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From Laboratory Design to Field Performance: A Self-Compacting Warm Mix Asphalt for Localized Pavement Maintenance

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Abstract

The mechanical compaction required for conventional warm mix asphalt (WMA) can be difficult to achieve in confined areas and during local bituminous pavement repairs. In this study, a self-compacting warm mix asphalt (SC-WMA) was developed without external compaction using EM1 (Evotherm M1), SBS (styrene–butadiene–styrene), CF (cellulose fiber), and HL (hydrated lime). Four test mixtures were fabricated with varying modifier contents and compared using Marshall, rotational viscosity, and an adapted spread test to identify the best-performing SC-WMA mixture. The SC-WMA3 mix turned out to be the most suitable mixture based on the selected design criteria. It achieved a Marshall stability of 20.2 kN, bulk density of 2.381 g/cm^3, optimum binder content of 5.9%, rotational viscosity of 0.600 Pa·s, and an average spread diameter of 265 mm. These results indicated that the mixture had sufficient workability to provide good stability in shape without grade segregation or binder drainage. The Hamburg Wheel Tracking Test (HWTT) was used to evaluate the performance of the adopted SC-WMA mixture in comparison with the conventional WMA mixture. The measured rut depth was 7.48 mm after 20,000 wheel passes, compared with 7.12 mm for conventional WMA. Preliminary application observations were conducted on pothole repairs, pavement crack repairs, and raveled surface repairs to verify the practical applicability of the developed SC-WMA3. In addition, the repaired areas remained stable after 30 days of traffic exposure, providing short-term field observations without mechanical compaction and supporting the suitability of this mixture for localized pavement maintenance.

Keywords: conventional warm mix asphalt (WMA); self-compacting warm mix asphalt (SC-WMA); styrene–butadiene–styrene (SBS); cellulose fiber (CF); hydrated lime (HL); Hamburg wheel tracking test (HWTT)

Received: 06 August 2026
Revised: 09 September 2026
Accepted: 10 September 2026
Published: 15 September 2026

1. Introduction

1.1. Research Background

Asphalt pavements deteriorate under traffic loading and environmental conditions, resulting in defects, such as potholes, rutting, cracking, and raveling [1]. If these defects are not repaired in time, they continue to develop, increasing maintenance costs and reducing pavement service life, as demonstrated in Figure 1. The quality of a repair depends not only on the repair material but also on achieving adequate density after placement [1].

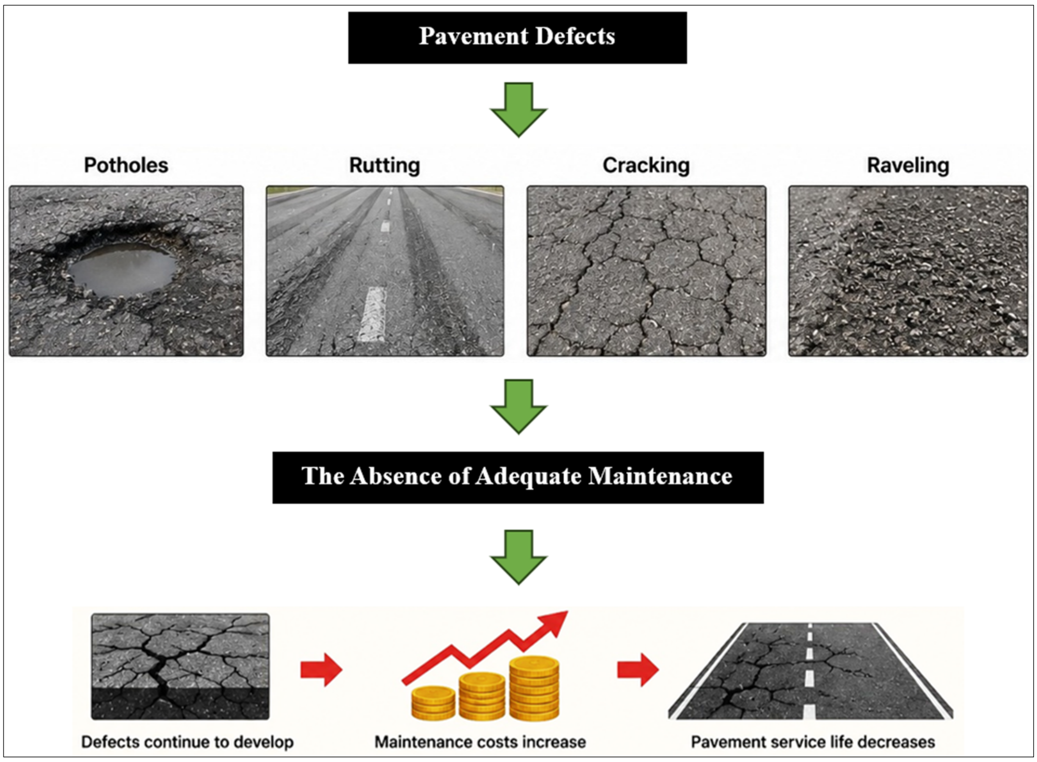

Figure 1. Pavement Deterioration Process.

Traditional materials used for asphalt repair need to be compacted mechanically to achieve the required density. However, in the field, for pothole repairs, utility trench additions, or maintenance in confined areas, the use of compaction tools can be troublesome [2]. As a result, repaired areas could have a high number of air voids in the surface layer, allowing water to enter the mixture and, thus, degrade the pavement faster.

Warm mix asphalt (WMA) is a suitable basis for developing a self-compacting asphalt mixture as it is more workable during mixing and placement than traditional hot mix asphalt [3]. The better workability allows the mixture to spread more easily in the repair area before cooling and is a suitable candidate for maintenance applications where compaction is limited [4].

Evotherm M1 (EM1) is one of the WMA technologies that is selected to enhance the workability and coating of the asphalt mixture [5]. Because higher workability may lower the stability of the mixture, styrene–butadiene–styrene (SBS) is added to enhance the binder cohesion after cooling [6]. Cellulose fiber (CF) is added to improve the stability of the binder and limit drain-down during placement, and hydrated lime (HL) is added for improved bonding between the binder and aggregates to reduce moisture damage [7].

Aggregate gradation is another key factor in developing a self-compacting asphalt mixture [8]. A higher percentage of fine aggregates helps in packing particles together, so that friction is reduced and the mixture can flow more quickly to irregular repair spots

https://doi.org/10.3390/constrmater6050066

and remain stable when it cools down [8]. Hence, the aggregate structure and binder modification are both necessary for self-compacting behavior.

Cold mix asphalt and cold-patching materials are widely used for localized pavement repairs because they can be placed without heating. However, they may have limitations, such as lower early strength, moisture susceptibility, poor adhesion, and shorter service life [4]. Modified binders, fibers, and other additives have been used to improve their performance.

This study develops a self-compacting warm mix asphalt using 60/70 penetration-grade bitumen modified with EM1, SBS, CF, and HL, in addition to an optimized aggregate gradation. The developed self-compacting warm mix asphalt was evaluated through physical, mechanical, and self-compaction tests. Physical properties included bulk density and air voids. Mechanical performance was assessed using Marshall stability and Wheel Tracking Tests. Furthermore, to verify the practical applicability of the developed SC-WMA mixtures, preliminary application observations were carried out for pothole, crack, and raveling repairs. The repaired sections were then monitored under actual traffic conditions to evaluate the performance of the mixtures and their suitability for localized pavement maintenance.

1.2. Literature Review

The literature review presents previous studies related to warm mix asphalt technology, EM1, SBS, CF and HL functions, the effect of aggregate gradation on asphalt mixtures, and current pavement maintenance practices. It also highlights the limitations of prior studies and stresses the relevance of developing a self-compacting warm mix asphalt mixture for rapid pavement maintenance. Awuah FK et al. [9] proposed an automated pothole repair system that used asphalt cartridges and a screw-extrusion mechanism to fill pavement defects. Their results showed that the repaired sections achieved about 86% of the rutting resistance of conventional repairs, with the lower performance mainly attributed to insufficient compaction. The authors recommended developing self-compacting asphalt mixtures to overcome this limitation. The present study addresses this recommendation by developing a self-compacting warm mix asphalt capable of achieving adequate density with minimal or no mechanical compaction. The proposed mixture combines EM1, SBS, CF, HL, and an optimized aggregate gradation to improve workability while maintaining mechanical performance. In addition, its self-compaction behavior is evaluated using performance indicators that have not been considered in previous studies. Duan S et al. [10] developed a semi-self-compacting cold mix polyurethane mixture (CMPU-10) using an optimized aggregate gradation and polyurethane binder to improve flowability while maintaining mechanical performance.

