al-Mammori, ZA, Al-Janabi, IMK, Abbas, GH, Aziz, DH, Alaaraji, FH, Abbas, ES, AL-shimmery, BM, Hashim, TM, Al-Jameel, GQ, Shubbar, A and Nasr, MS

Mechanical and Performance Characteristics of Warm Mix Asphalt Modified with Phase Change Materials and Recycled Cigarette Filters

CivilEng

Article

Mechanical and Performance Characteristics of Warm Mix Asphalt Modified with Phase Change Materials and Recycled Cigarette Filters

Zahraa Ahmed al-Mammori [1], Israa Mohsin Kadhim Al-Janabi [2], Ghadeer H. Abbas [3], Doaa Hazim Aziz [3], Fatin H. Alaaraji [4], Elaf Salam Abbas [4], Beshaer M. AL-shimmery [4], Tameem Mohammed Hashim [2], Ghanim Q. Al-Jameel [5], Ali Shubbar [5,*] and Mohammed Salah Nasr [6]

1 Technical Institute of Babylon, AL-Furat AL-Awsat Technical University (ATU), Najaf 54003, Iraq
2 Building and Construction Techniques Engineering Department, College of Engineering and Engineering Techniques, Al-Mustaqbal University, Babylon 51001, Iraq; tameemmohammed@uomus.edu.iq
3 Department of Prosthetics and Orthotics Engineering, College of Engineering and Engineering Technologies, Al-Mustaqbal University, Babylon 51001, Iraq
4 Department of Architecture, College of Engineering, University of Babylon, Babylon 51002, Iraq
5 School of Civil Engineering and Built Environment, Liverpool John Moores University, Liverpool L3 5UX, UK
6 College of Engineering, University of Babylon, Babylon 51002, Iraq; eng511.mohammed.nasr@uobabylon.edu.iq
* Correspondence: a.a.shubbar@ljmu.ac.uk

Abstract

With rising global temperatures and increasing sustainability demands, the need for advanced pavement solutions has never been greater. This study breaks new ground by integrating phase change materials (PCMs), including paraffin-based wax (Rubitherm RT55), hydrated salt (Climator Salt S10), and fatty acid (lauric acid), as binder modifiers within warm mix asphalt (WMA) mixtures. Moving beyond the traditional focus on binder-only modifications, this research utilizes recycled cigarette filters (CFs) as a dual-purpose fiber additive, directly reinforcing the asphalt mixture while simultaneously transforming a major urban waste stream into valuable infrastructure. The performance of the developed WMA mixture has been evaluated in terms of stiffness behavior using an Indirect Tensile Strength Modulus (ITSM) test, permanent deformation using a static creep strain test, and rutting resistance using the Hamburg wheel-track test. Laboratory tests demonstrated that the incorporation of PCMs and recycled CFs into WMA mixtures led to remarkable improvements in stiffness, deformation resistance, and rutting performance. Modified mixes consistently outperformed the control, achieving up to 15% higher stiffness after 7 days of curing, 36% lower creep strain after 4000 s, and 64% reduction in rut depth at 20,000 passes. Cost–benefit analysis and service life prediction show that, despite costing USD 0.71 more per square meter with 5 cm thickness, the modified WMA mixture delivers much greater durability and rutting resistance, extending service life to 19–29 years compared to 10–15 years for the control. This highlights the value of these modifications for durable, sustainable pavements.

Keywords: warm mix asphalt (WMA); phase change materials (PCMs); cigarette filters (CFs); pavement sustainability; rutting resistance; service life prediction; cost–benefit analysis

check for updates

Academic Editors: Angelo Luongo and Luis Picado-Santos

Received: 30 June 2025
Revised: 26 July 2025
Accepted: 29 July 2025
Published: 5 August 2025

Citation: al-Mammori, Z.A.; Al-Janabi, I.M.K.; Abbas, G.H.; Aziz, D.H.; Alaaraji, F.H.; Abbas, E.S.; AL-shimmery, B.M.; Hashim, T.M.; Al-Jameel, G.Q.; Shubbar, A.; et al. Mechanical and Performance Characteristics of Warm Mix Asphalt Modified with Phase Change Materials and Recycled Cigarette Filters. *CivilEng* **2025**, *6*, 41. https://doi.org/10.3390/civileng6030041

1. Introduction

1.1. Research Background

In hot climate regions, asphalt pavements often suffer from excessive heat accumulation, leading to premature distress such as rutting, bleeding, and surface degradation [1], as shown in Figure 1. This is particularly evident in regions like Iraq, where the average annual air temperature exceeds 25 °C and summer pavement surface temperatures can reach up to 70 °C [2]. In contrast, Central European regions experience significantly lower average annual temperatures, typically below 15 °C, across elevations ranging from 0 to 1100 m above sea level [3]. To address this thermal challenge, phase change materials (PCMs) have emerged as a promising solution due to their ability to absorb, store, and release heat during phase transitions, thereby regulating pavement temperature [4].

Figure 1. Heat-induced distress on asphalt pavement in hot climate regions.

This study explores the integration of paraffin-based wax (Rubitherm RT55), hydrated salt (Climator Salt S10), and fatty acid (lauric acid) as PCMs in warm mix asphalt (WMA) mixtures to enhance thermal regulation and reduce production temperatures. In addition, shredded cigarette filters (CFs) are introduced as a novel waste-derived micro-fiber additive, contributing to sustainability by utilizing a persistent and toxic urban waste. The combination of PCMs and CFs aims to improve the mixture's heat resistance, workability, and environmental footprint, offering a multi-functional and eco-friendly approach to asphalt pavement design [5].

Paraffin-based wax (Rubitherm RT55) is a synthetic phase change material with a melting point of around 55 °C, used in warm mix asphalt (WMA) to absorb excess heat and stabilize pavement temperature [6]. Hydrated salt (Climator Salt S10) is designed to undergo a solid–liquid phase change at approximately 10 °C, absorbing heat during melting and releasing it upon solidification [7]. Fatty acid (lauric acid) is a natural PCM derived from coconut or palm oil, with a melting point of approximately 44 °C, offering biodegradable, non-toxic thermal regulation within WMA mixtures [8]. In addition, cigarette filters (CFs) are among the most commonly littered waste materials globally, with an estimated 4.5 trillion improperly discarded each year [9]. They are composed primarily of non-biodegradable cellulose acetate fibers. Incorporating PCMs into asphalt binder helps lower peak pavement temperatures and reduce rutting in hot climates, while adding CFs as a waste-derived fiber enhances mixture stability and promotes sustainability by utilizing a common urban litter [9]. The developed WMA mixtures are evaluated using key performance tests, including indirect tensile stiffness modulus (ITSM), creep strain analysis, and the Hamburg wheel-tracking test, to assess their mechanical behavior and resistance to rutting. Besides that, a cost–benefit analysis is performed to compare the cost of construction materials and additives used in both the control and modified WMA mixtures, and an analytical prediction of their service life is presented based on rutting performance.

