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Viability of producing sustainable asphalt mixtures with crumb rubber bitumen at reduced temperatures

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HIGHLIGHTS

- Asphalt mixtures with 20% crumb rubber are manufactured at 150 and 130 °C.
- High penetration bitumen and two additives are used to reduce viscosity.
- Asphalt mixtures are designed and mechanically characterised.
- Rubberised asphalt mixtures could be adequately manufactured at 130 °C.
- Their mechanical performance was not adversely affected.

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ABSTRACT

The construction and maintenance of road pavements need to be undertaken to ensure proper economic and social growth. Considering the high environmental impact that the production of asphalt mixtures for road pavements entails, in terms of energy consumption and greenhouse gas (GHG) emissions, these operations must follow the global transition towards more sustainable development practices. In response to this, previous research has been focused on the development of manufacturing low temperature asphalt mixtures and the use of recycled modifiers such as tire crumb rubber to improve their durability. However, the use of high dosages of the latter reduces mixture workability, thus requiring high manufacturing temperatures to reduce the viscosity of the binder, and therefore limiting the advancement towards more sustainable mixtures. In this regard, further knowledge is needed on this topic to promote the combination of such techniques to maximise their advantages. This study aims to check the viability of producing asphalt mixtures with high crumb rubber contents at reduced temperatures, testing their workability, stiffness, cohesion, resistance to permanent deformations and resistance to moisture damage. Results show that it is possible to manufacture viable, warm, rubberised asphalt mixtures at 150 °C using a high penetration bitumen and reduce this temperature to 130 °C (45 °C less than conventional rubberised asphalt mixtures) by including warm additives, without compromising their mechanical performance.

1. Introduction

The optimal performance of road transportation networks is a key factor for the economic and social development of any country. Therefore, the construction and maintenance of road pavements need to be undertaken in accordance with the required sustainability targets as a matter of urgency [20]. One of the main concerns regarding these activities is the high environmental impact incurred during the production of asphalt mixtures for road pavements, in terms of energy consumption and greenhouse gas (GHG) emissions [4]. To tackle this issue, the reduction of the manufacturing temperature of asphalt mixtures has been a hot topic in pavement engineering research for decades and has been proven to efficiently decrease such environmental impacts [44,46,53], as well as have associated social benefits, such as reducing health and safety risks for workers [43]. Depending on the manufacturing temperatures, asphalt mixtures are classified as hot mix asphalt

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(>150 °C), warm mix asphalt (100–140 °C), half-warm mix asphalt (60–100 °C) and cold mix asphalt (0–40 °C). Despite their advantages, the use of lower temperature asphalt mixtures is limited in high traffic volume road pavements as there are some concerns related to their mechanical performance in comparison to hot mix asphalt [43,50], since their application should not comprise the performance of the road.

In this regard, the use of bitumen modifiers helps improve the performance of asphalt mixtures, and if these materials come from end-of-life products, their utilisation also represents a sustainable practice for promoting recycling, reducing landfill and reducing costs. One of these materials is rubber from end-of-use tires, which is currently highly valued in transport infrastructure engineering [31,47]. Tire crumb rubber has already been proven to enhance the mechanical performance of asphalt mixtures in terms of resistance to fatigue, rutting and thermal susceptibility, increasing therefore the durability of the pavement [9,22,26,37,33,27,28]. In addition, it improves the skid resistance, reduces tire-pavement interaction noise due to traffic [45] and is being used in hot recycling of asphalt mixtures [7,10,57]. Furthermore, several studies have demonstrated the importance of the modifier content in the binder [17,18,21,32] and that the advantages of using this modifier increase when its content increases in asphalt mixtures [35,19,39].

Nevertheless, the introduction of tire crumb rubber in asphalt mixtures in high contents does also significantly increase the viscosity of the original bitumen and thus requires the use of high manufacturing temperatures (>175 °C) to ensure the correct coating of the aggregates, and adequate workability and cohesion of the final compacted asphalt mixture [38]. In this regard, if the advantages of high tire crumb rubber content and low manufacturing temperatures are to be combined to produce more sustainable asphalt mixtures, further modifications, such as the use of warm additives, need to be introduced in their composition [50,51].

