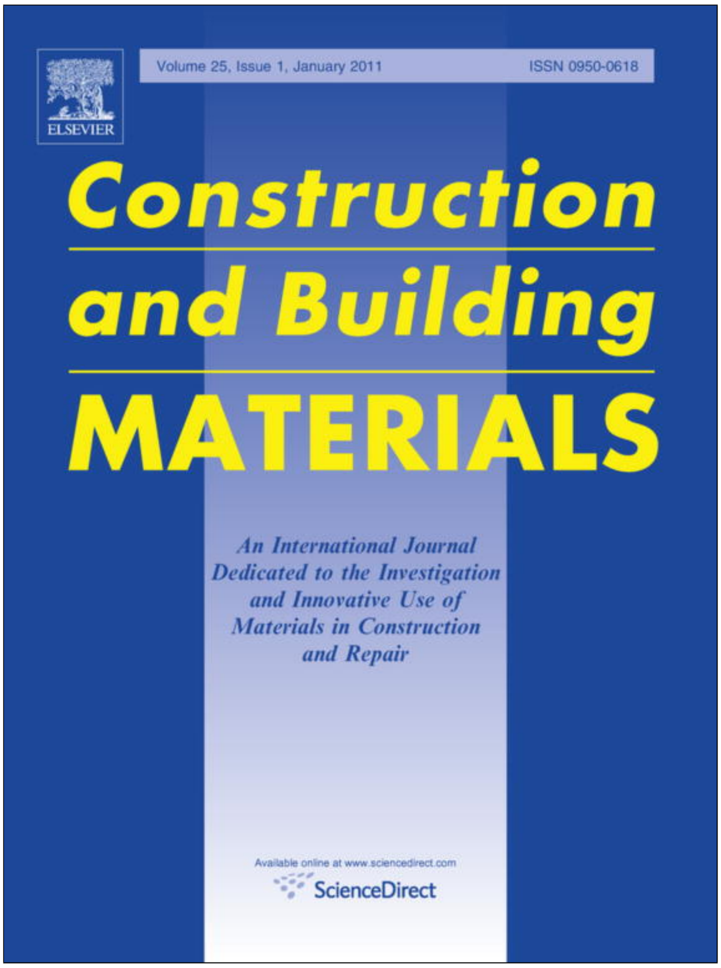
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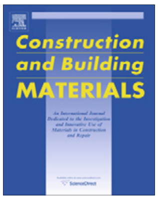

Rheological properties of asphalt binders with chemical tensoactive additives used in Warm Mix Asphalts (WMAs)

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A B S T R A C T

Warm Mix Asphalts (WMAs) have been developed with the objective of minimizing the CO_2 emissions in the production and placement process of Hot Mix Asphalts (HMAs) by reducing temperatures at which these are mixed and compacted. However, this reduction must not affect the manufacturability and final performance of the mixture. WMA additives allow reducing the production temperature while maintaining mixture workability during the mix process and without compromising the final performance of concrete asphalt. There are different additives, some of which modify the rheological behavior of asphalts (wax or paraffin) while others, in theory, allow for unaffected rheological behavior (chemical additives).

In this work the differences between the rheological properties of conventional and polymer modified asphalts, with and without chemical tensoactive additives, obtained from HMA and WMA, were studied by a Dynamic Shear Rheometer (DSR). Additionally, rutting resistance and moisture susceptibility were evaluated in these mixtures.

The rheological properties of polymer modified asphalt were affected by the WMA additives, while in the conventional asphalt the rheological properties were not significantly affected. The WMA additives improved the workability of the mixtures in the production process. Performance improvements in the submerged wheel-tracking test were observed for WMA when additives were used, yielding results similar to HMA.

1. Introduction

Due to the importance of environmental concerns in the manufacture of Hot Mix Asphalts (HMAs), new technologies have been developed. Warm Mix Asphalt (WMA) has appeared with the objective of minimizing CO_2 emissions in the production and placement process of HMA by reducing the temperatures at which these are mixed and compacted. This not only allows minimizing the amount of energy required, it also reduces emissions and odors and improves the welfare of workers.

Other important aspects of WMA are its paving benefits, including the ability to pave in cooler temperatures, to haul the mix longer distances, to compact the mixture with less effort and the possibility to pave and open to traffic in a short time period.

Traditionally, conventional temperatures used to produce HMA attempt to achieve a good coating of the aggregate and help in the laying process of mixture. The reduction of mixing and compaction temperatures can bring problems in the final mixture properties; therefore, it is important to consider this when trying to maintain an acceptable pavement performance for a mixture. Research studies have reported a reduction in rutting performance and moisture damage with some of the WMA technologies used. Su and coworkers [1] found lower rutting performances and increased moisture damage of WMA produced with the inclusion of a chemical synthetic wax to the mixture. Hurley and Prowell [2] found that the rutting potential did increase with decreasing mixing and compaction temperatures and conclude that the lower compaction temperature used when producing WMA may increase the potential of moisture damage.

The different WMA technologies seek to improve the workability and compactability of mixtures and can be classified into two major types: those that use water and those that use some form of additive incorporated into the asphalt to obtain the temperature reduction [3].

Processes that introduce small amounts of water into hot asphalt, either via a foaming nozzle or a hydrophilic material such as zeolite, or damp aggregate, rely on the fact that when a given volume of water is dispersed in hot asphalt, it results in an expansion of the binder phase and a corresponding reduction in the mix viscosity; making it possible to reduce the temperature in this way [3].