1.2. Literature Review

The incorporation of phase change materials (PCMs)—including Rubitherm RT55, Climator Salt S10, and lauric acid—into warm mix asphalt (WMA) mixtures demonstrates notable potential for improving both thermal regulation and mechanical performance. Jamshidi A. et al. [10] reported that WMA modified with Sasobit® also showed improved stiffness and rutting resistance due to wax crystallization within the binder. However, unlike Sasobit®, the PCMs in the present study offer dynamic thermal regulation by absorbing and releasing heat during phase transitions, providing both structural and thermal benefits, while the inclusion of cigarette filters (CFs) as a waste-derived fiber enhances mixture stability and contributes to sustainability. Similarly, Ma F. et al. [11] investigate the integration of microencapsulated binary eutectic phase change materials (PCMs) into asphalt binders, demonstrating significant improvements in thermal energy storage and pavement temperature regulation. Their study highlights the effectiveness of PCM microcapsules in reducing temperature-induced damage, while maintaining the mechanical integrity of the asphalt. In the present study, Rubitherm RT55, Climator Salt S10, and lauric acid are selected as potential PCMs for warm mix asphalt (WMA) mixtures to achieve similar thermal regulation benefits. Furthermore, Fu Z. et al. [12] investigated the rheological behavior of asphalt binders modified with low-temperature microencapsulated eutectic phase change materials (PCMs). Their findings indicated that the incorporation of these PCMs enhanced the binder's resistance to thermal fluctuations, particularly at low service temperatures, while preserving satisfactory viscoelastic properties. In comparison, in addition to exploring various PCM candidates for thermal regulation across both binder and mixture levels in WMA, the study also utilizes shredded cigarette filters (CFs) as a reinforcing waste material, introducing a parallel sustainability strategy through waste valorization. While Fu Z. et al. focus primarily on binder-scale rheological properties, the current research expands the investigation to include mixture-scale mechanical performance.

Milad A. et al. [13] conducted a comparative review of hot and warm mix asphalt technologies, focusing on their environmental and economic impacts. Their findings emphasized the advantages of WMA in reducing energy consumption, greenhouse gas emissions, and overall production costs, positioning WMA as a more sustainable alternative to conventional hot mix methods. Building on this foundation, the present study explores the integration of PCMs into WMA mixtures to further enhance sustainability by improving thermal regulation and extending pavement service life. In addition, Saboo N. and Das A. [14] reviewed the state of asphalt pavement design and performance in the context of Indian transportation infrastructure, highlighting challenges related to increasing traffic loads, temperature extremes, and material limitations. Their work emphasized the need for innovative materials and technologies to enhance pavement durability and adapt to evolving climate and loading conditions. In response to these challenges, this study explores the use of PCMs in WMA mixtures to enhance thermal regulation and mechanical performance, while also introducing CFs as a novel fiber reinforcement to support environmental sustainability and material efficiency.

1.3. The Novelty of the Study

This study introduces the use of PCMs, Rubitherm RT55, Climator Salt S10, and lauric acid into WMA mixtures to enhance thermal regulation and rutting resistance in hot climates. Unlike previous studies focused on binder-level modifications, this research evaluates PCM effects at the mixture scale. To further support sustainability, shredded CFs are incorporated as a waste-derived fiber additive, offering reinforcement benefits while addressing a major urban litter issue. Additionally, a cost–benefit analysis compares the material and additive costs of control and modified WMA mixtures. Their service life is analytically predicted based on rutting performance, which is considered the dominant distress mechanism under Iraq's high-temperature climate and heavy traffic conditions. Given the characteristics of WMA, resistance to permanent deformation is a primary concern for field performance.

1.4. The Objectives of the Study

This study aims to improve the performance of WMA mixtures by utilizing PCMs for enhanced thermal regulation and increased rutting resistance under elevated temperatures. Simultaneously, shredded CFs are incorporated as sustainable fiber reinforcement to improve mixture stability and promote waste valorization. The mechanical behavior of the modified mixtures is evaluated through laboratory testing. Additionally, a cost–benefit analysis compares the construction material and additive costs of control and modified WMA mixtures, while an analytical approach predicts their service life based on rutting performance. Collectively, these innovations support the development of more climate-resilient and environmentally responsible asphalt pavements.

2. Experimental Work

2.1. The Incorporated Materials

2.1.1. Asphalt Binder

Asphalt binder grade 60/70 or PG 64-16 is a medium-hard penetration grade bitumen, widely used in road construction, particularly in hot-to-moderate climates. It has a penetration range of 60 to 70 (0.1 mm) at 25 °C, indicating a balance between flexibility and stiffness. This makes it suitable for resisting rutting under high temperatures while maintaining good workability during mixing and compaction. In WMA applications, 60/70 binder is often preferred for its compatibility with additives and its ability to perform well under reduced production temperatures [15]. The main physical properties of the used binder are shown below in Table 1.

Table 1. The main physical properties of 60/70 asphalt binder.

Test Property	Result	Requirement
Penetration @ 25 °C	64 dmm	60–70
Softening Point (R&B)	52 °C	48–56 °C
Ductility @ 25 °C	110 cm	≥100 cm
Flash Point	240 °C	≥230 °C
Specific Gravity @ 25 °C	1.03	1.01–1.06
Viscosity @ 135 °C	400 cP	300–600 cP

2.1.2. The Adopted Aggregate

Crushed basalt is used as the coarse aggregate due to its high strength, as shown in Figure 2, angularity, and excellent resistance to rutting and deformation, making it ideal for hot climate conditions. For the fine aggregate, basalt sand derived from crushed gravel, as shown in Figure 3, is selected for its adequate gradation and ability to fill voids, improving workability and compaction. This combination ensures a strong interlock, good binder adhesion at lower mixing temperatures, and overall durability of the WMA mixture [16]. The physical properties of both coarse and fine aggregates are shown below in Tables 2 and 3.

Figure 2. Coarse aggregate crushed basalt.

Figure 3. Fine aggregate crushed gravel.

Table 2. Coarse crushed basalt physical properties.

Test Property	Result	Standard	Requirement
Specific Gravity	2.85	ASTM C127 [17]	≥2.5
Water Absorption	1.2%	ASTM C127 [17]	≤3%
Los Angeles Abrasion	25%	ASTM C131 [18]	≤40%
Bulk Density	1550 kg/m^3	ASTM C29 [19]	-

Table 3. Fine crushed gravel physical properties.

Test Property	Result	Standard	Requirement
Specific Gravity	2.65	ASTM C128 [20]	≥2.5
Water Absorption	1.0%	ASTM C128 [20]	≤3%
Fineness Modulus	2.8	ASTM C136 [21]	-
Bulk Density	1550 kg/m^3	ASTM C29 [19]	-
Silt Content	1.5%	ASTM C117 [22]	≤3%

The middle aggregate gradation from Iraqi specifications for roads and bridges (SCRB, R/9), [23] was used for the surface wearing course in this study, as shown below in

Figure 4. It provided a balanced mix that improved strength, workability, and durability, ensuring good resistance to rutting and cracking while matching local materials and construction practices.

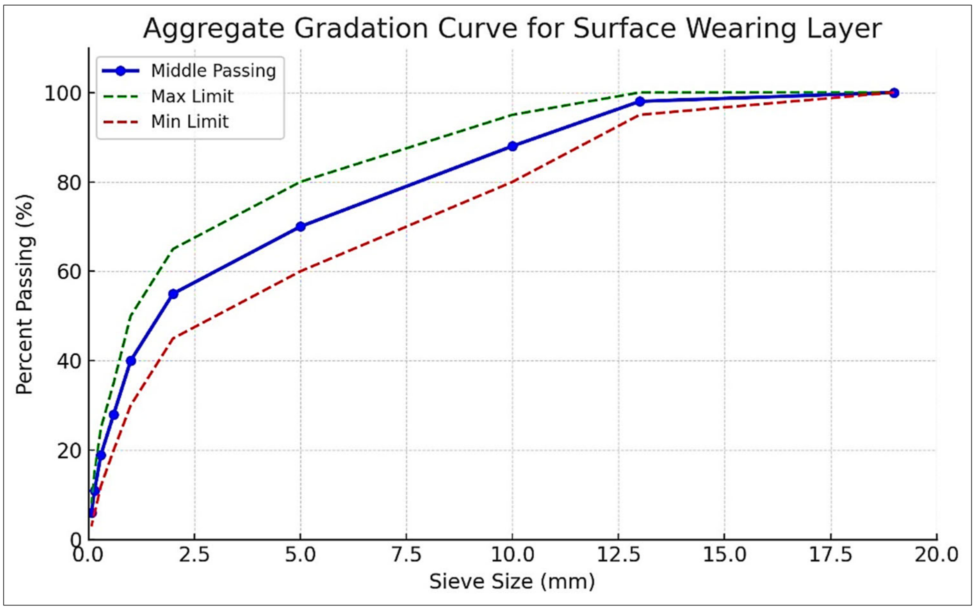

Figure 4. The middle aggregate gradation for the surface wearing layer.

