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Study of Asphalt Binder's Rheological Properties Extracted from Warm Mix Asphalts

Reference

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ABSTRACT

The long-term performance of Warm Mix Asphalts (WMAs) is relatively unknown because this technology is fairly new. A critical question is how much the production temperature can be cut down in these mixtures without reducing performance and durability. In order to answer such a question, it is necessary to study different variables, such as type of warm additive and sort of binder, in relation to temperature reduction and how they all can influence and limit the mixture behavior. The study of rheological properties of "warm" binders related to pavement failure (fatigue and rutting) is a way to explore the potential performance of WMA. This work examines the rheological properties of different asphalt binders extracted from WMAs that were elaborated at temperatures 20°C and 30°C lower than hot mix asphalts. WMAs were produced with two different warm mix additives and two types of asphalt binders (one straight-run and one polymer-modified). The results show that rheological properties of WMA binders with a 20°C temperature reduction were similar or slightly better than those of the control asphalt binders in the case of modified asphalt. The warm straight-run binders present a worse rutting response, independent of the type of additive used. With a 30°C temperature reduction, no improvements were reached for either type of warm binder.

Keywords

rheological properties, fatigue, rutting, warm mix asphalts

Introduction

Warm Mix Asphalt (WMA) is an environmentally friendly pavement technology. The main objective of WMAs is to decrease the carbon dioxide emissions that occur during the production and placement processes in comparison with hot mix asphalts (HMAs) by reducing the temperatures at which they are elaborated. Additionally, the working environment and the conditions of the mixture placement are improved (in cold weather, it allows hauling the mix longer distances and compacting with less effort) [1]. However, the temperature reduction must not affect the workability and final performance of the mixture (rutting and fatigue). Generally, the performance required for a WMA should be similar to or better than the traditional HMA.

The long-term performance of WMAs is relatively unknown because this technology is fairly new. A critical question is how much the production temperature can be decreased in these mixtures without reducing the performance and durability of the material. In order to answer such a question, it is necessary to study different variables, such as type of additive, sort of binder, and temperature reduction, to see how they might influence and limit the mixture behavior.

Research studies have reported reductions in rutting performance and moisture damage with some of the WMA technologies used. Su, Maekawa, and Hachiya [2] found that WMA produced with a chemical synthetic wax included in the mixture had lower rutting performances and increased moisture damage. Hurley and Prowell [3] found that the rutting potential incremented with decreased mixing and compaction temperatures and concluded that the lower compaction temperature used in WMA might increase the potential of moisture damage.

Since the Strategic Highways Research Program was created in the United States, rheological measures have been employed to evaluate the asphalt binder properties associated with asphalt mixture performance (fatigue and rutting). Different parameters or tests like $G^{*}.\sin\delta$, Dissipated Energy Ratio (DER), or Linear Amplitude Sweep (LAS) tests are related to the fatigue process in the mixture [4–6], whereas tests such as Multiple Stress Creep Recovery (MSCR), $G^{*}/\sin\delta$, or Low Shear Viscosity are connected to mixture rutting performance [7,8]. An example can be found in the work of Zhang et al. [9], who used rheological properties to evaluate the fatigue resistance of modified asphalt.

The rheological properties can be used to evaluate the effect of warm mix additives just as Ma et al. [10] showed in their work. In previous research, rheological properties associated with performance were evaluated in WMA binders and compared against the rheological properties of control binders [11]. Additionally, the performance response of these mixtures was assessed. In that previous work, the degree to which the temperature reduction affected the performance of some WMAs and their asphalt binders, even with warm mix additives, was observed. There, the temperatures were significantly reduced in comparison with traditional HMAs. It follows that temperature cannot be arbitrarily reduced because this substantially controls the performance and durability of the mixture.

