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Warm-Mix Asphalt Containing Reclaimed Asphalt Pavement: A Case Study in Switzerland

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Abstract: Among the technologies proposed for achieving carbon neutralization in asphalt road pavements, warm-mix asphalt (WMA) has garnered increasing attention in recent years. While WMA holds the potential for various environmental and technical benefits, a comprehensive understanding of its implementation, technology selection, and additives is essential for successful application. This study presents a case where a bio-based chemical additive was employed to produce WMA containing 50% reclaimed asphalt pavement (RAP) for a surface course in Bern, Switzerland. To minimize additional variables during testing and analysis, no other additive or rejuvenator was introduced into the mixtures. The testing plan encompassed laboratory tests on samples collected during material placement and recompacted at varying temperatures in the laboratory, as well as cores extracted from the job site. As anticipated, the presence of the chemical WMA additive did not alter the rheological properties of the reference bitumen. Although in the mixture-scale tests, the WMA mixture exhibited comparable properties to the control hot-mix asphalt (HMA), it is not expected that the small dosage of the chemical additive functions the same grade after reheating and compaction. Nevertheless, the cores extracted from the job site proved the efficiency of the applied WMA technology. In addition, consistent with existing literature, the cracking tolerance (CT) index values of 62 for HMA and 114 and 104.9 for WMA mixtures indicated that the latter is less susceptible to cracking. Consequently, this characteristic could contribute to the enhanced durability of asphalt pavements.

Keywords: warm-mix asphalt (WMA); chemical additive; surface course; reclaimed asphalt pavement (RAP); hot-mix asphalt (HMA)

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Citation: Bueche, N.; Probst, S.; Eskandarsefat, S. Warm-Mix Asphalt Containing Reclaimed Asphalt Pavement: A Case Study in Switzerland. *Infrastructures* **2024**, *9*, 79. https://doi.org/10.3390/infrastructures9050079

Academic Editor: Rui Micaelo

Received: 18 March 2024
Revised: 25 April 2024
Accepted: 28 April 2024
Published: 29 April 2024

1. Introduction

Warm-mix asphalt (WMA) is the generic term for a variety of technologies that allow producers of hot-mix asphalt (HMA) pavement material to lower temperatures at which the material is mixed and placed on the road. WMA is a well-known technology that can lead to reduced compaction energy and extend the paving season [1,2]; reduce asphalt aging [3–5]; allow asphalt mix to be hauled longer distances [6]; secure the workplace by reducing exposure to fuel emissions, fumes, and odors [7,8]; and reduce the paving costs. Nevertheless, it is noteworthy that some of the mentioned items are circumstance-specific and not applicable to all conditions. As one of the asphalt pavement decarbonization solutions, several WMA technologies have been developed, introduced, and applied in the industry.

Chemical additives or surfactants: These products act at the microscopic interface of the aggregates and bitumen and allow reducing the friction forces. In this way, the asphalt mixture particles move over each other more easily, which, in turn, results in a lower level of mixing and compaction energy required, which enables the lowering of mixing temperature [9,10]. Chemical WMA additives generally improve the adhesion of binder and aggregates as well. Thus, these additives could eliminate the need for additional adhesion-promoting additives [11]. Chemical additives are used in a small dosage and designed not to change the binder's rheological properties (if so, insignificantly). Consequently, the job mix formula and the performance of the asphalt mixture can remain unchanged.

Organic additives: Above their melting point, organic (wax) additives reduce the viscosity and increase the lubricity of the binder. During the mixing time, this allows the coating of the aggregates at lower temperatures; after the pavement has cooled and the additives crystallize, they tend to increase the stiffness of the binder and asphalt's resistance against plastic deformation. However, the type of wax must be carefully selected to ensure that its melting point is higher than the expected in-service temperature and to minimize embrittlement of the asphalt mixture at low temperatures [11]. The three most used organic additives are (I) Fischer–Tropsch molecules (waxes/paraffines), (II) Montan waxes, and (III) fatty acid amides [12].

Mineral additives: Mineral WMA additives can be considered an indirect foaming technique, and hydrophilic minerals from the natural and synthetic zeolite family are commonly used additives.

Foaming process: In this technique, the aggregates are heated at a lower temperature than the equivalent HMA, and the viscosity of the binder is reduced through foaming. For this purpose, various means can be adopted to introduce small amounts of water into the hot bitumen. The water turns to steam, increases the volume of the bitumen, and reduces its viscosity for a short period. It is essential that the water evaporates completely; otherwise, it has negative effects during winter frost periods.

Regardless of the applied WMA technology, the lower mixing and paving temperatures minimize fume and odor emissions and create safer working conditions for the asphalt workers. It is estimated that the release of fume is reduced by around 50% for each 12 °C reduction in temperature [12]. In this context, a recent study compared 11 different road sections where both WMA and HMA were laid. According to the results of this study, compared with HMA, the WMA significantly reduced the geometric mean air concentration of asphalt vapor, organic carbon, and respirable particulate matter [13]. This means that it can be safely used in tunnels and on days when air quality is low, and other types of asphalt resurfacing and paving jobs would be with delays.

However, despite the proven environmental and health advantages, WMA is still not well accepted by the pavement industry. Besides the lack of knowledge (standards) on the WMA technologies, the uncertainty on the long-term performance and the interest in increasing reclaimed asphalt pavement (RAP) content in all asphalt layers are recognized as obstacles. The presence of reclaimed asphalt can exacerbate the moisture sensitivity and reduce the durability of the recycled-produced asphalt mixture [14,15].

Consequently, many research works have concentrated on the durability and long-term performance of WMA, which determines the sustainability of the technology in the Life Cycle Assessments (LCA) of a pavement. To cope with all these concerns regarding the performance and durability of WMA mixes, several laboratory-mix design and assessment procedures for WMA technologies have been developed and introduced to the industry, i.e., AASHTO R35-15. This practice guide provides special mix design considerations for WMA mixes that include tests concerning moisture durability and coating.