Organic additives (Fischer–Tropsch, montan waxes and fatty amides [3]) or chemical tensoactive additives [4] are also incorporated into asphalts. The former ones produce a decrease in asphalt viscosity when the mixing and placement temperatures

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are above the melting point of the wax, while the other additives reduce the surface tension of the asphalt binder without modifying, in theory, the rheological properties.

Several studies refer to the use of zeolites and waxes and their related mixture performances [5–8]. Little information can be found regarding the use of tensoactive additives in WMA and its related asphalt properties and mixture performances [9].

In this work the rheological properties of conventional and polymer modified asphalts, with two types of chemical tensoactive additives were extracted from the WMAs and their resistances to rutting and moisture susceptibilities were evaluated. Additionally, the same properties for traditional HMA and WMA (made without additive) were studied to compare with the former ones.

2. Experimental

2.1. Test program

The objective of this work was to observe changes in the asphalt rheological properties in samples extracted from three different mixes (HMA, WMA and WMA with tensoactive additives) while reducing their mixing and placement temperatures. These properties were analyzed in a Dynamic Shear Rheometer (DSR). At the same time, rutting and moisture susceptibility performance tests were evaluated for the different asphalt mixtures.

First, HMA and WMA samples were made with pure asphalt (without additives) to observe the rheological properties and mixture performances while reducing the mixing and placement temperatures.

Afterwards, WMA samples were made with two types of tensoactive additives and their rheological properties and mixture performances were compared to the WMA samples without additives.

The HMA batches were mixed and compacted at conventional temperatures (T_1) at traditional viscosity values of 0.17 and 0.28 Pa s.

The WMA batches were made at temperatures (T_2), following the recommendation of Khatri et al. [10] using the Zero Shear Viscosity (ZSV) concept, at viscosity values of 0.75 and 1.4 Pa s for mixing and compacting.

The asphalt binders for rheological analysis were extracted directly from the mixture after performance tests according to the ASTM D 1856 (2003).

The frequency sweep and Multiple Stress Creep Recovery were the rheological test procedures selected to study the different asphalts, meanwhile, rutting performances in the Wheel Tracking Test ($\mathrm{WTT_{air}}$) and moisture damage in submerged Wheel Tracking Test ($\mathrm{WTT_{water}}$) were evaluated for the different mixtures.

2.2. Materials and mixture

2.2.1. Asphalts

In this work, two commercial asphalt binders in Argentina, Conventional (C) and Polymer Modified asphalt (PM), were used. Table 1 presents their main characteristics including penetration, softening point (R&B), Brookfield viscosity at 60 °C and their Performance Grades (PGs) according to ASTM D 6373. Table 1 also shows the mixing and compaction temperatures for T_1 and T_2 criteria related to these asphalt binders.

2.2.2. Additives

Two different chemical tensoactive additives (A and B) were used to make the WMA more workable. The tensoactive additives that reduce the asphalt surface tension and decrease the contact angle with the aggregate also act as lubricants to improve the workability of the mix.

Table 1
Asphalt binder properties.

Asphalt		C	PM
Modification		–	SBS
Classification IRAM Argentina		Pen 70/100	AM3-C
Penetration a 25 °C	(d mm)	88	64
Softening point (R&B)	(°C)	47.6	95.5
Brookfield viscosity at 60 °C	(Pa s)	150.8	–
Torsional recovery	(%)	–	77.2
PG[a]		58–22	70–22
Mixing and compaction temperatures			
T1 (0.17 y 0.28 Pa s)	(°C)	152–140	194–184
T2 (0.75 y 1.40 Pa s)	(°C)	120–109	157–149
ΔT	(°C)	32–31	37–35

[a] Performance grades (ASTM D 6373 1999).

The A additive (liquid) contained surface active agents and was added to the asphalt at 0.4% by weight of binder. Meanwhile, the B additive (in pellet) contained resins, polymers and an adhesive agent and was incorporated into the asphalt at 2% by weight of binder.

Both additives were incorporated into the asphalts prior to working the mixtures. The asphalts were heated for 2 h in an oven at temperatures that ensured a proper blend and a viscosity of 0.3 Pa s (150 °C and 180 °C for C and PM, respectively). In these conditions, the additives were incorporated and blended by means of a pallet stirrer.

2.2.3. Mixture

A coarse dense grade gradation (D-12), see Fig. 1, was used to evaluate the HMA and WMA mixture performances. Two coarse aggregates and crushed sand from the province of Buenos Aires in Argentina were used. The gradations, specific gravities and proportions in mixture of each aggregate are shown in Table 2.

The Marshall method (ASTM D 1599) was used to design the HMA and the optimal asphalt content was found at 5% for both types of asphalt (C and PM). Table 3 presents the other main characteristics determined for the design including density, air voids, stability and flow. Likewise, the WMAs were made according to this design in respect to asphalt content and Table 3 also presents the main properties of these mixtures.

2.3. Test procedures

2.3.1. Rheological tests

A Dynamic Shear Rheometer (DSR) from Paar Physica SM-KP with a Rheolab MC-100 was used to evaluate the rheological behavior of the asphalts. The equipment has a thermo stabilizer to allow the temperature to be set in a range from 0 to 90 °C through a water recirculation system that surrounds the asphalt sample. The frequency sweep and Multiple Stress Creep Recovery (MSCR) tests were selected to characterize the rheological behavior.