The mixture exhibited excellent rutting resistance, low-temperature cracking resistance, and moisture resistance, demonstrating that self-compacting mixtures can achieve satisfactory engineering performance without conventional rolling compaction. However, the study was based on a polyurethane binder rather than conventional asphalt. The present study differs by developing a self-compacting warm mix asphalt using conventional bitumen for rapid pavement maintenance. The proposed mixture combines EM1, SBS, CF, HL, and optimized aggregate gradation to achieve adequate density with minimal or no mechanical compaction.

In addition to conventional asphalt performance tests, the mixture is evaluated using self-compaction performance indicators, making it suitable for practical pavement repair applications. Furthermore, Tantri A et al. [11] investigated the use of reclaimed asphalt pavement (RAP) and cashew-nut-shell ash in the development of self-compacting concrete. The developed mixtures exhibited satisfactory flowability, filling ability, and mechanical performance, demonstrating that recycled asphalt materials can be

https://doi.org/10.3390/constrmater6050066

successfully incorporated into self-compacting cementitious composites. However, the study focused on self-compacting concrete rather than asphalt mixtures. The present study differs by developing a self-compacting warm mix asphalt using conventional bitumen for rapid pavement maintenance. The proposed mixture combines EM1, SBS, CF, HL, and optimized aggregate gradation to achieve adequate density with minimal or no mechanical compaction. Unlike the previous study, the self-compacting behavior is developed and evaluated within an asphalt mixture, together with its physical, mechanical, and self-compaction performance.

1.3. Research Novelty

This study addresses a gap in the existing literature by developing a self-compacting warm mix asphalt (SC-WMA) based on conventional bitumen for rapid pavement maintenance. The blending method used in the proposed mixture is different from that of previous studies, which focused on traditional mechanical properties, as the new proposal can acquire sufficient density using little or no mechanical compaction due to EM1 + SBS + CF + HL and an optimized aggregate gradation, with an adequate balance between flowability and mechanical stability. This study also outlines a framework for laboratory evaluation of the self-compaction performance of SC-WMA concerning Marshall stability, bulk density, air void content, rotational viscosity and an adapted spread test. In addition, the practical applicability of the developed SC-WMA was assessed through preliminary applications involving pothole, crack, and raveling repairs under actual traffic conditions.

1.4. Research Objectives

The objective of this study was to develop a self-compacting warm mix asphalt (SC-WMA) for rapid pavement maintenance using EM1, SBS, CF, HL, and an optimized aggregate gradation. The developed mixture was evaluated through physical, mechanical, and self-compaction performance tests to determine its ability to achieve adequate density with minimal or no mechanical compaction while maintaining satisfactory pavement performance.

A preliminary application observation was conducted through pothole, crack, and raveling repairs to evaluate the performance of the developed SC-WMA under actual traffic and environmental conditions.

2. Experimental Procedures

2.1. Materials Used in This Study

2.1.1. The Adopted Bitumen

The base binder used in this study was a 60/70 penetration-grade bitumen. This binder is commonly used for asphalt mixtures and served as the control binder in developing the self-compacting warm mix asphalt. Its mechanical properties were evaluated in accordance with ASTM standard test methods, as shown below in Table 1.

Table 1. Mechanical properties of the used bitumen.

Property	Test Result	Specification Requirement	Test Standard
Penetration @ 25 °C	64 dmm	60–70 dmm	ASTM D5 [12]
Softening Point	51 °C	≥49 °C	ASTM D36 [13]
Ductility at 25 °C	128 cm	≥100 cm	ASTM D113 [14]
Specific Gravity @ 25 °C	1.03 g/cm^3	1.01–1.06 g/cm^3	ASTM D70 [15]
Flash Point	290 °C	≥232 °C	ASTM D92 [16]

2.1.2. The Selected Aggregate

In Iraq, crushed coarse and fine aggregates were used in the SC-WMA mixtures. The coarse aggregate provided the structural skeleton of the mixture, while the fine aggregate and mineral filler occupied the voids between particles. The aggregate gradation was optimized to achieve dense particle packing and facilitate self-compaction without compromising mixture stability. The mechanical properties of both coarse and fine aggregates are presented in Tables 2 and 3 below.

Table 2. Mechanical properties of the coarse aggregate.

Property	Test Result	Specification Requirement	Test Standard
Specific Gravity (SSD)	2.68	2.5–2.8	ASTM C127 [17]
Water Absorption (%)	0.85	≤2.0	ASTM C127
Los Angeles Abrasion Value (%)	18.5	≤30	ASTM C131 [18]

Table 3. Mechanical properties of the fine aggregate.

Property	Test Result	Specification Requirement	Test Standard
Specific Gravity (SSD)	2.64	2.5–2.8	ASTM C128 [19]
Water Absorption (%)	1.2	≤2.0	ASTM C128
Fineness Modulus (FM)	2.75	2.3–3.1	ASTM C136 [20]

A dense aggregate gradation with a nominal maximum aggregate size of 9.5 mm was selected in accordance with the Iraqi Standard Specification for Roads and Bridges, SCRB [21], for wearing course mixtures. The gradation was chosen to achieve dense particle packing and adequate aggregate interlock, making it suitable for the proposed self-compacting warm mix asphalt, as shown in Table 4 below.

Table 4. The adopted gradation of aggregate.

Sieve Size (mm)	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Min. Limit (%)	100	90	47	32	23	16	10	7	2
Adopted Gradation (%)	100	95	58	42	31	23	15	10	6
Max. Limit (%)	100	100	67	50	39	30	21	16	10

2.1.3. The Selected Filler

Portland cement was used as the mineral filler in the warm mix asphalt mixtures to improve binder–aggregate adhesion and moisture resistance. The mechanical properties of the adopted filler are presented in Table 5 below.

Table 5. Mechanical properties of the adopted filler.

Property	Test Result	Specification Requirement	Test Standard
Bulk Density (g/cm^3)	1.42	1.10–1.60	ASTM C188 [22]
Specific Gravity	3.16	3.10–3.20	ASTM C188
Fineness (m^2/kg)	330 (Blaine)	≥300 (Blaine method)	ASTM C204 [23]

2.1.4. Evotherm M1 (EM1)

A chemical warm mix additive, Evotherm M1, was used in the current study, as shown in Figure 2. It was incorporated into the asphalt binder to improve workability and facilitate mixture production at reduced temperatures. The mechanical properties of EM1 are presented in Table 6.

https://doi.org/10.3390/constrmater6050066

Figure 2. Evotherm M1.

Table 6. The mechanical properties of EM1.

Property	Test Result	Specification Requirement	Test Standard
Appearance	Dark amber liquid	Dark amber liquid	Visual inspection
Density @ 25 °C (g/cm³)	1.0	0.98–1.02	ASTM D4052 [24]
Dynamic Viscosity @ 25 °C (mPa·s)	127	≤150	Brookfield Viscometer (ASTM D4402) [25]
Boiling Point (°C)	212	≥200	ASTM E1719 [26]
Flash Point (°C)	263	≥250	ASTM D93 [27]

2.1.5. Styrene–Butadiene–Styrene (SBS)

SBS is a thermoplastic polymer widely used to modify asphalt binders, as shown in Figure 3. In the current study, SBS was added to improve the elasticity and deformation resistance of the binder, thereby enhancing the performance of the self-compacting warm mix asphalt. The mechanical properties of the SBS modifier are presented in Table 7.

Figure 3. SBS.

Table 7. The mechanical properties of SBS.

Property	Test Result	Specification Requirement	Test Standard
Appearance	White granules	White granules	Visual inspection
Density @ 25 °C (g/cm³)	0.94	0.93–0.95	ASTM D792 [28]
Melt Flow Index (g/10 min)	2.5	2.0–3.0	ASTM D1238 [29]
Tensile Strength (MPa)	22	≥20	ASTM D412 [30]

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2.1.6. Cellulose Fiber (CF)

CF was used in the current study as a stabilizing additive, as shown in Figure 4. It is composed of fine natural fibers that absorb a small amount of asphalt binder and help retain it within the mixture. This reduces binder drain-down and improves the uniformity and stability of the asphalt mixture. The physical properties of the cellulose fiber are presented in Table 8.