Nevertheless, regardless of the uncounted advantages within WMA, recycling/re-using, designing, and executing such mixtures have yet to be practiced and investigated. The rejuvenation of the aged bitumen, besides additives, technically requires a certain temperature to be activated and diffused with the added bitumen [16]. In addition, from a logistical perspective, the introduction of several liquid additives at the same time is not easy in many asphalt plants.

The presented research work aimed to achieve the following main objectives:

(I) Conducting laboratory and in situ investigations to assess the efficiency of a bio- based chemical additive for high RAP-content WMA (warm-mix asphalt) in alignment with Swiss asphalt standards and best practices.
(II) Evaluating the performance and functionality of chemical additives with relatively small dosages after asphalt mixture production and reheating.
(III) Comparing the visible fumes and emissions during the HMA and WMA asphalt production and laying.
(IV) Investigating the practical challenges that may occur during the production and laying of WMA with relatively high reclaimed asphalt content.

The specimen manufacturing temperature was selected based on the main one of the targets of this investigation, which was the presence of WMA chemical additive after multiple reheating and further changes in mechanical properties. The outputs of this study could provide perspectives on the future design and application of WMA containing a chemical additive, which is receiving increasing attention in asphalt industry decarbonization strategies. The following sections introduce the technical details implemented successfully during the construction of the test section of this study. The knowledge provided in this paper can bring light to future research and real-scale similar jobs.

2. Materials

The testing asphalt mixture produced and studied in this project was AC 11 S (according to Swiss specs) dense-graded asphalt mixture (the Nominal Maximum Size (NMS) of the aggregates' blend was 11 mm) containing 50% reclaimed asphalt pavement (RAP). For this purpose, the reclaimed asphalt pavement was analyzed first, and the results were considered during the mix design. Figure 1 shows the RAP grading curve, and Table 1 summarizes the RAP analysis results. It is worth mentioning that in Figure 1, the grading curve of the RAP is shown within the standard wearing course grading curve. This can help to understand the continuity and consistency of the RAP grading curve compared with the applied blend grading curve. During the mix design procedure performed at BFH laboratory, the mixture was optimized with 5.5% of total Optimum Bitumen Content (OBC), from which, considering the aged bitumen via RAP, 3.2% was determined as the fresh bitumen. The fresh bitumen added in this study was a paving grade bitumen with 200 plus actual penetration. Further information and measured parameters are provided in the following dedicated section of results and analysis.

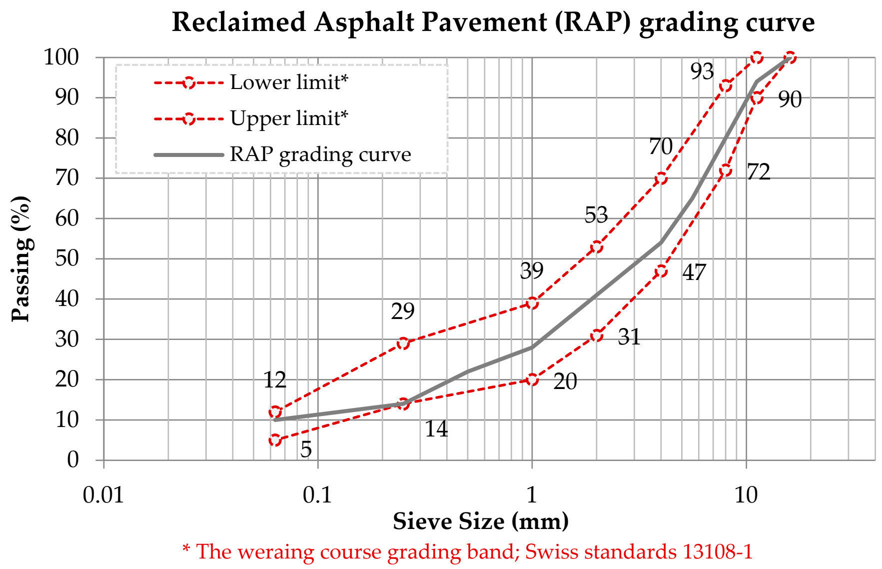

Figure 1. The grading curve of the reclaimed asphalt pavement.

Table 1. Reclaimed asphalt pavement analysis results.

Property	Unit	Value
NMS	mm	11
Bulk density	kg/m^3	2512
Binder content	%	4.6
Aged bitumen penetration	dmm	29
Aged bitumen softening point	°C	61

The WMA chemical additive (ITERLOW ECO) used in this project was a bio-based additive composed of vegetal derivatives. The applied dosage was 0.4% on the design mass of the overall bitumen content (aged bitumen via RAP + added bitumen) of the mixtures. It is worth mentioning that the choice of dosage was based on the additive's Technical Data Sheet (TDS) and the recommendation of the additive supplier experts. This dosage was selected based on some preliminary binder-scale investigations. Additionally, there are always technical and economic limitations. Adopting a higher dosage could cause premature rutting and compaction difficulties. In fact, the results complied with the technical specifications. The additive was added to the bitumen scale right before the bitumen was added to the hot aggregates. Table 2 represents some of the given physical properties of the additive.

Table 2. Physical properties of the WMA chemical additive.

Property	Unit	Value
Aspect	–	Liquid
Colour	–	Light Brown
Density @ 25 °C	g/cm^3	0.85–0.95
Viscosity @ 25 °C	cP	15–60
Flash point	°C	>155
Pour point	°C	≥0

3. Methodology

3.1. Research Project Plan

The applied experimental plan of this study was divided into three phases. The first phase was centered on the rheological/physical properties of the bitumen with and without the chemical additive. The second phase was set to construct a test section for in situ evaluations, collect the testing materials, and have a reference section for long-term monitoring. The third phase was first focused on the consistency of the produced mixtures (collected from the test section) in terms of constituents and grading curves and, second, the mechanical and performance properties of the mixtures (collected from the test section) according to the European/Swiss testing methods conducted in different laboratories in Switzerland and Italy. The tests were conducted using both manufactured specimens in the laboratory and cores drilled from the test section of the project.

It is noteworthy that for the WMA specimens manufactured in the laboratory, the reheating temperature was 160 °C and the compaction temperatures were 140 °C, 130 °C, and 120 °C. Instead, for the HMA specimens, the sample was reheated at 160 °C and compacted by means of 50 blows Marshall hammer (both faces) at 140 °C. The goal was to understand whether the chemical additive, present in low quantities, would remain/react in the mixture and function after multiple heating cycles.

