

Assessment of the Performance of Warm Mix Asphalts in Road Pavements

Hugo M.R.D. Silva¹⁺, Joel R.M. Oliveira¹, Cláudia I.G. Ferreira², and Paulo A.A. Pereira³

Abstract: Several processes and products are available to produce warm mix asphalt (WMA). These may reduce the mixing and compaction temperatures in relation to hot mix asphalt (HMA), ensuring the necessary performance in the pavement. Lower plant mixing temperatures mean reduction in fuel consumption and lower emissions, possibly contributing to diminish health and odour problems and to decrease costs. During this work, two commercial additives (Sasobit® and Cecabase®) were used to produce WMAs, which were compared with a conventional HMA. Initially, the mixtures were designed, the amount of additive was selected (based on the binder characterization) and the mixing temperatures of the WMAs were chosen by means of EN 12697-10 compactability comparison. Then, a road trial was built and test specimens were collected (both of HMA and WMA) for volumetric composition and mechanical behaviour assessment. This study essentially provides a better understanding of the good performance capabilities of WMA mixtures.

Key words: Asphalt additives; Mix performance; Pavement trial; Temperature reduction; Warm mix asphalt.

Introduction

HMA is produced at temperatures between 140 and 160°C. These temperatures ensure that the aggregate is dry, the asphalt binder coats the aggregate, and the HMA mix has a suitable workability. HMA needs to be workable, so that it can be transferred into storage silos, transported, placed, and compacted. Even higher temperatures are used for HMA mixtures containing polymer-modified and crumb rubber asphalt binders.

WMA technology is now available to decrease HMA production temperatures as much as 40°C. These relatively new processes and products use various physical-chemical means (usually additives, including waxes) or two phase bitumen introduction in the mixtures (softer and harder bitumen) to reduce the shear resistance of the HMA at construction temperatures while reportedly maintaining or improving pavement performance. Reducing HMA production and placement temperatures will provide several benefits, including reduced emissions, fumes, and odors as well as a cooler work environment. An energy saving from lower production temperatures is evident with the use of warm mix asphalt technologies.

The quality of the HMA construction and the performance may also be improved when production temperatures are lower. Workability improvements may result in higher in-place density, reducing the permeability of the WMA, the long-term or in-service hardening of the asphalt binder and the water damage that can occur in the mix. Workability improvements also have the potential to extend the construction season and the time available for the

placement of the asphalt mixture during a certain day. Lower production temperatures for asphalt paving mixtures will decrease the aging of the asphalt binder during production. This decrease in aging can improve thermal and fatigue cracking resistance.

However, the use of WMA/half-WMA technologies has some potential engineering challenges. Since the asphalt binders may not harden so much at lower production temperatures, a softer binder is likely to be found in these mixtures when the pavement is opened to traffic, and the mixture may have a greater potential for rutting. In addition, traffic may not be allowed on the pavement at the conclusion of the compaction process until the mixture cools beyond what is normally required for conventional HMA. Basically, the relationship between engineering properties of such mixtures and their field performance need to be investigated to facilitate the implementation of this technology.

In order to answer to these requirements, this work includes the investigation of the performance of two representative samples of WMA technologies evaluated in a real scale pavement trial, with tests carried out at the pre-construction and post-construction stages. Thus, the objectives of this work are to determine relative measures of performance between WMA and conventional HMA pavements, compare production and lay down practices between WMA and HMA pavements, and assess the engineering properties and the field performance of WMA binders and mixtures using those technologies.

Literature Review on Warm Mix Asphalts

A number of new processes and products that have the capability of reducing the temperature at which HMA is mixed and compacted, apparently without compromising the performance of the pavement, has become available. Some methods are used to classify these technologies. One is classifying the technologies by the degree of temperature reduction. In Fig. 1, it can be observed that WMA are separated from half-WMA by the resulting mix temperature [1]. These new products can reduce production temperatures by as much as 40% [2].

Another way to classify the WMA technologies is by separating

¹ PhD, Assistant Professor, Department of Civil Engineering, University of Minho, Campus de Azurém, 4800-058 Guimarães, Portugal.

² MSC, P.E., Construções Gabriel A.S. Couto S.A., 4770-464 Famalicão, Portugal.

³ PhD, Professor, Construções Gabriel A. S. Couto, S.A., Rua S. João Pedra Leital, n.º 1000, Requião - Vila Nova de Famalicão, 4770 - 464 Requião, Portugal.

⁺ Corresponding Author: E-mail hugo@civil.uminho.pt

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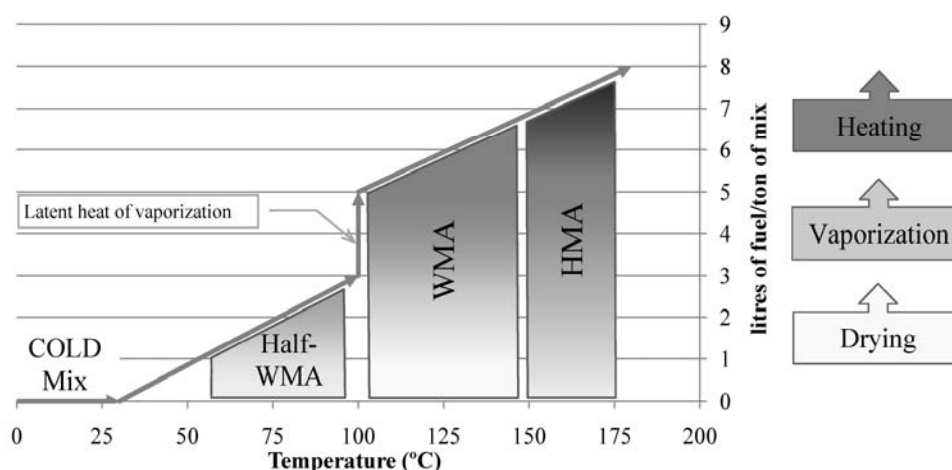