Figure 4. CF.

Table 8. The mechanical properties of CF.

Property	Test Result	Specification Requirement	Test Standard
Appearance	Gray cylindrical pellets	Gray cylindrical pellets	Visual inspection
Density @ 25 °C (g/cm^3)	0.38	0.30–0.45	STM D1895 [31]
Moisture Content (%)	4.0	≤5.0	ASTM D4442 [32]

2.1.7. Hydrated Lime (HL)

Hydrated lime (HL) was incorporated into the self-compacting warm mix asphalt as a mineral additive, as shown in Figure 5. It was used to improve the bond between the asphalt binder and aggregates and to increase the mixture's resistance to moisture damage. The physical properties of the hydrated lime are presented in Table 9.

Figure 5. HL.

Table 9. The mechanical properties of HL.

Property	Test Result	Specification Requirement	Test Standard
Appearance	White fine powder	White fine powder	Visual inspection
Density @ 25 °C (g/cm^3)	0.56	0.40–0.70	ASTM C110 [33]

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Moisture Content (%)	0.80	≤1.00	ASTM C25 [34]
Fineness (Passing 0.075 mm, %)	98.5	≥95	ASTM C110 [33]

2.2. Preparation of SC-WMA Mixtures

Since the conventional WMA and the developed SC-WMA differ in composition and intended performance, the optimum binder content (OBC) was determined separately for each mixture using the Marshall mix design method. This approach ensured that each mixture was evaluated under its optimum design condition, allowing a fair comparison of their volumetric, mechanical, and self-compaction performance. For the conventional WMA, the binder and aggregates were heated to 150 °C and 140 °C, respectively. The heated materials were then mixed at 140 °C, and the resulting mixture was compacted at 120 °C in accordance with ASTM D6926 [35]. The OBC for the conventional WMA mixture was found to be 5.2%, corresponding to maximum Marshall stability and density and 4% air voids. Four trial mixtures were developed for the production of SC-WMA mixtures based on an extensive review of the published literature and the findings of previous studies. The mixing proportions of the additives were as follows:

1. (0.3, 0.4, 0.5, and 0.6%) of EM1 by weight of the used bitumen.
2. (2, 3, 4, and 5%) of SBS by weight of the used bitumen.
3. (0.2, 0.3, 0.4, and 0.5%) of CF by weight of the total mix.
4. (0, 25, 50, 75%) of HL by weight of the used filler.

The employed bitumen was heated to 170 °C. SBS was gradually added to the hot bitumen and blended using a high-shear mixer (locally manufactured, Babylon, Iraq), as shown in Figure 6, at 4000 rpm for 60 min to obtain a homogeneous polymer-modified binder, following the procedure reported for SBS-modified asphalt binders by Esmaeili N. et al. [36]. The binder temperature was then reduced to 155 °C, and EM1 was incorporated and mixed at 1000 rpm for an additional 10 min. Aggregates were heated to 140 °C and dry-mixed with CF and HL for 1 min in accordance with the laboratory mixture preparation procedure of ASTM D6926. The modified binder was then added to the aggregate blend, and mixing was continued for approximately 3 min at 140 °C using a mechanical asphalt mixer (CONTROLS S.p.A., Cernusco sul Naviglio, Italy), as shown in Figure 7, until a uniform coating of all aggregate particles was achieved, producing the SC-WMA mixture without any compaction efforts.

Figure 6. Laboratory high-shear mixer.

Figure 7. Asphalt mechanical laboratory mixer.

Four SC-WMA trial mixtures were prepared. Each trial mixture was produced using four different bitumen contents (4.5, 5.0, 5.5, and 6.0%) to determine the optimum binder content (OBC). The OBC was selected based on the bitumen content corresponding to the maximum Marshall stability, the maximum bulk density, and 4% air voids, following the Marshall mix design procedure.

2.2.1. SC-WMA1 (0.3% EM1 + 2% SBS + 0.2% CF + 0% HL)

Marshall specimens were prepared at four different bitumen contents to determine the optimum binder content (OBC). Based on the Marshall mix design criteria, the OBC was determined to be 5.5%, corresponding to the bitumen content that satisfied the requirements of maximum Marshall stability, maximum bulk density, and the target air void content of 4%.

2.2.2. SC-WMA2 (0.4% EM1 + 3% SBS + 0.3% CF + 25% HL)

Marshall specimens were produced at four different bitumen contents to establish the optimum binder content (OBC). Based on the Marshall mix design criteria, the OBC was determined to be 5.7%, corresponding to the bitumen content that provided the highest Marshall stability, the maximum bulk density, and the target air void content of 4%.

2.2.3. SC-WMA3 (0.5% EM1 + 4% SBS + 0.4% CF + 50% HL)

Marshall specimens were prepared at four different bitumen contents to determine the optimum binder content (OBC). Based on the Marshall mix design criteria, the OBC was found to be 5.9%, corresponding to the bitumen content that achieved the highest Marshall stability, the maximum bulk density, and the target air void content of 4%.

2.2.4. SC-WMA4 (0.6% EM1 + 5% SBS + 0.5% CF + 75% HL)

Marshall specimens were prepared at four different bitumen contents to determine the optimum binder content (OBC). Based on the Marshall mix design criteria, the OBC was determined to be 6.0%, corresponding to the bitumen content that produced the highest Marshall stability, the maximum bulk density, and the target air void content of 4%.

Figure 8 demonstrates the four groups of SC-WMA mixture specimens.

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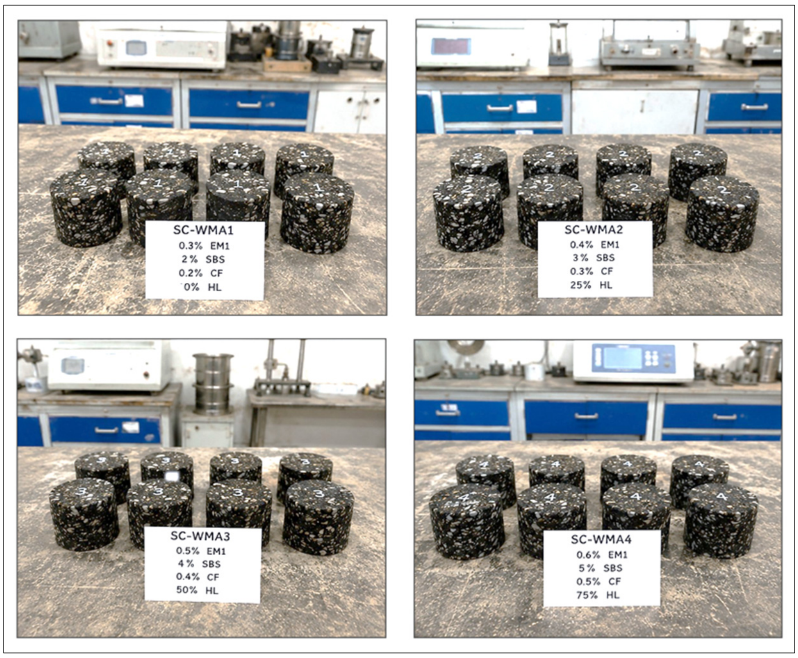

Figure 8. The Developed SC-WMA Mixture Specimens.

2.3. Selection of the Most Suitable SC-WMA Mixture

The most suitable SC-WMA mixture was selected based on the combined evaluation of workability, self-compaction characteristics, and mechanical performance. Rotational viscosity was used as a supporting measure of binder workability, while the flow and self-compaction of the complete mixtures were assessed using the adapted spread test as follows:

2.3.1. Rotational Viscosity

Rotational viscosity was measured in accordance with ASTM D4402 using a Brookfield rotational viscometer, as shown in Figure 9. It was used to assess the workability of the (EM1 + SBS)-modified binder, which plays an important role in the workability of the asphalt mixture. In addition, EM1 and SBS were used as binder modifiers and were first blended with the base binder before being incorporated into the asphalt mixture. The modified binder was heated and conditioned at 135 °C for approximately 15 min to ensure a uniform temperature before testing. A suitable spindle was immersed in the binder and rotated at 20 rpm, while the instrument continuously measured the torque required to rotate the spindle. The viscosity was automatically calculated and recorded in Pa·s. Lower viscosity indicated better flowability for aggregate coating and asphalt mixture production at reduced temperatures.