Researchers have investigated this topic in the last decade mostly focusing on the binder's properties, due to its significant impact on the asphalt mixture's performance [30,32,50]. Warm mix additives can be classified as organic (wax-based) or chemical [43], and in general they all produce the desired effect on the modified binder with tire crumb rubber; reducing its viscosity and complex modulus at high temperatures to allow the reduction in manufacturing temperatures [2,25,42,56,40]. However, the mechanical response of the tire crumb rubber modified binder with warm mix additives has been found to be highly dependent on the type of additive used, and therefore it is not possible to draw clear conclusions when needing to select additives [2,49,24,40,23,54]. In addition, several studies have shown that warm rubberised asphalt mixtures exhibit equivalent or improved mechanical performance when compared with hot rubberised asphalt [36,27,28,41,52,55,58]. Nevertheless, in these studies, the manufacturing temperatures were reduced only to 145 °C, which is in the limit between hot and warm mix asphalt. Hence, more research is needed to provide a higher confidence in these type of asphalt mixtures.

Therefore, the aim of this study is to advance the development of warm rubberised asphalt mixtures, via the use of a high tire crumb rubber content and lower manufacturing temperatures, in order to achieve more sustainable asphalt mixtures. For this purpose, warm rubberised asphalt mixtures were produced at 150 °C and 130 °C using a high penetration bitumen (to allow the reduction in manufacturing temperatures), a 20% tire crumb rubber content (in weight of bitumen) and two warm additives. To quantify the viability of the performance of the binders and mixtures tested, they were characterised and compared to conventional mixtures.

2. Materials and methods

2.1. Binders

For the purpose of this investigation, four binders were studied: one control binder and three tire crumb rubber modified binders (one standard, and two with additives). A styrene–butadienestyrene polymer modified binder (PMB 45/80-65), commonly used for asphalt mixtures in wearing courses, was selected as the control binder. This PMB has a penetration between 45 and 80 mm^{-1} and a softening point higher than 65 °C. A high penetration grade bitumen (70/100) was chosen to be modified with 20% of tire crumb rubber, per bitumen mass, which is defined as a high tire rubber content according to Spanish standards [6] and its use results in a high-viscosity binder. This combination was chosen in order to balance the increase in viscosity (due to the presence of tire crumb rubber), with the low viscosity of the high penetration bitumen and target low manufacturing temperatures. The tire crumb rubber properties are shown in Table 1. It has to be noticed that 20% tire crumb rubber content is used for hot mix asphalt applications, while the challenge of this investigation is to use it at reduced manufacturing temperatures, since it could be an obstacle to obtain the desired density and mechanical performance of the asphalt mixture. The Rubber Modified Binder (RMB) was manufactured by heating the bitumen up to a stable temperature of 165 °C, and then blended with the tire crumb rubber in a high-shear device at 3500 rpm for 60 min [3,5].

Two warm mix additives were investigated, namely: a wax (W) (Sasobit®) and a surfactant (S) (Zycotherm®). Waxes are organic additives completely soluble in bitumen at temperatures higher than 120 °C. These additives reduce bitumen viscosity at high temperatures, allowing therefore the reduction of the manufacturing temperatures of asphalt mixtures, and improve their resistance to rutting due to their complete crystallisation at 65 °C. Surfactants are able to reduce the surface tension of bitumen by improving the aggregates' coating, adhesion and cohesion properties in asphalt mixtures [8]. Both additives were blended with the RMB to produce RMB-W (RMB + 3% W) and RMB-S (RMB + 0.05% S) respectively, using the dosage recommended by the additive suppliers. To manufacture RMB-W and RMB-S, the previously produced RMB was heated up to 165 °C and then blended with the additives at 300 rpm for another 60 min.

2.2. Asphalt mixtures

Asphalt mixtures were manufactured using the PMB, RMB, RMB-W and RMB-S, separately, at three different temperatures: 175, 150 and 130 °C. The asphalt mixtures were designed for "BBTM 11A" wearing courses, which stands for "Beton Bitumineux Tres Minces" and are gap-graded asphalt mixtures for thin surface courses with maximum aggregate size of 11 mm. The BBTM 11A with PMB was manufactured at 175 °C, the mixture with RMB was manufactured at the three aforementioned temperatures, and the BBTM11A with RMB-W and RMB-S were manufactured at 150 °C and 130 °C, given that the purpose of this investigation is to study their performance at low manufacturing temperatures. For the mineral skeleton of the mixture, limestone aggregates were used for the fine fraction (0/6 mm), ophitic aggregates were used for the coarse fraction (6/12 mm) and cement was used as filler. The gradation of the BBTM 11A asphalt mixtures is shown in Fig. 1. The binder content chosen was 5% of the total weight of the asphalt mixture. Aggregate gradation and binder content were fixed for all of the asphalt mixtures, so that the binder type and manufacturing temperature were the only variables in the study.