Fig. 1. WMA Technology Classification Based on the Reduction of the Mixing Temperature [1].

those that use water from those that use some form of organic additive or wax to affect the temperature reduction. These methods are based on process engineering, aerogenous agents or special bitumen and additives [3]. Thus, several WMA techniques are available and have been studied by several authors, namely the double-coating or two-phase mixing method [4], the application of the double-barrel green process (with reductions of 10 to 30°C) [5], and the half-warm mix asphalt technologies that use water or vapor, being produced at 90-100°C with foamed bitumens [6, 7] or at 70-115°C with emulsions [8]. The emulsion can be produced using a chemical package designed to enhance coating, adhesion, and workability, named Evotherm® [9] in which the majority of the water flashes off as steam when the emulsion is mixed with the aggregates. Other WMA techniques are carried out by modifying the binder or mixture, namely by using aerogenous agents (reductions of 30°C) that are based on chemically bound water that is released during asphalt mixing due to the addition of zeolites [10] and by using additives, such as Fischer-Tropsch synthetic paraffin waxes (namely the Sasobit® process), that incorporate a low melting point component that chemically changes the temperature-viscosity curve of the binder [11-13], low molecular weight ester compounds, or additives containing surface active agents (namely Cecabase® additive) that improve the asphalt workability for a reduction in the production temperature up to 30-40°C during mixing [14].

Lower plant mixing temperatures mean fuel cost savings to the contractor and findings have shown that lower plant temperatures can lead to a significant reduction in fuel energy consumption [15] and emissions that may contribute to health, odor problems, or greenhouse gas emissions [16]. In this context, typical expected reductions are 30-40% for CO₂ and SO₂, 50% for volatile organic compounds, 10-30% for CO, 60-70% for nitrous oxides, and 20-25% for dust. Also savings in the amount of fuel consumed in the burner devices for warming the aggregates that can reach 35% are an important argument. Moreover, its lower production temperature allows the compaction of the mixture at a lower temperature on site, without compromising the desired densities of the resulting layers. The reduction in the exposition to fumes by the workers is another important advantage of this type of mixes, with reductions of 30-50% in relation to conventional hot mix asphalts

[17]. WMAs also allow longer haul distances, a longer construction season, and minimized oxidative hardening, since the mixes are produced closer to the operating temperatures.

According to Park et al. [18], the emissions resulting from the production of asphalt mixtures can significantly vary according to the selected materials, equipment, or production modes. Reducing the environmental impacts caused by the industrial activities, namely by using WMA technologies, is a basic condition to adapt the new circumstances of development to the present requests of sustainability.

However, as stated previously, it is essential that the overall performance of WMA is truly as good as that of HMA. On a life-cycle basis, if WMA does not perform well, there will not be long-term environmental benefits or energy savings. Thus, several authors have been studying the performance of the WMA additives, binders [19], and mixtures [12, 17, 20] in order to improve their behavior.

While there is a great deal of promise that comes along with lower temperatures, there are also concerns [2, 21] about some field performance characteristics of WMA mixtures. Thus, this work was carried out in order to answer some questions that are still open about WMA performance in laboratory and in situ.

Laboratorial Study of Warm Mix Asphalts

Mix Design

In the present study, three bituminous mixtures were studied in order to evaluate the characteristics of WMA vs. HMA technologies. One of those was a conventional HMA (control mixture), typically used in Portuguese roads (AC 14 surf 50/70), while the other two were “new” WMA mixtures with the same composition but using binders modified with different commercial additives (Sasobit® and Cecabase®).

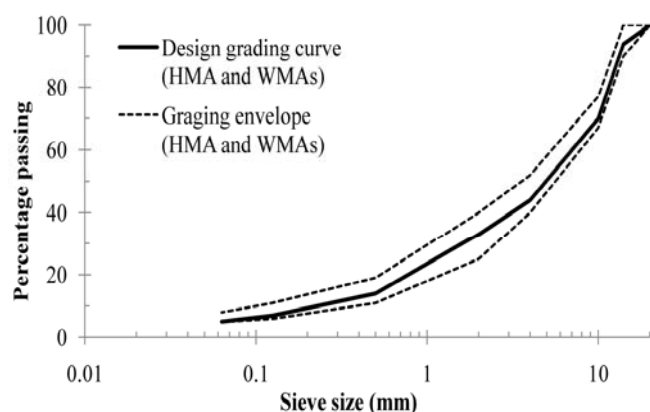
Sasobit® is a Fischer-Tropsch (F-T) or synthetic wax that is created during the coal gasification process and that has been used as a compaction aid and a temperature reducer. The Sasobit® process incorporates a low melting point additive that chemically changes the temperature-viscosity curve of the binder [12]. Sasobit®

Table 1. Properties of the Aggregates.