The frequency sweeps were done from 1 to 10 Hz in the temperature range between 10 and 80 °C at 10 °C steps. The plate–plate configuration, 25 mm diameter and 1 mm gap sample geometry, was used. The frequency sweeps were done inside the linear viscoelastic region of the studied asphalts.

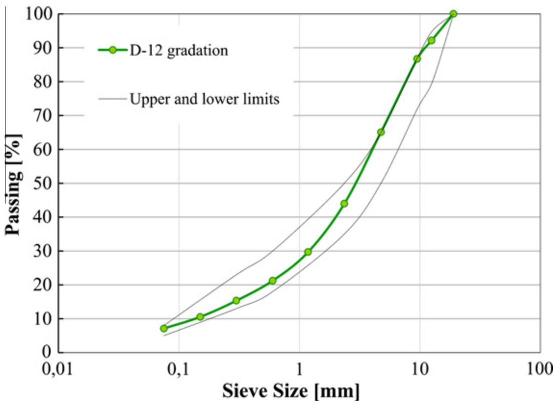

Fig. 1. Mixture gradation.

Table 2
Aggregate properties.

Sieve size (mm)	Passing (%)		
	Coarse aggregates		Crushed sand
	6–20 mm	6–12 mm	0–6 mm
25.40	100	100	100
19.00	99.1	100	100
12.50	60.4	99.8	100
9.50	37.5	98.5	100
4.75	6.0	8.5	94.8
2.36	2.8	3.1	65.4
1.18	2.2	2.2	45.7
0.60	1.9	1.7	32.8
0.30	1.5	1.3	23.4
0.15	1.1	0.9	15.9
0.0075	0.8	0.3	11.1
G_s (g/cm^3)	2.727	2.724	2.521
Proportion in mixture (%)	20	15	65

Table 3
Properties of mixtures.

Mixture asphalt	HMA C	WMA C	WMA C + A	WMA C + B	HMA PM	WMA PM	WMA PM + A	WMA PM + B
Asphalt content (%)	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Density (g/cm^3)	2.349	2.348	2.314	2.335	2.351	2.345	2.370	2.353
Air void (%)	6.6	6.6	7.7	6.8	6.5	6.7	5.1	5.9
Stability (kN)	15.8	14.5	10.2	12.0	20.3	20.0	19.7	18.6
Flow (mm)	2.8	2.7	2.8	2.8	4.1	2.9	4.5	4.8

The MSCR is based on the repeated creep recovery test [11]. Here the DSR was used to apply a constant stress on an asphalt sample for 2 s, and afterwards the load was removed; then the sample was allowed to relax for 18 s. This cycle was applied seven times at 100 Pa of stress and then another seven cycles (2 s of load and 18 s of recovery) were applied at 3200 Pa. This test methodology is similar to the standard ASTM D 7405, with the only difference in the use of 20 total cycles of 1 s of load and 9 s of recovery. This test configuration could not be applied due to DSR limitations. The test was chosen to be carried out at a constant temperature of 60 °C; which is the temperature of the wheel tracking test in air and similar to that of the wheel tracking test under water.

During the test the asphalt strain was measured for the fourteen cycles. Then the average of percentage recovery (% ε_r) for the seven cycles at each stress level and the non-recoverable creep compliance (*Jnr*) at the end of the test were calculated as indicated in the following equations:

$$\%\varepsilon_r(0.1\ \text{kPa}) = \frac{1}{7}\cdot\sum_{i=1}^{7}\frac{(\varepsilon_{2s}-\varepsilon_{20s})}{\varepsilon_{2s}}\bigg|_i \times 100 \qquad (1)$$

$$\%\varepsilon_r(3.2\ \text{kPa}) = \frac{1}{7}\cdot\sum_{i=8}^{14}\frac{(\varepsilon_{2s}-\varepsilon_{20s})}{\varepsilon_{2s}}\bigg|_i \times 100 \qquad (2)$$

$$Jnr = \frac{\textit{Final accumulated strain}}{3.2}\left[\frac{1}{\text{kPa}}\right] \qquad (3)$$

where % ε_r is the average of percentage strain recovery at specified stress, ε_{2s} is the strain value at the end of the creep portion after 2 s of load in the *i* cycle and ε_{20s} is the strain value at the end of recovery portion at 20 s in cycle *i*.

The MSCR is an asphalt test related with rutting behavior created to complement the performance grade classification of modified asphalt binders in ASTM D 6373. This method was designed to evaluate the elastomeric response of modified asphalt. The percent of recovery (ε_r) obtained can be used to detect the ability of modified asphalt binder to maintain elastic response at different stress levels. A decrease of 15% in ε_r from 0.1 to 3.2 kPa ($\Delta\varepsilon_r$), as indicated in Eq. (4), is considered a limit for determining if the binder has a suitable elastomeric response.

$$\Delta\varepsilon_r = \varepsilon_r(3.2\ \text{kPa}) - \varepsilon_r(0.1\ \text{kPa}) \qquad (4)$$

The *Jnr* is a measure of the permanent deformation at the end of the test. While higher the *Jnr*, weaker is the resistance to deformation induced by creep and recovery solicitation under different stress levels. High *Jnr* values are supposed to mean low resistance to permanent deformation. The *Jnr* requirement is 4.0 kPa^{-1} for standard fast moving traffic, while for slow moving or higher traffic, the required *Jnr* value would be 2.0 or 1.0 kPa^{-1}, corresponding to a more rut resistant material [12].