3.2. Testing Methods

The choice of testing methods was guided by AASHTO guidelines and practices for warm-mix asphalt (WMA) [17]. In alignment with the primary objectives of this research, European testing methods were adopted. The first phase of the tests concentrated on binder analysis, where both virgin and extracted binders were tested, and the results were compared with those of other reference bitumen. These tests were carried out by means of conventional and DSR as follows:

- Penetration, softening point, and viscosity measurement tests according to EN standards EN 1426, EN 1427, and EN 13302, respectively.
- PG grading was conducted according to EN 14770.

In the next stage, as one of the main steps of mix design and quality control, the RAP and produced mixtures' grading curves were investigated according to the Swiss SN EN 13108-1.

For the mixture scale tests, the experimental plan included the required analysis defined by the project specifications and the target of the project as follows:

- Marshall stability and flow were conducted based on the European standard EN 12697-34.
- Indirect tensile strength (ITS) and Indirect Tensile Strength Ratio (ITSR) were carried out on 50 blows Marshall compacted specimens according to European standards EN 12697-23 and EN 12697-12, respectively.
- Indirect Tensile Stiffness Modulus (ITSM) was conducted based on the European standard EN 12697-26 IT CY at 20 °C. According to the standard and based on the diameter of the specimens, 7.5 μm was the maximum horizontal deformation.
- Ideal CT, according to ASTM D 8225 [18], was conducted to investigate the mixtures' resistance to cracking. The test is elaborated in the NCHRP report No. 195 [19]. For this study, the test was realized at 25 °C. The cracking tolerance (CT) index was calculated using Equation (1):

$$CT_{Index} = \frac{t}{62} \times \frac{l_{75}}{D} \times \frac{Gf}{|m_{75}|} \times 10^6 \quad (1)$$

  where G_f = failure energy in (J/m^2); $|m_{75}|$ = the absolute value of the post-peak slope at 75% of the peak load; l_{75} = displacement at 75% of peak load after peak; t = specimen thickness in mm; and D = diameter in mm.
- A shear bond test (Leutner) was conducted to determine the interlaminar bonding strength between the layers of the asphalt core samples according to SN EN 12697-48 at 20 °C.

4. Test Section Profile

The test section constructed during this research was part of an access road, Bottigenstrasse (after Niederriedweg), on the western side of the city of Bern in Switzerland. The road was a single-carriageway, two-lane road. The project consisted of resurfacing the pavement with 40 mm AC 11 S over a newly laid 60 mm 100% RAP-containing asphalt mixture produced with foam technology. The tested WMA was placed in the northern lane. Considering the objectives of this study, two sets of asphalt mixtures were investigated, including a WMA and a reference HMA. The applied temperatures were carefully controlled at each stage of production, placement, and compaction. Figures 2 and 3 show the temperatures during the WMA and the control HMA mixture laying, respectively.

For the lab testing, the sample of the added bitumen was collected directly from the asphalt plant, and the asphalt mixture samples were collected behind the finisher. This allowed us to have the most representative properties of the materials possible. Regarding the mixtures, the collected loose mixtures were heated and recompacted to manufacture the testing specimens. Table 3 summarizes the applied temperatures and the resulting temperatures during the production in the asphalt plant and different stages of pavement installment. It is worth mentioning that a significant fume was noticed during HMA discharging and spreading behind the finisher.

Figure 2. WMA section temperature 123.9 °C.

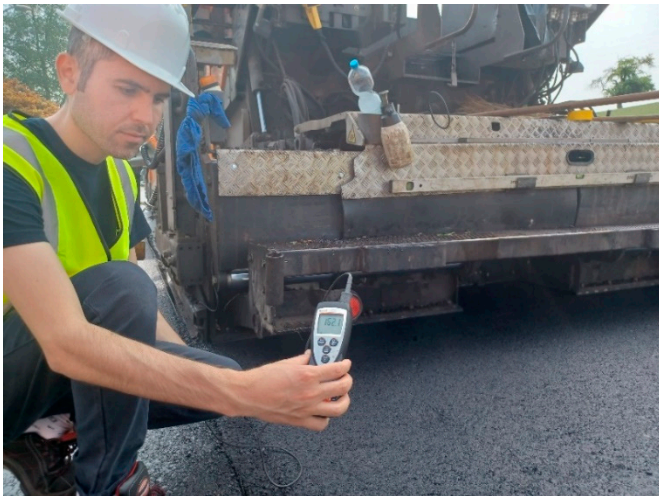

Figure 3. HMA section temperature 162.1 °C.

Table 3. Applied and resulting temperatures in situ and lab reproduction of specimens.

Material	Measured Time	Temperature * (°C)	
		WMA	HMA
Hot aggregates	In the batch	200	230
RAP	In the parallel drum	110	110
Bitumen	In the silo	150	150
Recovered Filler	In the silo	50	50
Added Filler	In the silo	20	20
Asphalt mixture	In the truck (plant)	140	165
	Behind the finisher	130	155
Compaction	On the site	120	145
Ambient temperature	During the compaction	15	25

* All temperatures shall be considered with ±2 °C of tolerance.

5. Results and Analysis

5.1. Aggregates' Blend Grading Curve Control

As a routine quality control (QC) practice, the grading curves of the mixtures were controlled and compared with the grading band of Swiss SN EN 13108-1 specification [20]. As shown in Figure 4, the mean results of the HMA and WMA mixture grading curves complied with the specification's grading band and were very similar to each other. This would ensure that no impact from differences in the grading curve would occur in the performance of the two mixtures.