2.1.3. The Elected Filler

Ordinary Portland Cement (OPC) was used as a filler in the asphalt mixture to improve its mechanical properties. The addition of OPC enhanced the stiffness and early strength of the mixture, enabling it to better withstand traffic loads and environmental conditions [24]. Furthermore, the cement improved adhesion between the asphalt binder and aggregate, which helped reduce stripping and moisture damage. Due to its availability and cost-effectiveness, OPC proved to be a practical filler choice for enhancing the performance of the warm asphalt mixture [24]. Its main physical properties are shown below in Table 4.

Table 4. Ordinary Portland Cement physical properties.

Test Property	Result	Standard	Requirement
Fineness (m^2/kg)	330	ASTM C204 [25]	≥320
Specific Gravity	3.12	ASTM C188 [26]	3.10–3.15

2.1.4. Paraffin-Based Wax (Rubitherm RT55)

Paraffin-based wax, specifically Rubitherm RT55, is a phase change material commonly used to improve thermal performance in various applications, as shown in Figure 5. With a melting point around 55 °C, it absorbs and releases heat during phase transitions, helping regulate temperature and reduce thermal fluctuations. In asphalt mixtures, Rubitherm RT55 can be added to enhance temperature stability, reduce thermal cracking, and improve durability by moderating the temperature changes during heating and cooling cycles [27]. Its main physical properties are shown below in Table 5.

Figure 5. Rubitherm RT55.

Table 5. Rubitherm RT55 physical properties.

Test Property	Result	Standard	Requirement
Appearance	White waxy solid	Visual inspection	White, waxy solid
Melting Point (°C)	55	ASTM D3418 [28]	51–57 °C
Heat of Fusion (kJ/kg)	190	ASTM D3418 [28]	180–200 kJ/kg
Density (kg/m^3)	780	ISO 1183 [29]	770–790 kg/m^3
Flash Point	210	ASTM D93 [30]	190–230 °C

2.1.5. Hydrated Salt (Climator Salt S10)

Climator Salt S10 is a hydrated salt-based phase change material (PCM) extensively utilized in thermal energy storage systems due to its high latent heat capacity and reliable phase transition characteristics, as shown below in Figure 6. This material exhibits efficient thermal regulation by absorbing and releasing significant amounts of latent heat during melting and solidification processes.

Figure 6. Climator Salt S10.

Its consistent melting point and thermal stability render it particularly suitable for incorporation into construction materials, such as asphalt mixtures, where it can mitigate thermal stresses, enhance temperature uniformity, and ultimately improve material durability and performance under fluctuating temperature conditions [31]. Its main physical properties are shown below in Table 6.

Table 6. Climator Salt S10 physical properties.

Test Property	Result	Standard	Requirement
Appearance	White crystalline solid	Visual Inspection	White/off-white crystals
Melting Point (°C)	30	ASTM D3418 [28]	28–32 °C
Heat of Fusion (kJ/kg)	175	ASTM D3418 [28]	150–200
Density (kg/m^3)	1650	ISO 1183 [29]	1600–1700
Thermal Conductivity (W/m·K)	0.6	ASTM C177 [32]	0.5–0.7

2.1.6. Fatty Acid (Lauric Acid)

Lauric acid, chemically known as dodecanoic acid, is a saturated medium-chain fatty acid commonly found in natural oils such as coconut oil and palm kernel oil, as shown in Figure 7. It has favorable thermal properties, including a suitable melting point and high latent heat capacity, which make it an effective PCM for temperature regulation in asphalt mixtures. Its inclusion contributes to improved thermal stability and energy efficiency in pavement applications [33]. Its main physical properties are shown below in Table 7.

Figure 7. Lauric acid.

Table 7. Lauric acid physical properties.

Test Property	Result	Standard	Requirement
Appearance	White crystalline solid	Visual Inspection	White waxy solid
Melting Point (°C)	43.8	ASTM D3418 [28]	43.5–44 °C
Density (g/cm^3)	0.85	ASTM D4052 [34]	0.84–0.85
Flash Point (°C)	200	ASTM D93 [30]	200–210 °C

2.1.7. Cigarette Filters (CFs)

Cigarette filters (CFs) are one of the most prevalent forms of urban litter, composed primarily of non-biodegradable cellulose acetate fibers. In this study, CFs were collected mainly from local cafés, offering a readily available and underutilized waste stream as shown in Figure 8. Their incorporation into asphalt mixtures presents a sustainable approach to waste management, while potentially enhancing pavement performance through fiber reinforcement [35]. Before incorporating CFs into asphalt mixtures, proper preparation is essential to ensure safety, performance, and compatibility. Below are the recommended steps:

- Air-dry in a ventilated area or oven-dry at 80–100 °C for 24–48 hr.
- Cut or shred CFs into small fibers or flakes, as shown in Figure 9.
- Store shredded CFs in dry, sealed bags or containers to prevent moisture reabsorption and contamination.

Figure 8. Collected cigarette filters.

Figure 9. Shredded flakes of CFs.

2.2. Lab-Based Performance Analysis

2.2.1. Asphalt Binder Modification Process

The additive dosages used in this study were determined based on the findings from earlier research and practical insights into asphalt binder modification, as well as after many mixing trials to determine the optimum dosages that achieved high Marshall stability and density at 4% air voids for generated WMA specimens:

- The adopted dose of paraffin-based wax (Rubitherm RT55) is 2% by weight of binder [6].

- The adopted dose of hydrated salt (Climator Salt S10) is 1% by weight of binder [36].
- The adopted dose of fatty acid (lauric acid) is 1% by weight of binder [37].

Rubitherm RT55 at 2% effectively reduces mixing and compaction temperatures, consistent with the typical 1–3% range for paraffin-based waxes [6]. Climator Salt S10 at 1% aligns with the effective range of hydrated salts used to promote binder foaming and improve workability [36]. A 1% dosage of lauric acid was selected based on preliminary mixing trials, which yielded high Marshall stability values. This aligns with typical practices for fatty acid-based additives, ensuring improved thermal performance without compromising binder integrity [37]. These dosages represent balanced, mid-range values that ensure efficient modification while maintaining mix integrity.

The mixing process begins by heating the 60/70 asphalt binder to 140–150 °C until it reaches a fully fluid state, ensuring uniform temperature through gentle stirring. Once the binder is adequately heated, it is transferred into a metal mixing container placed under a fabricated high-shear mixer, as shown in Figure 10. The mixer is initially set to a low speed (1000 rpm) to avoid splashing. Rubitherm RT55 (2% by weight of binder) is added first, as it melts and disperses quickly, followed by Climator Salt S10 (1%), which may be pre-dried to eliminate moisture and prevent foaming. Finally, lauric acid (1%) is introduced due to its fast-reacting and low-melting characteristics. After all additives are added, the mixing speed is gradually increased to 3000–4000 rpm and maintained for 30–45 min at a constant temperature (140–150 °C) to ensure thorough dispersion and homogeneous modification of the binder [38]. The developed binder was then evaluated in terms of its new physical properties, as shown below in Table 8.