In this work, different rheological properties that are related to rutting and fatigue were measured in binders extracted from WMAs that were elaborated with different warm mix additives. The purpose of this work was to observe how different variables like the type of warm additive, type of asphalt, and temperature reduction modified the rheological properties of warm binders. The objective is to analyze the WMAs throughout the binder rheological properties that are related to rutting and fatigue and use them to define the corresponding optimum temperature reduction to better understand how the different additives work in the mixture. Two different types of binders and two ranges of temperature reduction were evaluated to make observations and compare their performance with their reference HMA binders.

Experimental

TEST PROGRAM

During the research, different rheological properties of binders extracted from the WMAs were measured. In the first place, eight different WMAs were made with two types of binders, two types of warm mix additives, while using two temperature reductions (20°C and 30°C less than the traditional HMAs). The control HMAs were made at conventional temperatures without additives.

The different mixtures were left to cool and then the asphalt binders were extracted directly from the mixture according to ASTM D1856, *Standard Test Method for Recovery of Asphalt from Solution by Abson Method* [12]. A total of ten binders (two control HMA binders and eight WMA binders) were obtained for rheological analysis.

Fatigue at constant strain, linear amplitude sweep, frequency sweep, and MSCR were the rheological test procedures selected to study the different asphalt binder performances. The different tests were carried out on at least two samples for each condition studied.

MATERIALS

Asphalts

Two asphalts were used: one conventional (C) and one Styrene-Butadiene-Styrene polymer (SBS)-modified asphalt (M). Table 1 presents their main characteristics, including penetration, softening point (R&B), Brookfield viscosity at 60°C, and their performance grades according to ASTM D6373, *Standard Specification for Performance Grade Asphalt Binder* [13]. Table 1 also shows the normal production temperatures used for both asphalt binders. These binders represent the most common asphalts used in Argentina.

Additives

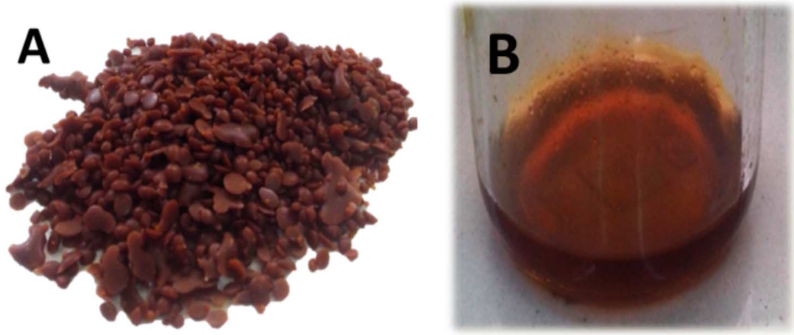
Two chemical warm mix additives (A and B) were used to elaborate the WMA. Warm mix additives primarily act as surfactants to reduce the asphalt surface tension and decrease the contact angle with the aggregate and also act as lubricants to improve the workability of the mix. The additives contain resins, polymers, and an adhesive agent. Additive A came in pellet form and Additive B in liquid form, as seen in Fig. 1. These were incorporated at 1.4

TABLE 1
Asphalt binder's properties.

Binder		C	M
Penetration at 25°C	(0.1 mm)	55	64
Softening Point (R & B)	(°C)	51.8	95.5
Viscosity at 60°C	(Pa.s)	297.6	–
Torsional Recovery	(%)	–	77.2
Performance Grade (PG)		64–16	70–22
Modifier		–	SBS Polymer
Traditional Mixing Temperatures	(°C)	160–150	175–165

FIG. 1

Pictures of additives.



and 0.6 % by weight of binder, respectively, as recommended by their manufacturers. The additives were incorporated into the asphalt binders prior to contact with the aggregate. The asphalts were heated for 2 hours in an oven at temperatures that ensured a proper blend (150°C and 180°C for C and M, respectively). In these conditions, the additives were incorporated and mixed by means of a pallet stirrer.