Table 1
Properties and composition of the tire crumb rubber used.

Properties					
Density (g/cm^3)	1.17				
Color	Black				
Particle morphology	Irregular				
Moisture content (%)	<0.75				
Textile content (%)	<0.5				
Metal content (%)	<0.1				
Grain size					
Sieve (mm)	0.6	0.5	0.25	0.125	0.063
% material passing	100	74	19	2	0
Composition	Min. (%)			Max. (%)	
Cetonic extract	7.5			17.5	
Natural rubber (NR)	21.0			42.0	
Polymers (NR/SBR)	50.0			55.0	
Sulfur	–			5.0	
Carbon black	20.0			38.0	
Ash	–			18.5	

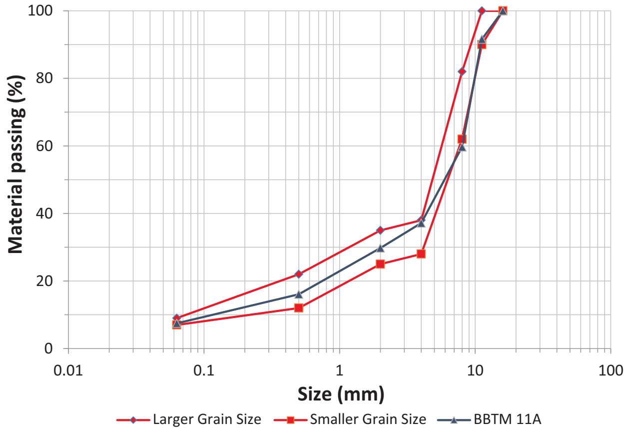

Fig. 1. BBTM11A asphalt mixture gradation.

Table 2
Testing programme summary.

Phase I	Binder	Tests	Property
Binder rheological characterisation	PMB RMB RMB – W RMB – S	Frequency and temperature sweeps	Consistency and viscoelasticity
Phase II	**Asphalt mixture**	**Tests**	**Property**
Warm rubberised asphalt mixture design (selection of the type of additive and manufacturing temperature)	BBTM 11A PMB @ 175 °C BBTM 11A RMB @ 175 °C BBTM 11A RMB @ 150 °C BBTM 11A RMB @ 130 °C BBTM 11A RMB-W @ 150 °C BBTM 11A RMB-W @ 130 °C BBTM 11A RMB-S @ 150 °C BBTM 11A RMB-S @ 130 °C	Compactability Stiffness Triaxial Particle loss	Workability Bearing capacity Permanent deformation Cohesion
Phase III	**Asphalt mixture**	**Tests**	**Property**
Warm rubberised asphalt mixture complete mechanical characterisation	BBTM 11A RMB @ 175 °C BBTM11A RMB – additive? temperature? (to be selected in Phase II)	Wheel track Indirect Tensile Strength dry and wet	Rutting resistance Water sensitivity

2.3. Testing method

The testing method was divided into three phases: (1) the rheological characterisation of the binders; (2) the design of the warm rubberised asphalt mixtures with high tire crumb rubber content (selection of the type of additive and manufacturing temperature); (3) the complete mechanical characterisation of the warm rubberised asphalt mixtures with high tire crumb rubber contents. The first phase is dedicated to the study of binders to understand the performance of the highly modified high penetration bitumen with tire crumb rubber and the additives. The purpose of the second phase is to analyse the influence of the additives and manufacturing temperatures, to then select the best combination to produce warm rubberised asphalt mixtures with high tire crumb rubber content. In the third phase, the hot rubberised asphalt mixtures are further characterised and compared to finalise their mechanical performance classification according to Spanish standards. Table 2 shows a summary of the testing programme. The precise testing carried out in each phase is described in details in the sections below.

