer and more brittle due to oxidation over its service life. Blending this stiff binder with fresh binder at high temperatures is necessary to soften and mobilize it, but even then, excessive RAP can lead to insufficient blending and poor coating. If not properly rejuvenated, high RAP content may cause poor workability, insufficient coating, or increased risk of cracking [49].

How WMA Supports Higher RAP Percentages

Warm Mix Asphalt, when combined with natural additives such as vegetable

oils, bio-oils, or certain bio-binders, helps to mitigate these challenges. These additives act as **natural rejuvenators**, softening the aged binder by restoring its maltene content and lowering its viscosity. This rejuvenation effect allows the RAP binder to blend more uniformly with the virgin binder at lower temperatures than in conventional HMA [50].

Additionally, the improved workability provided by WMA additives means that RAP-containing mixes can still achieve good aggregate coating and compactability even when the total mix temperature is 20°C - 40°C lower. Natural zeolites can also help by improving coating through micro-foaming, ensuring that both virgin and RAP aggregates are thoroughly coated [51].

Practical Benefits and Evidence

Numerous laboratory and field studies have demonstrated that using WMA technologies makes it feasible to increase RAP content from typical levels of 20% - 30% to 40% or more, depending on local specifications and binder properties. Some agencies and contractors have successfully placed WMA pavements with RAP contents as high as 50% when rejuvenating additives are used [52].

The combined effect is a significant reduction in demand for virgin bitumen and aggregates, which lowers raw material extraction impacts, transport emissions, and project costs. This directly supports circular economy goals by closing the loop on end-of-life asphalt materials [53].

Important Considerations

To fully benefit from increased RAP usage with WMA:

- The condition, gradation, and binder content of RAP must be properly evaluated and controlled.
- Additive type and dosage should be optimized to ensure sufficient rejuvenation without over-softening the final binder blend.
- Effective mixing and quality control are essential to achieve uniform distribution of RAP throughout the mix.

5.5. Contribution to Circular Economy

Warm Mix Asphalt (WMA) technologies, especially when enhanced with natural and renewable additives, strongly align with the principles of the **circular economy**—an economic model that aims to minimize waste, maximize resource efficiency, and keep materials in use for as long as possible through recycling, recovery, and reuse [54].

Closing the Loop in Asphalt Production

Traditional Hot Mix Asphalt (HMA) production relies heavily on non-renewable virgin aggregates and petroleum-based bitumen, both of which involve energy-intensive extraction and refining processes. Large amounts of old asphalt pavement are also generated each year during road rehabilitation and resurfacing. Without effective recycling, this material often ends up in landfills or as low-value fill, representing a loss of embedded resources [55].

WMA technologies help close this loop by:

- **Lowering production temperatures**, which conserves energy and reduces greenhouse gas emissions compared to HMA.
- **Enabling higher RAP content**, which keeps reclaimed asphalt materials in productive use rather than sending them to waste streams.
- **Encouraging the use of renewable or waste-derived additives** such as vegetable oils, lignin, waste cooking oil, or bio-oils that partially replace virgin bitumen, a finite resource.
- **Supporting local resource utilization**, for example, by using locally available natural zeolites or regionally abundant agricultural by-products as modifiers.

Resource Efficiency through Renewable Additives

The use of bio-based waxes, vegetable oils, and other natural modifiers replaces a portion of fossil-derived chemical additives. Many of these materials come from agricultural or forestry side streams (e.g., rice bran wax, lignin from pulp mills, waste cooking oil from restaurants), creating new markets for by-products that might otherwise require disposal. This reduces waste and provides added economic value to other industries.

By partially replacing virgin bitumen with bio-binders or rejuvenators, WMA with natural additives also lowers the overall demand for petroleum resources, helping reduce the carbon footprint of road construction [56].

Socioeconomic and Local Benefits

A shift toward circular economy practices in asphalt production can generate local economic benefits by:

- Creating local supply chains for bio-based or waste-derived additives.
- Supporting local industries such as agriculture, forestry, and food processing through value-added by-product markets.
- Reducing the need for long-distance transport of virgin materials by maximizing the reuse of locally sourced RAP.

In addition, the reduced energy requirements and lower emissions from WMA support broader sustainability targets set by governments and road agencies to cut carbon footprints and meet climate commitments [57].

Integration with Other Sustainable Practices

The principles of the circular economy can be further amplified when WMA is combined with other sustainable construction practices, such as:

- Use of recycled aggregates from construction and demolition waste.
- Incorporation of reclaimed fillers or alternative binders.
- Adoption of life cycle assessment (LCA) and environmental product declarations (EPD) to measure and communicate environmental impacts transparently.

5.6. Field Performance and Durability

Beyond laboratory-scale studies and pilot projects, the **field performance and long-term durability** of Warm Mix Asphalt (WMA) pavements are critical for demonstrating the practical viability of these technologies under real traffic and

environmental conditions. While the primary goal of WMA is to enable lower production and compaction temperatures, its sustained field performance must match or exceed that of conventional Hot Mix Asphalt (HMA) to justify widespread adoption [58].

Demonstrated Pavement Lifespan

Over the past two decades, a growing number of countries have trialed and deployed WMA technologies at scale, often with natural or bio-based additives. Performance monitoring data from these projects generally show that when properly designed and constructed, WMA pavements exhibit comparable—and in some cases superior—durability to conventional HMA pavements [59].