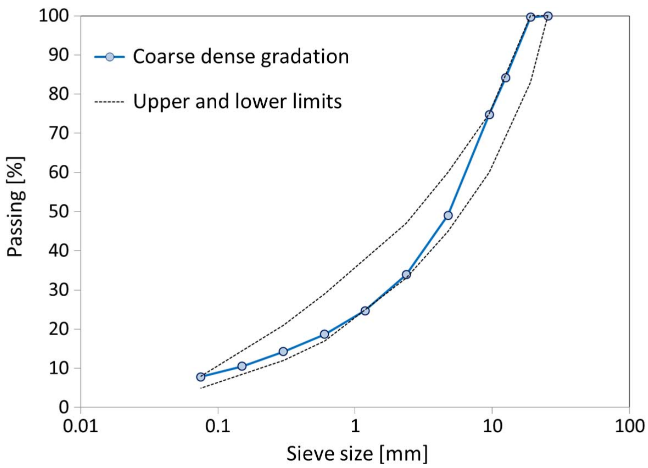
Mixtures

A coarse dense gradation, see Fig. 2, was selected to make the HMAs and WMAs and is composed of two coarse aggregates and crushed sand. The HMAs and WMAs were elaborated with a design asphalt content of 5 % for both types of binders (C and M).

The HMAs were prepared at 160°C and 175°C for C and M binders, respectively. The WMAs were made with temperature reductions that were 20°C and 30°C lower than the production temperature of HMAs. The mixtures were left to cool. Then, the asphalt binders were extracted from mixtures according to ASTM D1856. In the following sections, each binder was classified according to the type of binder (C or M), the additive used (A or B), and the reduction in temperature (none for the HMA, −20°C or −30°C for WMA).

FIG. 2

Aggregate gradation of mixture.



TEST METHODS

Fatigue Test—DER Approach

This test procedure is proposed in the NCHRP 9-10 Report 459 [4]. It is used to evaluate the fatigue life of asphalt binders using the concept of the DER. The DER is associated with the asphalt binder fatigue resistance and can be linked to fatigue in asphalt concrete. The dissipated energy is the energy lost in the process of deformation under each load cycle. In this test procedure, the asphalt is submitted to 6,000 load-unload cycles at constant strain and fixed frequency (10 % and 1.59 Hz, respectively) in a Dynamic Shear Rheometer (DSR). The number of loading cycles in this procedure was fixed in NCHRP 459 with the objective of ensuring that the test time is not too long. The test temperature was 20°C in all cases. The complex modulus (G^*) and phase angle (δ) are recorded at each cycle during the test. From this data, it is possible to calculate the dissipated energy in each cycle through Eq 1. Then, the DER is calculated for each cycle through Eq 2.

$$W_i = \pi.\varepsilon_0.G*_i \,.\, \sin\,\delta_i \tag{1}$$

where W_i = dissipated energy in i cycle, ε_0 = controlled strain, G^*_i = complex modulus in the i cycle, and δ_i = phase angel in the i cycle.

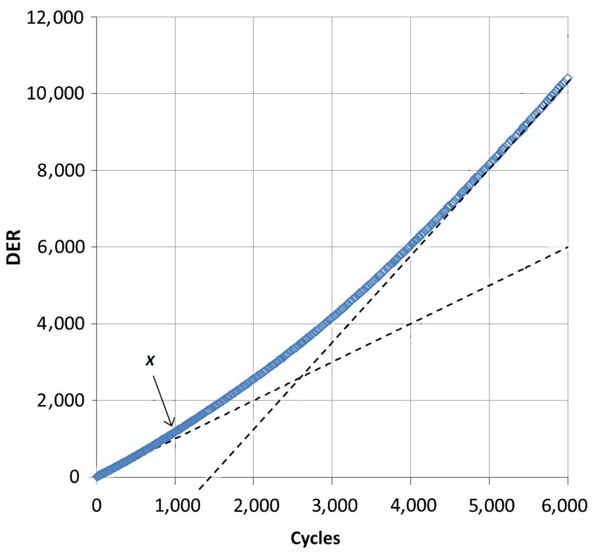
$$\mathrm{DER} = \frac{\sum_{i=1}^{n} W_i}{W_n} \tag{2}$$

where ΣW_i is the sum of accumulated dissipated energy for cycle 1 to n, and W_n is the dissipated energy in the n cycle.