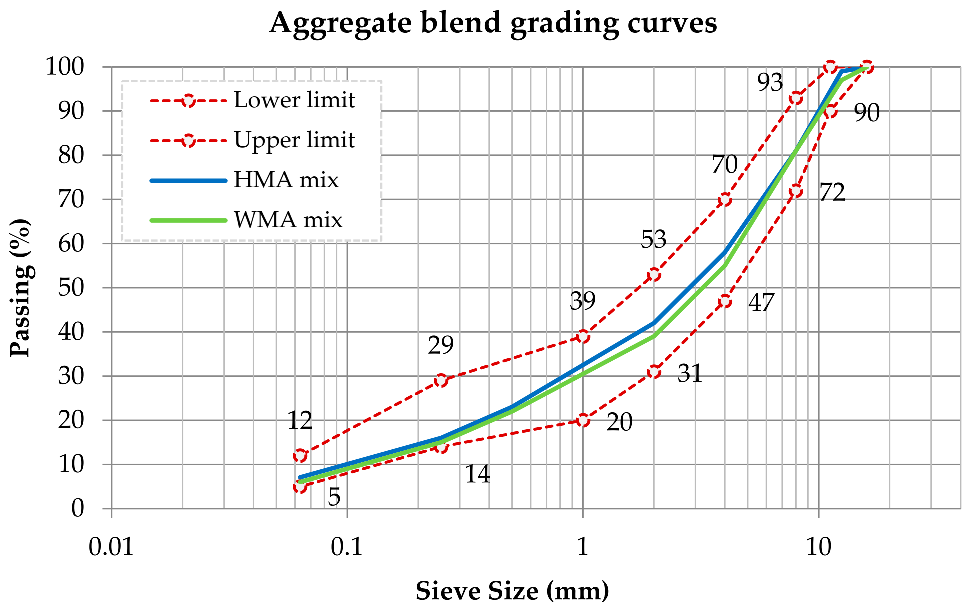

Figure 4. Grading curve control.

5.2. Binder Analysis

The first phase of this study was dedicated to the binder-scale analysis, including the conventional tests and rheological analysis using a Dynamic Shear Rheometer (DSR). All the tests were carried out based on the European testing methods. The three sets of testing bituminous binders were the added bitumen with and without additive, the extracted bitumens, and a typical 50/70 bitumen in a virgin and short-term aged (Rolling Thin Film Oven (RTFO)) sate. The latter was considered in this analysis for two reasons: to compare the final binder grade of the mixtures and to improve the understanding of the level of short-term aging during production. It should be noted that since the transportation distance was too short, the produced mixtures were not fully subjected to short-term aging, which generally happens in a paving project. According to the results shown in Table 4, the following can be deduced:

- The combination of the added bitumen with the aged bitumen of the RAP perfectly resulted in a typical 50/70 bitumen. In addition, the results of the tests also complied with a typical PEN 70/100 bitumen range, as required by the local specifications.
- Either in a virgin or aged (extracted) state, as expected, the presence of the chemical additive changed the original properties.
- The extracted binder showed small changes compared to the HMA, which is technically attributed to the aging phenomenon during production. However, it should be noted that compared with the typical 50/70 bitumen, due to the short transportation distance, the short-term aging was not significant.

Table 4. Binder-scale tests' results.

Test	Unit	Standard Testing Method	Virgin Added Bitumen		Extracted Bitumen		Typical PEN 50/70 Bitumen		Typical PEN 70/100 Bitumen
			Without WMA Additive	With WMA Additive	HMA Mix	WMA * Mix	Virgin State	RTFO State	Virgin State
Penetration @ 25 °C	dmm	EN 1426:2015	204	197	53	57	55	35	40–75
Softening point	°C	EN 427:2015	39.4	39.0	55.4	53.6	51.0	57.8	45–62
Dynamic viscosity @ 135 °C	Pa s	EN 13302: 2018	0.269	0.264	0.685	0.630	0.630	0.990	–
Exact Upper PG	°C	EN 14770: 2012	56.8	55.8	74.5	72.4	71.5	77.9	–

* The mixture contained the WMA additive just during its plant production.

5.3. Mixture-Scale Tests

The mixture-scale tests were conducted in two phases: testing the collected material from the job site and examining the cores taken from the installed pavements. For the collected materials, the asphalt mixtures underwent reheating and re-compaction at different temperatures. Specifically, for hot-mix asphalt (HMA), the compaction temperature was set at 140 °C. In contrast, the warm-mix asphalt (WMA) mixture was compacted at both 140 °C and 120 °C. This choice was driven by the fact that WMA chemical additives, even with relatively small dosages, lose effectiveness after the second heating cycle. As previously mentioned, the compaction of the specimens was carried out using 50 blows of a Marshall hammer, adhering to Swiss specifications.

Regarding the cores, they were extracted 4 months after construction. This time lag was intentionally introduced to allow for early-stage changes in pavement materials during service. All tests were performed in accordance with the relevant European standard testing methods, which are detailed in the following sections.

5.3.1. Marshall Stability and Flow

Despite its shortcomings, the Marshall method is still probably the most widely used mix design method and investigation method. Marshall stability is a test parameter that represents the resistance of bituminous materials to distortion, displacement, rutting, and shearing stresses. The stability is derived mainly from internal friction and cohesion. Cohesion is the binding force of binder material, while internal friction is the interlocking and frictional resistance of aggregates. Particularly for the bituminous pavements that are subjected to heavy traffic loads, it is necessary to adopt bituminous material with good stability and flow [21]. From another perspective, the test could be an efficient technique for revealing the presence of oily components via WMA chemical additives. Technically, the presence of oily components results in decreased stability and potential rutting.

Based on the results shown in Figures 5 and 6, it can be concluded that the obtained values align with the type of tested mixtures commonly experienced in other projects. With a deviation of approximately 5%, the obtained values are comparable, and therefore, no significant engineering difference was observed. It is noteworthy that the comparable stability could also ensure resistance to rutting and oil-free chemical WMA used. This matter has also been investigated within the other completed tests.