Evaluated Properties	Specifications	Aggregate 8/14	Aggregate 4/10	Washed Sand 0/4	Dust 0/5	Filler
Los Angeles Abrasion (%)	Max. 30%	27	—	—	—	—
Flakiness Index (%)	Max. 25%	14	12	—	—	—
Shape Index (%)	Max. 25%	25	14	—	—	—
Sand Equivalent (%)	Min. 60%	—	—	—	83	—
Methylene Blue	Max. 0.8	—	—	—	—	—
Particle Density (g/cm^3)	—	2.53	2.54	2.58	2.52	2.71
Water Absorption (%)	Max. 2%	1.0	1.0	1.0	1.9	—

Table 2. Properties of the Bitumen.

Bitumen Penetration grade	Penetration at 25 °C (d mm)	Ring & Ball Temperature (°C)
50/70	52	51.9

**Fig. 2.** Design Grading Curve Used in the Studied Mixtures.

melts at approximately 100°C and reduces the viscosity of the base bitumen. It increases the asphalt resistance to deformation throughout the operating temperature range without affecting the low temperature properties of the mixture, which are determined by the characteristics of the base bitumen [22]. Sasobit® is completely soluble in bitumen at temperatures above 115°C. It forms a homogeneous solution with base bitumen on stirring, reducing its viscosity. This also enables reducing the mixing and handling temperatures of the asphalt by 10–30°C [13]. According to Hurley and Prowell [11], Sasobit® has shown to improve the compactability of mixtures in both the shear gyratory compactor and vibratory compactor. Statistics indicated an overall reduction in air voids. Improved compaction was noted at temperatures as low as 88°C. The addition of Sasobit® does not increase the rutting potential of asphalt mixtures.

Cecabase® is an additive containing surface active agents that, when mixed with asphalt, allows a reduction on the road surface application temperature of about 50°C with no effect on performance of the material [14]. Compared to the classical paving process, the use of this additive reduces energy consumption by 20 to 50%, depending on the process, and considerably reduces dust emission [14]. According to the producers, the incorporation of this additive in the production of bituminous mixtures (2 to 4 kg per ton of asphalt binder) enables the application temperature to be reduced

to 120°C and, at the same time, it enables the WMA layer to retain the same properties as a classical layer with HMA produced at 160–180°C.

The main idea of the chosen WMA technologies is to use an additive in order to reduce the production temperature. Thus, the additive content and the mixing/compaction temperature were the only variables evaluated in the following sections. All other composition parameters (type of aggregates, grading curve, type of base bitumen, and binder content) were maintained identical for the three studied mixtures. The voids content should also be maintained constant for all mixtures, but this volumetric parameter is very dependent on the temperature used to produce the WMA mixtures, thus it was used as a control value to select the optimum mixing temperature.

Considering the previous statements, the mix design (selection of aggregates, bitumen, grading curve, and binder content) was only carried out for the HMA control mixture, and the final results were used for all studied mixtures. Since these mixtures were also used to construct a pavement trial, the aggregates and the 50/70 grade bitumen were imposed by the road owner. Their characteristics are presented, respectively, in Tables 1 and 2.

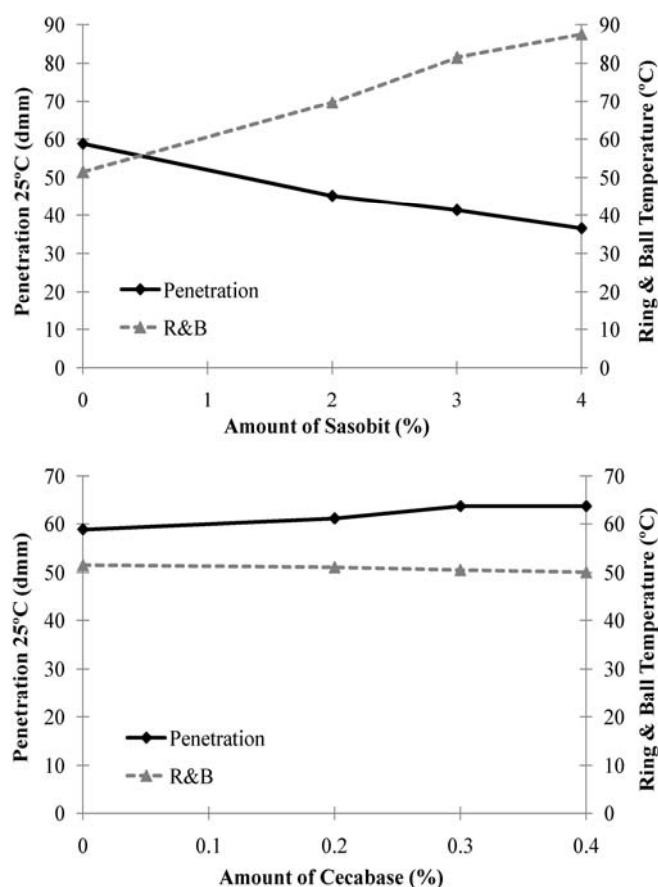
Fig. 2 presents the grading envelope imposed for the HMA mixture and the design grading curve obtained through the combination of the several aggregates and filler in order to fulfill the envelope limits.