A typical plot of DER versus the number of cycles is shown in Fig. 3. According to Anderson et al. [14], DER increases linearly with cycles in the initial stages. Then DER starts to rise more rapidly until it reaches a secondary slope. This change occurs because the properties modify very rapidly with load repetitions and material starts to suffer internal damage. In his work, Pronk [15] used the intersections of the two asymptotes shown

FIG. 3

DER versus load cycles.



in **Fig. 3** as a fatigue life criterion. However, Pronk later considered that this method could overestimate the fatigue life of the material because the transition between the two phases could be wide. Finally, he defined failure as the point where the curve becomes nonlinear, Point X in **Fig. 3**.

LAS

This test is in accordance with the standard AASHTO TP 101-14, *Standard Test Method for Estimating Damage Tolerance of Asphalt Binders Using the Linear Amplitude Sweep* [16], and is used to evaluate asphalt binder ability to resist damage by adding cyclic loads that linearly increased in amplitude throughout the assay. This procedure is normally done in the asphalt binder aged in rolling thin film oven test and pressure ageing vessel [17,18]. In this work, the asphalt binders were extracted directly from the asphalt mixtures with the aging produced during the production itself. The objective was to compare how the different conditions (warm or hot mix production) modified the rheological properties.

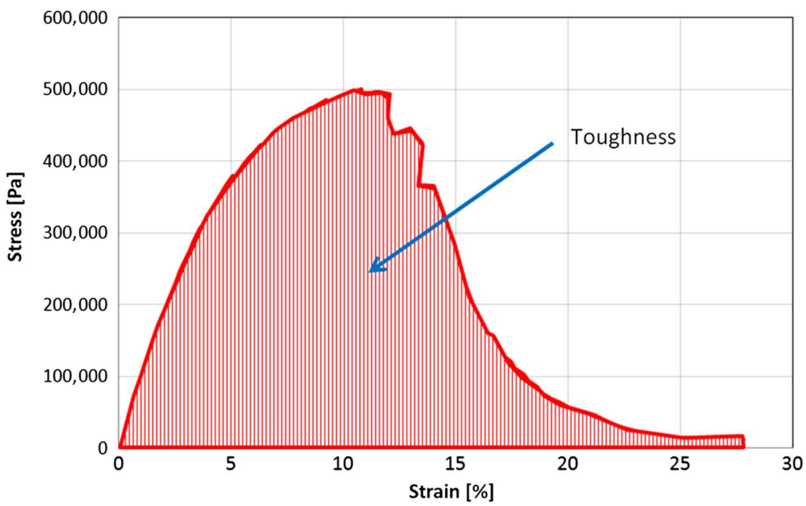
This test procedure is used to calculate the asphalt's accumulated damage according to the Kim model and obtain the fatigue parameters of asphalt [19]. In this work, the stress-strain curve obtained from the test was used to calculate the toughness (area below the curve), see **Fig. 4**. The toughness is related to the effort employed to fracture the material; meanwhile, the higher the toughness the more work is needed to fracture the asphalt, and, in consequence, the mixture has more resistance to traffic loading and greater fatigue resistance [20].

MSCR

The MSCR was done in a DSR applying load and recovery cycles (2 and 18 s, respectively) over an asphalt sample. This cycle was applied seven times at 0.1 kPa and then another seven cycles (2-s load and 18-s recovery) at 3.2 kPa. This test methodology is similar to ASTM D7405, *Standard Test Method for Multiple Stress Creep Recovery (MSCR) of Asphalt Binder Using a Dynamic Shear Rheometer* [21]. The principal differences are in the cycle number and load recovery time. The ASTM test configuration could not be applied because of the limitations and resolution of the DSR. The test was chosen to be carried out at

FIG. 4

Stress versus strain curve of the LAS test.



a constant temperature of 60°C that clearly represents a high temperature at which rutting usually occurs in asphalt concretes. During the assay, the asphalt strain was measured against time.