Key performance measures include:

- **Rutting Resistance:** Many field trials have found that WMA pavements maintain similar or slightly better rutting resistance compared to HMA, partly due to improved compaction at lower temperatures and the stiffening effects of additives such as bio-waxes.
- **Fatigue and Cracking:** The reduced binder aging during production and placement helps maintain binder flexibility, which in turn delays the onset of fatigue and thermal cracking, especially in cold climates.
- **Moisture Damage:** When WMA additives with adhesive or anti-stripping properties (e.g., vegetable oils, lignin) are used, field sections have shown good stripping resistance, maintaining high levels of tensile strength retention over multiple years.

Performance Monitoring Data

Studies conducted in Europe, North America, and Asia have demonstrated that WMA pavements perform satisfactorily under various climatic conditions and traffic loads:

- In Germany, sections constructed with zeolite-based WMA have been monitored for over 10 years, showing rutting depths and surface conditions equivalent to or better than adjacent HMA sections.
- In the United States, multiple state Departments of Transportation (DOTs) have placed WMA pilot projects using natural waxes, waste oils, or foaming additives. These sections continue to exhibit good ride quality, smoothness, and structural integrity.
- In China, growing adoption of bio-based additives such as vegetable oils and rice bran wax in WMA has shown promising field performance, particularly in regions with high RAP use [60].

Long-Term Durability Considerations

To ensure WMA pavements deliver full design life:

- Proper mix design and quality control are essential to achieve target density and binder coating at reduced temperatures.
- The dosage and compatibility of natural additives must be optimized for local climate and traffic conditions.
- Monitoring programs are needed to track performance indicators such as rut-

ting, cracking, and moisture susceptibility over time.

- Combining WMA with high RAP content or recycled materials requires careful balance to avoid over-softening or durability loss.

Long-term studies continue to expand the evidence base supporting the reliable field performance of WMA with natural additives. As agencies gain experience and confidence in the technology, these solutions are being increasingly incorporated into national standards and specifications for sustainable pavement construction [61] (Table 5).

Table 5. Field applications of natural and renewable additives in Warm Mix Asphalt (WMA).

Country/Region	Additive Type	Project Example	Observed Field Performance	Key Notes
Germany	Natural Zeolite (Clinoptilolite)	Autobahn test sections	Rutting depth and cracking comparable to HMA after 10+ years	Zeolite foaming provided reliable coating and compactability
United States	Bio-Based Wax (Fischer-Tropsch or Montan Wax)	State DOT pilot roads in Texas, Virginia	Good rutting resistance, stable binder, extended paving window	Bio-waxes improved compaction in cooler climates
United States	Waste Cooking Oil (WCO)	Trial projects in Florida and California	Improved workability, successful high RAP use, no early cracking	WCO acted as a rejuvenator for aged RAP binder
China	Vegetable Oil (Rapeseed Oil, Rice Bran Wax)	Urban and rural WMA overlays	Better workability at low temps, good surface durability	Increasing adoption with local agricultural by-products
Sweden	Bio-Oil (Pyrolysis Oil)	Test stretches on municipal roads	Maintained flexibility, delayed thermal cracking	Limited large-scale use due to sourcing and consistency
Multiple Countries	Zeolite + Bio-Wax Hybrid	Various European projects	Reliable workability, high TSR values, long-term durability	Hybrid approaches combine foaming and viscosity reduction

6. Limitations and Challenges

Despite the clear environmental and performance benefits of Warm Mix Asphalt (WMA) technologies enhanced with natural additives, several limitations and practical challenges must be addressed before widespread adoption can be achieved globally. Understanding these challenges is critical for researchers, industry stakeholders, and policymakers to design effective solutions and develop reliable guidelines for implementation [62].

6.1. Variability and Quality Control

A major challenge associated with natural additives is the potential variability in their physical and chemical properties. For example, the composition of bio-based waxes, vegetable oils, and waste-derived additives can differ significantly based on

their source, extraction process, and storage conditions. Beeswax quality can vary depending on bee species and regional flora; similarly, the fatty acid composition of waste cooking oil is inconsistent due to variations in food types and cooking practices.

This variability can lead to unpredictable impacts on asphalt mix properties, including viscosity, stiffness, and aging resistance. Ensuring consistent quality and performance requires the development of standardized processing methods, stringent quality control measures, and clear specifications for sourcing and handling natural additives [63].

6.2. Potential Performance Trade-Offs

While natural additives can enhance workability and reduce production temperatures, excessive softening of the binder may lead to decreased rutting resistance at high service temperatures. For instance, some vegetable oils or bio-oils can overly reduce binder stiffness if dosages are not carefully optimized, potentially causing deformation under heavy traffic loads.

Finding the optimal dosage and balancing short-term workability with long-term performance remain critical technical challenges that require more extensive laboratory testing and field validation [64].

6.3. Limited Long-Term Field Data

Although numerous laboratory studies have demonstrated the potential of bio-based and natural additives in WMA, long-term performance data from actual pavements remain relatively scarce. Many experimental field trials have been conducted on a small scale or in limited climatic conditions, and monitoring periods are often too short to fully capture aging effects, fatigue cracking, or moisture-related distress over the pavement's service life [65].

To gain broader industry and regulatory acceptance, comprehensive, long-term field studies are needed to confirm durability, validate laboratory findings, and demonstrate cost-effectiveness under diverse traffic volumes and environmental conditions [66].