Figure 9. Rotational Viscometer of Brookfield.

2.3.2. Adapted Spread Test

This method was adapted from the asphalt work of Chen F et al. [37], who demonstrated that a slump-flow approach can be used to characterize the flow behavior of uncompacted asphalt mixtures. As no standardized method is currently available to directly evaluate the flow and self-compaction abilities of asphalt mixtures, an adapted slump-flow (spread) test was used as a supplementary procedure to compare the workability and free-flow behavior of the developed SC-WMA mixtures. The test also allowed the combined effects of the additives on mixture flow and self-compaction to be assessed, which are not reflected by the rotational viscosity of the modified binder. CF and HL were first mixed with the aggregate and filler, followed by the addition of the EM1 + SBS-modified binder to form the complete asphalt mixture. The fresh mixture was placed into a cylindrical mold positioned on a smooth steel plate without external compaction. The mold was then lifted vertically, allowing the mixture to spread freely under its own weight, as shown in Figure 10. The average spread diameter was measured in two perpendicular directions after the flow ceased. Larger spread diameters indicated better workability and greater self-compaction potential, provided that the spread remained uniform and free from visible segregation, binder drainage, or excessive binder migration. Thus, spread performance was evaluated based on both the measured diameter and the visual appearance of the spread.

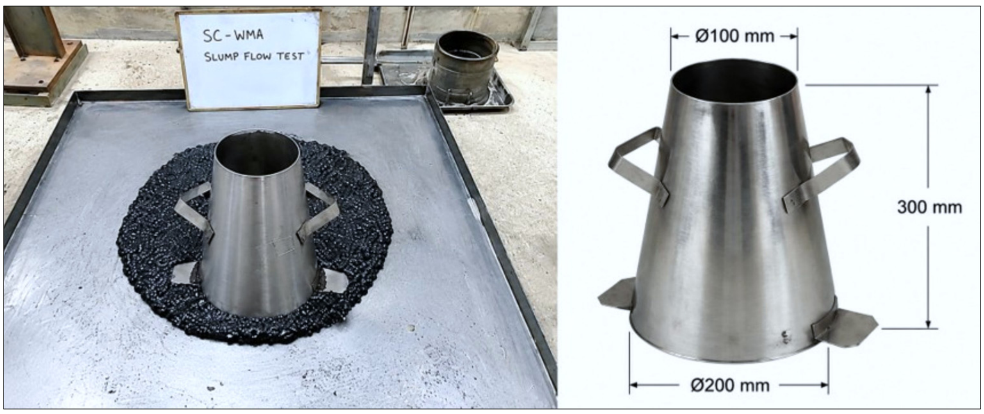

Figure 10. Adapted Spread Test for the Developed SC-WMA Mixtures.

2.3.3. Hamburg Wheel Track Test

The Hamburg Wheel Tracking Test (HWTT) was conducted in accordance with AASHTO T324 [38] to evaluate the rutting and moisture resistance of the developed most suitable SC-WMA mixture in comparison with the conventional WMA mixture, rather than as a criterion for mixture selection. Specimens were prepared at their respective optimum binder contents. The conventional WMA specimens were compacted using a Superpave Gyratory Compactor in accordance with AASHTO T312 [39] to produce cylindrical specimens measuring 150 ± 2 mm in diameter and 62 ± 2 mm in height. In contrast, the SC-WMA specimens were prepared by placing the mixture directly into the specimen mold without applying external mechanical compaction, allowing the mixtures to attain their final shape through their self-compaction capability. All specimens were then conditioned in a water bath maintained at 50 ± 1 °C, as shown in Figure 11. The specimens were then subjected to repeated loading using a 705 N steel wheel for up to 20,000 passes, while the rut depth was continuously recorded. The test results were used to compare the performance of the developed SC-WMA mixtures with that of a conventional warm mix asphalt (WMA) mixture and to identify the best-performing mixture.

Figure 11. WMA Specimens' Production in Accordance with AASHTO T312.

3. Results and Discussion

3.1. Marshall Properties of the Trial SC-WMA Mixtures at Their OBC

Three replicate specimens for each mix were prepared to determine the Marshall properties at the corresponding optimum binder contents (OBCs) of the developed SC-WMA mixtures, based on the mean values, as presented in Figure 12. The results show that the incorporated additives had a noticeable influence on the mixture performance. The Marshall stability and bulk density from SC-WMA1 to SC-WMA3 increased in a stepwise manner, while the OBC showed a slight increase (5.5–5.9%). This behavior showed that the combination of EM1, SBS, CF and HL improved the compaction of asphalt mastic and increased the strength of the aggregate skeleton. The gradual increment in OBC corresponds to higher binder demand due to the increased contents of SBS, cellulose fiber, and hydrated lime that also require more binder in order to reach the target air void content of 4%. The OBC increased further to 6.0% for SC-WMA4, while Marshall stability and bulk density decreased slightly. Therefore, the Marshall results were considered at the respective OBC of each trial mixture, and the differences in stability and bulk density reflect the response of each complete mixture at its corresponding binder content. Since EM1, SBS, CF, and HL were varied together, the individual effect of each additive cannot be separated from the present results.

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These findings indicate that the effectiveness of aggregate interlock under loading was maximized at the last stage due to increased material demand. Of all the developed mixtures, SC-WMA3 yielded a sufficiently balanced combination of Marshall stability, bulk density and optimum binder content, as it possessed a better mix between workability and strength.

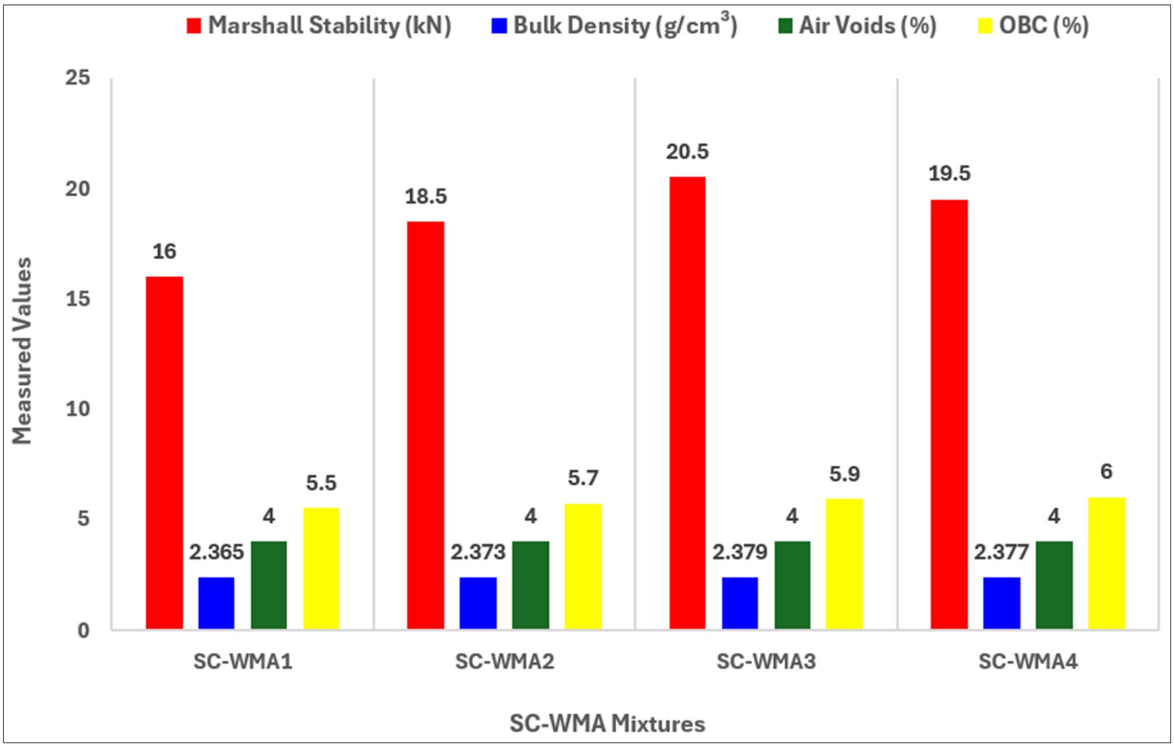

Figure 12. Marshall Properties of the Trial SC-WMA Mixtures.