Figure 10. Fabricated high-shear mixer.

Table 8. The physical properties of the developed binder.

Test Property	Result	Standard
Penetration @ 25 °C	58 dmm	ASTM D5 [39]
Softening Point (R&B)	53 °C	ASTM D36 [40]
Ductility @ 25 °C	78 cm	ASTM D113 [41]
Flash Point	272 °C	ASTM D92 [42]
Specific Gravity @ 25 °C	1.04	ASTM D70 [43]
Viscosity @ 135 °C	355 cP	ASTM D4402 [44]

2.2.2. WMA Specimen Preparation

Determining the optimum binder content is a key part of designing WMA mixtures. Using the Marshall method, engineers test properties like stability, flow, air voids, and density to find the best balance for durability and performance. In this study, the optimum binder content for the WMA surface layer was determined to be 4.6%, which ensures a strong, long-lasting, and sustainable pavement. After determining the optimum binder content, WMA specimens were prepared by heating aggregates and the binder to the required mixing temperature (115–135 °C) and then thoroughly mixing them with WMA additives. The mixture was molded and compacted using standard procedures, making the specimens ready for testing. Three groups of specimens were prepared. The first group, which is the control, consisted of an unmodified WMA mixture produced using the selected binder and aggregate gradation without any additives. The second group is a WMA mixture modified with PCMs, which were blended into the binder at specified percentages. The third group is a WMA mixture modified with both PCMs and CFs, with CFs added based on the filler weight. All other mix design parameters were kept consistent across the groups, as shown in Figure 11. Based on previously published works, the mixing percentage of CFs was investigated as a partial replacement for mineral filler in WMA mixtures within the range of 2% to 6% by weight of the filler. For this study, 3% CFs by weight of the filler were selected as the adopted replacement percentage for further evaluation [45].

Figure 11. WMA specimens.

2.2.3. The Indirect Tensile Stiffness Modulus (ITSM) Test

The ITSM test is widely used to assess the stiffness characteristics of asphalt mixtures, including WMA specimens, under conditions similar to those experienced in the field. Following ASTM D4123 [46], the test involves placing cylindrical WMA specimens, typically 100 mm in diameter and 63.5 mm in height, in the horizontal direction between two loading strips inside a compression testing machine. Repeated load pulses, typically 5 to 10 cycles with a haversine waveform, are applied vertically along the central axis of the specimen, generating indirect tensile stress in the horizontal direction across the sample, as shown in Figure 12. Horizontal deformation is captured by a sensitive gauge, and the stiffness modulus is then calculated as the ratio of applied stress to the resulting strain. Conducted at a controlled temperature (25 °C), this test provides a reliable measure of the mix's elastic response and overall structural performance, which is essential for evaluating its suitability for road applications.

Figure 12. ITSM test apparatus.

2.2.4. Static Creep Strain Test

The creep strain test is a fundamental laboratory procedure for evaluating the resistance of asphalt mixtures to permanent deformation when exposed to prolonged loading. In this study, the test was performed following ASTM D5365 [47]. Cylindrical specimens measuring 100 mm in diameter and 63.5 mm in height were subjected to a constant static load at a temperature of 40 °C, as shown in Figure 13. The accumulated strain was continuously recorded and expressed as a percentage over a test period ranging from 1000 to 4000 s. This approach closely simulates the long-term stresses pavement materials experience in service. Lower percentages of accumulated strain indicate better rutting resistance, providing a reliable measure of the asphalt mixture's durability and structural performance.

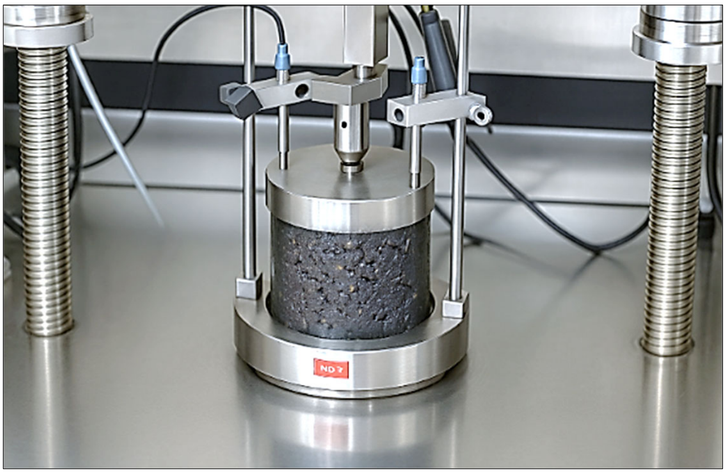

Figure 13. Creep strain test apparatus.

2.2.5. Hamburg Wheel-Track Test (HWTT)

The HWTT, conducted according to the European standard EN 12697-22 [48], is a key laboratory method for evaluating the rutting of warm mix asphalt (WMA) mixtures. In this procedure, WMA is compacted into rectangular slab specimens, typically 260 mm × 320 mm × 50 mm, using a roller compactor to ensure uniform density and air voids, as shown in Figure 14. The slab is then placed in the wheel-tracking device, where a steel wheel applying a standard load of 700 N repeatedly rolls over the specimen surface at a controlled temperature, commonly 50 °C, as shown in Figure 15. The device automatically records the development of rut depth as the wheel passes back and forth for a set number of cycles, providing a direct measure of the mixture's resistance to rutting damage. This European slab-based method offers a realistic and reliable evaluation of WMA performance under simulated traffic loading conditions.

Figure 14. A roller compactor.

Figure 15. HWTT apparatus.

3. Results and Discussion

For each laboratory test, three specimens were prepared and tested for each mixture type (control WMA, modified WMA with PCMs, and modified WMA with PCM + CF) to reduce experimental variability and improve the reliability of the findings. The average of the test results was used for analysis.

3.1. The Results of the ITSM Test

The results of the indirect tensile stiffness modulus (ITSM) test at different curing periods reveal a clear improvement in stiffness performance for the modified WMA mixtures compared to the control mix. After just 1 day of curing, the control specimen registered an ITSM value of 4000 MPa, while the mixture containing PCMs reached 4400 MPa, showing a notable increase of 10%. Incorporating 3% cigarette filters further elevated the ITSM to 4700 MPa, which is a 15% improvement over the control. As the curing period extended to 3 days, all mixtures demonstrated increased stiffness.

The control mix rose to 4200 MPa, the PCM-modified mix reached 4650 MPa, and the mix with both PCMs and cigarette filters climbed to 4960 MPa. By the seventh day, this positive trend became even more pronounced: the control achieved 4450 MPa, while the PCM-based modified specimen reached 4870 MPa, roughly a 9% improvement. The inclusion of cigarette filters led to the highest ITSM at 5200 MPa, outperforming the control by approximately 15%. Figure 16 demonstrates the achieved results of the ITSM test.

Overall, these results indicate that adding PCMs, and especially CFs, not only boosts the initial stiffness of WMA but also promotes better stiffness development over time. This suggests a strong potential for these additives to enhance the durability and mechanical properties of warm mix asphalt in practical applications.