Results and Discussion

The WMA must have good performance and durability. Thus, it is important and necessary to study how much the production temperatures can be reduced in order to obtain an environmental gain without affecting the mixture performance and durability. Rheological

FIG. 5

MSCR test results of C binders.

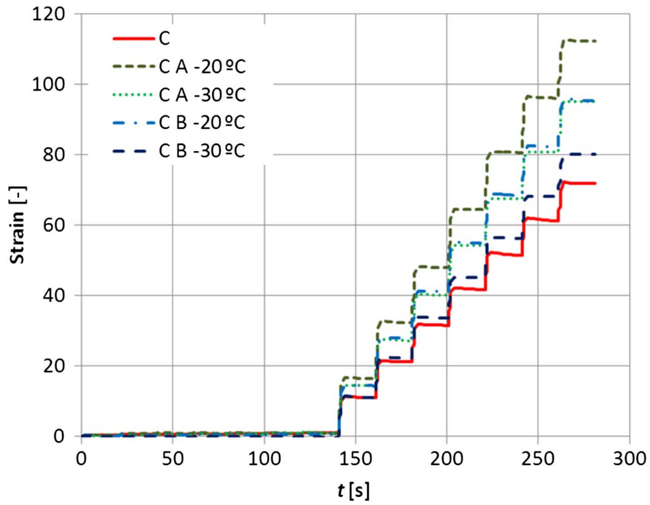


FIG. 6

MSCR test results of M binders.

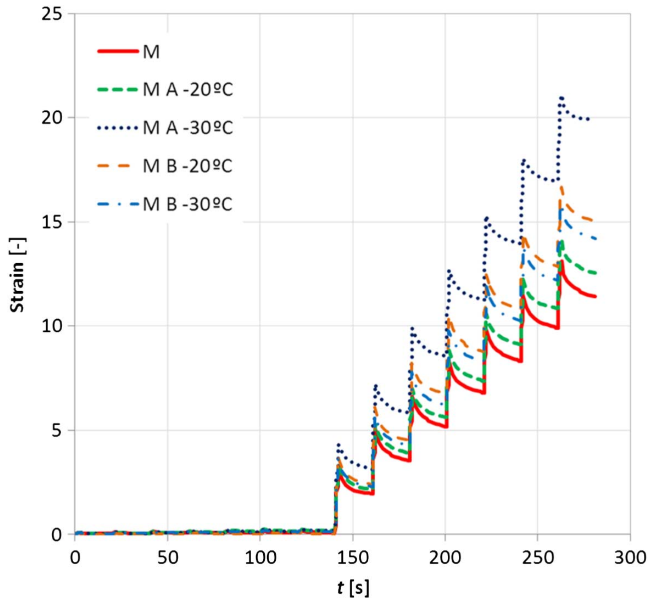
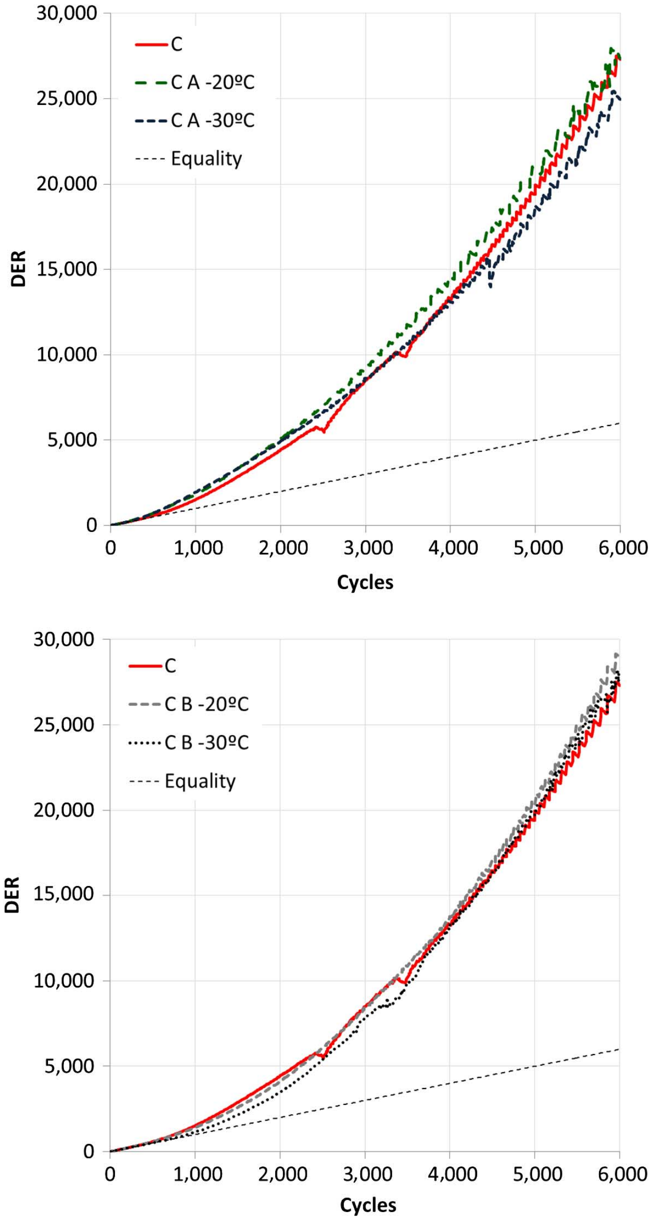


