Warm Mix Asphalt / Low temperature asphalt

Analysis of the long-term performance of sustainable asphalt mixtures under high-volume traffic

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Abstract

One of the current challenges in road pavements focuses on using more durable and sustainable materials by valorising wastes and carrying out more environmentally friendly constructive techniques. Additionally, these materials must present a good long-term performance to minimize the environmental, social and economic costs associated with the interventions for pavement conservation and rehabilitation. In this context, the objective of the present paper consists of evaluating the long-term performance of sustainable asphalt mixtures used as surface layer in roads with high traffic volumes. For this purpose, a complete study from laboratory phase to road trial sections has been carried out, analysing aspects such as material workability, resistance to ageing, to plastic deformations, and to fatigue and low temperature cracking, among others. The results have demonstrated that sustainable mixtures could offer similar or even better mechanical behaviour to that measured for traditional asphalt mixtures. Based on these considerations, the use of these materials could be an interesting solution to offer more durable asphalt pavements while reducing the environmental impacts.

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1. INTRODUCTION

The economic and social developments of recent decades have led to the need for more efficient and sustainable road infrastructures. In this regard, efforts have been focused on developing more durable materials that allow for increasing the service life of road pavements (by, for instance, optimizing economic investment while minimizing the social impact by reducing traffic interruption and pollution) [1]. Similarly, more sustainable products and construction processes are being developed to minimize the consumption of raw materials and energy while reducing the pollution that is generated during construction, maintenance, or renewal activities. Thus, one of the current challenges in the road pavement industry concerns the implementation of a circular economy in which materials are reused whilst applying more environmentally friendly construction techniques [2, 3].

Based on these considerations, and that in the following years maintenance works will be the most frequent task in roads and highways (as most of the road network has been already constructed), the Ministry of Public Works and Housing of Andalucía (Junta de Andalucía), the construction company Pérez Jiménez, and the Laboratory of Construction Engineering of the University of Granada, have carried out a research project focused on developing a high-performance sustainable asphalt mixture that could be used as an overlay in the rehabilitation of a road subjected to a high volume of traffic and/or severe climate conditions.

To meet this goal, it was decided to use crumb rubber from end-of-use tyres as bitumen modifier and to manufacture the asphalt mixture at a low temperature (by using additives to obtain warm mix asphalts) [4, 5]. The use of crumb rubber as a bitumen modifier is a sustainable solution to obtain high viscosity binders [6], which allows for higher dosages of bitumen in the asphalt mixtures and provide greater resistance to cracking [7, 8], whilst also reducing permanent deformations, binder ageing and susceptibility to in-service temperature fluctuations [9, 10]. In addition, the use of additives to reduce the manufacture temperature helps to minimize the negative impact of the high viscosity of the binder in the workability of the mixture (the high viscosity increases the risk of applying these materials in cold climates or in situations that involve long transport distances).

This paper presents the main findings from the laboratory phase of developing this mixture (binder and mixture level), its production in plant, and its application in the rehabilitation of a pavement section in the A-92 Highway (in the province of Granada, Spain).

2. METHODOLOGY

2.1. Materials

Given the need to obtain a high-performance and sustainable asphalt mixture (for the rehabilitation of deteriorated road pavements to improve safety and comfort), the type of mixture selected for this study was a BBTM 11 (EN 13108-2 [11]). This material has a high air void content (12-18%) and it is commonly used as surface layer with a thickness of around 3-4 cm, providing a significant reduction in noise while increasing vehicle-road adherence and reducing water splash.

For the design of this mixture, limestone aggregates were used for the fine fraction (0/2 mm), ophitic aggregates for the coarse fraction (6/12 mm), and cement as filler (all these materials have appropriate characteristics for the manufacturing of asphalt mixtures according to the Spanish Standard PG-3). For the binders, two types of high-performance bitumens were used: a crumb rubber (CR) modified bitumen (referred in this article as CRMB) and a SBS polymer modified bitumen (referred to as PMB) used as a reference to evaluate the effect of crumb rubber.