6.4. Economic Feasibility

Cost considerations can pose a barrier to the widespread adoption of natural additives in WMA, especially when competing with well-established, mass-produced synthetic additives. While some natural additives, such as waste cooking oil or agricultural by-products, are inexpensive or even cost-negative due to their waste status, others—such as high-quality bio-waxes—may be more expensive due to limited production scales and processing requirements [67].

Additionally, transportation costs and supply chain logistics for bio-resources can vary regionally, affecting overall economic feasibility. Conducting detailed life cycle cost analyses (LCCA) can help demonstrate the long-term financial benefits of using natural additives by accounting for extended pavement life and reduced

environmental penalties [68].

6.5. Standardization and Regulatory Barriers

Many national and regional standards and specifications for asphalt paving have been developed based on conventional Hot Mix Asphalt practices. These standards may not yet fully recognize or accommodate the unique properties and behaviors of WMA mixtures containing bio-based or waste-derived additives [69].

The lack of clear technical guidelines can discourage contractors and agencies from using innovative natural additives due to uncertainties in approval, quality assurance, and performance guarantees. Collaborative efforts between researchers, industry stakeholders, and transportation authorities are needed to update standards, develop certification systems, and build trust in the performance of natural additive-based WMA [70].

6.6. Research Gaps and Knowledge Transfer

Finally, wider implementation depends on continued **research and knowledge transfer**:

- More life cycle assessments (LCA) are needed to quantify the full environmental benefits of using natural additives.
- Practical design methods for balancing binder viscosity, rejuvenation, and aging control should be developed.
- Field monitoring results should be shared through open-access databases to build trust among road agencies, contractors, and policymakers.

7. Future Research and Development Directions

To fully realize the environmental and performance benefits of Warm Mix Asphalt (WMA) enhanced with natural additives, focused research and technological development must continue addressing current limitations while expanding knowledge on emerging opportunities. This section outlines key research directions and innovation priorities that can support the large-scale adoption of sustainable WMA solutions globally [71].

7.1. Advanced Material Characterization

Future studies should invest in deeper material characterization of natural additives. This includes identifying the chemical composition, molecular structure, and thermal properties of bio-waxes, vegetable oils, natural zeolites, and bio-binders. Improved understanding at the molecular level can help predict how these materials interact with bitumen and aggregates under various temperature and loading conditions [72].

Advanced analytical methods, such as Fourier Transform Infrared Spectroscopy (FTIR), Thermogravimetric Analysis (TGA), and Differential Scanning Calorimetry (DSC), should be widely applied to evaluate additive consistency and optimize formulations for stable, repeatable performance [73].

7.2. Life Cycle Assessment and Carbon Footprint Analysis

While laboratory experiments highlight the environmental potential of WMA with natural additives, comprehensive Life Cycle Assessments (LCAs) are needed to quantify actual benefits in real-world scenarios. LCAs should account for feedstock cultivation or sourcing, processing, transportation, mixing, paving, maintenance cycles, and end-of-life scenarios.

Detailed carbon footprint analyses comparing WMA with natural additives to conventional HMA and synthetic WMA additives will strengthen the evidence base for sustainability claims and guide policymakers in setting climate goals for the road construction sector [74].

7.3. Long-Term Field Monitoring and Performance Modeling

To address uncertainties regarding long-term behavior, more large-scale pilot projects and demonstration pavements should be implemented in diverse climates and under various traffic loads. Continuous field monitoring over 5 - 10 years would provide robust data on rutting, cracking, moisture damage, and aging performance.

Additionally, advanced performance modeling tools, such as mechanistic-empirical design methods and finite element simulations, can help predict the life cycle behavior of WMA with natural additives and optimize mix designs for different service conditions [75].

7.4. Development of Hybrid and Multifunctional Additives

Emerging research is exploring hybrid additives that combine the benefits of multiple natural sources or integrate nano-modified components for enhanced performance. For example, bio-based waxes blended with nano-clays or nano-silica could improve both workability and high-temperature rutting resistance.

Multifunctional additives that combine viscosity reduction, rejuvenation, anti-stripping, and self-healing properties are an exciting frontier for WMA innovation. Research in this area can create more efficient, versatile solutions for sustainable pavements [76].

7.5. Integration with High RAP and Circular Economy

Another promising research area is the combined use of WMA with natural additives and high Reclaimed Asphalt Pavement (RAP) content. Bio-oils and vegetable oils have demonstrated effectiveness as rejuvenators for aged binders, enabling higher RAP percentages without compromising mix performance.

Future work should focus on optimizing RAP-WMA-natural additive systems, evaluating their mechanical behavior, economic viability, and environmental impact. This synergy aligns directly with circular economy principles by extending the useful life of resources and minimizing waste [77].

7.6. Policy Support and Standardization

Finally, researchers should collaborate with industry stakeholders and transpor-

tation authorities to develop updated technical standards, performance specifications, and certification systems for natural additive-based WMA. Demonstrating compliance with regulatory requirements and facilitating practical adoption will be essential to bridge the gap between laboratory success and field implementation.

Policy frameworks that incentivize the use of renewable and waste-derived additives, encourage recycling, and support local sourcing can accelerate the transition to greener road construction practices [78].

8. Conclusions

Warm Mix Asphalt (WMA) has proven to be a transformative technology for reducing the environmental impact of asphalt pavement construction by significantly lowering production and compaction temperatures compared to conventional Hot Mix Asphalt (HMA). By doing so, WMA reduces fuel consumption, greenhouse gas emissions, and workers' exposure to harmful fumes—aligning with global sustainability and climate goals.