FIG. 7

DER results for C binders.



properties related to mixture performance were used in this work to estimate how different variables (type of additive, type of binder, and temperature reduction) can modify and limit behavior.

Figs. 5 and 6 show the MSCR results for the different binders. It can be observed in Fig. 5 how the C binders from the WMAs show more accumulated strain in the MSCR test in comparison to the control binder (from HMA). The additives for WMA don't help to improve or maintain the behavior of C. In the case of M binders (Fig. 6), only the binder with the Additive A and temperature reductions of 20°C is there obtained a behavior similar to that of the control binder (M). In contrast, Additive B does not produce any improvement.

Fig. 7 shows the fatigue tests on C binders. It can be observed, regardless of the temperature reduction and type of additive, that the DER of the WMA binders (CA-20, CA-30, CB-20, and CB-30) does not show significant differences with respect to the HMA binders (C). Therefore, the fatigue response of the WMAs with C binder will be similar to that of the HMA. In the case of M binders, see Fig. 8, it is observed that Additive B improves the fatigue behavior of WMAs with respect to HMAs for both temperature reductions. The WMA binders showed lower DERs at the end of the test compared to the HMA binder. On the other hand, the M binder with Additive A showed the same behavior that the HMA binder did for both temperature reductions. In the cases of Additive A, no improvement was observed, but the WMAs did have a similar behavior as that of

FIG. 8

DER results for M binders.