Using these materials, two different hot mix asphalt BBTM 11 were designed: CRMB-HMA and PMB-HMA (manufactured at 175 °C with the same mineral skeleton and binder content, but using CRMB and PMB, respectively). Additionally, a third asphalt mixture was developed using the same mineral skeleton and the CRMB, but its manufacturing temperature was reduced to obtain warm-mix asphalt (CRMB-WMA). For this purpose, a chemical additive was used during the manufacturing of the CRMB-WMA.

2.2. Testing plan

The testing plan followed in this study was divided into three main stages: (i) laboratory study (assessment of binders and design of the asphalt mixtures); (ii) analysis of mixture reproducibility in plant; (iii) application of the mixture in a trail section.

The first stage, conducted in laboratory, consisted of evaluating the characteristics of both types of binders as well as the properties of the designed mixtures. To assess the rheological behaviour of the CRMB in comparison with the traditional PMB, complex modulus and phase angle were measured at different temperatures (10, 20, 30, 40, 45, 52, 58, 64, 70, 80°C) and a range of frequencies (from 0.1 Hz to 20 Hz), using a Dynamic Shear Rheometer (DSR) through a shear loading at a constant amplitude of 0.1% strain. Similarly, this equipment was used to carry out the MSCRT (Multiple Stress Creep and Recovery Test) to evaluate the resistance of the binders to permanent deformations, along with their ability to recover the elastic strain under different levels of stress (0.1 and 3.2 kPa, applying loading cycles consisting of 1 second loads and a 9-second recovery phase) at various temperatures (45, 65, and 70°C).

Regarding the design of the PMB-HMA and CRMB-HMA hot mixtures, the water sensitivity test (EN 12697-12 [12]), wheel tracking test (EN 12697-22 [13]), bulk density test (EN 12697-6 [14]) and air void content test (EN 12697-8 [15]) were conducted to determine optimal binder content. Following this, and using the same design as that used for the CRMB-HMA, the workability of the CRMB-WMA at lower manufacturing temperatures (150 °C and 130 °C) was assessed in comparison with the conventional RMB-HMA (which was manufactured at 175 °C). For this purpose, the density of the mixtures as a function of the compaction energy at different temperatures was analysed (using a gyratory compactor), while evaluating the stiffness modulus at 20 °C (EN 12697-26 annex C [16]) and loss of particles at 25 °C (EN 12697-17 [17]) of the specimens obtained following the compaction process. Additionally, having selected the most appropriate manufacturing temperature of the RMB-WMA, its properties and mechanical performance were compared with the conventional hot mixtures PMB-HMA and RMB-HMA using the same tests described previously (water sensitivity, wheel- tracking, bulk density, and air void content).

In a second study stage, following the design and evaluation of the mixtures at laboratory level, a series of mixing processes were carried out in a real asphalt plant for each type of mixture (PMB-HMA, CRMB-HMA, and CRMB-WMA) to test their reproducibility. For this purpose, after their manufacture in the plant, the samples were taken to evaluate their mechanical response in the laboratory using the water sensitivity test (EN 12697-12 [12]) and wheel-tracking test (EN 12697-22 [13]). Additionally, to assess their performance under severe climatic actions, the particle loss test (EN 12697-17 [17]) was also carried out under the following conditions: the response to water action was tested by comparing the results at 25 °C after conditioning in hot water at 60 °C for 24 hours in comparison with those obtained when tested in dry conditions at 25 °C; the effect of temperature was tested by conducting the test at 10, 25, and 60 °C; and the effect of ageing was tested after conditioning at 165 °C for 12 hours. Furthermore, the bearing capacity of the mixtures manufactured in plant was assessed through the stiffness test (EN 12697-26 annex C [16]) at 5, 20, and 40 °C; cracking resistance was assessed at low temperatures using the TSRST (Thermal Stress Restrained Specimen Test, EN 12697-46 [18]) and fatigue cracking was evaluated using the UGR-FACT (University of Granada - Fatigue Asphalt Cracking Test) at 10, 20, and 30°C [19, 20].