During the Marshall mix design, used in Portugal as the “standard” mix design method to obtain the optimum binder content, five mixing batches were prepared and specimens were compacted with 75 blows in each face and with different binder contents (with a variation of 0.5% between them). The medium binder content used in the studied mixture was 5.0%. The maximum density of the mixing batches was assessed and all the volumetric characteristics of the Marshall specimens (voids content, VMA, and volume of bitumen and aggregates) were calculated. Finally, all specimens were tested by using the Marshall test procedures, registering the load and deformation values during the tests. In general, it was observed that the characteristics of the designed mixture were in conformity with the Portuguese specifications, and its optimum binder content was 5.0%.

An additional study was carried out to validate the mix design. Thus, water sensitivity and wheel tracking tests (WTTs) were performed on three bituminous mixtures (one with the optimum binder content determined previously and the other with a variation of $\pm 0.5\%$). Water sensitivity tests were carried out according to the EN 12697-12 standard. This type of test comprises the assessment

Table 3. Validation Test Results of the Conventional HMA Mix Design.

Evaluated Properties	Binder Content (%)		
	4.5	5.0	5.5
WTS Air ($\text{mm}/10^3$)	0.06	0.08	0.09
ITSR (%)	39.9	42.1	41.9
Voids Content (%)	4.4	3.5	2.7
VMA (%)	14.7	14.9	15.3
VFB (%)	70.0	76.6	82.3

**Fig. 3.** Evolution of the Penetration and Ring & Ball (R&B) Values of the Binders with the Amount of Additive.

of the indirect tensile strength (ITS), carried out according to EN 12697-23, of two identical groups of specimens conditioned in different environments (dry and wet with the application of vacuum). The test procedure includes also the evaluation of the indirect tensile strength ratio (ITSR) between the average indirect tensile strength results of both groups of specimens (wet over dry) in order to assess the water sensitivity of the mixture. In this study, the determination of the resistance to permanent deformation was carried out using the wheel-tracking test (according to EN 12697-22 standard). The susceptibility of the mixtures to deform was assessed by measuring the rut depth formed by repeated passes of a loaded wheel at a temperature of 50°C (maximum pavement temperature typically observed during summer in several regions of Portugal). The main parameter used to rank the permanent deformation

performance of the mixtures is the wheel tracking slope in air (WTS air) measured between the 5000th and the 10000th load passes. The values obtained in this study are listed in Table 3.

The analysis of the water sensitivity and wheel tracking tests results as well as the volumetric evaluation of the specimens (voids content, voids in the mineral aggregate (VMA), and voids filled with bitumen (VFB) confirmed the optimal binder content of 5.0% determined by the Marshall mix design method.

Selection of Additive Content

The selection of the optimum WMA additive content was based on the binder characterization present below. Six samples of modified binders were prepared in the laboratory for a thorough characterization (penetration, softening point, and dynamic viscosity). These samples comprised the addition of three percentages of each additive to the 50/70 grade bitumen. For economical reasons and based on the recommendations of the additive producers, 2 and 4% of Sasobit[®] and 0.2, 0.3, and 0.4% of Cecabase[®] were added to the conventional bitumens. The modified binders were obtained by mixing the bitumen with the additive for a period of five minutes at a temperature of 130°C. By choosing 130°C, it was granted that both additives and bitumen would be liquid in order to obtain a homogeneous mixture. Five minutes was the necessary time to achieve that homogeneity. Higher temperatures or mixing times could result in binder ageing.

In order to classify the binders used in this study, a basic characterization was performed in accordance with the EN 12591 standard. This included the tests of penetration at 25°C (following the EN 1426 standard) and of softening point (also known as Ring & Ball temperature, R&B, according to the EN 1427 standard). The results obtained for the paving grade bitumens and for those obtained by the addition of a certain amount of additive are summarized in Fig. 3.

The addition of up to 0.4% of Cecabase[®] to the original bitumen does not change its classification (penetration and R&B temperature is barely altered), while the addition of Sasobit[®] significantly modifies its properties (which can be classified as a hard binder type 35/50, thus changing the penetration grade).

In order to evaluate the properties of the several binders at higher temperatures (100 to 170°C) in which the bituminous mixtures are mixed and applied, their dynamic viscosity was accessed using a rotating spindle apparatus (according to the EN 13302 standard). During the test, the torque (relative resistance of the spindle to rotation) applied to a spindle rotating in a special sample container, enclosing the binder, measured its dynamic viscosity. According to EN 13302, after setting the test temperature and lowering the spindle into the binder, the system temperature should equilibrate after 15 to 30 minutes (lab practice showed that the usual equilibrium time is 18 minutes). Then, at least three readings were taken during the next 3 minutes for each evaluated temperature. The dynamic viscosity at each temperature is the arithmetic mean of the three readings taken between the 18th and 21st minute of the test. The method used to evaluate the dynamic viscosity of the binders at different temperatures is described in detail in Silva et al. [23].

The evolution of the dynamic viscosity with the temperature for different types of paving grade bitumens, before and after their

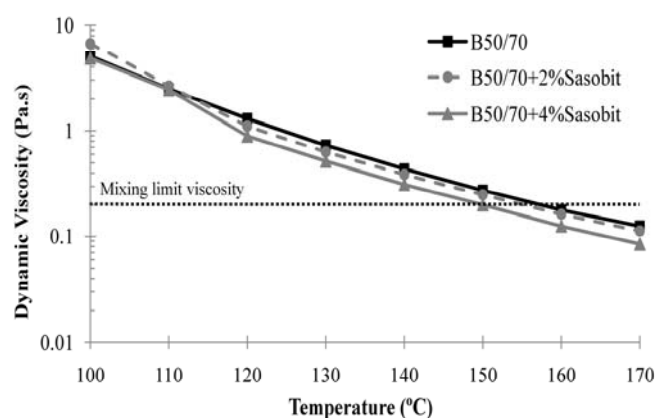


Fig. 4. Dynamic Viscosity of the Sasobit® Modified Binders (Rotating Spindle Apparatus).