2.3.1. Binder rheological characterisation

All binders were rheologically characterised using a Dynamic Shear Rheometer (DSR) to perform frequency sweeps (0.1 Hz to 20 Hz) at different temperatures (10 °C – 80 °C). The tests were carried out from 10 °C to 45 °C using the 8 mm parallel-plate geometry and from 30 °C to 80 °C using the 25 mm parallel-plate geometry. The complex modulus and phase angle were measured and displayed in Black diagrams for the analysis of the different rheological responses. The Black diagrams were used to select the data for the overlapping temperatures tested using with both geometries [1].

2.3.2. Design of the warm rubberised asphalt mixture with high tire crumb rubber content (selection of the type of additive and manufacturing temperature)

The four BBTM11A asphalt mixtures were manufactured at different temperatures and mechanically characterised to determine their workability, stiffness, resistance to permanent deformations and cohesion properties.

The workability was monitored during the manufacturing of the asphalt mixtures specimens by mean of the gyratory compactor, recording their density and fixing the compaction energy at 150 gyros.

The stiffness modulus was determined following the standard EN 12697-26 Annex C (2018) [15]. In this test, 15 loading pulses are applied to a cylindrical specimen (100 mm of diameter and 60 mm of height) in two perpendicular diameters. The first 10 pulses are used to condition the specimen and the 5 next pulses are used to measure the stiffness modulus. For each specimen, the stiffness modulus is the average of the measurement of the two diameters. For the asphalt mixture, the stiffness modulus is the average of the three specimens.

The resistance to permanent deformation was characterised through triaxial tests (EN 12697-25, Method B 2016) [14]. In the triaxial test, a cylindrical specimen is subjected to a confinement load (120 kPa) and an axial load (300 kPa) at a frequency of 3 Hz for 10,000 cycles. In this test, the creep ratio and the permanent deformation are obtained as the average of the results of three specimens.

The cohesion properties of the asphalt mixtures were studied using the particles loss test [12]. In this test, a cylindrical specimen conditioned at 25 °C is introduced in Los Angeles device applying 300 gyrations. The mass of the specimen is measured before and after the test and the particle loss is obtained as a measure of the cohesion of the asphalt mixture (from the average particle loss of three specimens).

2.3.3. Complete mechanical characterisation of the warm rubberised asphalt mixtures with high tire crumb rubber content

In order to finalise their mechanical performance characterisation according to Spanish standards [29], the water sensitivity and rutting resistance of the BBTM11A with RMB manufactured at 175 °C and a warm mix asphalt, which was selected depending on the performance criteria in the previous phase. The water sensitivity of the two asphalt mixtures was characterised according to EN 12697-12 (2018) [11]. In this standard, the water sensitivity is determined by the Indirect Tensile Strength Ratio (ITSR), calculated as the ratio between the Indirect Tensile Strength of a set of three dry specimens (ITSd) and the Indirect Tensile Strength of a set of three specimens after wet conditioning (ITSw). The dry specimens are conditioned at room temperature (20 ± 5 °C), while the wet specimens are conditioned at 40 °C for 72 h after being subjected to vacuum at 6.7 ± 0.3 kPa. The six specimens are then tested to determine their ITS at 15 °C after being conditioned for 2 h.

Finally, the resistance to permanent deformations of the asphalt mixtures was further characterised using the wheel tracking test [13]. In this test, a slab specimen (408 mm × 256 mm × 60 mm) is subjected to a 700 N passing wheel load for 10,000 cycles at 60 °C. The permanent deformation is measured for each cycle and plotted versus the cycle number. The result of the test is given by rut depth (RD) and wheel track slope (WTS, mm/10^3 loading cycles), measured during the last 5,000 cycles, from the average of two specimens.