The findings of the present study are generally consistent with those reported by Li K and Guo DD [40], who investigated the performance of Evotherm® warm mix asphalt with and without anti-stripping agents. Their results showed that incorporating hydrated lime markedly improved the moisture resistance of Evotherm-modified mixtures and identified hydrated lime as a more effective anti-stripping agent than the liquid additive. Unlike their work, which focused mainly on moisture stability and compared different anti-stripping treatments, the present study developed a self-compacting warm mix asphalt (SC-WMA) by combining EM1, SBS, CF, and HL in different proportions. In addition to evaluating Marshall properties, the mixtures were assessed in terms of workability and self-compaction behavior.

3.2. Rotational Viscosity of the Modified Bitumen

The rotational viscosity results of the modified binders prepared for all four SC-WMA trial mixtures, based on the mean values obtained from three replicate samples for each adopted binder blend, are presented in Table 10 and Figure 13. The binder formulations were SC-WMA1 with 0.3% EM1 + 2% SBS, SC-WMA2 with 0.4% EM1 + 3% SBS, SC-WMA3 with 0.5% EM1 + 4% SBS, and SC-WMA4 with 0.6% EM1 + 5% SBS, as described previously. The viscosity increased gradually from 0.550 Pa·s for the binder of SC-WMA1 to 0.620 Pa·s for the binder of SC-WMA4, mainly due to the increasing SBS content, which enhanced the cohesion and elasticity of the binder. This increase remained moderate because the viscosity-reducing effect of EM1 partially offset the stiffening influence of SBS. All measured values were within the acceptable range for warm mix asphalt binders, indicating satisfactory workability during mixing and production.

Among the developed binders, the binder corresponding to the selected SC-WMA3 mixture exhibited a viscosity of 0.600 Pa·s, which was within the range measured for the developed binders and indicated satisfactory binder flowability under the adopted test conditions.

Table 10. Repeatability results of the rotational viscosity test.

SC-WMA Mixture	Rotational Viscosity (Pa.s)				SD (Pa·s)	CV (%)
	Sample 1	Sample 2	Sample 3	Mean		
SC-WMA1	0.513	0.530	0.607	0.550	0.05	9.11
SC-WMA2	0.546	0.560	0.604	0.570	0.03	5.31
SC-WMA3	0.570	0.585	0.645	0.600	0.04	6.61
SC-WMA4	0.570	0.590	0.700	0.620	0.07	11.29

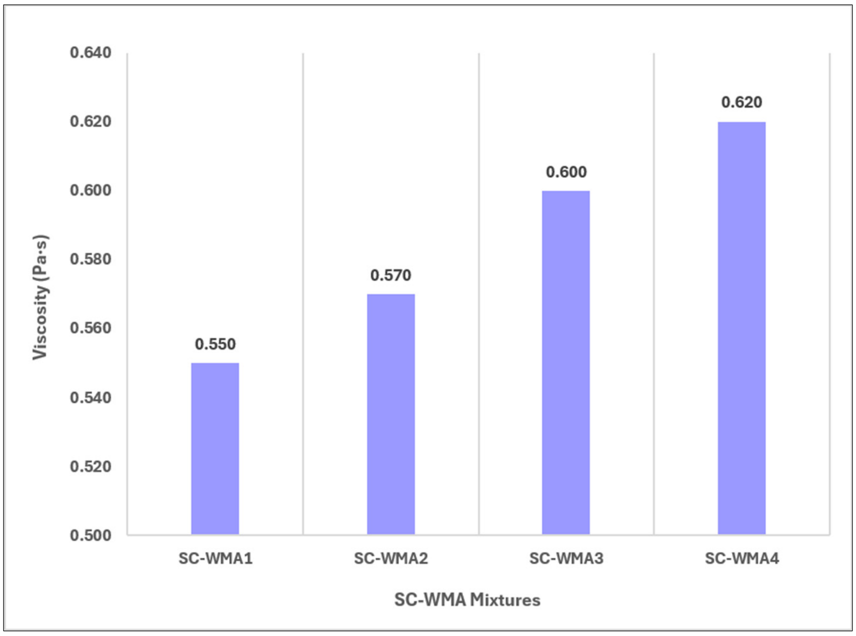

Figure 13. Results of Rotational Viscosity for the Trial SC-WMA Mixtures at Their OBC.

The rotational viscosity results were considered together with the corresponding standard deviation (SD) and coefficient of variation (CV). The SD values ranged from 0.030 to 0.070 Pa·s, while the CV values ranged from 5.31% to 11.29%, indicating acceptable repeatability among the replicate viscosity measurements under the adopted testing conditions.

The rotational viscosity results obtained in this study are consistent with the findings of Behnood A et al. [41], who reported that SBS modification increases binder viscosity, while the incorporation of EM1 moderates this increase and preserves the workability of warm mix asphalt binders. Similar behavior was observed in the present study, where the viscosity of the modified binders increased gradually with increasing SBS content but remained within the range suitable for warm mix asphalt production.

Unlike the work of Behnood A et al. [41], which focused on the rheological response of different warm mix additives and binder modifiers, the present study extended this concept by developing modified binders specifically designed for self-compacting warm mix asphalt (SC-WMA) and evaluating them as part of a complete mixture design that also incorporated CF and HL. This broader approach demonstrates that the modified binders not only maintained adequate workability but also contributed to the overall mechanical performance and self-compaction characteristics of the developed SC-WMA mixtures.

https://doi.org/10.3390/constrmater6050066

3.3. Adapted Spread Test Results

Three trials were conducted for each SC-WMA mixture to assess the repeatability of the adapted spread test. The mean spread diameter (the dependent value), standard deviation (SD), and coefficient of variation (CV), obtained from the repeated measurements, are shown in Table 11.

Table 11. Repeatability results of the adapted spread test.

SC-WMA Mixture	Spread Diameter (mm)				SD (mm)	CV (%)
	Trial 1	Trial 2	Trial 3	Mean		
SC-WMA1	286	292	289	289	3.00	1.04
SC-WMA2	271	278	279	276	4.36	1.58
SC-WMA3	262	267	266	265	2.65	1.00
SC-WMA4	241	246	245	244	2.65	1.08

The SD values ranged from 2.65 to 4.36 mm, with CV values ranging from 1.00% to 1.58%, demonstrating good consistency and repeatability of the spread-diameter measurements under the adopted testing conditions. The adapted spread test revealed a progressive decrease in the spread diameter with increasing modifier content, as shown in Table 12 below.

Table 12. Results of the adapted spread test for the developed SC-WMA mixtures.

SC-WMA Mixture	Average Spread Diameter (mm)	Visual Observation	Interpretation
SC-WMA1	289	Slight binder migration at the perimeter	Very high workability
SC-WMA2	276	Uniform spread with well-defined edges	Good workability
SC-WMA3	265	Uniform shape without segregation or binder drainage	Most suitable self-compaction characteristics
SC-WMA4	244	Limited spreading due to higher mixture stiffness	Reduced workability

SC-WMA1 showed the largest average spread (289 mm), indicating high flowability; however, slight binder migration was observed at the edges, suggesting limited mixture stability. The average spread decreased to 276 mm for SC-WMA2, while the mixture maintained a uniform shape without signs of segregation. SC-WMA3 achieved an average spread of 265 mm, providing adequate flow with good shape retention, which reflects an appropriate balance between workability and self-compaction. A further increase in the modifier contents reduced the average spread to 244 mm for SC-WMA4, indicating that the higher proportions of SBS, CF, and HL increased the mixture stiffness and restricted its ability to flow under its own weight. Overall, SC-WMA3 showed a uniform spread with a well-defined shape and no visible segregation or binder drainage, indicating adequate spreading while maintaining mixture stability. Although SC-WMA2 produced a larger spread, SC-WMA3 provided sufficient spreading with a uniform and stable appearance. Therefore, SC-WMA3 was considered the most suitable among the investigated mixtures based on its spreading characteristics and the absence of undesirable visual signs.