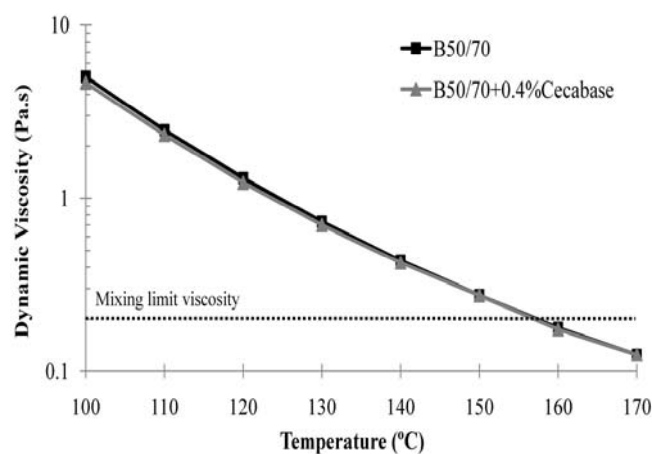


Fig. 5. Dynamic Viscosity of the Cecabase® Modified Binders (Rotating Spindle Apparatus).

modification with WMA additives, can be observed in Fig. 4 and 5, respectively, for the Sasobit® and Cecabase® modified binders.

Although other amounts of additive were used to modify the bitumen; for simplicity, only a few values are presented to demonstrate the evolution of the viscosity.

Fig. 4 shows that the addition of Sasobit® reduces the dynamic viscosity of the binder at production and application temperatures. Even though one of the objectives of using this additive in WMAs is to reduce application temperatures, changes observed at these temperatures are lower than those observed at in service conditions (penetration and R&B). After analyzing the temperatures at the limit equal-viscosity line for mixing (0.2 Pa.s), it can be concluded that the addition of 2% of Sasobit® allows reducing 2 to 4°C in comparison with the neat bitumen, while the binder modified with 4% Sasobit® presented higher reductions (7 to 9°C).

Fig. 5 shows that the addition of up to 0.4% of Cecabase® to the original bitumen barely changes its dynamic viscosity at the typical application temperatures. In fact, a minor reduction of viscosity can be observed after the addition of 0.4% of Cecabase® that allows a reduction of less than 1°C in the equal-viscosity line of 0.2 Pa.s.

It was concluded that a maximum temperature reduction was achieved using 4% of Sasobit®, while the addition of up to 0.4% of Cecabase® does not reduce the viscosity of the binder. Thus, the

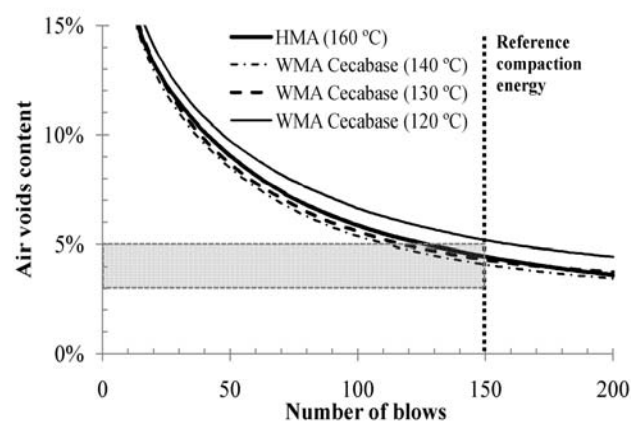
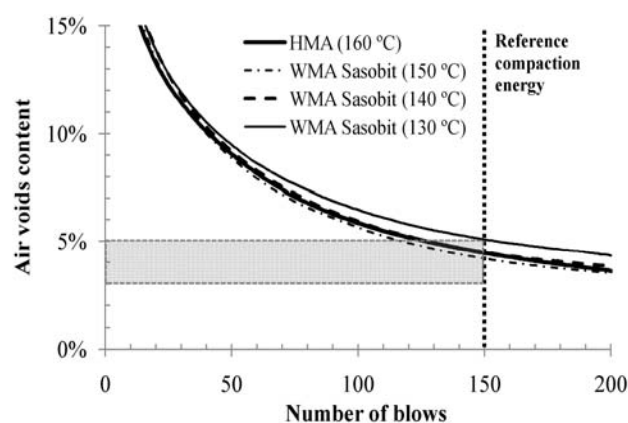


Fig. 6. Comparison between the Compactability Test Results Obtained for HMA and WMA Mixtures at Different Temperatures.

amount of Sasobit® selected to continue the study was 4% which, for economical reasons, is the higher limit suggested by the additive supplier. As the results of Cecabase® binder characterization were inconclusive, the amount of that additive selected to continue the study was 0.3% based on the supplier suggestions.

Selection of Mixing and Compaction Temperatures

After analyzing the viscosity results of the 50/70 pen grade bitumen, the target production temperature of 160°C (also defined by the EN12697-35 standard) was selected for the HMA control mixture. Also based on the previous viscosity characterization of the binders modified with Sasobit®, it was observed that, in comparison with the 50/70 pen grade bitumen, the mixing temperature can be reduced by about 10°C. The viscosity results obtained during the Cecabase® binder characterization were inconclusive.