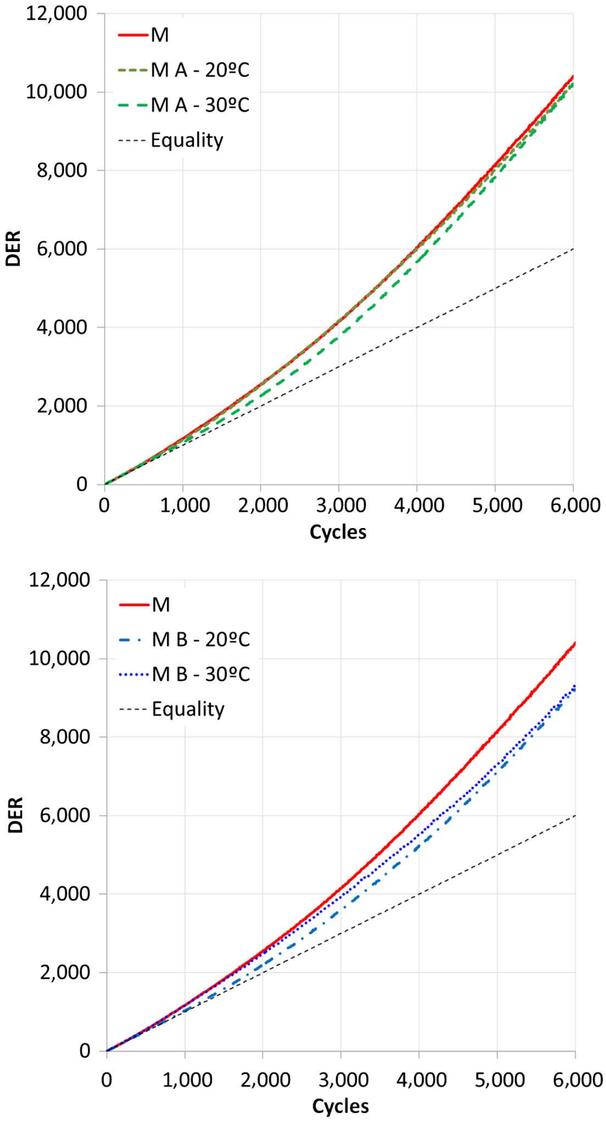


TABLE 2
Number of cycles to fatigue (*Nx*) calculated in DER tests (Pronk criteria).

		N [cycles]	
Binder		C	M
Warm additive	Temperature reduction		
–	0°C	390	540
A	20°C	180	710
	30°C	210	1,576
B	20°C	350	2,037
	30°C	920	439

the HMA with the plus of economic and environmental benefits that are due to temperature reduction in the production process. **Table 2** shows the number of cycles (*Nx*) to fatigue in the DER tests. *Nx* is the point in the test when the curve of DER against cycles becomes nonlinear (Pronk criterion [15]). These results follow those observed in **Figs. 7** and **8**. However, two observations should be mentioned. The first is in the case of CA-30°C, where its *Nx* value duplicated the *Nx* of C. However, the DER curves become similar at the end of the test. The other observation is in the case of MB-30°C, where the DER curve versus cycles for this binder becomes nonlinear at a number of cycles similar to the HMA binder. However, the DER at the end of the test was lower than that of the HMA binder (C).

Fig. 9 shows the progress of complex modulus (*G**) against cycles in the fatigue test for the M binders (control and WMA binders with 20°C temperature reduction). It is clearly observed how the Additive B improves the fatigue life of the M binder (M B - 20°C) in contrast to the control binder (M). **Table 3** shows the number of cycles required to obtain a 50 % reduction in complex modulus in comparison to the initial one, commonly used as a fatigue limit. It can be observed that the M B - 20°C doubled the life time in comparison with the control M binder.

FIG. 9
Complex modulus against load cycles in fatigue test.

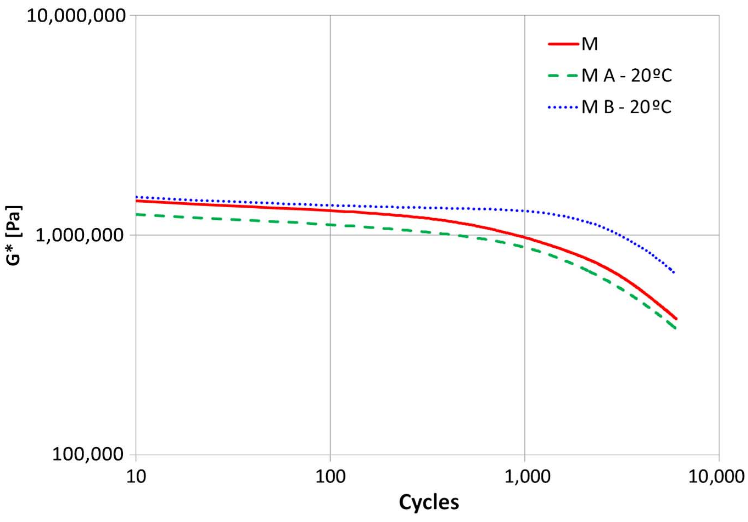


TABLE 3

Complex modulus results and cycles to fatigue for M binders.