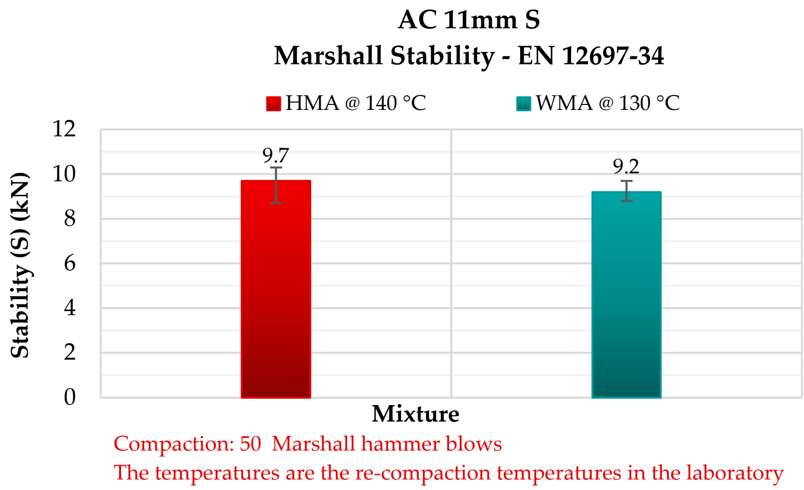

Figure 5. Marshall stability of the WMA and HMA mixtures.

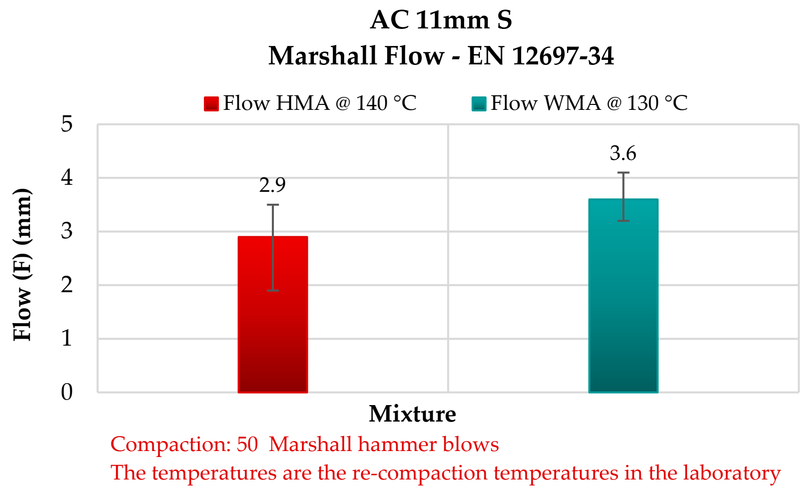

Figure 6. Marshall flow (F) of the WMA and HMA mixtures.

5.3.2. Indirect Tensile Strength

The indirect tensile strength (ITS) test is considered a common test to assess the cohesion and strength of asphalt mixtures resulting from mastic/aggregate incorporation [22]. A high tensile stress at failure indicates that the asphalt can tolerate higher strains before failing, which means it is more likely to resist the initiation of cracking. Within the literature, higher ITS values could represent superior resistance to permanent deformation [23,24].

The ITS values are shown in Figure 7. Based on the obtained results, all three testing mixtures showed similar values with a circa 9% difference when compared with WMA mixtures produced at 140 °C. The difference becomes more tangible when comparing the reference HMA mixture with the 120 °C mixture; however, the value complies with the specification. This discrepancy could be attributed to the lower production and compaction temperatures during the second time. In fact, during the second heating and compaction, the WMA chemical additive was not fully active as expected. Technically, the WMA should not remain or react after the first production and compaction phase.

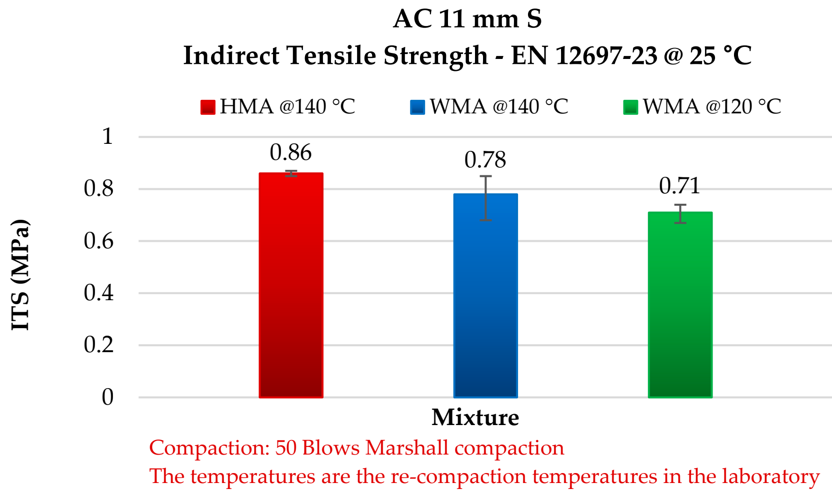

Figure 7. Indirect tensile strength values.

From another perspective, it is noteworthy that the obtained test results followed the same trend as the Marshall stability test results, which could show the validity of the results.

5.3.3. Indirect Tensile Strength Ratio

Resistance to water sensitivity has always been one of the major design and control testing parameters of technical specifications, especially for WMA and recycled asphalt mixtures. In fact, the test has been required in AASHTO R 35-15. For this purpose, the manufactured specimens were divided into two subsets of wet and dry conditioning, where they were maintained at an ambient temperature of 22 °C and a water bath of 40 °C for 72 h, respectively. Having completed the conditioning age, the specimens were subjected to indirect tensile stress at 22 °C, and the tensile strength was measured. The ratio of the dry and wet specimen results was considered for evaluating the water sensitivity.

Based on the ITS values of the dry- and wet-conditioned specimens, 89% and 88% were obtained for the WMA (compacted @ 140 °C) and reference HMA mixtures, respectively. Both mixtures showed quite the same values, and both mixtures complied with 70% as the minimum requirement of the specification. Accordingly, it can be deduced that the WMA technology did not impact the water sensitivity of the asphalt mixture.

5.3.4. Indirect Tensile Stiffness Modulus (ITSM)

The stiffness modulus of a pavement represents the ability of the bituminous mixtures to spread the vehicle-pass loads from the road's surface throughout the pavement layers [25]. Knowledge of the stiffness of a bituminous mixture is obviously a key element for the analysis and "rational" structural design of flexible pavements. Accordingly, stiffness modulus has been considered in many technical specifications for asphalt pavements.