The integration of natural and renewable additives into WMA technologies offers an additional layer of environmental and performance benefits. Bio-based waxes, vegetable oils, natural zeolites, and bio-binders derived from waste or renewable resources not only help lower mixing temperatures but also improve workability, enable higher use of reclaimed asphalt, and extend pavement life through reduced aging and better moisture resistance. These advantages contribute to a more circular economy by utilizing waste streams and renewable feedstocks that might otherwise be discarded or underutilized.

However, realizing the full potential of WMA with natural additives depends on overcoming several practical and technical challenges. Variability in natural feedstocks, uncertainties in long-term performance, and limited standardization remain significant barriers to large-scale implementation. Moreover, while laboratory studies consistently show promising results, robust long-term field trials and life cycle assessments are essential to build confidence among industry practitioners and policymakers.

Future research should prioritize advanced material characterization, innovative hybrid additive development, integration with high-Reclaimed Asphalt Pavement (RAP) systems, and comprehensive sustainability evaluations. Collaborative efforts between researchers, contractors, material suppliers, and regulatory bodies will be critical to update technical specifications, establish quality control frameworks, and incentivize the use of greener asphalt technologies.

In conclusion, the synergy of WMA and natural additives represents a compelling strategy to advance sustainable road construction. By addressing current limitations through science, innovation, and supportive policy, the industry can significantly reduce its carbon footprint and resource consumption, paving the way toward resilient and environmentally responsible infrastructure for future generations.

Author Contributions

Prodhan Md Safiq Raihan: Investigation, writing—original draft preparation; Robinson Vega Diaz: Writing original draft preparation; Lie Wan: Data analysis, review and editing, and checking the original draft.

Funding

National Natural Science Foundation of China (51708177).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Rubio, M.C., Martínez, G., Baena, L. and Moreno, F. (2012) Warm Mix Asphalt: An Overview. *Journal of Cleaner Production*, **24**, 76-84.
<https://doi.org/10.1016/j.jclepro.2011.11.053>
- [2] Zaumanis, M. (2014) Warm Mix Asphalt. In: *Green Energy and Technology*, Springer Berlin Heidelberg, 309-334. https://doi.org/10.1007/978-3-662-44719-2_10
- [3] Belc, A.L., Coleri, E., Belc, F. and Costescu, C. (2021) Influence of Different Warm Mix Additives on Characteristics of Warm Mix Asphalt. *Materials*, **14**, Article 3534. <https://doi.org/10.3390/ma14133534>
- [4] Belc, A.L., Ciutina, A., Buzatu, R., Belc, F. and Costescu, C. (2021) Environmental Impact Assessment of Different Warm Mix Asphalts. *Sustainability*, **13**, Article 11869. <https://doi.org/10.3390/su132111869>
- [5] Caputo, P., Abe, A.A., Loise, V., Porto, M., Calandra, P., Angelico, R., *et al.* (2020) The Role of Additives in Warm Mix Asphalt Technology: An Insight into Their Mechanisms of Improving an Emerging Technology. *Nanomaterials*, **10**, Article 1202. <https://doi.org/10.3390/nano10061202>
- [6] All States Materials Group: Warm Mix Additives. <https://asmg.com/division/asphalt-binder-additives/warm-mix-additives/>
- [7] Fuqiang, D., Lei, W., Jingtao, S., Xin, Y., Yong, J., Yusong, Z., *et al.* (2025) Functional Design of Warm Mix Additives and Its Influence on the Performance of High-Content Sbs-Modified Asphalt. *Case Studies in Construction Materials*, e05267. <https://doi.org/10.1016/j.cscm.2025.e05267>
- [8] Zhu, S., Chen, F. and Yin, H. (2017) Simulation and Validation of Asphalt Foaming Process for Virtual Experiments and Optimisation of WMA Production. *Road Materials and Pavement Design*, **18**, 144-164. <https://doi.org/10.1080/14680629.2017.1389093>
- [9] Chomicz-Kowalska, A. (2021) A Study of Adhesion in Foamed WMA Binder-Aggregate Systems Using Boiling Water Stripping Tests. *Materials*, **14**, Article 6248. <https://doi.org/10.3390/ma14216248>
- [10] Li, L.Y., Yang, X.L. and Cao, G. (2014) Pavement Performance of Foaming Warm Mix Asphalt with Rap. *Applied Mechanics and Materials*, **584**, 1066-1070. <https://doi.org/10.4028/www.scientific.net/amm.584-586.1066>
- [11] Warm Mix Asphalt: European Practice. https://international.fhwa.dot.gov/pubs/pl08007/index.cfm? gl=1*uf6gpb* ga*NzQ4NTI1NzczLjE3NTM5NTI1OTQ.* ga_VW1SFWI