The MSCR is not considered for conventional asphalts; however, it was measured because it represents a good parameter to compare the behavior of the different conventional asphalts studied (by reducing temperature, with or without additives). The percentage recovery was not measured for these kinds of asphalts.

2.3.2. Performance tests

The asphalt mixture performance was evaluated in respect to resistance to rutting and moisture susceptibility. The Wheel Tracking Test (WTT$_{\text{air}}$) [13] was used to characterize the asphalt mixture rutting performance under laboratory controlled conditions. The device consists of a solid rubber wheel, 207 mm diameter and 47 mm wide, loaded with 520 ± 5 N. The loaded wheel describes a simple harmonic motion with a total travel distance of 230 mm and a frequency of 21 cycles per minute over an asphalt concrete sample. Test samples were compacted to the design Marshall density. Rutting depth was measured at 1 min intervals through a LVDT during 120 min. The test temperature was 60 °C.

The submerged Wheel Tracking Test (WTT$_{\text{water}}$; AASHTO T 324) was used to characterize the asphalt mixture rutting performance under the action of traffic and water. The device consists in a solid steel wheel, 203.6 mm diameter and 47 mm wide, loaded with 705 ± 4.5 N. The loaded wheel describes a simple harmonic motion over an asphalt concrete sample with 7 ± 1% air voids. The wheel travels back and forth with a frequency of 25 cycles per minute during 360 min, if the maximum allowed deformation of 15 mm is not reached. The test temperature was 50 °C. Rut depth was measured at 1 min intervals through a LVDT during the test and the rut depth versus wheel passes was plotted. The curve can be divided into three parts. There is always a rut slope (corresponding to wheel load) followed by the striping slope if the mixture has moisture damage. Between these slopes appears the striping point which is a measure of mixture moisture susceptibility and is related to the adhesion failure in the interphase aggregate–asphalt.

3. Results and discussion

In this work the rheological properties of conventional and polymer modified asphalts, with and without chemical tensoactive additives (extracted from HMA and WMA), were studied. Additionally, the mixture resistances to rutting (WTT$_{\text{air}}$) and moisture susceptibility (WTT$_{\text{water}}$) of these mixtures were evaluated. It is important to mention that the WMAs were made following the recommendation of Khatri et al. [10]. With this consideration the reduction of temperature is between 30 °C and 35–40 °C for the C and PM asphalt, respectively (see Table 1). The following sections describe the results found.

3.1. Rheological properties of pure asphalts used in HMA and WMA

First, the rheological responses of asphalts without additives extracted from HMAs and WMAs were analyzed. Fig. 2 shows the values of complex modulus (|$G*$|, $G*$ from here on) and phase angle (δ) as a function of frequency for C and PM asphalts. The results

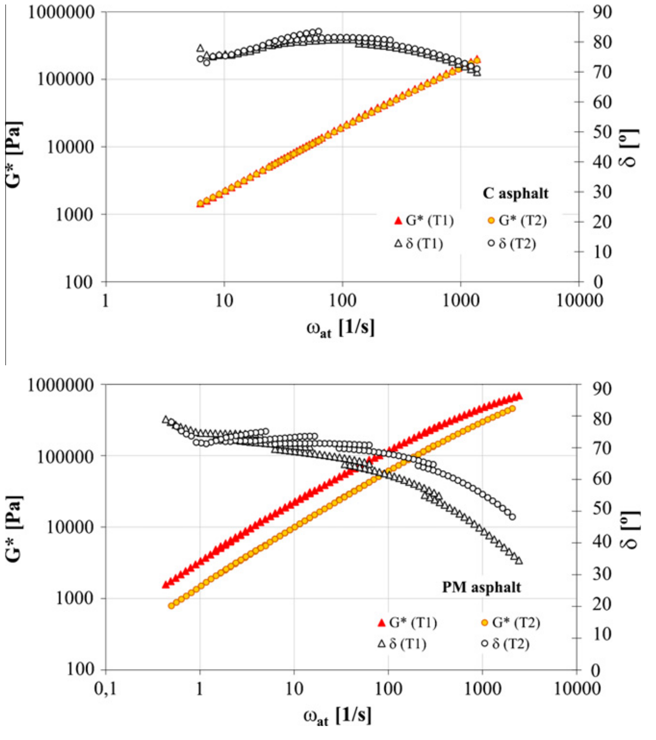

Fig. 2. Master curves at T_1 and T_2 (T_{ref} = 60 °C); C asphalt (above); PM asphalt (below).

were shown in master curves for the reference temperature of 60 °C. The rheological behavior of the C asphalt did not show any significant changes by reducing the mixing and compaction temperatures from T_1 (152–140 °C) to T_2 (120–109 °C). However, lower values of $G*$ for all frequency ranges of PM(T_2) when compared to PM(T_1) were measured. In a similar way δ for PM(T_2) shows higher values at high frequencies in respect to PM(T_1), and therefore the former has a more viscous response. As expected, the temperature reductions produced a lower aging of this asphalt. It is important to mention that for PM, T_1 and T_2 conditions corresponded to temperatures of 184–194 °C and 149–157 °C, respectively.

Fig. 3 shows the MSCR test results at 60 °C for pure C and PM asphalt at temperature conditions of T_1 and T_2. The WMA binder (T_2 condition) showed a higher accumulated strain than the HMA binder (T_1 condition) in both types of asphalts, although it was more pronounced in the Polymer Modified one (PM). This fact can be related with a lower aging of binder and increased rutting risk in mixtures.