Figure 8 shows the obtained values for the three sets of testing materials. According to the results, both recompacted WMA and HMA mixture at 140 °C showed similar results, while the WMA sample compacted at 120 °C showed a slightly inferior value. This occurrence can be attributed to the chemical additive's primary function, which is most effective during production and application. Given its minimal dosage, it does not exhibit optimal efficiency when the mixture is reheated and compacted. From another point of view, the similar values of the two WMA and HMA mixtures, recompacted at the same temperatures, prove that the chemical additive has not impacted the mechanical performance of the mixtures previously attested by rheological tests during the binder analysis.

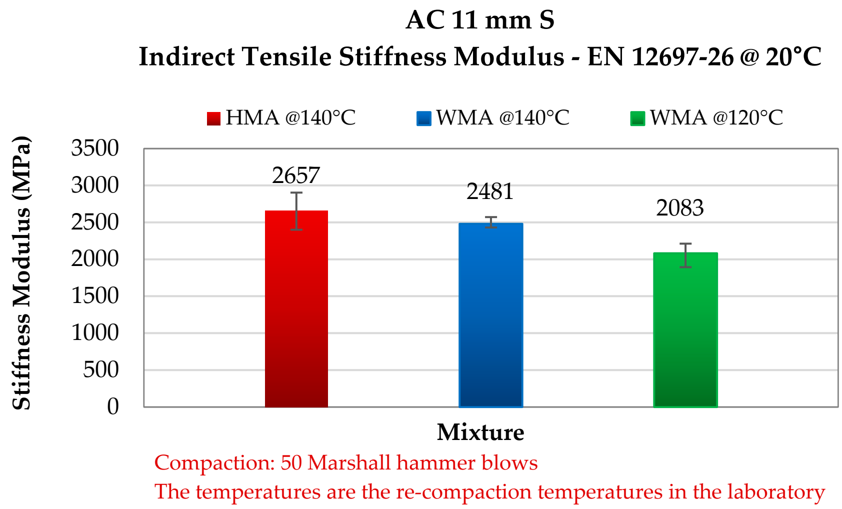

Figure 8. Stiffness moduli at intermediate temperature.

5.3.5. Ideal CT

Cracking susceptibility has always been one of the main concerns associated with recycled mixtures. Although the problem could be intensified with increased RAP content, technically, the problem could be managed by cautious material selection and mixed design. Figure 9 displays the averaged load-displacementcurves from three replicates. The CT-index calculated values for HMA, WMA at 140°C, and WMA at 120°C were 62.0, 114.9, and 104.9, respectively. These values, besides the load–displacement curves compared in Figure 8, show a higher resistance to cracking when the WMA technique is applied. The lower cracking performance of the HMA mixture is attributed to the short-term aging that occurred during the mixture production in the plant and the reheating of the material in the laboratory for specimen manufacturing. In addition, the presence of the bio-based WMA additive reach in aromatics could have an impact on reducing aging. However, this shall be further tested for approval. In this context, research work showed that the addition of liquid bio-additives can improve the resistance to cracking [26].

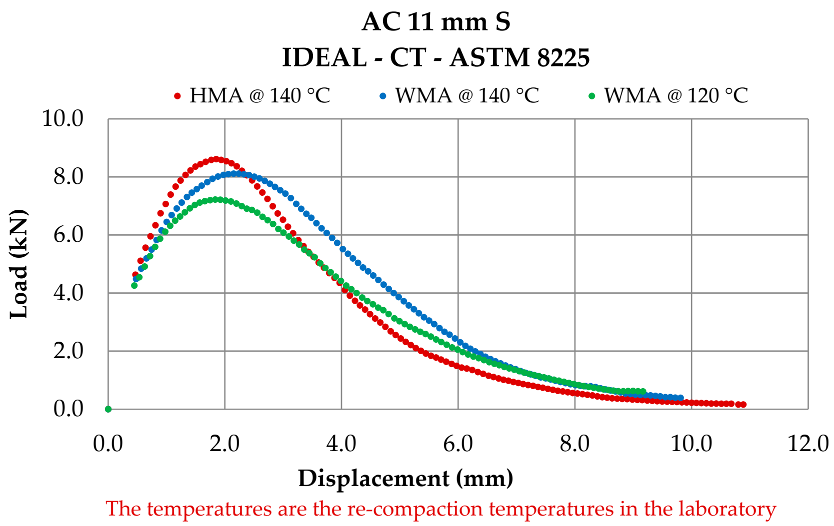

Figure 9. Load vs. displacement plots.

In addition to the discussed cracking tolerance, the failure energy of the testing samples was also calculated according to ASTM D 8225, explained in the test method sections. Based on the measured values, the failure energy for HMA, WMA at 140 °C, and WMA at 120 °C were 5309, 5700, and 5526 J/m^2, respectively. Accordingly, 7% and 4% differences were measured between the HMA and WMA @ 140 °C and WMA @ 120 °C, respectively. This could technically show that the cracking performance is not highly dependent on the level of tensile strength and modulus.

5.3.6. Core Analysis

To investigate the installed pavements and validate the performance of the mixture compacted in situ, the cores were drilled and tested in the laboratory. The testing plan included the volumetric as the most representative property and shear bond strength analysis as one of the WMA pavement concerns.

Given that pavement structures are made up of several layers of different materials, the long-term pavement performance and durability are likely to be affected by the loss of bond between the layers [27]. Should the bond at an interface be inadequate, the strains throughout the pavement may increase (under trafficking), and its life may consequently be reduced. While warm mix asphalt offers several advantages, engineers and researchers need to carefully evaluate its impact on the shear bond strength between asphalt layers. Figure 10 shows the test setup and one of the cores of the paved sections.

Figure 10. Shear bond test set up (**left**) and the core before and after the test (**right**).

Table 5 summarizes the obtained results. Based on these values, the followings can be deduced: (I) The reduction in production and compaction temperature did not impact the volumetric properties and, more importantly, the level of compaction. This consequently resulted in similar mechanical properties. This has been shown in the laboratory test results. (II) Both mixtures showed similar shear bond strength. Therefore, WMA technology, if applied at the right temperature and paving terms, would not decrease this property.