In the third phase of the study, the mixtures were used in the rehabilitation of a section of pavement on the A-92 highway (in the province of Granada, Spain). The location of the trial section was selected according to environmental and technical criteria. Regarding the first of these criteria, the section was placed in a mountain pass in a natural park where the use of CRMB-WMA (manufactured with recycled materials and at low temperatures) would help to reduce the negative impacts caused by road construction (in addition the type of mixture used could allow for reducing noise levels due to traffic rolling). Regarding the second criterion, the mixtures were evaluated under extreme conditions on account of the high volume of traffic (more than 18,000 vehicles per day, with a daily average of more than 2,600 heavy vehicles) and the extreme climate conditions (the section was placed at more than 1,400 m above sea level, with the presence of snow during winter, and high temperatures and many hours of solar radiation during summer) (Figure 1). In addition, this section was ideal for evaluating the real workability of the CRMB-WMA mixture since the transit time from plant to work-site was approximately 1 hour.

Figure 1: View of the A-92 Highway, in winter (left) and summer (right) periods.

Finally, to complete the assessment of the performance of the CRMB-WMA in reference to the conventional high-performance mixtures (RMB-HMA and PMB-HMA), a series of cores were obtained from the pavements to evaluate their bulk density (EN 12697-6 [14]) following compaction of the sections, whilst the stiffness test (EN-12697-26 annex C [16]) and UGR-FACT [20] (at 20 °C) were also carried out to evaluate their mechanical response.

3. ANALYSIS OF THE RESULTS

Figures 2 and 3 show the results obtained in the rheological study for the PMB and CRMB. Both binders presented similar visco-elastic behaviour with comparable Black diagrams (Figure 2a). Nonetheless, it is seen that the CRMB led to a slightly more elastic performance, particularly at high temperatures where it presents a lower phase angle (which is observed clearly in isochrones from Figure 2b). Figure 3 demonstrates that the CRMB offered higher elastic recovery and higher resistance to permanent deformations (around 40% lower Jnr values than conventional PMB), regardless of the test temperature.

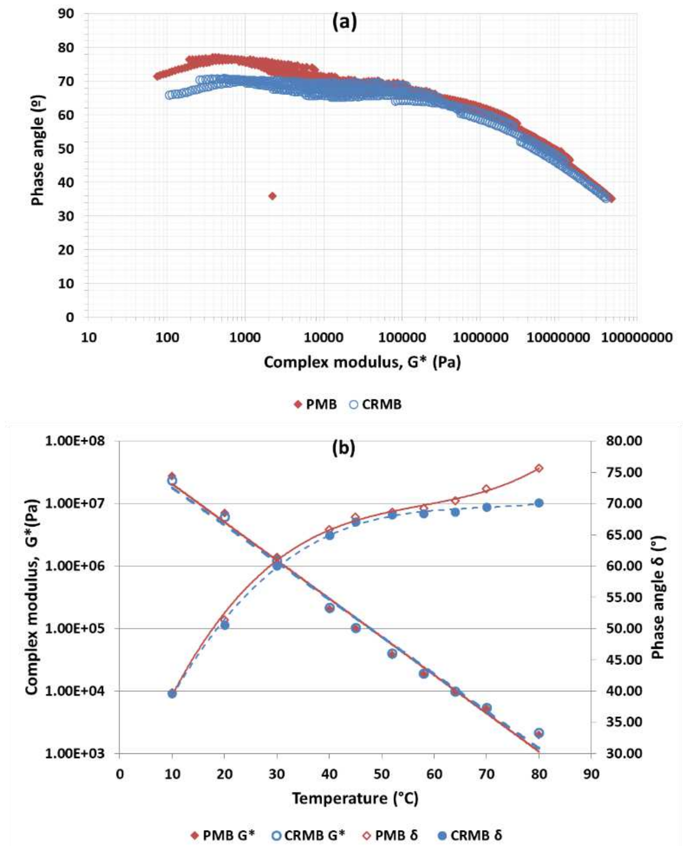

Figure 2: Results from the rheological study for the RMB and PMB: (a) Black diagram; (b) Isochrones at 5Hz.