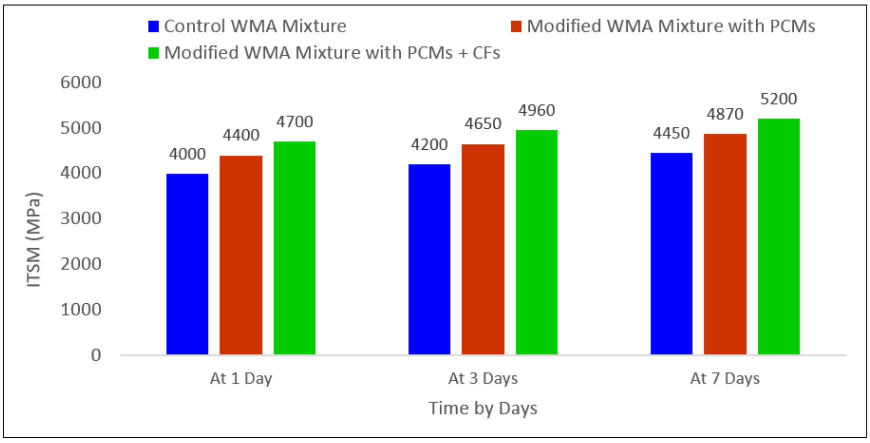

Figure 16. The results of the ITSM test for both control and modified WMA mixtures.

Mazhari Pakenari M. and Hamedi G.H. [49] investigated how different additives affect the stiffness modulus and fatigue cracking of warm mix asphalt. Their results showed that using conventional additives, such as organic waxes and chemical foaming agents, led to moderate improvements in the stiffness modulus. The maximum increase reported was around a 10% higher ITSM compared to the control mix. Although these additives enhanced stiffness and contributed somewhat to fatigue resistance, the overall performance gains remained within this limited range. Their work highlighted the potential of warm mix asphalt technologies but also pointed to the need for more effective, innovative solutions to achieve greater performance improvements. On the other hand, the current study introduces an innovative blend by incorporating not only paraffin-based wax, hydrated salt, and lauric acid, but also recycled cigarette filters as a sustainable approach. This combination resulted in stiffness modulus improvements of up to 16%, surpassing the gains reported in the previous study. Most importantly, the use of recycled cigarette filters as a functional additive is a novel approach not explored in earlier research, directly addressing environmental concerns and material sustainability. In summary, our results not only outperform prior laboratory outcomes but also fill a significant gap by demonstrating the mechanical benefits and environmental advantages of integrating recycled waste into WMA technology.

3.2. The Results of the Static Creep Strain Test

The creep strain test results clearly demonstrated differences in permanent deformation resistance among the studied WMA mixtures. After 4000 s, the control WMA exhibited the highest creep strain at 1.32%. The mixture modified with PCMs showed a reduced creep strain of 1.06%, representing a 20% decrease compared to the control. The most significant improvement was observed in the mixture containing both these additives and 3% CFs, which achieved a creep strain of just 0.84%, corresponding to a 36% reduction relative to the control. These findings highlight the effectiveness of both conventional and novel additives in enhancing the rutting resistance of WMA mixtures. Figure 17 demonstrates the achieved results of the creep strain test.

When compared to the findings of Abed A. et al. [50], who investigated WMA mixtures modified with various additives and typically reported final creep strain values in the range of 1.1% to 1.4% after similar loading periods, our study demonstrates notable advancements. While Abed et al. established that certain WMA additives could marginally improve resistance to permanent deformation, our results show a more substantial reduction, especially with the introduction of recycled cigarette filters, lowering the creep strain to 0.84% (a 36% reduction versus the control). By building on previous research and introducing innovative, sustainable additives, our study not only continues the exploration of WMA modification but also fills prior gaps, offering practical solutions for enhanced rutting resistance and material sustainability in asphalt technology.

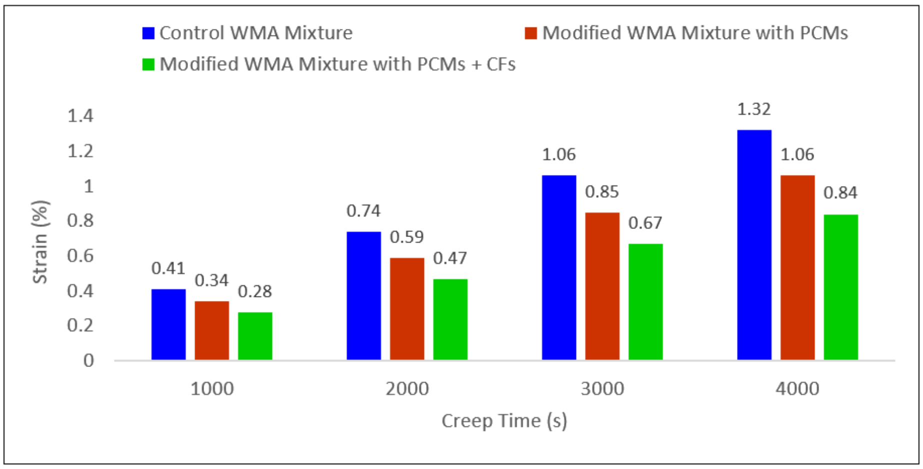

Figure 17. The results of the creep strain test for both control and modified WMA mixtures.

3.3. The Results of the Hamburg Wheel-Track Test (HWTT)

The Hamburg wheel-track test results demonstrated that the modified WMA mixture, incorporating PCMs and 3% CFs, significantly enhanced rutting resistance compared to the control WMA. After 20,000 passes, the control WMA exhibited a rut depth of 12.2 mm, while the PCM-modified mixture showed a rut depth of 7.0 mm, representing a 43% reduction compared to the control. Furthermore, the mixture modified with both PCMs and CFs achieved a substantially lower rut depth of 4.4 mm, corresponding to a 64% reduction. These results clearly highlight the effectiveness of the selected additives in reducing permanent deformation and improving the durability of WMA mixtures under repeated wheel loading. Figure 18 demonstrates the achieved results of the Hamburg wheel-track test.

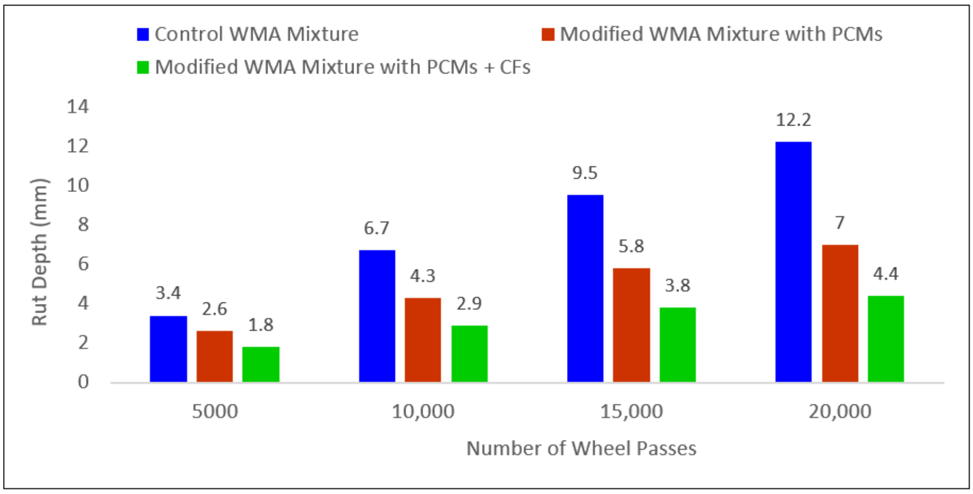

Figure 18. The results of the Hamburg wheel-track test for both control and modified WMA mixtures.