- [KBB*czE3NTM5NTI1OTQkbzEkZzEkdDE3NTM5NTI2NzUkajYwJGwwJGgw](https://doi.org/10.1016/j.conbuildmat.2023.133306)
- [12] Asphalt Warm Mix Additives. <https://www.cargill.com/bioindustrialanova/asphalt-warm-mix-additives>
- [13] Warm Mix Asphalt/Waxes. <https://valochem.com/warm-mix-asphalt-waxes>
- [14] de Sousa, T.M., de Medeiros Melo Neto, O., Elísio de Figueiredo Lopes Lucena, A. and Nóbrega, E.R. (2023) Enhancing Workability and Sustainability of Asphalt Mixtures: Investigating the Performance of Beeswax as a Novel Additive for Warm Mix Asphalt. *Construction and Building Materials*, **405**, Article ID: 133306. <https://doi.org/10.1016/j.conbuildmat.2023.133306>
- [15] De Sousa, T.M., Melo Neto, O.D.M., Lucena, A.E.D.F.L., Felipe, A.C.D.A., Bezerra, L.É.F., Nóbrega, E.R., et al. (2024) Analysis of Temperature Variation during Mixing and Compaction and the Impact of Beeswax on the Stiffness of Asphalt Mixtures. *Nativa*, **12**, 411-418. <https://doi.org/10.31413/nat.v12i3.17574>
- [16] Yousefi, A.A., Underwood, B.S., Ghodrati, A., Behnood, A., Vahidi, E., Nowrouzi, A., et al. (2025) Towards a Durable and Sustainable Warm Mix Asphalt: Techno-Economic and Environmental Evaluation Considering Balanced Mix Design Approach. *Journal of Cleaner Production*, **486**, 144311. <https://doi.org/10.1016/j.jclepro.2024.144311>
- [17] Usanga, I.N., Okafor, F.O. and Ikeagwuani, C.C. (2023) Effect of Recycled Vegetable Oil on the Performance of Nanomarl-Modified Asphalt Mixtures. *Journal of Infrastructure Preservation and Resilience*, **4**, Article No. 21. <https://doi.org/10.1186/s43065-023-00089-2>
- [18] Alternative Binder/Vegetable Oil. <https://valochem.com/alternative-binder-raw-materials-vegetable-oil>
- [19] Prakash, G. and Suman, S.K. (2021) An Intensive Overview of Warm Mix Asphalt (WMA) Technologies towards Sustainable Pavement Construction. *Innovative Infrastructure Solutions*, **7**, Article No. 110. <https://doi.org/10.1007/s41062-021-00712-9>
- [20] Bin, L. (2014) Research on Physical Properties of Recycled Asphalt with Waste Vegetable Oil. <https://www.semanticscholar.org/paper/Research-on-Physical-Properties-of-Recycled-Asphalt-Bin/a51ec6a46e77765eb6f4c4a80703e7f768251896>
- [21] Ahmad, M., Khedmati, M. and Haghshenas Fatmehsari, H. (2023) Using Crude Vegetable-Based Oils and Antioxidants to Improve the Performance of Asphalt Binders. *Transportation Research Record: Journal of the Transportation Research Board*, **2677**, 592-604. <https://doi.org/10.1177/03611981231161607>
- [22] Sengoz, B., Topal, A. and Gorkem, C. (2013) Evaluation of Natural Zeolite as Warm Mix Asphalt Additive and Its Comparison with Other Warm Mix Additives. *Construction and Building Materials*, **43**, 242-252. <https://doi.org/10.1016/j.conbuildmat.2013.02.026>
- [23] Marinković, M., Milović, T. and Matić, B. (2017) Zeolit kao aditiv u toplim asfaltnim Mešavinama. *Zbornik radova Građevinskog fakulteta*, **33**, 483-490. <https://doi.org/10.14415/konferencijagfs2017.051>
- [24] Luna, L. (2018) Indagine sperimentale sull'applicazione della Zeolite nei leganti bituminosi [Experimental Investigation on the Use of Zeolite in Bituminous Binders]. <https://www.semanticscholar.org/paper/Indagine-sperimentale-sull%E2%80%99applicazione-della-nei-%3D-Luna/75ba06f6e010f8eee06cd464684288c1fff8ad6f>
- [25] Droege, C. (2005) Verfahren zur Temperaturabsenkung-Mineralische Zusaetze zum Asphalt [Methods for Reduction of Temperature-Mineral Additives Used in Asphalt].