Table 4 shows the calculated parameters obtained in the MSCR tests for the different asphalts: ε_r (0.1 and 3.2 kPa), *Jnr* and the $\Delta\varepsilon_r$. It was found that the *Jnr* values of PM(T_1) were half that of the PM(T_2) values. Therefore, asphalt PM(T_2) is more susceptible to rutting than PM(T_1), as was previously stated. Meanwhile, the ε_r values for PM(T_1) and PM(T_2) showed a poor elastic response and a decrease higher than 15% was observed in ε_r with the change in stress level. It is important to note that a worse behavior was observed in PM(T_2).

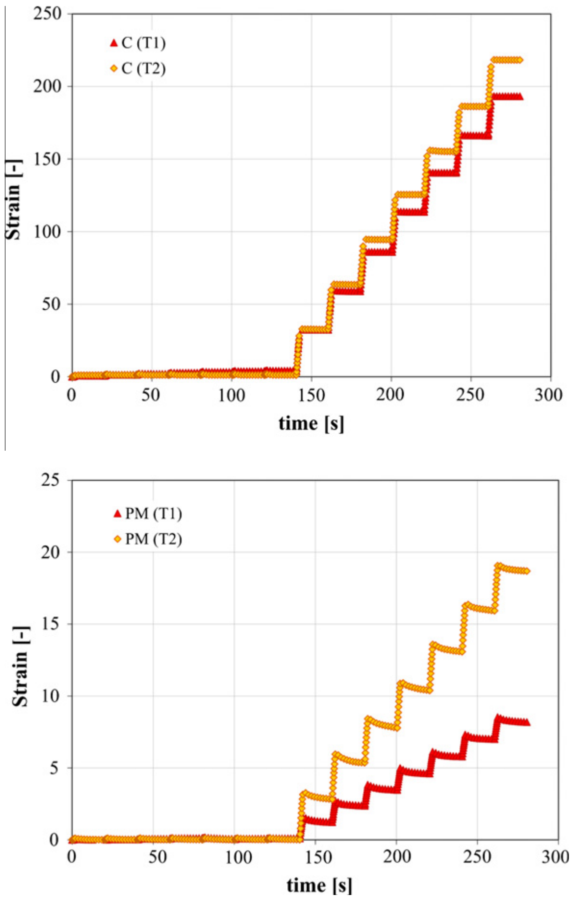

Fig. 3. MSCR tests at T_1 and T_2 (T_{test} = 60 °C); C asphalt (above); PM asphalt (below).

Table 4
MSCR test results for asphalt without additives from HMAs and WMAs.

MSCR parameters	Specification limits	C(T_1)	C(T_2)	PM(T_1)	PM(T_2)
% ε_r (0.1 kPa)		–	–	100	97.7
% ε_r (3.2 kPa)		–	–	22.9	14.8
Jnr (1/kPa)	<4	60.4	68.2	2.6	5.8
$\Delta\varepsilon_r$ (%)	<15			77.1	82.9

In the cases of C asphalt both *Jnr* values were found to be similarly high. Considering the results, mixtures prepared with these particular asphalts are susceptible to suffer rutting as temperatures increase beyond 60 °C.

Considering the rheological results, the reduction of temperatures did not produce significant changes in the pure C asphalt behavior; however, the results of the pure PM asphalt reflect that this lower temperature has increased the rutting risk of the mixture. This is due basically to a less aging of the asphalt binder and must be take into account.

3.2. Traditional asphalt tests

Previous to rheological testing, viscosity and penetration tests of different asphalts extracted from WMAs (with and without additives) were performed. As Table 5 shows, the WMA additive (A or B) had no impact on the penetration and viscosity values taken for the C asphalt. Meanwhile the PM asphalt with additives showed slight increments in penetration and viscosities. In general, no significant differences were observed between the pure and additive asphalts in these tests.

In respect to the performance grade high temperature (T_{high}) of the ASTM D 6373, no significant changes were observed in the C asphalts. T_{high} values of 59.0, 59.5 and 59.5 °C were obtained for the C, C + A and C + B asphalts, respectively. In the case of PM asphalt, the additives slightly increase the T_{high} results. Values of 74.5, 79.0 and 75.8 °C were obtained for PM, PM + A and PM + B, respectively. The A additive produced a change in the PG from 70 to 76 for the PM asphalt; however, the maximum temperature was only increased by 4.5° after incorporating the additive.

3.3. Rheological properties of asphalt with and without additives used in WMA

The main objective of this work was to observe if the chemical tensoactive additives incorporated into the asphalt binders caused some effect on the rheological properties, thus frequency sweep and MSCR tests were done on the asphalts with additives, extracted from WMAs. Fig. 4 shows the $G*$ and δ measure in the DSR as a function of frequency with the results shown in master curves for the reference temperature of 60 °C. Fig. 4 also shows the results obtained for the asphalts without additives, C(T_2) and PM(T_2), as control. It can be seen that the effect of additives did not change the rheological behavior of C asphalt. However, a different behavior was observed in the PM asphalts with additives (PM + A and PM + B) when compared to the asphalt alone. While the $G*$ values slightly change, the δ values decrease notably for low frequencies. This is translated into a more elastic behavior as can be seen in the Cole–Cole diagram, see Fig. 5, where the

Table 5
Traditional rheological properties of asphalt from WMAs.