		M	M A - 20°C	M B - 20°C
G^*_{initial}	(kPa)	1,435.2	1,243.9	1,491.5
$G^*_{\text{50 \% of initial}}$	(kPa)	717.6	621.9	745.8
N_f (Cycles)[a]	–	2,562	2,642	5,125

Note: [a] Number of cycles to reach a G^* of 50 % of the initial one.

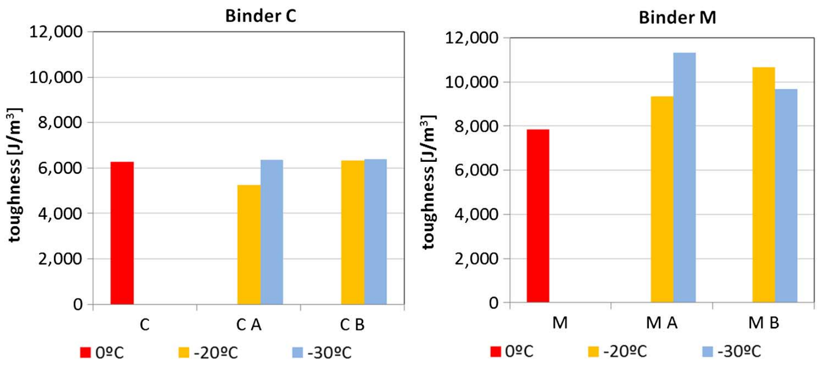


FIG. 10

Toughness calculated from the LAS test.

Fig. 10 shows the calculated toughness results (area below the stress-strain curve) from the LAS tests where the results for both binders studied (C and M) can be seen for both WMAs and HMAs. Fig. 10, on the left, shows that the toughness of the WMA binders (CA and CB) gives a similar result to the toughness of the HMA binder (C). On the other hand, Fig. 10, on the right, indicates a little improvement in the WMA binders (MA and MB) with regard to the HMA binder (M). The higher values of toughness reflect a better response by the WMA binders to fracture and fatigue.

Conclusions

WMAs must present good performance and durability. Thus, it is important to determine how much the production temperature can be reduced in WMAs in order to obtain an environmental gain without affecting the performance and durability of the mixture in each case. Rheological properties related to mixture performance are used as a tool to analyze binder response and predict the possible mixture performance. This work presents a way to analyze WMAs by studying different rheological properties of their binders related to rutting and fatigue to define how much the temperature can be reduced without affecting the performance. Additionally, it provides the means to study different additives and how they work and respond to different reductions in production temperatures. The followed protocol measures rheological properties of binders with different warm mix additives extracted from the WMAs. Two different binder types (straight-run and SBS-modified), two ranges of temperature reduction, and two warm mix additives were evaluated. The main conclusions of this case study are indicated as follows.

The conventional binders of WMA presented more accumulated strain in the MSCR test than the conventional binder of HMA in all cases studied, despite the type of additive used, therefore resulting in worse rutting behavior.

In the modified binder, only one additive and the lesser of the two temperature reductions showed a similar behavior comparable to the control binder in MSCR. In contrast, the other binders of the WMAs showed a worse behavior than the control binder for both temperature reductions studied.

In the fatigue test, the additive in pellets (A) improved or maintained a similar behavior for the asphalt binders of the WMA with a 20°C temperature reduction when compared to the control binder. The liquid additive improved the response to a lesser degree than the pellet additive. However, the liquid additive is the only one that improved the response of the modified binder in the fatigue test.

Both of the studied additives maintained a similar response in terms of toughness in the conventional binders of the WMAs with respect to the control binder of HMAs. For the modified binders of the WMAs, the additives that were studied slightly improved the toughness with reference to the control binder of the HMA.

In general terms, the reductions in temperature used for the production of warm asphalt mixtures must be carefully studied for each mixture. In this work, a reduction of 30°C in the production temperatures produced negative changes in most of the rheological properties, especially rutting. A worse rutting performance was observed in comparison to that of the HMA binders. Something similar can be said regarding the additives used. Not all additives can effectively work in all cases.

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