However, there are other factors influencing the compaction of bituminous mixtures, namely the surface tension between the binder and the aggregates. For example, Cecabase® additive acts as a surfactant, reducing the surface tension and allowing the reduction of the mixing temperature, nearly without changing the binder viscosity. Thus, the mixing temperatures of the WMA mixtures produced with both additives were mainly chosen by means of EN 12697-10 compactability comparison with the HMA mixture (Fig. 6), using as control parameter of the voids content for the reference compaction energy.

Table 4. Properties of the Laboratory Studied Mixtures.

Binder Type	Standard	50/70	50/70 with Sasobit®	50/70 with Cecabase®
Bitumen Content (%)	EN 12697-1	5.0	5.0	5.0
Voids Content (%)	EN 12697-8	3.0	3.5	3.0
WTS Air ($mm/10^3$)	EN 12697-22	0.08	0.10	0.11
ITSR (%)	EN 12697-12	47	42	52
VMA (%)	EN 12697-8	14.5	14.9	14.5
VFB (%)	EN 12697-8	79.3	76.6	79.3

The compactability tests were carried out according to the EN 12697-10 standard, using the impact compactor (the same used in the Marshall method), monitoring the thickness of each specimen during the compaction operation (by using a displacement sensor, such as a linear variable differential transformer (LVDT)), and by recording the corresponding number of blows. Three different temperatures were used for the WMAs in order to determine the one that would result in an air voids content of the mixture closest to that of the HMA. For each set of mixture/temperature, three specimens were produced and the average was calculated to account for some common variability.

The comparison between the voids content of the HMA control mixture and those of the WMA mixtures produced with Sasobit®, and compacted at different temperatures, allowed to conclude that it is possible to reduce the mixing temperature up to 20°C without varying the compactability of the mixture. However, taking into account the viscosity result presented in the previous section (maximum reduction of 10°C), it was decided to reduce the mixing temperature by 15°C.

Regarding the comparison between the voids content of the HMA control mixture and those of the WMA mixtures produced with Cecabase®, it was concluded that the mixing temperature can be reduced up to 30-35°C without varying significantly the compactability of the mixture.

Laboratorial Characterization of the WMA and HMA Designed Mixtures

After determining the amount of additive and the production temperature for the WMA mixtures and based on the mix design carried out for the conventional mixture, an assessment of the properties of the final mixtures was made to validate the lab results before starting the production in the asphalt plant. Thus, water sensitivity and wheel tracking tests were carried out; the summary of which is presented in Table 4.

Apart from the values of the ITSR, which are lower than expected (this can be explained by the type of aggregate used, which has poor binder aggregate adhesion, as presented by Silva et al. [23]), all the other values are similar and within the expected results (namely, the permanent deformation resistance and the volumetric properties). Therefore, knowing that the less satisfactory results were associated with the type of aggregate, which was imposed by the road owner, the following step was to start the asphalt plant production.

Pavement Trial Construction and Assessment of

Final Performance of Warm Mix Asphalts

General Statements

The pavement trial was constructed in the southern part of Portugal in a region known as the Algarve, close to the new Algarve Motor Park (Autódromo Internacional do Algarve), near the city of Portimão. For the whole construction, the support given by the companies that were building the roads around the Park was essential. Due to restrictions in the time available for the construction, the trial had to be constructed in the winter during which the weather, and particularly the temperatures, are usually lower than desirable for asphalt laying operations. During the week before the construction of the pavement trial, some rain occurred in the area and, therefore, the aggregates were not completely dry. This was considered as a situation that could possibly occur in the production of WMAs and, therefore, the production of the mixtures was made as scheduled. Thus, it would be possible to assess whether or not this kind of technology can be used in less favorable conditions. On the trial construction day, the air temperature was just above 10°C at the beginning of the works in the morning and slightly increased during the day. However, the asphalt plant was located on site, so the travel time was not significantly influent for reducing the temperature of the mixture before the laying and compaction operations.

Production in the Asphalt Plant

Due to technical restrictions (related to the delivery of the modified binders) the warm mix asphalts could not be produced in the same day. Thus, the conventional mixture and that produced with the Sasobit® additive were produced and applied in one day and the mixture with Cecabase® additive was produced in the following day. Based on the results obtained for the mixing temperature reduction, as discussed before, the temperature used for the production of the conventional HMA was 160°C, while for WMA with Sasobit® it was 145°C. With the objective of testing the actual limits of Cecabase® to reduce the production temperature, this WMA mixture was produced at 125°C (corresponding to the maximum temperature reduction of 35°C, previously observed). In Fig. 7, the temperatures measured in the skip (immediately after mixing in the asphalt plant) with an infrared thermometer are presented for the three studied mixtures.

Two of the advantages of using WMAs instead of HMAs, generally mentioned in literature are (1) the better working conditions provided to the paving crew due to the lower temperature that the workers have to withstand and (2) the reduction of their exposition to fumes. At this pavement trial construction, both could be observed, the latter being visible in Fig. 8 (on the left-hand side photo, the fumes released while loading the truck with the conventional mixture are clearly visible, which does not happen on the photo on the right hand side for the WMA).