	C	C + A	C + B	PM	PM + A	PM + B
Penetration at 25 °C (d mm)	54	52	51	30	44	41
viscosity (Pa s)						
135 °C	0.45	0.44	0.40	2.07	4.03	4.55
150 °C	0.22	0.22	0.20	0.89	1.43	1.43
170 °C	0.10	0.10	0.09	0.34	0.46	0.44
190 °C	–	–	–	0.16	0.20	0.19

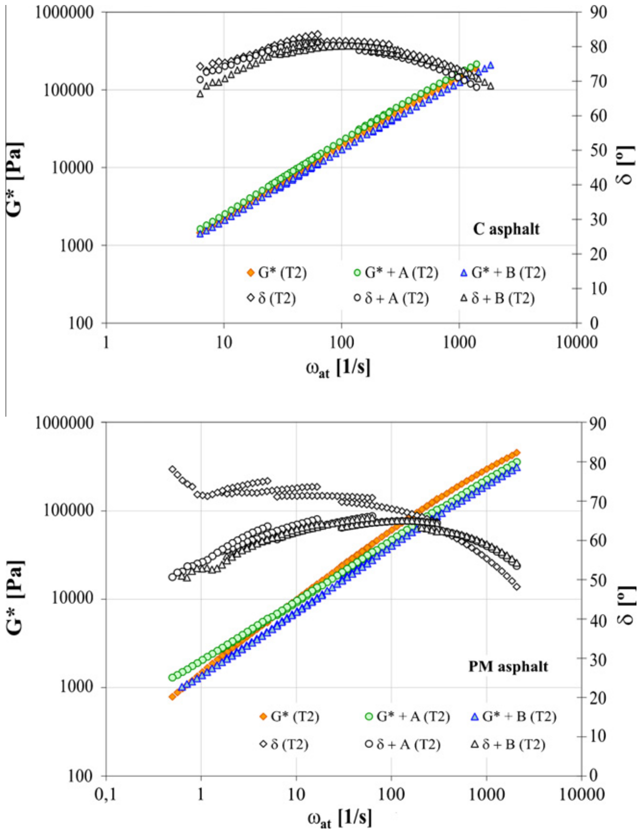

Fig. 4. Master curves at T_2 (T_{ref} = 60 °C); C, C + A and C + B asphalt (above); PM, PM + A and PM + B asphalt (below).

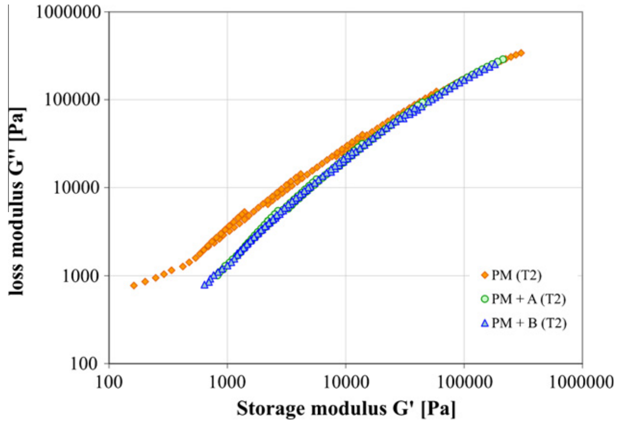

Fig. 5. Cole–Cole diagram for PM, PM + A and PM + B asphalt at T_2.

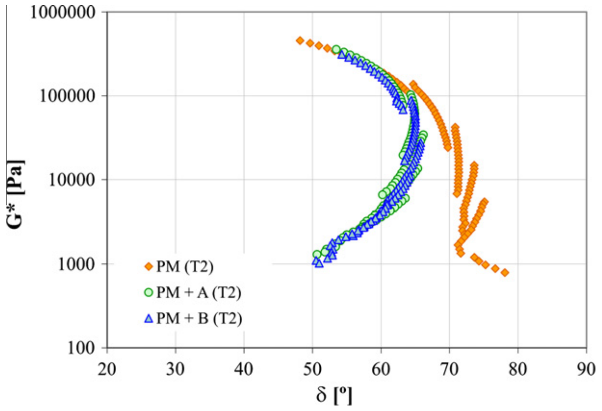

Fig. 6. Black diagram for PM, PM + A and PM + B asphalt at T_2.

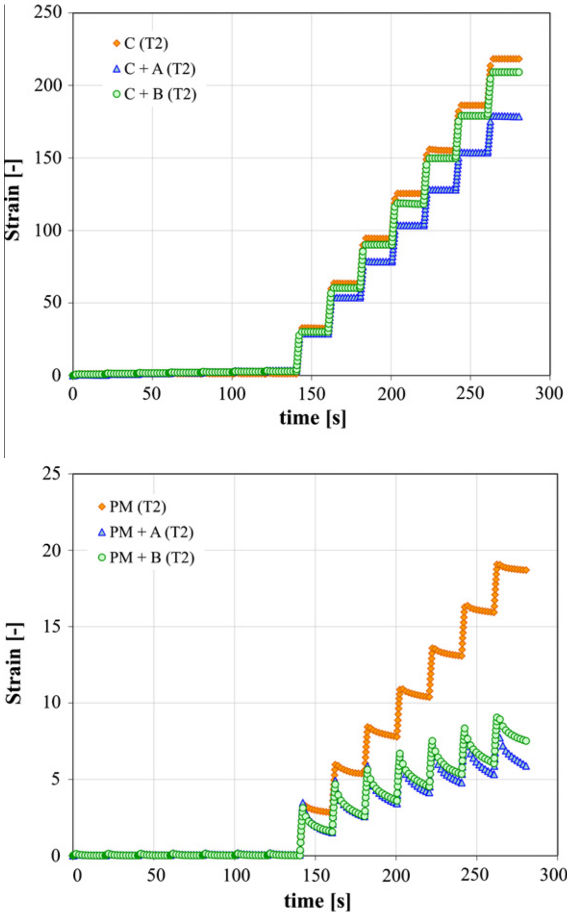

Fig. 7. MSCR tests at T_2 (T_{test} = 60 °C); C, C + A and C + B asphalt (above); PM, PM + A and PM + B asphalt (below).