The decrease in spread diameter observed with increasing modifier content agrees with the findings of Yilmaz M and Yalcin E [42], who reported that the combined use of SBS and hydrated lime increases the stiffness of asphalt mixtures and enhances their resistance to deformation. In addition, Betti G et al. [43] concluded that hydrated lime and cellulose-based additives improve mixture cohesion and help minimize binder drainage during placement.

A similar response was obtained in the current study, where the spread diameter gradually decreased from SC-WMA1 to SC-WMA4. Although SC-WMA1 showed the greatest ability to spread, slight binder migration was noticed around the edges. SC-WMA3 maintained adequate spreading while preserving its shape without visible segregation or binder drainage. Further increasing the modifier contents in SC-WMA4 reduced the spread, indicating that the mixture became stiffer and less capable of flowing under its own weight.

From a mechanistic perspective, the self-compacting behavior of SC-WMA results from the balance between mixture mobility and internal stability. At the mixture scale, aggregate rearrangement under self-weight is controlled by binder viscosity, aggregate packing, particle interlock, and mastic cohesion. EM1 improves binder mobility and facilitates aggregate movement, while SBS increases binder cohesion and elasticity. CF helps retain the binder and limit migration, whereas HL strengthens the fine mastic and binder–aggregate interaction. Thus, the modifiers act together to provide sufficient flow without excessive segregation or loss of stability. This behavior is reflected in the experimental results, where viscosity increased only moderately from 0.550 to 0.620 Pa·s, while the spread diameter decreased from 289 mm to 244 mm with increasing modifier contents. SC-WMA3 achieved a 265 mm spread with a uniform shape and no visible segregation or binder drainage, while also providing the highest Marshall stability. The results indicate that self-compaction is governed by an optimum balance between binder mobility, aggregate rearrangement, and internal cohesion, which was achieved by SC-WMA3.

It should be noted that the adapted spread test was used as a comparative measure of mixture flowability and self-compaction potential, since no standardized asphalt test is currently available for this purpose. The mixture was allowed to spread freely under its own weight, and the final diameter was measured in two perpendicular directions. In addition, because EM1, SBS, CF, and HL were varied simultaneously in the trial mixtures, the individual contribution of each modifier cannot be isolated from the present experimental program. Therefore, the observed changes in spread and mixture performance are considered to represent the combined effect of the multi-modifier system, rather than the effect of any single additive.

The selection of SC-WMA3 was based on its overall balance of workability, self-compaction, and mixture stability, considering rotational viscosity, spread diameter, Marshall stability, bulk density, and optimum binder content. These properties were considered together to identify a balanced formulation in all aspects. Accordingly, SC-WMA3 was considered the most suitable formulation among the mixtures investigated under the adopted criteria.

3.4. Hamburg Wheel Tracking Performance

Two replicate samples were prepared for each mix to conduct the WTT, and the results were based on the mean values, as shown in Table 13. The results show that the rut depth increases steadily with increasing wheel passes for both mixtures, as presented in Figure 14. The conventional WMA specimens had a bulk density of 2.388 g/cm^3, whereas the SC-WMA3 specimens had a bulk density of 2.379 g/cm^3, with a difference of 0.009 g/cm^3 (about 0.38%). Both mixtures also exhibited an air void content of about 4.0%, indicating closely comparable volumetric conditions despite the different specimen preparation methods. The conventional WMA developed a rut depth of 7.12 mm after 20,000 passes, while the SC-WMA3 reached 7.48 mm under the same loading conditions. Although the SC-WMA3 specimens were not exposed to external mechanical compaction,

https://doi.org/10.3390/constrmater6050066

the rut depth of the SC-WMA3 specimens was within the same range as that of the conventional WMA specimens. The close similarity in the volumetric characteristics and rutting behavior supports a reliable comparison of the two mixtures under the adopted HWTT conditions and demonstrates that EM1, SBS, CF, and HL improved the internal structure of the mixture and enabled it to resist permanent deformation. In addition, both mixtures remained well below the adopted 12.5 mm rut-depth criterion, indicating satisfactory resistance to permanent deformation under the wet HWTT conditions. However, the rut-depth criterion alone was not considered conclusive evidence of moisture damage resistance.

Table 13. Repeatability results of the HWTT.

No. of Passes	Conventional WMA					SC-WMA3				
	Rutting Depth (mm)			SD (mm)	CV (%)	Rutting Depth (mm)			SD (mm)	CV (%)
	Sample 1	Sample 2	Mean			Sample 1	Sample 2	Mean		
5000	1.65	1.71	1.68	0.042	2.53	1.79	1.85	1.82	0.042	2.33
10,000	3.13	3.23	3.18	0.071	2.22	3.30	3.42	3.36	0.085	2.53
15,000	4.96	5.08	5.02	0.085	1.69	5.21	5.35	5.28	0.099	1.88
20,000	7.04	7.20	7.12	0.113	1.59	7.38	7.58	7.48	0.141	1.89

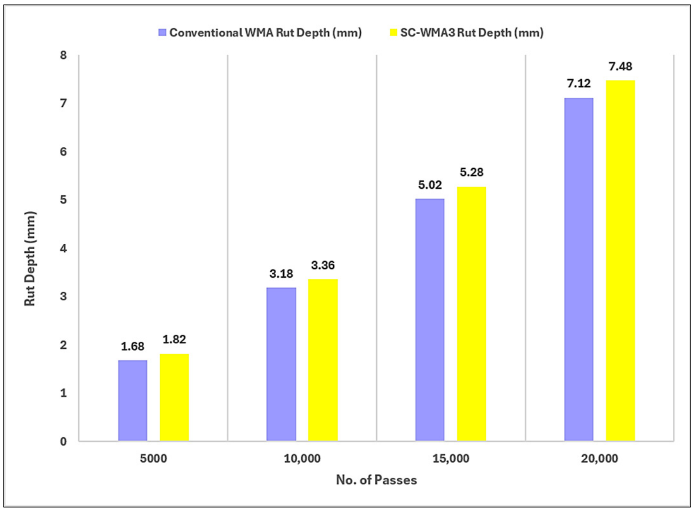

Figure 14. Rut-Depth Comparison between Conventional WMA and Self-Compacting WMA.

The SD values ranged from 0.042 to 0.113 mm for conventional WMA and from 0.042 to 0.141 mm for SC-WMA3. The CV values were below 2.6% for both mixtures, showing good repeatability of the HWTT results. Overall, SC-WMA3 recorded slightly higher rut depths than conventional WMA, while both mixtures showed a similar rutting trend as the number of passes increased.

The results obtained in this study are consistent with the findings of Özen H [44], who reported that the combined use of SBS and hydrated lime enhances the rutting resistance of asphalt mixtures. Although SC-WMA3 was evaluated without external mechanical compaction, it exhibited rutting performance comparable to that of the gyratory-compacted conventional WMA mixture.

This indicates that the combined effect of EM1, SBS, CF, and HL provided sufficient internal stability to resist permanent deformation, confirming the effectiveness of the proposed SC-WMA mixture for improving rutting performance while maintaining satisfactory field applicability.

4. Preliminary Application Observation (Case Study)

A preliminary application observation was conducted to assess the practical performance of the developed SC-WMA3 under actual traffic conditions. The mixture was used for pothole, crack, and raveling repairs without mechanical compaction, and the repaired areas were visually monitored for 30 days. Since no in situ density or water permeability measurements were performed, the field results are considered preliminary application evidence. The laboratory bulk density and air void content of SC-WMA3 were also used as indirect support for the field observations.

4.1. Pothole Repair

To demonstrate the ability of the most suitable SC-WMA to fill localized cavities without mechanical compaction, a pavement pothole was selected for repair based on the following characteristics:

- Road class: local residential road;
- Traffic volume: approximately 300 vehicles/day;
- Heavy-vehicle share: approximately 4%;
- Pothole location: within the traffic lane, close to the pavement edge;
- Distance from pavement edge: 0.5 m;
- Repair dimensions: 0.5 m × 0.6 m;
- Pothole depth: 70 mm.