From a statistical perspective, based on the individual values, the standard deviation of the density for the HMA and WMA cores will be 17.81 and 13.51, respectively. Additionally, when considering the air void content, the HMA and WMA cores are calculated to be 0.58 and 0.45, respectively. Notably, lower standard deviations have been observed for the WMA mixtures in both cases. A smaller standard deviation indicates that the data points are relatively more consistent and less widely dispersed from the mean value. Consequently, when the standard deviation is low, it inspires greater confidence in the reliability of the measurements.

Table 5. Laboratory test results of the cores.

Test Item	Unit	WMA			HMA			Specification (VSS 40 430)
		C1	C2	C3	C1	C2	C3	
G_{mB} Mean G_{mB}	kg/m^3	2399	2372 2385	2385	2421	2386 2402	2397	–
G_{mm}	kg/m^3		2465			2475		–
Reference Density	kg/m^3		2400			2422		–
Degree of compaction	%		99.4			99.2		≥97
Air void content Mean Air void content	%	2.7	3.8 3.2	3.2	1.8	3.2 2.6	2.7	2.5–6.0
Shear stress	kN		21.8			21.7		≥15

6. Conclusions

In summary, the project's laboratory and real-scale investigation demonstrated that it is technically feasible to produce WMA (warm-mix asphalt) even when using a substantial amount of reclaimed asphalt. For this target, chemical WMA additives that are used in a small dosage and do not pose any impact on the rheological and mechanical properties of asphalt binder and mixture could be technically the most promising technology. The tests carried out in this study showed that the chemical additives do not react after reheating. Technically, this is one of the genuine characteristics of chemical additives that are used in a very small dosage. Based on the in situ observations and laboratory analysis on the recompacted specimens and cores drilled from the job site of this study, the following highlights are summarized:

- Due to the nature of the WMA chemical additives as a surfactant and the very small dosage generally applied (150–350 g/ton of asphalt), the additives did not change the rheological properties of the bitumen and consequently the mechanical performance of the final mixture. In fact, it should be noted that the chemical additives do not act similarly to the first production and compaction during the reheating, mixing, and recompacting. Technically, this is a desired characteristic of the WMA chemical additives.
- Overall, no significant difference was observed between the mechanical and performance properties in terms of Marshall stability, water sensitivity, Indirect Tensile Modulus (ITSM) and Strength (ITS) of the HMA mixture and WMA mixture reheated and recompacted specimens, particularly when the WMA specimens were reheated at 30 °C and 140 °C.
- Attested by the Ideal CT test, the HMA mixture showed a higher susceptibility to cracking than WMA mixtures. According to the results, two short-term aging times (during the production and transportation of the mixture and reheating) significantly decreased the mixtures' flexibility.
- According to the shear bond stress test results of this investigation, it can be deduced that applying the right temperature and paving terms could guarantee the bond properties between the pavement layers.
- As the most representative parameter, the volumetric properties of the laid WMA and HMA mixtures were examined by testing the cores drilled from the job site. Independent of reheating and the function of chemical additives during reheating and compaction for the laboratory manufacturing specimens, similar values were obtained for both WMA and HMA testing mixtures for the cores from the field. In addition to the efficiency of the used additive, this inspires greater confidence in the realistic conditions and properties of the laid and studied pavements.

- As anticipated, no fumes were observed either during the production and discharge of the mass into the truck or at the job site during the laying and compaction of the warm-mix asphalt (WMA) mixture.

7. Future Works

To complete the knowledge obtained during this full-scale study, the constructed test sections will be monitored, and pavement conditions will be assessed using regular pavement expert surveys. This would include the measurement of rutting by means of a straight edge.

Author Contributions: Conceptualization, N.B.; methodology, N.B. and S.P.; validation, N.B., S.P. and S.E.; formal analysis, N.B., S.P. and S.E.; investigation, N.B. and S.E.; resources, N.B.; data curation, S.E.; writing—original draft preparation, S.E.; writing—review and editing, N.B., S.P. and S.E.; visualization, S.E.; supervision, N.B.; project administration, N.B.; funding acquisition, N.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the city of Bern (Tiefbauamt Stadt Bern), Switzerland in the framework of the collaboration between the city of Bern and the Bern University of Applied Sciences (BUAS)—competence center in transport infrastructure.

Data Availability Statement: Data are available upon request from the corresponding author.

Acknowledgments: The authors would like to acknowledge all the individuals from the funder, Weibel AG, Bern University of Applied Sciences (BFH), and Iterchimica S.p.A. for their collaboration and availability in this project.

Conflicts of Interest: This research and article was led by Professor Nicolas Bueche and coauthored with Samuel Probst, the head of bituminous building materials and surfacing plants at Weibel AG, and Shahin Eskandarsefat, Senior Researcher at Iterchimica S.p.A. Each author played a distinct role in conducting a purely scientific laboratory and in-situ investigations, ultimately contributing to the completion of the presented paper. The authors explicitly state that the name of the testing material used was included just upon request of the academic editor of the journal. The authors believe that the knowledge presented in this paper can help address various uncertainties related to WMA (Warm Mix Asphalt) chemical technologies. More information is provided within the letter of Disclosure of Potential Conflicts of Interest.