Pavement Trial Construction

As previously stated, the temperature reduction between the production

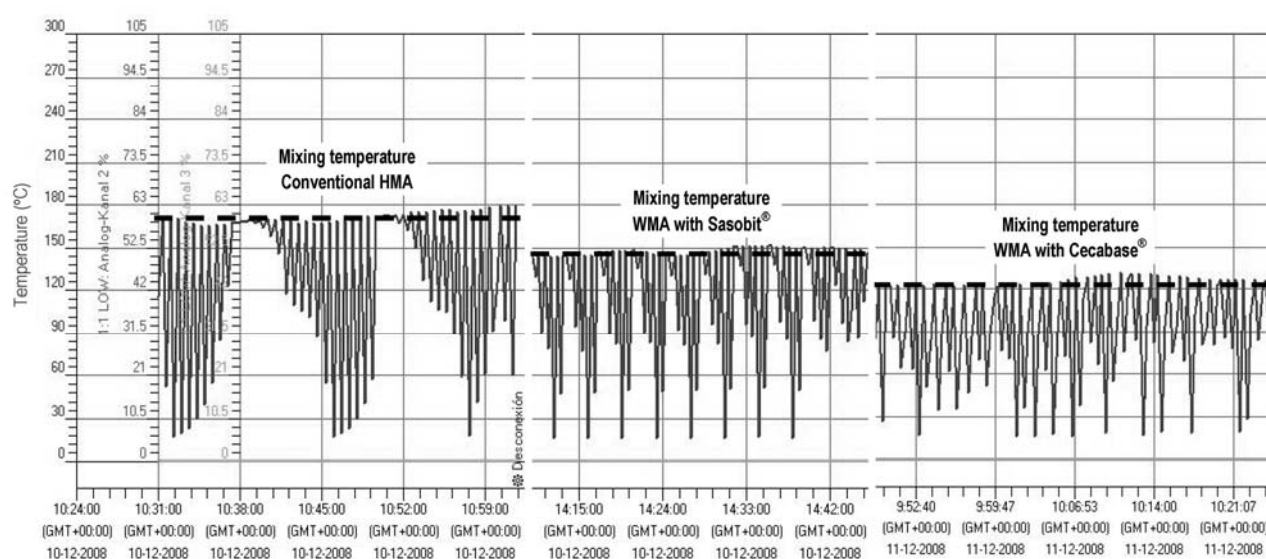


Fig. 7. Temperature Records Obtained Directly from the Asphalt Plant Equipment.

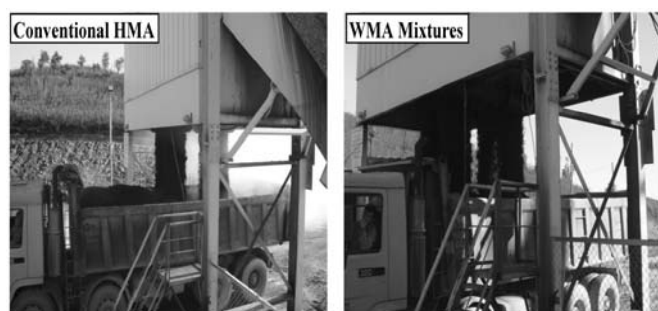


Fig. 8. Fumes Observed during Truck Loading at the Asphalt Plant.

Table 5. Properties of the Mixtures Applied in the Pavement Trial.

Binder Type	Standard	50/70	50/70 with Sasobit®	50/70 with Cecabase®
Bitumen Content (%)	EN 12697-1	5.0	5.1	5.3
Voids Content (%)	EN 12697-8	2.4	2.1	3.4
WTS Air ($mm/10^3$)	EN 12697-22	0.25	0.29	0.69
ITSR (%)	EN 12697-12	85.8	85.2	67.0
VMA (%)	EN 12697-8	14.0	13.9	15.5
VFB (%)	EN 12697-8	82.8	84.9	78.0

and the application/compaction was not significant (the values observed showed a reduction of approximately 10 to 15°C between the asphalt plant and the site). Since the results of this trial were going to be used for research purposes and since this was one of the first experiences with WMA technologies in Portugal, particular attention was paid to the temperature control. Also the compaction effort (number of passes of each roller compactor) was maintained constant for the three mixtures.

The pavement structure comprised a surface course (with the three mixtures under study applied over a length of about 400 meters each) over a bituminous binder course with 7cm and granular base with 20cm. The thickness of the surface course was

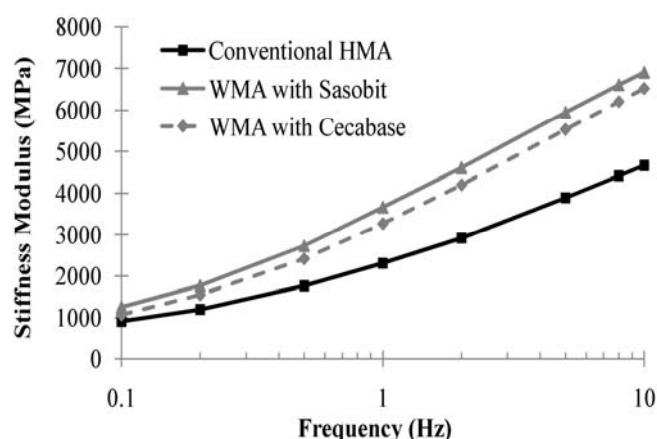


Fig. 9. Stiffness Moduli of the Studied Mixtures at Different Frequencies.

designed for approximately 5cm in order to allow the extraction of specimens for further mixture characterisation. The quality control procedures adopted resulted in consistent thickness over the length of the pavement trial (between 4.9 and 5.3cm). The longitudinal profile of the road where the trial was constructed was mainly horizontal, with short lengths on slopes.