The pothole was first cleaned to remove loose asphalt, dust, and other debris and then trimmed to form vertical edges, creating a sound boundary for repair. The SC-WMA3 mixture was placed directly into the prepared pothole and distributed uniformly until the cavity was completely filled. The surface was finished by leveling with a hand tool and matching the surrounding pavement without mechanical compaction. After cooling, the repaired section was reopened to normal traffic and remained in service for 30 days to evaluate its short-term field performance under actual traffic and environmental conditions, as shown in Figure 15.

Figure 15. Field Repair of a Pothole using the Developed Most Suitable SC-WMA.

4.2. Surface Crack Repair

A longitudinal crack in the pavement was selected for repair based on the following characteristics:

- Road class: mall parking area;
- Traffic volume: approximately 500 vehicles/day;
- Heavy-vehicle share: approximately 2%;
- Crack location: within the parking lane;
- Crack length: 2.8 m;
- Crack depth: 40 mm.

The cracked pavement was first cleaned to remove dust, loose particles, and other contaminants from the damaged area. The cracks were then prepared to ensure that the repair material would bond well. The SC-WMA3 mixture was placed directly into the cracks and distributed uniformly until the voids were completely filled. The repaired surface was finished by leveling with a hand tool to provide a smooth profile with the surrounding pavement without mechanical compaction.

After cooling, the repaired section was reopened to normal traffic and remained in service for 30 days to assess the short-term field monitoring in real traffic and environmental conditions, as shown in Figure 16.

Figure 16. Field Repair of Pavement Cracks using the Developed Most Suitable SC-WMA.

4.3. Raveling Repair

A raveled area in the pavement was selected for repair based on the following characteristics:

- Road class: highway;
- Traffic volume: approximately 1500 vehicles/day;
- Heavy-vehicle share: approximately 15%;
- Raveling location: at the center of the road;
- Repair dimensions: 1.5 m × 0.8 m;
- Raveling depth: 30 mm.

The raveled area was cleaned, and any loose or deteriorated material was removed before repair. The developed SC-WMA3 mixture was then placed over the prepared surface, spread uniformly, and leveled to match the surrounding pavement without mechanical compaction. After cooling, the repaired section was reopened to traffic and monitored for 30 days to evaluate its initial field performance, as shown in Figure 17.

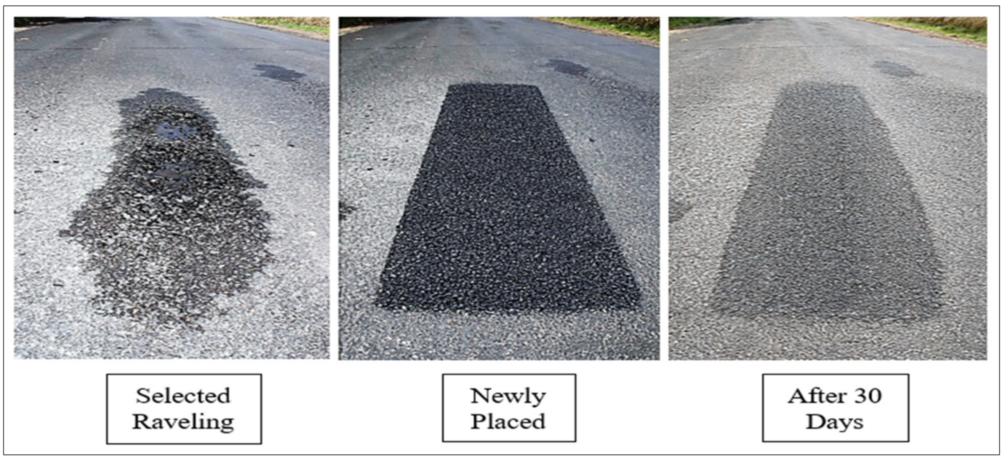

Figure 17. Field Repair of Pavement Raveling using the Developed Most Suitable SC-WMA.

The volumetric indicators, including bulk density and air void content, were used as indirect laboratory support for the field application. The SC-WMA3 laboratory specimens prepared without external mechanical compaction had a bulk density of 2.379 g/cm^3 and an air void content of about 4.0%.

The 30-day field observations indicate that SC-WMA3 maintained a satisfactory surface condition under actual traffic without visible displacement, raveling, or deterioration in the repaired areas. The mixture was placed and leveled without mechanical compaction and remained stable during the observation period, supporting its practical applicability for localized pavement maintenance. These field observations are consistent with the laboratory results, particularly the satisfactory rutting resistance obtained from the HWTT.

5. Conclusions

This study developed and evaluated a self-compacting warm mix asphalt (SC-WMA) by incorporating EM1, SBS, CF, and HL into the asphalt mixture. The performance of the developed most suitable mixture was assessed through Marshall properties, rotational viscosity, adapted spread, and HWTT, followed by preliminary application observation using typical pavement repairs. Based on the experimental and field results, the following conclusions can be drawn.

1. A SC-WMA was successfully developed by incorporating EM1, SBS, CF, and HL. The combined use of these modifiers improved the workability and mechanical performance of the mixtures while maintaining the characteristics required for warm mix asphalt production.
2. The Marshall test results showed that increasing the modifier content improved the mechanical properties up to SC-WMA3 (0.5% EM1 + 4% SBS + 0.4% CF + 50% HL), beyond which no further improvement was obtained. SC-WMA3 achieved the most suitable combination of Marshall stability, bulk density, and optimum binder content, indicating the best balance between strength and mixture composition.
3. The modified binders exhibited only a moderate increase in rotational viscosity despite the increasing SBS content, confirming that the viscosity-reducing effect of EM1 maintained adequate workability for mixing and placement. The binder corresponding to SC-WMA3 provided the most favorable balance between flowability and consistency.
4. The adapted spread test demonstrated that the developed mixtures possessed self-compacting capability. Although the spread diameter decreased as the modifier content increased, SC-WMA3 maintained sufficient flow while preserving its shape without segregation or binder drainage, indicating the most appropriate self-compaction behavior.
5. The HWTT confirmed that the SC-WMA3 mixture developed satisfactory resistance to permanent deformation. Despite being evaluated without mechanical compaction, its rutting performance remained comparable to that of the conventional warm mix asphalt, demonstrating the effectiveness of the proposed self-compacting mixture.
6. Preliminary application observations involving pothole, crack, and raveling repairs verified the practical applicability of SC-WMA3. The mixture was placed and leveled without mechanical compaction and remained stable after 30 days of traffic exposure in the short term during the short-term field monitoring, supporting its suitability for localized pavement maintenance.
7. The laboratory volumetric results provided indirect support for the field application, with SC-WMA3 specimens prepared without external mechanical compaction, achieving a bulk density of 2.379 g/cm^3 and an air void content of about 4.0%. The

field assessment was limited to preliminary observations, as quantitative in situ density and water permeability measurements were not conducted.

8. Overall, SC-WMA3 was found to be the best mixture, combining workability, self-compaction capability, mechanical strength, and rutting resistance. The proposed mixture is useful for pavement maintenance where conventional compaction equipment is difficult or undesirable.

The developed mixture showed promising performance based on the laboratory tests and preliminary application observations. However, the field assessment was limited to 30-day visual observations, without quantitative in situ density or water permeability measurements. In addition, the individual effects of the additives and binder content could not be isolated because their contents varied simultaneously among the trial mixtures. Further research should, therefore, examine moisture susceptibility, freeze–thaw resistance, fatigue resistance, low-temperature cracking, long-term aging, durability, and long-term field performance under different traffic and environmental conditions.

Author Contributions: Conceptualization, S.A.S., B.S.M. and T.M.H.; methodology, T.M.H.; formal analysis, S.A.S., B.S.M. and T.M.H.; investigation, T.M.H.; writing—original draft, S.A.S., B.S.M. and T.M.H.; writing—review and editing, S.A.S., B.S.M., T.M.H., M.S.N. and A.S.; supervision, M.S.N. and A.S.; project administration, M.S.N. and A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The datasets used and analyzed in this study can be obtained from the corresponding author upon reasonable request.