When compared to the findings of Fakhri M et al. [51], who reported rut depths of 8–13 mm for various glass fiber-modified WMA mixtures after 20,000 Hamburg wheel passes, our results demonstrate a notable advancement in rutting resistance. While their study established the positive impact of glass fibers on rutting performance in WMA, our work further enhances this approach by introducing a multi-component modification, combining paraffin-based wax, hydrated salt, lauric acid, and recycled cigarette filters. As a result, our modified mixture achieved a rut depth as low as 4.4 mm after 20,000 passes, representing a substantially greater reduction compared to both their control and fiber-modified WMA. By integrating additional sustainable additives and thoroughly evaluating performance, our research builds upon previous work and addresses existing gaps, offering a more robust and environmentally conscious solution to improving the durability and rutting resistance of WMA pavements.

4. Analytical Assessment

4.1. Cost–Benefit Analysis

The following cost–benefit analysis compares control and modified WMA mixtures using up-to-date prices for construction materials and additives based on current market rates in Iraq. This approach ensures that the calculated costs and economic comparisons accurately reflect the real-world conditions and material expenses relevant to local pavement construction practices. The prices of construction materials and additives are presented in Table 9.

Table 9. Local prices of construction materials and additives in Iraq.

Used Material	Price in USD
Aggregates	USD 15 per ton = USD 0.015 per kg
60/70 Asphalt Binder	USD 195 per ton = USD 0.195 per kg
Filler	USD 82 per ton = USD 0.082 per kg
Paraffin Wax (Rubitherm RT55)	USD 3.30 per kg
Hydrated Salt (Climator Salt S10)	USD 0.75 per kg
Lauric Acid	USD 5.0 per kg
Cigarette Filters (CFs)	USD 0.5 per kg

The quantities of construction materials and additives used to cast the 1 $m^2 \times 0.05$ m WMA slab were determined based on the selected aggregate gradation, the optimum binder content, and the specified percentages of PCMs and CFs.

The measured density of the control compacted WMA mixture was 2350 kg/m^3; therefore, the weight of the slab was calculated as 1 $m^2 \times 0.05$ m $\times$ 2360 kg/m^3 = 118 kg. These details are summarized in Table 10 below.

Table 10. The quantities of construction materials within the control WMA mixture.

Component	Conducted Percentage	Amount by kg
Aggregates	88.4% by mix	$0.884 \times 118 = 104.3$
Filler	7% by mix	$0.07 \times 118 = 8.26$
Binder	4.6% by mix	$0.046 \times 118 = 5.43$

The cost of construction materials to cast a 1 $m^2 \times 0.05$ m control WMA slab is as below:

- Aggregates: 104.3 kg $\times$ USD 0.015 = USD 1.57
- Filler: 8.26 kg $\times$ USD 0.082 = USD 0.68
- Binder: 5.43 kg $\times$ USD 0.195 = USD 1.06
- Total: USD 3.31

The measured density of the modified compacted WMA mixture was 2330 kg/m^3; therefore, the weight of the slab was calculated as (1 m^2 × 0.05 m × 2330 kg/m^3 = 116.5 kg). These details are summarized in Table 11 below

Table 11. The quantities of construction materials and additives within the modified WMA mixture.

Component	Conducted Percentage	Amount by kg
Aggregates	88.4% by mix	0.884 × 116.5 = 103
Filler	7% by mix	0.07 × 116.5 = 8.16
Binder	4.6% by mix	0.046 × 116.5 = 5.36
Paraffin Wax	2% of binder	0.02 × 5.36 = 0.108
Hydrated Salt	1% of binder	0.01 × 5.36 = 0.053
Lauric Acid	1% of binder	0.01 × 5.36 = 0.053
CFs	3% of filler	0.03 × 8.16 = 0.245

The cost of construction materials to cast a 1 m^2 × 0.05 m modified WMA slab is as below:

- Aggregates: 103 kg × USD 0.015 = USD 1.55
- Filler: 8.16 kg × USD 0.082 = USD 0.65
- Binder: 5.36 kg × USD 0.195 = USD 1.04
- Paraffin Wax: 0.108 kg × USD 3.30 = USD 0.36
- Hydrated Salt: 0.053 kg × USD 0.75 = USD 0.04
- Lauric Acid: 0.053 kg × USD 5.0 = USD 0.26
- CFs: 0.245 kg × USD 0.5 = 0.12
- Total: USD 4.02

The difference in cost between the control and modified WMA mixtures equals USD 4.02 − USD 3.31 = USD 0.71; the modified WMA mixture costs approximately USD 0.71 more per square meter than the control mixture for a 5 cm thick slab.

4.2. Analytical Prediction of Service Life

Step 1: Choosing the Design Service Life of the Control WMA Mixture

Most agencies and specifications (AASHTO and Iraqi SCRB) assume 10–15 years as the typical design service life for surface asphalt, depending on road class and traffic; therefore, the lower bound is 10 years and the upper bound is 15 years.

Step 2: Calculating the Service Life of the Modified WMA Mixture Using the Rut Depth Ratio

The measured rut depths for both control and modified WMA mixtures at 20,000 passes were 12.2 mm and 4.4 mm, respectively. Therefore, the life ratio is calculated as

$$Life\ Ratio = \frac{Rut\ Depth\ for\ Control\ WMA}{Rut\ Depth\ for\ modified\ WMA} = \frac{12.2}{4.4} = 2.77 \quad (1)$$

The life ratio was based on rut depths at 20,000 passes, assuming proportional rutting beyond that point for comparative purposes.

Step 3: Projected Service Life for Modified WMA Mixture

$$Modified\ Service\ Life(lower\ bound) = 10\ years \times 2.77 = 27.7\ years \quad (2)$$

$$Modified\ Service\ Life(upper\ bound) = 15\ years \times 2.77 = 41.6\ years \quad (3)$$

Step 4: Applying a Correction Factor

To ensure that laboratory-based service life predictions more accurately reflect real-world pavement performance, a field correction factor, typically ranging from 0.5 to 0.7, is applied to the lab-measured values. This adjustment accounts for the effects of weathering, environmental exposure, traffic variability, construction inconsistencies, and other service conditions that are not fully replicated in laboratory testing. The use of such correction factors is widely supported in the literature, including Pavement Analysis and Design (2nd Edition) [52] and Federal Highway Administration (FHWA) TechBriefs [53], where it is recognized that ideal laboratory conditions often overestimate the actual durability of pavement mixtures in the field. By introducing this calibration, the projected service lives of the control and modified mixtures become more representative of their expected field performance.

$$Correcting\ the\ Modified\ Service\ Life(lower\ bound) = 0.7 \times 27.7\ years = 19.4\ years \quad (4)$$

$$Correcting\ the\ Modified\ Service\ Life(upper\ bound) = 0.7 \times 41.6\ years = 29.1\ years \quad (5)$$

The control WMA mixture is assumed to have a service life of 10–15 years, while the modified WMA mixture with both PCMs and CFs is estimated to achieve a service life of 19–29 years after applying a field correction factor. This demonstrates a substantial enhancement in pavement durability as a result of the modification.