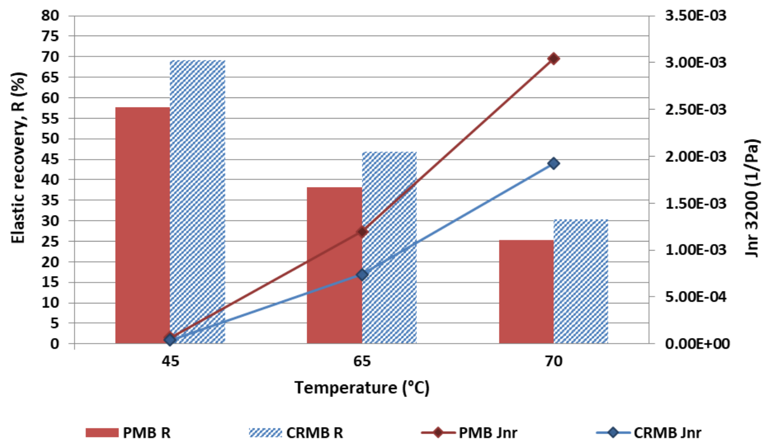

Figure 3: Results of the MSCRT at different temperatures.

Using both binders, two hot asphalt mixtures were designed (PMB-HMA and CRMB-HMA) with the same optimal binder content (4.75% over the total weight of the mixture in both cases). Based on the design of the CRMB-HMA, CRMB-WMA manufactured at lower temperature was designed (using the same binder content and different additives to improve the workability of the mixture). Figure 4 presents the results obtained from studying the workability of the CRMB-WMA manufactured at 150 °C in reference to the conventional CRMB-HMA manufactured at 175 °C. The results confirmed that the use of additives allows a workability similar to that offered by the hot mixture, in spite of the 25 °C of reduction in manufacture temperature. Figure 5 shows that using additives the cohesion of CRMB-WMA manufactured at 150 °C is comparable to the conventional CRMB-HMA at 175 °C, although the stiffness is reduced in a 45% due to the lower oxidation of the binder. Table 1 shows the main properties of the three mixtures (PMB-HMA, CRMB-HMA and RMB-WMA). It is observed that CRMB-WMA presents similar density to the traditional high-performance mixtures manufactured with PMB as well as comparable tensile strength, susceptibility to water action, and resistance to permanent deformations.

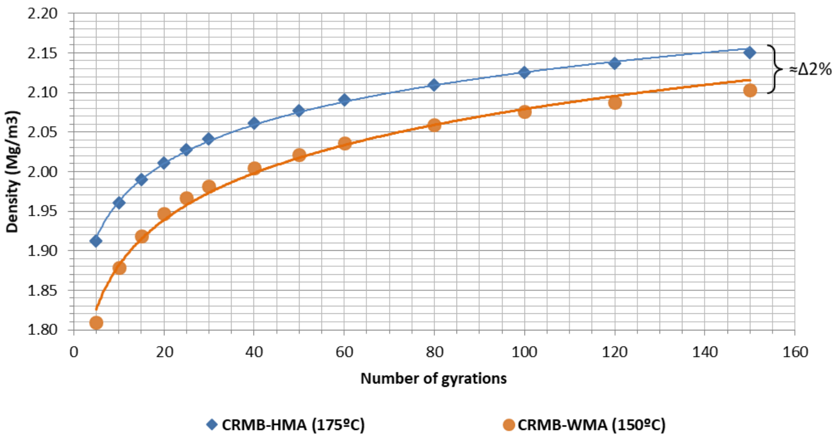

Figure 4: Curves of density versus energy of compaction at different temperatures.

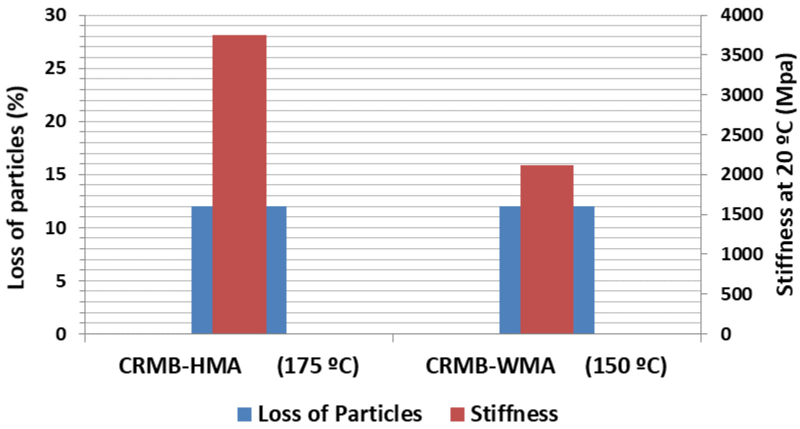

Figure 5: Results of the mechanical response of the CRMB mixtures (particle loss and stiffness at 20°C).