- <https://www.semanticscholar.org/paper/Verfahren-zur-Temperaturabsenkung-Mineralische-zum-Droege/b1d0aff37c2760ed256a301e45bc64718acfff7e>
- [26] Trgo, M. (2009) Natural Zeolites as Multifunctional Environmental Friendly Materials. <https://www.semanticscholar.org/paper/Natural-zeolites-as-multifunctional-environmental-Trgo/83abf7fe633380297053c37230352f8e3457540c>
- [27] Chomicz-Kowalska, A., Gardziejczyk, W. and Iwański, M.M. (2016) Moisture Resistance and Compactibility of Asphalt Concrete Produced in Half-Warm Mix Asphalt Technology with Foamed Bitumen. *Construction and Building Materials*, **126**, 108-118. <https://doi.org/10.1016/j.conbuildmat.2016.09.004>
- [28] (2024) What Is a Bio Binder? <https://www.petronaftco.com/bio-binder/>
- [29] Thibault, M.C. (2021) Lignin from Canadian Forests: The Secret Ingredient for Greener Roads. FPInnovations. <https://web.fpinnovations.ca/lignin-from-canadian-forests-the-secret-ingredient-for-greener-roads/>
- [30] Mazuck, L. (1993) Tall Oil Pitch Modified Asphalt—Properties and Use in Road Construction and Maintenance Operations. <https://www.semanticscholar.org/paper/TALL-OIL-PITCH-MODIFIED-ASPHALT-PROPERTIES-AND-USE-Mazuck/ab9098d9bfd5100bc94f6b8be4cbb927f1878a3>
- [31] Barzegari, S. (2020) Application of Bio-Binders as Sustainable Alternative to Conventional Asphalt Binders. <https://etda.libraries.psu.edu/catalog/17256sub276>
- [32] Bilema, M., Aman, M.Y., Hassan, N.D.A., Al-Saffar, Z., Rogo, K. and Abdullah, N.F.A. (2021) Influence of Crumb Rubber Incorporated with Different Warm Mix Asphalt Additives on the Mechanical Performance of WMA Mixture. *Journal of Rehabilitation in Civil Engineering*, **9**, 1-11.
- [33] Podolsky, J., Buss, A., Williams, R. and Cochran, E. (2018) Civil, Construction and Environmental Engineering 7-2015 Investigation of Performance Tests Using Bio-Derived/Chemical Additives. <https://www.semanticscholar.org/paper/Civil-%2C-Construction-and-Environmental-Engineering-Podolsky-Buss/ab97175c28e28cb5d3908676f9dfab99308cf403>
- [34] Kataware, A.V. and Singh, D. (2018) Effect of Short-Term Ageing on High-Temperature Performance of SBS Modified Binder Containing Warm Mix Asphalt Additives. *Road Materials and Pavement Design*, **21**, 623-642. <https://doi.org/10.1080/14680629.2018.1509804>
- [35] Raihan, P.M.S. and Hossain, M.M. (2025) Enhancing Sustainability and Performance of Warm Mix High Volume Rubber Composite Modified Asphalt for Road Construction. *World Journal of Engineering and Technology*, **13**, 234-253. <https://doi.org/10.4236/wjet.2025.132015>
- [36] Ali, A., Kabir, S.F., Ali, A., Elshaer, M., Mehta, Y. and Nazzal, M. (2023) Compactibility and Performance of Warm-Mix Additives at Lower than Traditional Compaction Temperatures. *Journal of Materials in Civil Engineering*, **35**, Article ID: 04023475. <https://doi.org/10.1061/jmcee7.mteng-16309>
- [37] Yan, T., Cash, K., Turos, M. and Marasteanu, M. (2023) High-Compactability Asphalt Mix Design Framework Based on Binary Aggregate Packing. *Construction and Building Materials*, **383**, Article ID: 131315. <https://doi.org/10.1016/j.conbuildmat.2023.131315>
- [38] Braham, A., Lynn, T., Steger, R. and Pyle, R. (2015) Characterizing Compactability of High RAP and Warm Mix Asphalt Mixtures in the Superpave Gyrotory Compactor.

- Journal of Testing and Evaluation*, **43**, 535-543. <https://doi.org/10.1520/jte20130319>
- [39] Herrera de la Rosa, R., Alonso Aenlle, A. and Villegas Muñoz, N. (2018) Evaluation of Natural Additives for Warm Asphalt Mix. *Revista de la construcción*, **17**, 330-336. <https://doi.org/10.7764/rdlc.17.2.330>
- [40] Dokandari, P.A., Kaya, D., Sengoz, B. and Topal, A. (2017) Implementing Waste Oils with Reclaimed Asphalt Pavement. *World Congress on Civil, Structural, and Environmental Engineering*, Barcelona, 2-4 April 2017, 142-1-142-12. <https://doi.org/10.11159/icseem17.142>
- [41] Dhasmana, H., Ozer, H., Al-Qadi, I.L., Zhang, Y., Schideman, L., Sharma, B.K., et al. (2015) Rheological and Chemical Characterization of Biobinders from Different Biomass Resources. *Transportation Research Record: Journal of the Transportation Research Board*, **2505**, 121-129. <https://doi.org/10.3141/2505-16>
- [42] Ferrotti, G., Baaj, H., Besamusca, J., Bocci, M., Cannone-Falchetto, A., Grenfell, J., et al. (2018) Comparison between Bitumen Aged in Laboratory and Recovered from HMA and WMA Lab Mixtures. *Materials and Structures*, **51**, Article No. 150. <https://doi.org/10.1617/s11527-018-1270-4>
- [43] Somé, S.C., Barthélémy, J., Mouillet, V., Hammoum, F. and Liu, G. (2022) Effect of Thermo-Oxidative Ageing on the Rheological Properties of Bituminous Binders and Mixes: Experimental Study and Multi-Scale Modeling. *Construction and Building Materials*, **344**, Article ID: 128260. <https://doi.org/10.1016/j.conbuildmat.2022.128260>
- [44] Suo, Z., Chen, H., Yan, Q., Tan, Y., Li, X. and Zhang, A. (2021) Laboratory Performance Evaluation on the Recovering of Aged Bitumen with Vegetable Oil Rejuvenator. *Frontiers in Materials*, **8**, Article 650809. <https://doi.org/10.3389/fmats.2021.650809>
- [45] Baral, S.R., Rath, A., Behera, H.K. and Das, S.S. (2025) Evaluation of HMA and WMA RAP Mixture Using Hydrogenated Castor Oil Flakes. *Journal of Road Engineering*, **5**, 297-312. <https://doi.org/10.1016/j.jreng.2024.10.002>
- [46] Sol-Sánchez, M., Fiume, A., Moreno-Navarro, F. and Rubio-Gámez, M.C. (2018) Analysis of Fatigue Cracking of Warm Mix Asphalt. Influence of the Manufacturing Technology. *International Journal of Fatigue*, **110**, 197-203. <https://doi.org/10.1016/j.ijfatigue.2018.01.029>
- [47] Zhang, R., You, Z., Wang, H., Ye, M., Yap, Y.K. and Si, C. (2019) The Impact of Bio-Oil as Rejuvenator for Aged Asphalt Binder. *Construction and Building Materials*, **196**, 134-143. <https://doi.org/10.1016/j.conbuildmat.2018.10.168>
- [48] Hanz, A.J. and Bahia, H.U. (2013) Asphalt Binder Contribution to Mixture Workability and Application of Asphalt Lubricity Test to Estimate Compactability Temperatures for Warm-Mix Asphalt. *Transportation Research Record: Journal of the Transportation Research Board*, **2371**, 87-95. <https://doi.org/10.3141/2371-10>
- [49] Heijungs, R. (2022) The Revised Mathematics of Life Cycle Sustainability Assessment. *Journal of Cleaner Production*, **350**, Article ID: 131380. <https://doi.org/10.1016/j.jclepro.2022.131380>
- [50] Husillos Rodríguez, N., Martínez-Ramírez, S. and Blanco-Varela, M.T. (2016) Activated Carbon as an Alternative Fuel. Effect of Carbon Ash on Cement Clinkerization. *Journal of Cleaner Production*, **119**, 50-58. <https://doi.org/10.1016/j.jclepro.2016.01.093>
- [51] Çınar, M.E. and Kar, F. (2018) Characterization of Composite Produced from Waste PET and Marble Dust. *Construction and Building Materials*, **163**, 734-741. <https://doi.org/10.1016/j.conbuildmat.2017.12.155>