3. Results and discussion

3.1. Binder rheological characterisation

Fig. 2 shows the Black diagram of the PMB, RMB, RMB-W and RMB-S obtained from the frequency and temperature sweeps. This diagram displays the norm of the complex modulus versus the phase angle of a material for all the temperatures and frequencies tested, and is considered as the fingerprint of its viscoelastic behaviour. Those materials exhibiting a highly viscous behaviour are located at the bottom right corner of the graph, while those with a high elastic component are located in the top left corner. In the Black diagram, a conventional bitumen shows its thermorheologically simple behaviour by having a smooth and unique curve over all the range of temperatures and frequencies [1]. As a first observation, in Fig. 2, all RMBs shows a clear thermoreologically complex behaviour, as well as the PMB, since their curves are not unique nor smooth. Secondly, compared to the PMB, regardless of having a high penetration bitumen as base (70/100 penetration grade), the high tire crumb rubber content allows the RMBs to reach similar complex modulus to the PMB (slightly lower in the case of RMB-S). Finally, the three RMBs exhibit an increase of the elastic component at high temperatures (decrease of phase angle), which is more significant in the case of RMB and RMB-W and greater than that of the PMB, which is a sign of the predominance of the rubber's behaviour at such temperatures [48].

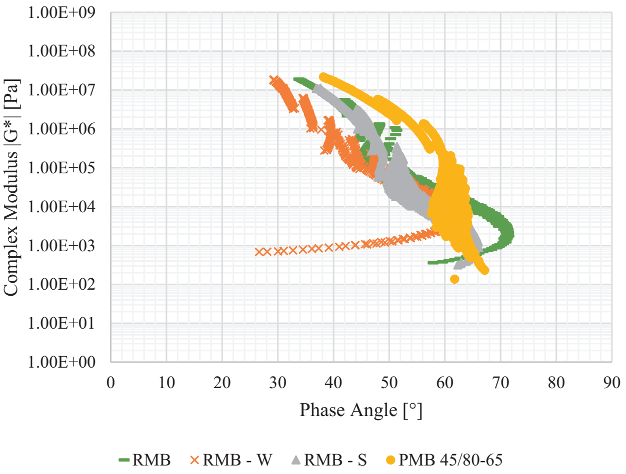

Fig. 2. Bitumen and binders' Black diagram.

Analysing the influence of the wax and surfactant, RMB-W was found to have a similar viscoelastic response to RMB, but with an increased elastic component (lower phase angles) compared to RMB, especially at high temperatures when the wax is more active, and which may increase the resistance to permanent deformations with respect to that of RMB. In addition, the wax modification increases the consistency of the binder showing the highest complex modulus among the three RMBs. On the other hand, RMB-S shows a more elastic response and lower complex modulus compared to RMB. These results are in accordance to those presented by other authors for the modification of a 50/70 bitumen using tire crumb rubber and waxes [16].

3.2. Design of the warm rubberised asphalt mixture with high tire crumb rubber content (selection of the type of additive and manufacturing temperature)

Table 3 shows the final density of the manufactured asphalt mixtures after 150 gyrations. It can be observed that the compactability of the asphalt mixtures increases with the addition of the wax and surfactant in comparison to the reference asphalt mixtures manufactured at 130 °C. This fact is particularly noticeable for the BBTM 11A with RMB-W, which reaches the same density values as the BBTM 11A with PMB and higher density than the BBTM 11A with RMB. These results reflect the improvement in workability that the additives provide to the highly modified crumb rubber asphalt mixtures, allowing a reduction in manufacturing temperatures up to 45 °C.

Table 3
Density of the manufactured asphalt mixtures and comparison of rubberised asphalt mixtures to reference.

Asphalt mixture	Density [Mg/m^3]	% Density achieved compared to BBTM 11A PMB
BBTM 11A PMB @ 175 °C	2.47	–
BBTM 11A RMB @ 175 °C	2.44	98,8%
BBTM 11A RMB @ 150 °C	2.43	98,4%
BBTM 11A RMB @ 130 °C	2.41	97,6%
BBTM 11A RMB-W @ 150 °C	2.42	98,0%
BBTM 11A RMB-W @ 130 °C	2.47	100,0%
BBTM 11A RMB-S @ 150 °C	2.43	98,4%
BBTM 11A RMB-S @ 130 °C	2.42	98,0%

Fig. 3 displays the results of the stiffness modulus according to EN 12697-26 Annex C (2018) measured at 5 °C, 20 °C and 40 °C. The first observation in Fig. 3 is that despite using a high penetration binder (70/100) as base for the modification, the high tire crumb rubber content allows obtaining high stiffness values for the asphalt mixtures compared to the one containing PMB, which is in accordance to the results of the rheology of the binders showed in Phase I of the investigation.