Table 1: Properties of the Mixtures Designed.

Characteristics	PMB-HMA	CRMB-HMA	CRMB-WMA
Bulk density (Mg/m^3), EN 12697-6	2.146	2.134	2.137
Air voids (%), EN 12697-8	16.5	18.0	17.9
Indirect tensile strength at 15 °C (kPa), EN 12697-23	1287	1161	1182
ITSR (%), EN 12697-12	91.9	90.7	94.0
WTS at 60 °C (mm/10^3 ciclos), EN 12697-22	0.056	0.054	0.068

After designing the mixtures in laboratory, they were manufactured in plant to analyse their reproducibility. Based on the results obtained in the previous stage, the manufacturing temperature used for the CRMB-WMA was set at 145 °C. Table 2 lists the data related to consumption and production measured during the manufacture of the mixtures

(CRMB-HMA and CRMB-WMA). Reducing the manufacturing temperature of the CRMB-WMA mixture led to an approximate 20-30% reduction in fuel consumption in the plant, which could partially compensate for the cost overrun associated with the use of the additives (the final extra cost estimated for the CRMB-WMA was lower than 0.6-0.7% in reference to the conventional HMA). Table 3 shows the mechanical performance of the mixtures manufactured in the asphalt plant. It is proven the reproducibility of them (obtaining similar results than in the mixtures manufactured in laboratory), and again presenting CRMB-WMA comparable results to those measured for the conventional hot mixtures with both types of high-performance bitumens (PMB-HMA and CRMB-HMA).

Table 1: Data from the production in plant of the mixtures manufactured with the CRMB.

Characteristics	CRMB-HMA	CRMB-WMA
Aggregates temperature (°C)	172-178	146-148
Flame of the drum dryer (%)	72-81	37-59
Fuel consumption (kg/tn)	6.8-7.2	5.4-5.9

Table 3: Results of the water sensitivity test and wheel-tracking tests for the mixtures manufactured in plant.

Characteristics	PMB-HMA	CRMB-HMA	CRMB-WMA
Indirect tensile strength at 15 °C (kPa), EN 12697-23	1,111	1,040	1,108
ITSR (%), EN 12697-12	90.5	90.9	90.1
WTS at 60 °C (mm/10^3 ciclos), EN 12697-22	0.048	0.066	0.056

Figures 6 displays the results obtained in the study of cohesion of the mixtures manufactured in plant at different temperatures. The results show that a slight decrease in particle loss could be obtained when using the CRMB at any temperature, while WMA presents similar behaviour than HMA despite the decrease in manufacturing temperature. In addition, WMA mixture shows similar susceptibility to the action of water (around 5-7%) and ageing (between 1-9%) than HMA (Figure 7). Figure 8 shows the stiffness of the mixtures at different testing temperatures (5, 20, and 40°C). Again it appears that the mechanical behaviour of the CRMB-WMA was similar to that shown for the CRMB-HMA, and both present values close to those measured for the mixture produced with the traditional polymer modified binder (PMB-HMA).