- [52] Nath, P. and Sarker, P.K. (2014) Effect of GGBFS on Setting, Workability and Early Strength Properties of Fly Ash Geopolymer Concrete Cured in Ambient Condition. *Construction and Building Materials*, **66**, 163-171. <https://doi.org/10.1016/j.conbuildmat.2014.05.080>
- [53] Houshyar, E., Dalgaard, T., Tarazkar, M.H. and Jørgensen, U. (2015) Energy Input for Tomato Production What Economy Says, and What Is Good for the Environment. *Journal of Cleaner Production*, **89**, 99-109. <https://doi.org/10.1016/j.jclepro.2014.11.022>
- [54] Pepè Sciarria, T., Vacca, G., Tambone, F., Trombino, L. and Adani, F. (2019) Nutrient Recovery and Energy Production from Digestate Using Microbial Electrochemical Technologies (METs). *Journal of Cleaner Production*, **208**, 1022-1029. <https://doi.org/10.1016/j.jclepro.2018.10.152>
- [55] Măță, L., Clipa, O., Cojocariu, V., Robu, V., Dobrescu, T., Hervás-Gómez, C., *et al.* (2021) Students' Attitude Towards the Sustainable Use of Mobile Technologies in Higher Education. *Sustainability*, **13**, Article 5923. <https://doi.org/10.3390/su13115923>
- [56] Wu, Y., Yin, X., Zhang, Q., Wang, W. and Mu, X. (2014) The Recycling of Rare Earths from Waste Tricolor Phosphors in Fluorescent Lamps: A Review of Processes and Technologies. *Resources, Conservation and Recycling*, **88**, 21-31. <https://doi.org/10.1016/j.resconrec.2014.04.007>
- [57] Xiao, J., Zhen, Z., Tian, L., Su, B., Chen, H. and Zhu, A.X. (2021) Green Behavior Towards Low-Carbon Society: Theory, Measurement and Action. *Journal of Cleaner Production*, **278**, Article ID: 123765. <https://doi.org/10.1016/j.jclepro.2020.123765>
- [58] Zhao, S., Huang, B., Shu, X., Jia, X. and Woods, M. (2012) Laboratory Performance Evaluation of Warm-Mix Asphalt Containing High Percentages of Reclaimed Asphalt Pavement. *Transportation Research Record: Journal of the Transportation Research Board*, **2294**, 98-105. <https://doi.org/10.3141/2294-11>
- [59] Zornberg, J.G. (2017) Functions and Applications of Geosynthetics in Roadways. *Procedia Engineering*, **189**, 298-306. <https://doi.org/10.1016/j.proeng.2017.05.048>
- [60] Wu, F., Yu, Q. and Brouwers, H.J.H. (2022) Long-Term Performance of Bio-Based Miscanthus Mortar. *Construction and Building Materials*, **324**, Article ID: 126703. <https://doi.org/10.1016/j.conbuildmat.2022.126703>
- [61] Abellán-García, J. and Guzmán-Guzmán, J.S. (2021) Random Forest-Based Optimization of UHPFRC under Ductility Requirements for Seismic Retrofitting Applications. *Construction and Building Materials*, **285**, Article ID: 122869. <https://doi.org/10.1016/j.conbuildmat.2021.122869>
- [62] Fernandes, J., Peixoto, M., Mateus, R. and Gervásio, H. (2021) Corrigendum to 'life Cycle Analysis of Environmental Impacts of Earthen Materials in the Portuguese Context: Rammed Earth and Compressed Earth Blocks' [J. Clean. Prod. 241 (2019) 118286]. *Journal of Cleaner Production*, **294**, Article ID: 126361. <https://doi.org/10.1016/j.jclepro.2021.126361>
- [63] Paloheimo, H., Lettenmeier, M. and Waris, H. (2016) Transport Reduction by Crowdsourced Deliveries—A Library Case in Finland. *Journal of Cleaner Production*, **132**, 240-251. <https://doi.org/10.1016/j.jclepro.2015.04.103>
- [64] Sanz-Hernández, A., Esteban, E. and Garrido, P. (2019) Transition to a Bioeconomy: Perspectives from Social Sciences. *Journal of Cleaner Production*, **224**, 107-119. <https://doi.org/10.1016/j.jclepro.2019.03.168>
- [65] Klopogge, J.T., Ponce, C.P. and Ortillo, D.O. (2021) X-Ray Photoelectron Spectroscopic Study of Some Organic and Inorganic Modified Clay Minerals. *Materials*, **14**,