References

1. Manolis, S.; Decoo, T.; Lum, P.; Greco, M. Cold weather paving using warm mix asphalt technology. In Proceedings of the Annual Conference of the Transportation Association of Canada, Toronto, ON, Canada, 21–24 September 2008.
2. Yu, S.; Shen, S.; Steger, R.; Wang, X. Effect of warm mix asphalt additive on the workability of asphalt mixture: From particle perspective. *Constr. Build. Mater.* **2022**, *360*, 129548. [CrossRef]
3. Milad, A.; Babalghaith, A.M.; Al-Sabaeei, A.M.; Dulaimi, A.; Ali, A.; Reddy, S.S.; Bilema, M.; Yusoff, N.I.M. 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]
4. Mohammad, L.; Raghavendra, A.; Medeiros, M.; Hassan, M.; King, W. *Evaluation of Warm Mix Asphalt Technology in Flexible Pavements*; FHWA/LA.15/553; Louisiana Transportation Research Center: Baton Rouge, LA, USA, 2018.
5. Qin, Y.C.; Wang, S.Y.; Zeng, W.; Shi, X.P.; Xu, J.; Huang, S.C. The effect of asphalt binder aging on fatigue performance of evotherm WMA. *Adv. Mater. Res.* **2012**, *535–537*, 1686–1692. [CrossRef]
6. Diab, A.; Sangiorgi, C.; Ghabchi, R.; Zaman, M.; Wahaballa, A. Warm Mix Asphalt (WMA) technologies: Benefits and drawbacks—A literature review. In Proceedings of the 4th Chinese European Workshop on Functional Pavement Design, Delft, The Netherlands, 29 June–1 July 2016. [CrossRef]
7. Federal Highway Administration. Warm Mix Asphalt Technologies and Research. Available online: https://www.fhwa.dot.gov/pavement/asphalt/wma.cfm (accessed on 13 March 2024).
8. Tutu, K.; Tuffour, Y. Warm Mix Asphalt and Pavement Sustainability: A Review. *J. Civ. Eng.* **2016**, *6*, 84–93. [CrossRef]
9. Andersen, E. *WAM Foam® an Environmental Friendly Alternative to Hot Mix Asphalt*; Presentation to WMA Scan Team; Norwegian Public Roads Administration: Oslo, Norway, 2007.
10. Li, X.; Wang, H.; Zhang, C.; Diab, A.; You, Z. Characteristics of a surfactant produced warm mix asphalt binder and workability of the mixture. *J. Test. Eval.* **2015**, *44*, 2219–2230. [CrossRef]
11. Zaumanis, M.; Smirnovs, J. Analysis of possibilities for use of warm mix asphalt in Latvia. In Proceedings of the 3rd International Conference on Civil Engineering, Jelgava, Latvia, 12–13 May 2011.

12. European Asphalt Pavement Association. The Use of Warm Mix Asphalt. Available online: https://eapa.org/warm-mix-asphalt/ (accessed on 15 March 2023).
13. Olsen, R.; Graff, P.; Daae, H.L.; Bryngelsson, L.; Molander, P.; Ellingsen, D.G. Occupational exposure during asphalt paving-comparison of hot and warm mix asphalt in field experiments. *Ann. Work. Expo. Health* **2021**, *65*, 446–457. [CrossRef] [PubMed]
14. Brown, D.C.; Warm Mix Asphalt: Proving Its Benefits. Asphalt, the Magazine of Asphalt Institute. Available online: http://asphaltmagazine.com/warm-mix-asphalt-proving-its-benefits/ (accessed on 27 October 2023).
15. Warming up to New Ideas: The Pros and Cons of Warm Mix Asphalt. Texas A&M Transportation Institute. Available online: https://tti.tamu.edu/researcher/warming-up-to-new-ideas-the-pros-and-cons-of-warm-mix-asphalt/ (accessed on 27 October 2023).
16. Botella, R.; Lo Presti, D.; Vasconcelos, K.; Specht, L.; Arámbula Mercado, E.; Menegusso Pires, G.; Pasquini, E.; Ogbo, C.; Preti, F.; Pasetto, M.; et al. Assessment of the Degree of binder Activity of Reclaimed Asphalt Pavement using Support Vector Regression and Clustering. In Proceedings of the 1st International Data Science for Pavements Symposium, McLean, VA, USA, 20–24 March 2022.
17. Bonaquist, R. *Draft Appendix to AASHTO R35: Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA)*; NCHRP Report 691; Transportation Research Board: Washington, DC, USA, 2011. Available online: https://www.co-asphalt.com/assets/docs/nchrp_rpt_691.pdf (accessed on 15 March 2024).
18. *ASTM D 8225*; Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature. ASTM International: West Conshohocken, PA, USA, 2019.
19. *Development of an IDEAL Cracking Test for Asphalt Mix Design, Quality Control and Quality Assurance*; Final Report for NCHRP IDEA Project 195; Transportation Research Board: Washington, DC, USA, 2019.
20. Bituminous Mixtures. *SN EN 13108-1*; Bituminous Mixtures. Materials Specifications—Part 1; Asphalt Concrete. National Appendix. European Committee for Standardization: Brussels, Belgium, 2022.
21. Behl, A.; Kumara, G.; Sharmaa, G.; Jaina, P.K. Evaluation of field performance of warm-mix asphalt pavements in India. In Proceedings of the 2nd Conference of Transportation Research Group of India, Agra, India, 12–15 December 2013.
22. Eskandarsefat, S.; Hofko, B.; Sangiorgi, C. A comparison study on low-temperature properties of stone mastic asphalts modified with PmBs or modified fibres. *Int. J. Pavement Eng.* **2020**, *21*, 1541–1549. [CrossRef]
23. Russo, F.; Eskandarsefat, S.; Venturini, L.; Viscione, N. A complete study on an asphalt mixture modified with graphene and recycled hard-plastic: A case study. *Case Stud. Constr. Mater.* **2022**, *17*, e01437. [CrossRef]
24. Zieliński, P. Indirect tensile test as a simple method for rut resistance evaluation of asphalt mixtures—Polish experience. *Road Mater. Pavement Des.* **2022**, *23*, 112–128. [CrossRef]
25. Eskandarsefat, S.; Dondi, G.; Sangiorgi, C. Recycled and Rubberized SMA Modified Mixtures: A comparison between polymer modified bitumen and modified fibres. *Constr. Build. Mater.* **2019**, *202*, 681–691. [CrossRef]
26. Abo-Shanab, Z.L.; Ragab, A.A.; Naguib Hamdy, M. Improved dynamic mechanical properties of sustainable bio-modified asphalt using agriculture waste. *Int. J. Pavement Eng.* **2021**, *22*, 905–911. [CrossRef]
27. Sangiorgi, C.; Collop, A.C.; Thom, N.H. Laboratory assessment of bond condition using the Leutner shear test. In Proceedings of the 3rd International Conference Bituminous Mixtures and Pavements, Thessaloniki, Greece, 21–22 November 2002. [CrossRef]