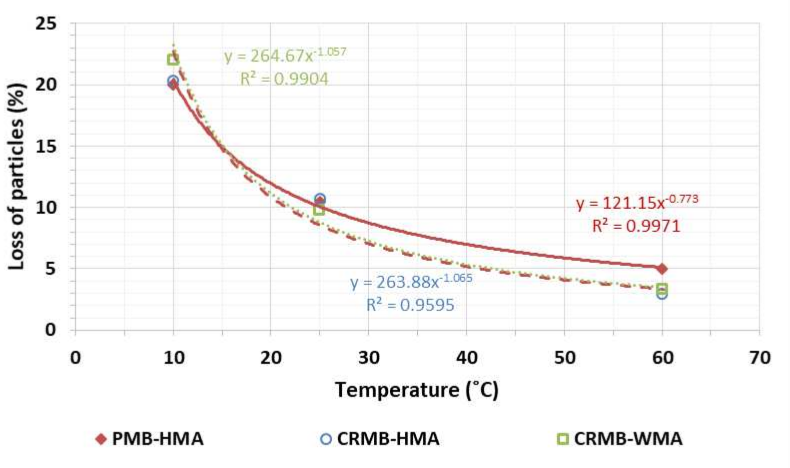

Figure 6: Results of particle loss at different temperatures.

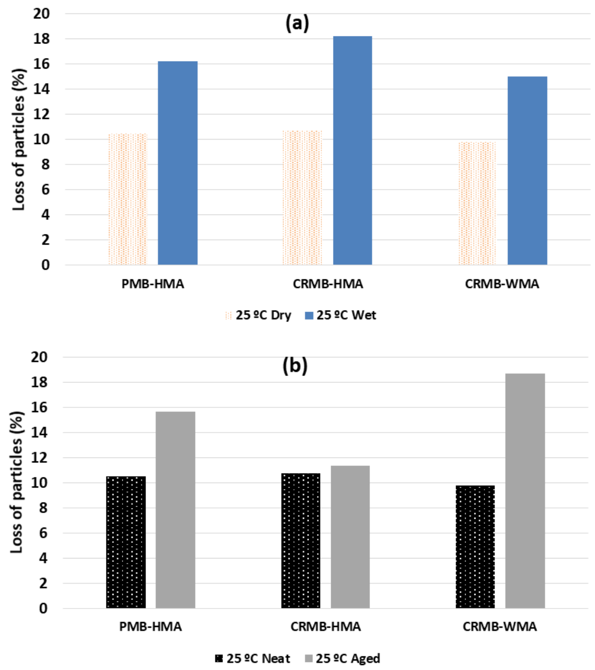

Figure 7: Particle loss for the mixtures following (a) water action and (b) ageing simulation.

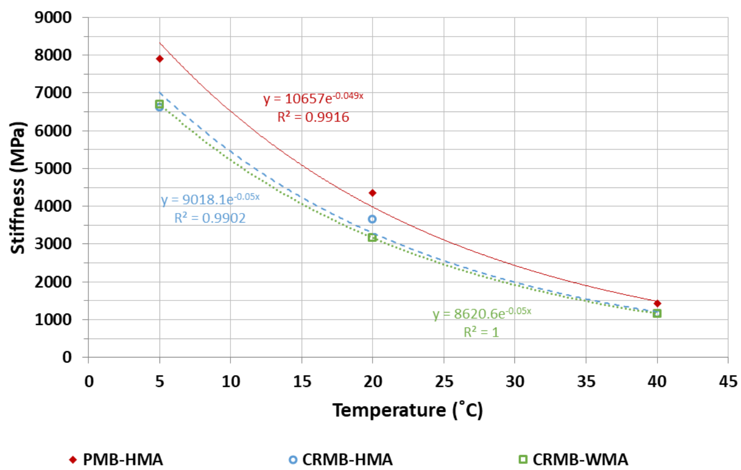

Figure 8: Stiffness at different temperatures for the mixtures manufactured in plant.

To analyse the resistance to cracking of the mixtures, Figure 9 displays the results of TSRST (which measures the development of the force acting on the specimen when decreasing the temperature up to material failure) and UGR-FACT (through the number of cycles to failure at different testing temperatures). The results show that the three asphalt mixtures presented comparable performance in terms of resistance to cracking. Nonetheless, it can be seen that, in general, the mixtures manufactured with CRMB showed slightly superior performance than the traditional PMB-HMA, regardless of the manufacturing temperature of the CRMB mixtures (showing higher resistance to cracking and lower temperature to failure; a slight increase in the number of cycles needed to produce fatigue cracking).