Characterization of Final Performance of Mixtures

After the conclusion of the pavement trial, several slabs were extracted from the three sections. The slabs were then cut into prismatic and cylindrical specimens and their volumetric characteristics, stiffness modulus, water sensitivity, and resistance to permanent deformation were determined. The results are presented in Table 5 and Fig. 9.

Based on the results presented in this section, it can be stated that the binder content is similar for the three studied mixtures although the WMA with Cecabase® shows a slightly higher value. The voids

Table 6. Analysis of the Total Production Costs of the Studied Bituminous Mixtures.

Type of Cost	Unit	HMA	WMA Sasobit®	WMA Cecabase®
Aggregates (A)	(€/ton Mix)	10.5	10.5	10.5
Binder (B)	(€/ton Mix)	17.5	20.7	18.2
Production (C)	(€/ton Mix)	7.27	6.7	6.47
Total Cost of the Mixture (A+B+C)	(€/ton Mix)	35.3	37.9	35.2

content and the VMA results obtained are generally low, except for the WMA with Cecabase®. The VFB values are generally high, due to the low VMA of the mixtures or to the high binder content. The combination of these results may be responsible for the worse resistance to permanent deformation of the mixtures. The VFB results can also explain the higher ITS values obtained for the conventional HMA and the WMA with Sasobit®.

In terms of stiffness modulus, the three mixtures presented values typical of conventional bituminous mixtures although the WMAs slightly outperformed the conventional mixture, which confirms that it is possible to produce WMA mixtures without compromising their performance in comparison to HMA mixtures, provided that an adequate quality control is assured.

Comparing these results with those obtained from the laboratory study, it is possible to highlight that the resistance to permanent deformation is approximately half of the lab results. This can be explained by the volumetric properties measured from the mixtures obtained on site, which may have resulted from their possible contamination with fuel during the heating of the aggregates (since this asphalt plant was used for the first time in the production of WMA mixtures and the adjustment of the amount of fuel was not efficiently made). Hurley and Prowell [24] have already referred that WMA mixtures have higher susceptibility to be contaminated with fuel because it is difficult to adjust burners with low production temperatures combined with low quantities produced, particularly in pavement trials (as occurred in this work). Also according to these authors, this highlights the need for preheating the fuel prior to production in order to remove any condensation that may cause contamination of the mixtures during the heating of the aggregates. This can also be solved by using a different type of heating energy (e.g., natural gas).

Finally, the particle size distribution of the three mixtures applied in the pavement trial is similar to that presented previously during the laboratorial mix design (Fig. 2) and, therefore, it is not responsible for any change in the performance of the mixtures.

Comparative Cost Analysis between HMA and WMAs

This section summarizes the economics associated with the production of the studied WMA mixtures when compared with the conventional HMA. WMA mixtures represent an important step towards sustainable development, while conserving natural resources and reducing the carbon footprint of the road construction sector. These factors should become an important economic advantage that road administrations and contractors should consider

in their projects.

The following paragraphs will only present the cost analysis regarding the production of the studied HMA and WMA mixtures, covering the extra cost of the additive compared to the direct benefit resulting from the reduction in the fuel consumption.

The total cost of the asphalt mixtures produced in this study was obtained by the sum of all costs related with the constituent materials (aggregates and binder, or A+B, including the additive costs), along with the production costs (C, including the fuel costs). Table 6 presents the final costs estimated for the three studied mixtures.

The cost of the WMA produced with Cecabase® is similar to that of the conventional HMA since the extra cost of the additive is counterbalanced by the reduction in the fuel consumption for aggregate heating. The cost of the WMA produced with Sasobit® is slightly higher (7%) than that of the above mentioned mixtures.

Conclusions

Based on the results presented in this paper and on their analysis, the main conclusions that can be drawn from this study are the following:

- It was observed that only Sasobit® changes the viscosity of the binder, allowing a reduction of the mixing temperature of about 10°C for the same viscosity when the maximum additive content of 4% was used.
- It was also concluded that Cecabase® only acts as surfactant (after the mixture of the binder with the aggregates) since it does not influence the binder viscosity.
- The compactability tests showed that it is possible to reduce the temperature of production by 20°C or 30-35°C, respectively, when using Sasobit® or Cecabase® without significant changes in the voids content of the WMA mixtures.
- The rutting resistance of the studied mixtures was severely affected during their production in the asphalt plant, probably influenced by the contamination of the mixtures with fuel during the heating of the aggregates.
- In order to obtain adequate results with WMA mixtures on site, it is essential to have a narrow control of the production procedures and temperatures in the plant.
- The water sensitivity results of the studied HMA and WMA mixtures were similar, while the stiffness moduli of both WMA mixtures were higher than those of the HMA control mixture.
- The costs of producing WMAs are similar to those obtained in the production of the HMA since the costs of the additives are similar to the benefits of the fuel consumption reduction.

Based on the conclusions listed above, it was demonstrated that the additive contents and the temperature reductions determined in this study, as well as the selection procedures, proved to be adequate for these types of WMA additives/mixtures. Therefore, this methodology can be seen as a step forward to develop a WMA mix design procedure.

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