Article 7115. <https://doi.org/10.3390/ma14237115>

- [66] Dong, F., Wang, Y., Su, B., Hua, Y. and Zhang, Y. (2019) The Process of Peak CO₂ Emissions in Developed Economies: A Perspective of Industrialization and Urbanization. *Resources, Conservation and Recycling*, **141**, 61-75. <https://doi.org/10.1016/j.resconrec.2018.10.010>
- [67] Cheng, Y., Zhang, S., Liu, S., Huang, J., Zhang, Z., Wang, X., et al. (2021) Fog Catcher Brushes with Environmental Friendly Slippery Alumina Micro-Needle Structured Surface for Efficient Fog-Harvesting. *Journal of Cleaner Production*, **315**, Article ID: 127862. <https://doi.org/10.1016/j.jclepro.2021.127862>
- [68] Taelman, S.E., De Meester, S., Schaubroeck, T., Sakshaug, E., Alvarenga, R.A.F. and Dewulf, J. (2014) Accounting for the Occupation of the Marine Environment as a Natural Resource in Life Cycle Assessment: An Exergy Based Approach. *Resources, Conservation and Recycling*, **91**, 1-10. <https://doi.org/10.1016/j.resconrec.2014.07.009>
- [69] Ahmadabadi, Z.N., Laville, F. and Guilbault, R. (2015) An Empirical Prediction Law for Quasi-Static Nail-Plywood Penetration Resistance. *Construction and Building Materials*, **88**, 126-133. <https://doi.org/10.1016/j.conbuildmat.2015.04.011>
- [70] Sáez, R. and Prats, X. (2023) Time-Based-Fuel-Efficient Aircraft Descents: Thrust-Idle Descents along Re-Negotiated Routes vs. Powered Descents along Published Routes. *Transportation Research Part D: Transport and Environment*, **114**, Article ID: 103563. <https://doi.org/10.1016/j.trd.2022.103563>
- [71] Wu, C.C., Raghavan, S., Pine, A., Alfaro, J., Love, B.J. and Collias, D.I. (2021) Dewatering of Super Absorbent Polymers: Alternatives to Thermal Desorption by Liquid Phase Extraction Using Dimethyl Ether. *Resources, Conservation and Recycling*, **171**, Article ID: 105641. <https://doi.org/10.1016/j.resconrec.2021.105641>
- [72] Mo, Z., Wang, R. and Gao, X. (2020) Hydration and Mechanical Properties of UHPC Matrix Containing Limestone and Different Levels of Metakaolin. *Construction and Building Materials*, **256**, Article ID: 119454. <https://doi.org/10.1016/j.conbuildmat.2020.119454>
- [73] Kafodya, I. and Okonta, F. (2018) Effects of Natural Fiber Inclusions and Pre-Compression on the Strength Properties of Lime-Fly Ash Stabilised Soil. *Construction and Building Materials*, **170**, 737-746. <https://doi.org/10.1016/j.conbuildmat.2018.02.194>
- [74] Vega A., D.L., Gilberto, M.A. and dos Santos, J.M.O. (2019) Life Cycle Assessment of Warm Mix Asphalt with Recycled Concrete Aggregate. *IOP Conference Series: Materials Science and Engineering*, **603**, Article ID: 052016. <https://doi.org/10.1088/1757-899x/603/5/052016>
- [75] Hossain, Z., Bairgi, B. and Belshe, M. (2015) Investigation of Moisture Damage Resistance of GTR-Modified Asphalt Binder by Static Contact Angle Measurements. *Construction and Building Materials*, **95**, 45-53. <https://doi.org/10.1016/j.conbuildmat.2015.07.032>
- [76] Salomone, R., Saija, G., Mondello, G., Giannetto, A., Fasulo, S. and Savastano, D. (2017) Environmental Impact of Food Waste Bioconversion by Insects: Application of Life Cycle Assessment to Process Using *Hermetia illucens*. *Journal of Cleaner Production*, **140**, 890-905. <https://doi.org/10.1016/j.jclepro.2016.06.154>
- [77] Maaroufi, M., Abahri, K., Hachem, C.E. and Belarbi, R. (2018) Characterization of EPS Lightweight Concrete Microstructure by X-Ray Tomography with Consideration of Thermal Variations. *Construction and Building Materials*, **178**, 339-348. <https://doi.org/10.1016/j.conbuildmat.2018.05.142>

- [78] Ivner, J. and Broberg Viklund, S. (2015) Effect of the Use of Industrial Excess Heat in District Heating on Greenhouse Gas Emissions: A Systems Perspective. *Resources, Conservation and Recycling*, **100**, 81-87.
<https://doi.org/10.1016/j.resconrec.2015.04.010>