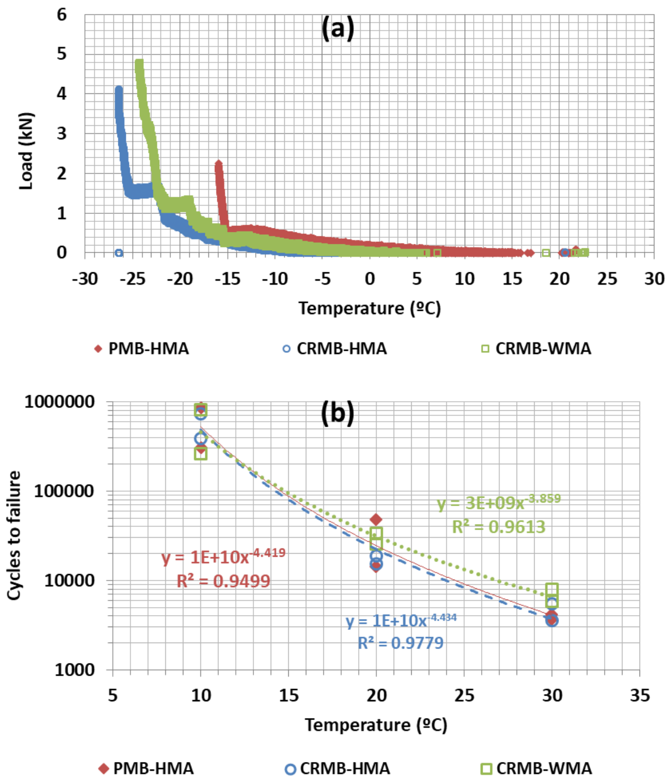

Figure 9: Results of TSRST (a) and UGR-FACT (b) for the different mixtures.

After verify the adequate performance of the CRMB-WMA manufactured in plant, some road sections were constructed on the A-92 highway (Granada, Spain), by using the equipment and machinery routinely employed with traditional mixtures. Figure 10 shows the temperature of spreading in the site and the final result of the CRMB-WMA after compaction. Figure 11 presents the density and stiffness at 20 °C for the cores extracted at the different kilometric points of the road section after construction. The density values for the mixtures were even slightly higher than those measured in laboratory (indicating adequate compaction of the materials), whilst the CRMB-WMA showed similar density and stiffness values to those of the reference mixtures, which confirms the satisfactory performance of this mixture in spite of the lower manufacturing temperature. Figure 12 displays the average results of failure cycle obtained in UGR-FACT at 20 °C for the various cores tested from each type of mixture. Results show that the fatigue life measured for the cores was slightly lower than that measured for the specimens manufactured in laboratory, regardless of the type of mixture. Nonetheless, the results again show that all the mixtures presented comparable results, with the CRMB-WMA achieving an even longer fatigue life than the conventional HMA, and thus providing evidence for the good response of this material in the long-term.

Figure 10: Images from the spreading and compaction of the CRMB-WMA.