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

References

1. Wang, H.P.; Guo, Y.X.; Wu, M.Y.; Xiang, K.; Sun, S.R. Review on structural damage rehabilitation and performance assessment of asphalt pavements. *Rev. Adv. Mater. Sci.* **2021**, *60*, 438–449.
2. Al Hawesah, H. Development of Polymer Modified Pelletised Bitumin for Utility Reinstatements and Emergency Pothole Repair. Ph.D. Thesis, Liverpool John Moores University, Liverpool, UK, 2022.
3. Ali, A.A.; Milad, A.; AL Mufargi, H.; Al-Sabaeei, A.M.; Babalghaith, A.M.; Abuthina, A.M.; Yusoff, N.I. Applications, Performance, and Future Directions of High Modulus Asphalt Concrete: A Review. *Int. J. Pavement Res. Technol.* **2026**, 1–26. https://doi.org/10.1007/s42947-026-00784-9.
4. Hafezzadeh, R.; Autelitano, F.; Giuliani, F. Performance-related methods for the characterization of cold mix patching materials used in asphalt pavements maintenance. *Case Stud. Constr. Mater.* **2023**, *19*, e02600.
5. Martínez, F.S. Laboratory Analysis and Evaluation of Additives for Characterizing Warm Mix Asphalt in Puerto Rico. Ph.D. Thesis, University of Puerto Rico Mayagüez Campus, Mayagüez, Puerto Rico, 2013.
6. Rahul, M.S.; Anjani, H.; Pavan, T.S.; Suresha, S.N. Effects of coconut shell charcoal powder combined with SBS on rheological properties of asphalt binder. *Constr. Build. Mater.* **2025**, *505*, 144742.
7. Abd Al Kareem, H.M.; Albayati, A.H. The possibility of minimizing rutting distress in asphalt concrete wearing course. *Eng. Technol. Appl. Sci. Res.* **2022**, *12*, 8063–8074.
8. Shi, C.; Qian, G.; Yu, H.; Zhu, X.; Yuan, M.; Dai, W.; Ge, J.; Zheng, X. Research on the evolution of aggregate skeleton characteristics of asphalt mixture under uniaxial compression loading. *Constr. Build. Mater.* **2024**, *413*, 134769.
9. Awuah, F.K.; Garcia-Hernandez, A.; Thom, N. Automating the repair of potholes using machine techniques and digitally crafted asphalt cartridges. *Constr. Robot.* **2024**, *8*, 1.
10. Duan, S.; Wu, X.; Wang, H.; Hu, J.; Luan, Y.; Ma, T. Design and evaluation of semi self-compacting cold mix polyurethane mixture for steel bridge deck pavement. *Constr. Build. Mater.* **2024**, *419*, 135490.
11. Tantri, A.; Nayak, G.; Kamath, M.; Shenoy, A.; Shetty, K.K. Utilization of cashew nut-shell ash as a cementitious material for the development of reclaimed asphalt pavement incorporated self compacting concrete. *Constr. Build. Mater.* **2021**, *301*, 124197.

12. *ASTM D5/D5M-20*; Standard Test Method for Penetration of Bituminous Materials. ASTM International: West Conshohocken, PA, USA, 2020.
13. *ASTM D36/D36M-23*; Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus). ASTM International: West Conshohocken, PA, USA, 2023.
14. *ASTM D113/D113M-17(2023)e1*; Standard Test Method for Ductility of Asphalt Materials. ASTM International: West Conshohocken, PA, USA, 2023.
15. *ASTM D70/D70M-21*; Standard Test Method for Density of Semi-Solid Bituminous Materials (Pycnometer Method). ASTM International: West Conshohocken, PA, USA, 2021.
16. *ASTM D92-24*; Standard Test Method for Flash and Fire Points by Cleveland Open Cup Tester. ASTM International: West Conshohocken, PA, USA, 2024.
17. *ASTM C127-25*; Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate. ASTM International: West Conshohocken, PA, USA, 2025.
18. *ASTM C131/C131M-20*; Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine. ASTM International: West Conshohocken, PA, USA, 2020.
19. *ASTM C128-25*; Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate. ASTM International: West Conshohocken, PA, USA, 2025.
20. *ASTM C136/C136M-25*; Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. ASTM International: West Conshohocken, PA, USA, 2025.
21. Abadel, A.A.; Nasr, M.S.; Shubbar, A.; Hashim, T.M.; Tuladhar, R. Potential use of rendering mortar waste powder as a cement replacement material: Fresh, mechanical, durability and microstructural properties. *Sustainability* **2023**, *15*, 11659.
22. *ASTM C188-26*; Standard Test Method for Density and Relative Density of Hydraulic Cement. ASTM International: West Conshohocken, PA, USA, 2026.
23. *ASTM C204-26*; Standard Test Methods for Fineness of Hydraulic Cement by Air-Permeability Apparatus. ASTM International: West Conshohocken, PA, USA, 2026.
24. *ASTM D4052-22*; Standard Test Method for Density, Relative Density, and API Gravity of Liquids by Digital Density Meter. ASTM International: West Conshohocken, PA, USA, 2022.
25. *ASTM D4402/D4402M-23*; Standard Test Method for Viscosity Determination of Asphalt at Elevated Temperatures Using a Rotational Viscometer. ASTM International: West Conshohocken, PA, USA, 2023.
26. *ASTM E1719-24*; Standard Test Method for Vapor Pressure of Liquids by Ebulliometry. ASTM International: West Conshohocken, PA, USA, 2024.
27. *ASTM D93-26*; Standard Test Methods for Flash Point by Pensky-Martens Closed Cup Tester. ASTM International: West Conshohocken, PA, USA, 2026.
28. *ASTM D792-20*; Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement. ASTM International: West Conshohocken, PA, USA, 2020.
29. *ASTM D1238-23a*; Standard Test Method for Melt Flow Rates of Thermoplastics by Extrusion Plastometer. ASTM International: West Conshohocken, PA, USA, 2023.
30. *ASTM D412-24*; Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers—Tension. ASTM International: West Conshohocken, PA, USA, 2024.
31. *ASTM D1895-24*; Standard Test Methods for Apparent Density, Bulk Factor, and Pourability of Plastic Materials. ASTM International: West Conshohocken, PA, USA, 2024.
32. *ASTM D4442-20*; Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Based Materials. ASTM International: West Conshohocken, PA, USA, 2025.
33. *ASTM C110-24*; Standard Test Methods for Physical Testing of Quicklime, Hydrated Lime, and Limestone. ASTM International: West Conshohocken, PA, USA, 2024.
34. *ASTM C25-24*; Standard Test Methods for Chemical Analysis of Limestone, Quicklime, and Hydrated Lime. ASTM International: West Conshohocken, PA, USA, 2024.
35. *ASTM D6926-20*; Standard Practice for Preparation of Asphalt Mixture Specimens Using Marshall Apparatus. ASTM International: West Conshohocken, PA, USA, 2020.
36. Esmaeili, N.; Alavi, M.Z.; Samadzad, M. Evaluation of the impacts of polymeric fibers and modifiers on the fracture properties of asphalt mixtures. *Results Eng.* **2025**, *25*, 103862.

37. Chen, F.; Jelagin, D.; Partl, M.N. Experimental and numerical analysis of asphalt flow in a slump test. *Road Mater. Pavement Des.* **2019**, *20*, S446–S461.
38. *AASHTO T 324-23*; Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures. AASHTO: Washington, DC, USA, 2023.
39. 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.
40. Li, K.; Guo, D.D. Study on water stability of Evotherm® warm asphalt mixture. *Adv. Mater. Res.* **2013**, *753*, 819–822.
41. Behnood, A.; Karimi, M.M.; Cheraghian, G. Coupled effects of warm mix asphalt (WMA) additives and rheological modifiers on the properties of asphalt binders. *Clean. Eng. Technol.* **2020**, *1*, 100028.
42. Yilmaz, M.; Yalcin, E. The effects of using different bitumen modifiers and hydrated lime together on the properties of hot mix asphalts. *Road Mater. Pavement Des.* **2016**, *17*, 499–511.
43. Betti, G.; Pinori, U.; Marradi, A. Preliminary evaluation of the effects of lime on stone mastic asphalt mixtures workability. In *Proceedings of the 6th International Conference on Bituminous Mixtures and Pavements, ICONFBMP, 28 July 2015*; CRC Press: Leiden, The Netherlands, 2015; pp. 469–478.
44. Özen, H. Rutting evaluation of hydrated lime and SBS modified asphalt mixtures for laboratory and field compacted samples. *Constr. Build. Mater.* **2011**, *25*, 756–765.