5. Conclusions

This study explored the incorporation of PCMs and shredded CFs into WMA mixtures to enhance thermal regulation, rutting resistance, and sustainability. By evaluating PCM effects at the mixture scale and comparing material costs and predicted service life, the research demonstrates practical improvements over conventional WMA approaches. Based on the study's findings and prior discussions, the following conclusions were reached:

1. Blending paraffin-based wax, hydrated salt, lauric acid, and recycled cigarette filters into warm mix asphalt is not just innovative; it delivers real results. Compared to the control, the modified mixes showed stiffness improvements of up to 10–15% after just 1 day, and by the 7th day, the specimen containing cigarette filters achieved a 15% higher stiffness modulus than the standard mix. This proves that not only do these additives, especially the recycled filters, make WMA stronger and more durable, but they also give a valuable new use for waste materials, turning trash into tougher roads.
2. The static creep strain test demonstrated that modifying WMA mixtures with PCMs and CFs significantly reduces permanent deformation under sustained loading. The observed decrease in creep strain values, up to 36% lower than the control, highlights the effectiveness of these additives in enhancing the long-term stability and durability of warm mix asphalt pavements.
3. The Hamburg wheel-track test results confirmed that modifying WMA mixtures with PCMs and CFs greatly improved rutting resistance, achieving up to a 64% reduction in rut depth compared to the control. The combination of additives, with or without CFs, effectively minimized permanent deformation and significantly enhanced the durability of WMA mixtures under repeated loading.
4. The modified WMA mixture costs USD 0.71 more per square meter than the control for a 5 cm thick slab, but this small increase is offset by its improved performance. With the inclusion of PCMs and recycled cigarette filters, the modified mixture shows higher rutting resistance and durability, resulting in an estimated service life of 19–29 years

compared to 10–15 years for the control. These results indicate that the modifications offer a practical and effective way to enhance pavement longevity and sustainability.

This study enhances WMA mixtures with PCMs and recycled fibers to improve performance and sustainability, evaluates their properties through lab tests, compares material costs, and predicts service life, supporting more climate-resilient asphalt pavements. However, a key limitation of this study is the absence of certain important performance evaluations, such as fatigue resistance, moisture susceptibility, aging characteristics, and low-temperature cracking. Without these additional assessments, the long-term durability and comprehensive behavior of the modified WMA mixtures under diverse service conditions remain uncertain. Future research should address these aspects to provide a more complete understanding of the mixtures' performance.

Author Contributions: Conceptualization, Z.A.a.-M. and I.M.K.A.-J.; methodology, D.H.A., G.H.A. and G.Q.A.-J.; validation, D.H.A., F.H.A. and E.S.A.; formal analysis, B.M.A.-s.; investigation, G.H.A.; writing—original draft preparation, I.M.K.A.-J.; writing—review and editing, Z.A.a.-M. and I.M.K.A.-J.; visualization, T.M.H.; supervision, A.S.; project administration, M.S.N., A.S., T.M.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article.

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

References

1. Almeida, A.; Picado-Santos, L. Asphalt road pavements to address climate change challenges—An overview. *Appl. Sci.* **2022**, *12*, 12515. [CrossRef]
2. Abbas, A.S. Temperature zoning of Iraq for asphalt mix design. *J. Eng. Sustain. Dev.* **2017**, *21*, 54–63.
3. Decky, M.; Hodasova, K.; Papanova, Z.; Remisova, E. Sustainable adaptive cycle pavements using composite foam concrete at high altitudes in central Europe. *Sustainability* **2022**, *14*, 9034. [CrossRef]
4. Nazir, H.; Batool, M.; Osorio, F.J.; Isaza-Ruiz, M.; Xu, X.; Vignarooban, K.; Phelan, P.; Kannan, A.M. Recent developments in phase change materials for energy storage applications: A review. *Int. J. Heat Mass Transf.* **2019**, *129*, 491–523. [CrossRef]
5. Vafaeva, K.M.; Zegait, R. Carbon nanotubes: Revolutionizing construction materials for a sustainable future: A review. *Res. Eng. Struct. Mater.* **2023**, *10*, 559–621. [CrossRef]
6. Barz, T.; Krämer, J.; Emhofer, J. Identification of phase fraction–temperature curves from heat capacity data for numerical modeling of heat transfer in commercial paraffin waxes. *Energies* **2020**, *13*, 5149. [CrossRef]
7. Thakkar, J. Optimizing Design of Salt Hydrate Phase Change Materials for Building and Cold Chain Efficiency Applications. Ph.D. Thesis, University of Massachusetts Lowell, Lowell, MA, USA, 2024.
8. Saleel, C.A. A review on the use of coconut oil as an organic phase change material with its melting process, heat transfer, and energy storage characteristics. *J. Therm. Anal. Calorim.* **2022**, *147*, 4451–4472. [CrossRef]
9. Torkashvand, J.; Farzadkia, M.; Sobhi, H.R.; Esrafili, A. Littered cigarette butt as a well-known hazardous waste: A comprehensive systematic review. *J. Hazard. Mater.* **2020**, *383*, 121242. [CrossRef]
10. Jamshidi, A.; Hamzah, M.O.; You, Z. Performance of warm mix asphalt containing Sasobit®: State-of-the-art. *Constr. Build. Mater.* **2013**, *38*, 530–553. [CrossRef]
11. Ma, F.; Hou, Y.; Fu, Z.; Qin, W.; Tang, Y.; Dai, J.; Wang, Y.; Peng, C. Microencapsulated binary eutectic phase change materials with high energy storage capabilities for asphalt binders. *Constr. Build. Mater.* **2023**, *392*, 131814. [CrossRef]
12. Fu, Z.; Hou, Y.; Ma, F.; Fu, Z.; Cui, J.; Liu, Z.; Liu, J. Investigation of rheological properties of asphalt modified with low-temperature microencapsulated eutectic phase change materials. *Case Stud. Constr. Mater.* **2024**, *20*, e03201. [CrossRef]
13. Milad, A.; Babalghaith, A.M.; Al-Sabaeei, A.M.; Dulaimi, A.; Ali, A.; Reddy, S.S.; Bilema, M.; Yusoff, N.I. A comparative review of hot and warm mix asphalt technologies from environmental and economic perspectives: Towards a sustainable asphalt pavement. *Int. J. Environ. Res. Public Health* **2022**, *19*, 14863. [CrossRef] [PubMed]
14. Saboo, N.; Das, A. Research Trends in materials and design of Asphalt Pavements. In *Transportation Research in India: Practices and Future Directions*; Springer: Singapore, 2022; p. 31.