PM + A and PM + B asphalt show higher storage moduli at low frequencies (or high temperatures) than the PM asphalt. Hence, the PM asphalt with additives may offer a better rutting response. Fig. 6 shows the black diagrams [14] of PM asphalts where the different behaviors can be seen.

Fig. 7 shows the MSCR tests at 60 °C of C and PM asphalts with additives and also shows the result obtained from the pure asphalt at T_2 as the control. In the same way as found in the frequency sweep tests, the MSCR tests show that the addition of WMA additives does not significantly change the rheological behavior of C asphalt. However, the PM asphalt with additives (PM + A or PM + B) show drastic changes in their behavior when compared to asphalt alone, PM(T_2). In the first place a decrease in the accumulated strains was observed at the end of the test (see Table 6) when compared with the pure WMA binder. The *Jnr* values were comparable to obtained for the asphalt of HMA (PM(T_1)), see Table 4. Additionally a significant improvement of the elastic recovery was observed with values of $\Delta\varepsilon_r$ ($\varepsilon_{r3.2kPa} - \varepsilon_{r0.1kPa}$) approaching the specification's 15% maximum for the case of PM + A asphalt. Despite that the PM + B asphalt did not fulfill the specification ($\Delta\varepsilon_r$ = 32.9%) a major improvement in the elastic response was observed when compared to PM alone ($\Delta\varepsilon_r$ = 82.9%). In consequence the incorporation of the additives improves the elastomeric response of PM asphalt, translating into a better response to rutting.

Table 6
MSCR test results for asphalt from WMAs.

MSCR parameters	Specification limits	C(T_2)	C + A(T_2)	C + B(T_2)	PM(T_2)	PM + A(T_2)	PM + B(T_2)
% ε_r (0.1 kPa)		–	–	–	97.7	92.3	97.7
% ε_r (3.2 kPa)		–	–	–	14.8	74.8	64.8
Jnr (1/kPa)	<4	68.2	55.8	65.3	5.8	1.8	2.3
$\Delta\varepsilon_r$ (%)	<15				82.9	17.5	32.9

3.4. Performance tests

The rutting performance and moisture susceptibility of HMAs and WMAs were studied by means of the WTT_{air} and WTT_{water} tests. These were selected because WMAs typically fail in these tests, according to reports by several researches [1,2].

Fig. 8 shows the permanent deformations of the studied mixtures measured in the WTT_{air} test. As the temperatures were reduced (from T_1 to T_2), performance worsened in the C asphalt mixtures (Fig. 8 above), and even with the incorporation of additives (A or B), the WMA rutting performance was not improved.

The WTT_{air} test for mixtures with PM asphalts (PM, PM + A or PM + B) did not show significant changes between the mixtures, even with the temperature reduction or the absence of additive (see Fig. 8 below). A possible explanation could be found in the shear stress applied during the test as it was performed. This shear stress could be insufficient to achieve changes in the behavior of the different mixtures made with PM, PM + A and PM + B at 60 °C. D'Angelo et al. [15] said that if the applied shear stress is too low, it does not produce enough stress in the modified asphalt to get the polymer chains to slip, and thus any differences in the behavior could not be observed. If a higher load over a longer period of time is applied, e.g. in WTT_{air} standard UNE 12697-22 [16], the differences in the behavior could be seen as it was observed in the rheological tests.

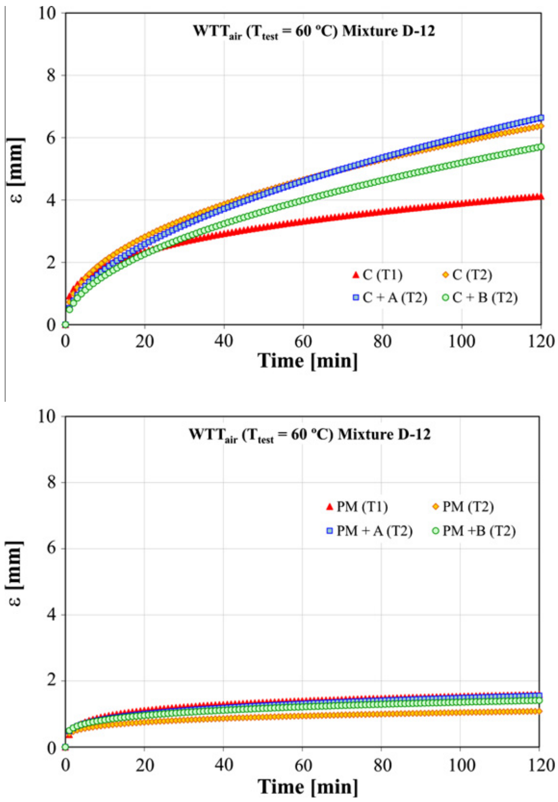

Fig. 8. Permanent deformation versus time in WTT_{air}; C asphalt (above), PM asphalt (below).