In terms of reduced manufacturing temperatures, Fig. 3 reveals a stiffness modulus reduction for each asphalt mixture, which is in agreement to previous research for warm rubberised asphalt mixtures [41]. Nevertheless, regarding the influence of the additive, the use of the wax at 150 °C and 130 °C provides a higher stiffness modulus in comparison to the hot rubberised asphalt mixture at any manufacturing temperature, which does not occur using the surfactant. This effect of the wax was observed by [55], but with manufacturing temperatures going down only to 160 °C and using a 50/70 penetration grade bitumen as base for crumb rubber modification. This highlights the benefits in the presented investigation of using (1) a high penetration grade binder (70/100) to further reduce manufacturing temperatures and (2) a high rubber content to maintain the increase in stiffness. This result implies that the bearing capacity of the warm rubberised asphalt mixtures with wax is not compromised by the reduction of the manufacturing temperature.

Fig. 4 shows the results of the creep ratio and permanent deformation obtained in the triaxial test according to 12697-25 (2016) performed at 60 °C. In general, the presence of rubber provides high resistance to permanent deformations regardless of the use of additives and manufacturing temperature [34]. Moreover, the results evidence that, despite the fact that a decrease in manufacturing temperature should imply an increase in permanent deformation, the use of additives reduces this effect; in particular for asphalt mixtures manufactured at 130 °C, where the surfactant was found to be more efficient in this case. This result highlights those seen in the rheology of the binders (Fig. 2), having a high elastic behaviour at high temperatures, compensating the possible detrimental effect of the low manufacturing temperature.

Fig. 5 presents the particle loss of the asphalt mixtures. All the rubberised asphalt mixtures present a higher particle loss than the control mixture, hence showing a reduced resistance to abrasion. However, it is important to highlight that a particle loss lower than 20% is considered as an adequate performance of asphalt mixtures for wearing courses [29]. In terms of manufacturing temperature, the rubberised asphalt mixtures without additives (mixtures with RMB) show an increase in the particle loss as the manufacturing temperature decreases, therefore displaying a reduced cohesion. Regarding the influence of additives, Fig. 6 shows that they improve the cohesion of the warm rubberised asphalt mixtures, especially at 130 °C and when using the wax.

In the light of the results obtained, it can be said that the combination of a high penetration binder with a high tire crumb rubber content provides satisfactory results at 150 °C, due to having equivalent results to the mixture manufactured at 175 °C. However, if the manufacturing temperature is to be reduced to 130 °C, the use of additives becomes necessary in order to obtain the desired mixture performance. In this regard, among the two additives used in this study, the warm rubberised asphalt mixture manufactured using RMB-W at 130 °C exhibited the best performance in terms of workability, stiffness, permanent deformation and cohesion. Therefore, this asphalt mixture and the BBTM 11A with RMB manufactured at 175 °C (reference hot rubberised asphalt mixture), were selected for mechanical characterisation according to Spanish standards [29].

3.3. Warm rubberised asphalt mixture with high tire crumb rubber content complete mechanical characterisation

Fig. 6 displays the results of the Indirect Tensile Strength (ITS) of the dry and wet specimens and their Indirect Tensile Strength

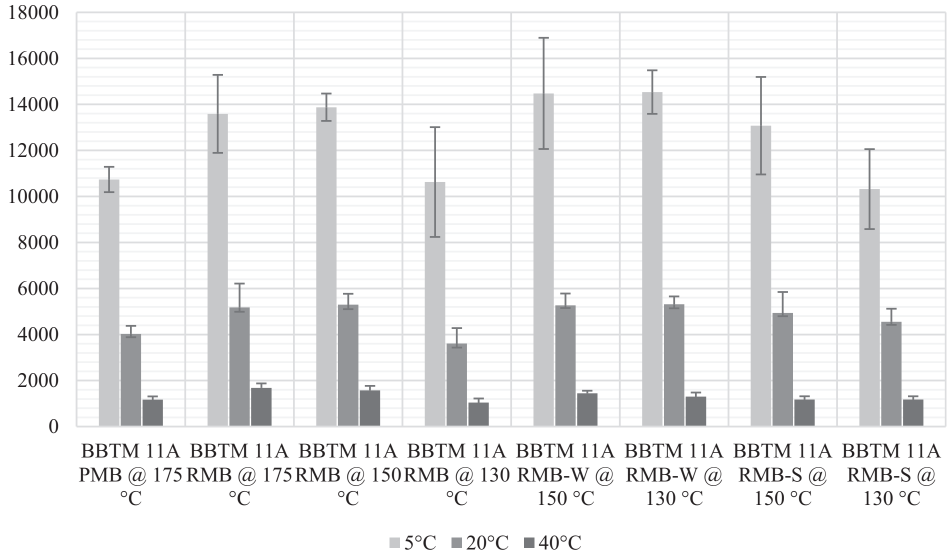

Fig. 3. Stiffness modulus at different temperatures of the asphalt mixtures.