15. Obaid, H.A.; Hashim, T.M.; Al-Abody, A.A.; Nasr, M.S.; Abbas, G.H.; Kadhim, A.M.; Sadique, M. Properties of modified warm-mix asphalt mixtures containing different percentages of reclaimed asphalt pavement. *Energies* **2022**, *15*, 7813. [CrossRef]
16. Sukhija, M.; Saboo, N.; Pani, A. Effect of warm mix asphalt (WMA) technologies on the moisture resistance of asphalt mixtures. *Constr. Build. Mater.* **2023**, *369*, 130589. [CrossRef]
17. *ASTM C127-24*; Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate. ASTM International: West Conshohocken, PA, USA, 2015.
18. *ASTM C131/C131M-14*; Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine. ASTM: West Conshohocken, PA, USA, 2014.
19. *ASTM C29/C29M-23*; Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate. ASTM International: West Conshohocken, PA, USA, 2023.
20. *ASTM C128-22*; Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate. ASTM International: West Conshohocken, PA, USA, 2022.
21. *ASTM C136*; Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. ASTM International: West Conshohocken, PA, USA, 2006.
22. *ASTM C117-17*; Standard Test Method for Materials Finer than 75-µm (No 200) Sieve in Mineral Aggregates by Washing. American Society for Testing and Materials: West Conshohocken, PA, USA, 2020.
23. AL Sa'adi, A.H.; Al-Khafaji, F.F.; Hashim, T.M.; Hussein, M.L.; Ali, Y.A.; Ali, A.H.; Jebur, Y.M.; Ali, L.H.; Al-Mulali, M.Z.; Al-Khazraji, A.A. Prospect of using geotextile reinforcement within flexible pavement layers to reduce the effects of rutting in the middle and southern parts of Iraq. *J. Mech. Behav. Mater.* **2022**, *31*, 323–336. [CrossRef]
24. Gu, P.; Wu, H.; Li, L.; Li, Z.; Hong, J.; Zhuang, M.L. Effect of Traffic Vibration on Compressive Strength of High-Strength Concrete and Tensile Strength of New-to-Old Concrete Interfaces. *Buildings* **2024**, *14*, 3765. [CrossRef]
25. *ASTM C204*; Standard Test Methods for Fineness of Hydraulic Cement by Air-Permeability Apparatus. ASTM: West Conshohocken, PA, USA, 2023.
26. *ASTM C188-17*; Standard Test Method for Density of Hydraulic Cement. ASTM International: West Conshohocken, PA, USA, 2017.
27. Yu, H.; Leng, Z.; Zhou, Z.; Shih, K.; Xiao, F.; Gao, Z. Optimization of preparation procedure of liquid warm mix additive modified asphalt rubber. *J. Clean. Prod.* **2017**, *141*, 336–345. [CrossRef]
28. *ASTM D3418-21*; Standard Test Method for Transition Temperatures and Enthalpies of Fusion and Crystallization of Polymers by Differential Scanning Calorimetry. ASTM: West Conshohocken, PA, USA, 2021.
29. *DIN EN ISO 1183-1:2024*; Plastics—Methods for Determining the Density of Non-Cellular Plastics—Part 1: Immersion Method, Liquid Pycnometer Method and Titration Method. DIN Deutsches Institut für Normung e.V.: Berlin, Germany, 2024.
30. *ASTM D93-20*; Standard Test Methods for Flash Point by Pensky-Martens Closed Cup Tester. ASTM International: West Conshohocken, PA, USA, 2020.
31. Fabiani, C.; Piselli, C.; Pisello, A.L. Thermo-optic durability of cool roof membranes: Effect of shape stabilized phase change material inclusion on building energy efficiency. *Energy Build.* **2020**, *207*, 109592. [CrossRef]
32. *ASTM C177-19*; Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus. ASTM (American Society for Testing and Materials): West Conshohocken, PA, USA, 2019.
33. Sarı, A.; Karaipekli, A.; Alkan, C. Preparation, characterization and thermal properties of lauric acid/expanded perlite as novel form-stable composite phase change material. *Chem. Eng. J.* **2009**, *155*, 899–904. [CrossRef]
34. *ASTM D4052-22*; Standard Test Method for Density and Relative Density of Liquids by Digital Density Meter. ASTM International: West Conshohocken, PA, USA, 2022.
35. Vanapalli, K.R.; Sharma, H.B.; Anand, S.; Ranjan, V.P.; Singh, H.; Dubey, B.K.; Mohanty, B. Cigarettes butt littering: The story of the world's most littered item from the perspective of pollution, remedial actions, and policy measures. *J. Hazard. Mater.* **2023**, *453*, 131387. [CrossRef]
36. Abidoye, N.A. Impact of Blended Salt Anti-icers/Deicers on Properties of Asphalt Binders. Master's Thesis, Geogia Southern University, Statesboro, GA, USA, 2021.
37. Sharma, N.; Verma, M.; Sharma, P. Influence of Lauric acid on mechanical properties of Portland cement. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1116*, 012153. [CrossRef]
38. Pinheiro, C.; Landi, S., Jr.; Lima, O., Jr.; Ribas, L.; Hammes, N.; Segundo, I.R.; Homem, N.C.; Castelo Branco, V.; Freitas, E.; Costa, M.F.; et al. Advancements in phase change materials in asphalt pavements for mitigation of urban heat island effect: Bibliometric analysis and systematic review. *Sensors* **2023**, *23*, 7741. [CrossRef] [PubMed]
39. *ASTM D5*; Standard Test Method for Penetration of Bituminous Materials. American Society for Testing and Materials: West Conshohocken, PA, USA, 2006.
40. *ASTM D36-06*; Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus). ASTM International: West Conshohocken, PA, USA, 2020.

41. *ASTM D113*; Standard Test Method for Ductility of Bituminous Materials. Annual Book of ASTM Standards USA; American Standard Testing Methods: West Conshohocken, PA, USA, 2007.
42. *ASTM D92-24*; Standard Test Method for Flash and Fire Points by Cleveland Open Cup Tester. ASTM International: West Conshohocken, PA, USA, 2018.
43. *ASTM D70*; Standard Test Method for Specific Gravity and Density of Semi-Solid Bituminous Materials (Pycnometer Method). ASTM International: West Conshohocken, PA, USA, 1997.
44. *ASTM D4402*; Standard Test Method for Viscosity Determination of Asphalt at Elevated Temperatures Using a Rotational Viscometer. American Society for Testing Materials (ASTM): West Conshohocken, PA, USA, 2015.
45. Tataranni, P.; Sangiorgi, C. A preliminary laboratory evaluation on the use of shredded cigarette filters as stabilizing fibers for stone mastic asphalts. *Appl. Sci.* **2021**, *11*, 5674. [CrossRef]
46. Baldo, N.; Dal Ben, M.; Pasetto, M.; Van de Ven, M.; Molenaar, A.A. Indirect tensile test for the determination of the stiffness and the resilient modulus of asphalt concretes: Experimental analysis of the EN 12697-26 and the ASTM D 4123 standards. In Proceedings of the 11th International Conference on Asphalt Pavements, Nagoya, Japan, 1–6 August 2010; pp. 796–878.
47. Kim, S.H.; Yoon, S.J.; Choi, W. Experimental Study on Long-Term Ring Deflection of Glass Fiber-Reinforced Polymer Mortar Pipe. *Adv. Mater. Sci. Eng.* **2019**, *2019*, 6937540. [CrossRef]
48. Hashim, T.M.; Nasr, M.S.; Jebur, Y.M.; Kadhim, A.; Alkhafaji, Z.; Baig, M.G.; Adekunle, S.K.; Al-Osta, M.A.; Ahmad, S.; Yaseen, Z.M. Evaluating rutting resistance of rejuvenated recycled hot-mix asphalt mixtures using different types of recycling agents. *Materials* **2022**, *15*, 8769. [CrossRef]
49. Mazhari Pakenari, M.; Hamedi, G.H. Investigating the effective laboratory parameters on the stiffness modulus and fatigue cracking of warm mix asphalt. *Int. J. Civ. Eng.* **2021**, *19*, 685–698. [CrossRef]
50. Abed, A.; Thom, N.; Lo Presti, D.; Airey, G. Thermo-rheological analysis of WMA-additive modified binders. *Mater. Struct.* **2020**, *53*, 52. [CrossRef]
51. Fakhri, M.; Maleki, H.; Hosseini, S.A. Investigation of different test methods to quantify rutting resistance and moisture damage of GFM-WMA mixtures. *Constr. Build. Mater.* **2017**, *152*, 1027–1040. [CrossRef]
52. Papagiannakis, A.T.; Masad, E.A. *Pavement Design and Materials*; John Wiley & Sons: Hoboken, NJ, USA, 2024.
53. Badgley, J.; Fowler, J.; Mahavier, K.; Peirce, S. *FHWA Research and Technology Evaluation TechBrief: Innovative Intersection Design. United States*; Federal Highway Administration. Research and Technology Evaluation: Washington, DC, USA, 2021.