Fig. 9 shows the permanent deformations measured in the submerged Wheel Tracking Test (WTT_{water}). Changes in the performance of the mixtures could be seen as the temperature was reduced and as WMA additives were included. In first place, the temperature reduction produced an important decrease in the performance of WMAs made with both asphalts, C(T_2) and PM(T_2), when compared to the HMAs. The results show that the HMA with C asphalt is a mixture with poor moisture damage resistance and this is significantly diminished when mixed at reduced temperatures. The case of the PM mixture is worse, showing moisture damage (striping slope) when mixed at lower temperatures (WMA) which was not present in the HMA results.

The inclusion of additives (A and B) improves the performance of WMAs made with PM asphalt (Fig. 9 below), obtaining similar performance as those obtained for HMA (T_1 condition). In WMAs made with C asphalt, the addition of chemical tensoactive B to the binder improved the performance of the mixture, resulting in a similar performance as the HMAs. On the other hand, additive A did not cause any improvement in the performance of the WMAs.

The WTT_{water} performance tests showed similar results to those observed in rheological tests, especially in the MSCR test. This performance test appears to be an efficient tool to show the effects

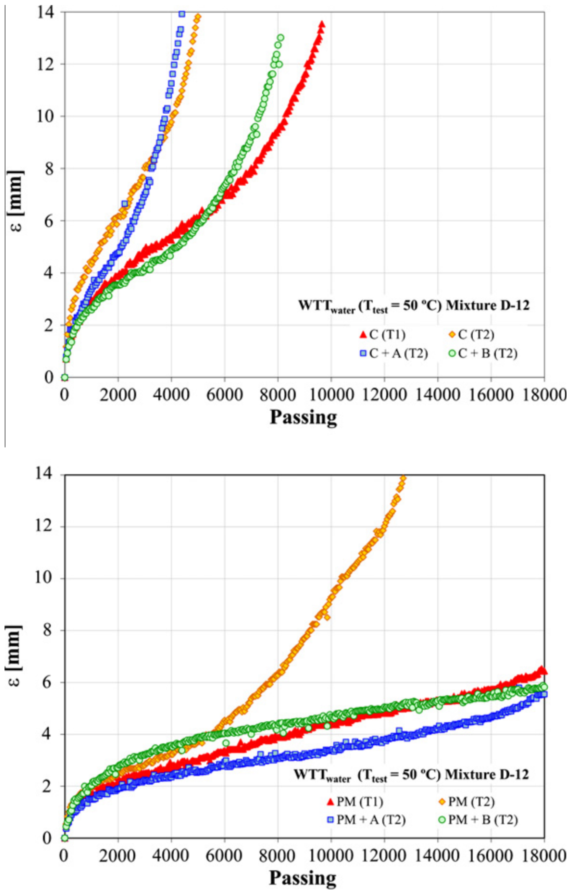

Fig. 9. Permanent deformation versus time in WTT_{water}; C asphalt (above), PM asphalt (below).

of reducing the mixing and placement temperatures and also shows the positive effect of WMA additives used.

4. Conclusions

The rheological properties of Conventional (C) and Polymer Modified (PM) asphalt, with and without additives, were studied after extracting samples from various Hot Mix Asphalts (HMAs) and Warm Mix Asphalts (WMAs). Additionally, the rutting resistance in wheel tracking (WTT_{air}) and moisture susceptibility in submerged wheel tracking (WTT_{water}) of these mixtures were evaluated. The main conclusions are indicated as follows.

The rheological properties of the C asphalt did not show significant changes, neither at lower mixing and compaction temperatures nor by the addition of the WMA additives used in any of the rheological tests performed.

The rheological properties observed in the PM asphalt without additives reveal worsening behavior when the manufacturing temperatures are lowered. These results can especially be seen in the Multiple Stress Creep Recovery (MSCR) test and imply an increase in rutting risks if used in mixtures. This is basically due to lower aging of the asphalt binder and must be take into account.

The C and PM asphalts without additives, extracted from WMAs, present higher accumulated strains in the MSCR than those corresponding to the HMAs. The former appear as asphalts prone to suffer rutting. In addition the elastic response of PM asphalts without additives is greatly debilitated at lower temperatures.

The additives incorporated into the WMAs improved the rheological behavior of the PM asphalt when compared to the control (WMA with pure asphalt). The elastic response of these PM asphalts with tensoactive additives is improved, as observed at low frequencies in the frequency sweep test. In addition, they show a significant reduction of the accumulated strain in the MSCR test, similar to the PM asphalt extracted from HMA.

The Wheel Tracking Test (WTT_{air}) for the C asphalt mixture revealed a worsening performance with temperature reduction. Additionally, incorporating additives into the C asphalt did not improve the rutting behavior of the WMAs.

In contrast to the rheological improvements observed in the PM asphalts with additives, the rutting performance tests with PM asphalts did not show significant changes among the studied cases, either by temperature reduction or with additives incorporated into the asphalt. A possible explanation could be found in the load applied during the test. This load could not produce enough shear stress in the modified asphalt to get the polymer chains to slip, which is necessary in order to observe any possible differences.

An important decrease in the performance of the mixtures made with both asphalts was observed during the submerged wheel tracking test as the mixing and compaction temperatures were reduced. Improvements in the performance of the PM asphalt were observed when both types of additive (A and B) were incorporated; whereas the C asphalt only showed improvement when additive B was integrated.

The submerged wheel tracking test appears as an efficient tool to show the effects of lowering the mixing and placement temperatures and also shows the positive effect of WMA additives.

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