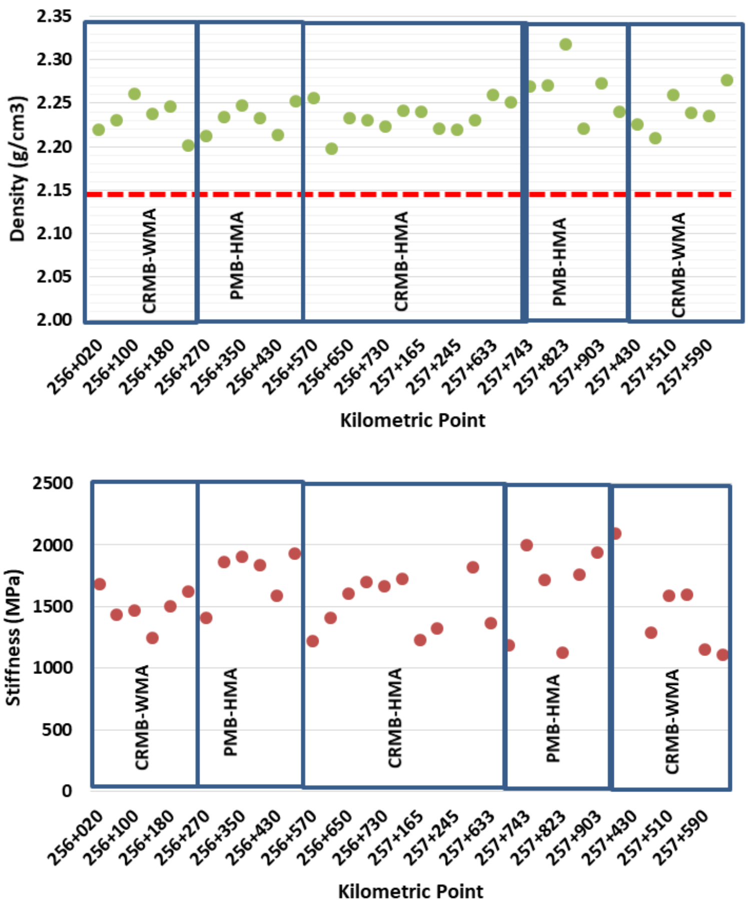

Figure 11: Results of density and stiffness (20°C) for the cores obtained from different points of each road section with the different mixtures analysed.

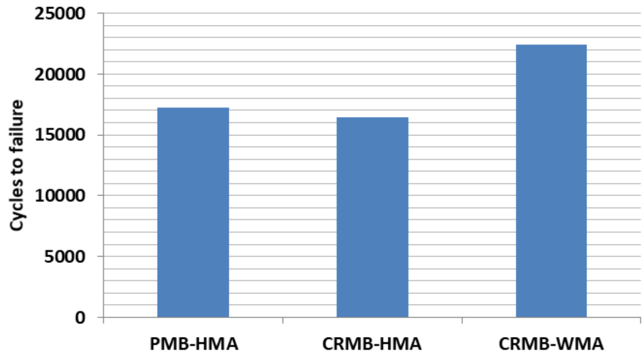

Figure 12: Average results of UGR-FACT for the cores obtained from road sections.

4. CONCLUSIONS

This paper presents the results obtained in a research project focused on developing sustainable high-performance asphalt mixtures for use in the construction/rehabilitation of road pavements subjected to high traffic volumes and severe climate conditions. For this purpose, warm mix asphalt manufactured with crumb rubber modified bitumen was designed and its mechanical behaviour was compared with two reference hot mix asphalts (one manufactured with the same crumb rubber modified bitumen and the other with a SBS polymer modified bitumen). The project was divided into three different stages: the design in laboratory, the study of reproducibility in a real asphalt plant, and application in a road section of a highway. On the basis of the results obtained, the following conclusions can be drawn:

- The rheological performance of the crumb rubber modified bitumen at different frequencies and temperatures was similar to that of a conventional SBS polymer Modified Binder, presenting an even more elastic behaviour at high temperatures, which could improve its resistance to permanent deformations.

- The laboratory design of the mixtures revealed that the high-performance sustainable mixture (manufactured with crumb rubber modified bitumen at 30 °C lower than the hot conventional mixtures) led to a mechanical performance comparable to that recorded for traditional high-performance hot mixtures.

- The study of reproducibility in plant demonstrated that the high- performance sustainable mixture can be manufactured in a conventional asphalt plant and spread with conventional equipment, achieving a material with a similar mechanical response to that of the reference hot mixtures (even higher in terms of resistance to fatigue and thermal cracking, particle loss, and permanent deformations). In addition, the cost overrun associated with the use of additives for lowering the temperature can be partially compensated by the reduced energy consumption in plant.

- From the trial sections constructed, it can be concluded that in spite of the long transport distance involved, the spreading and compaction of the high- performance sustainable mixture (CRMB-WMA) was similar to that of the reference mixtures, offering adequate workability. In addition, the cores obtained from the pavement showed comparable performance of all mixtures, regardless of the type of bitumen and manufacturing temperature.

Taken together, these findings suggest that sustainable high-performance mixtures could offer an interesting alternative to conventional hot mixtures for improving the durability of road pavements whilst reducing the environmental impacts associated with their construction/rehabilitation.

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