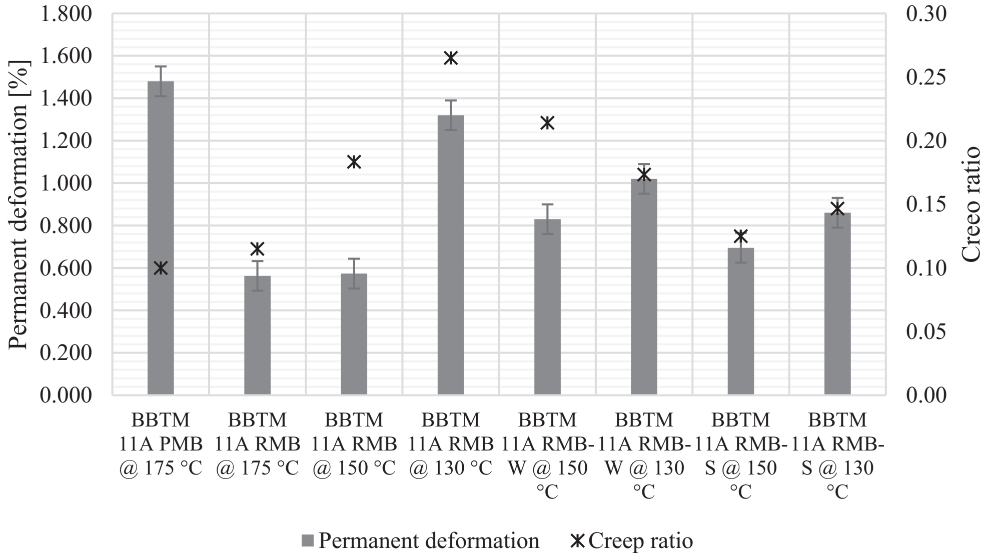

Fig. 4. Creep ratio and permanent deformations of asphalt mixtures.

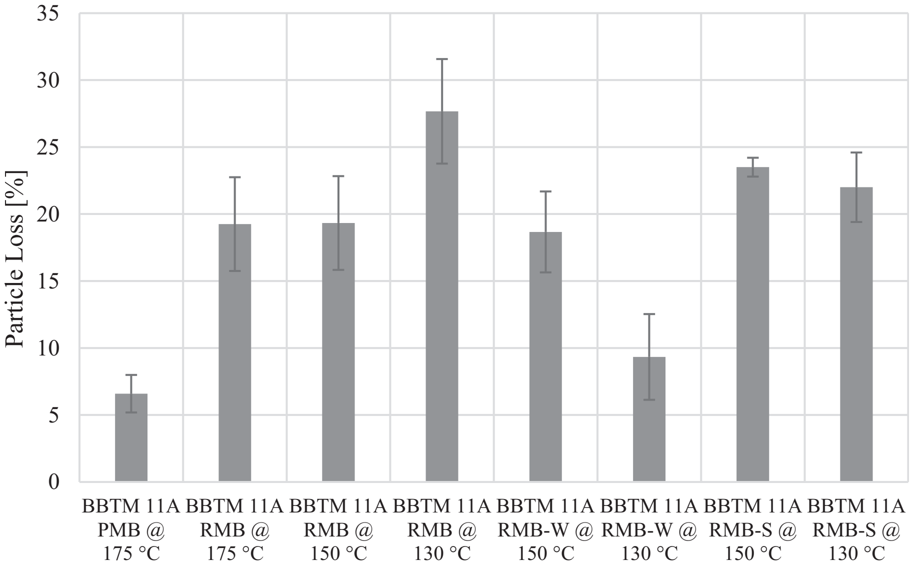

Fig. 5. Particle loss of the asphalt mixtures.

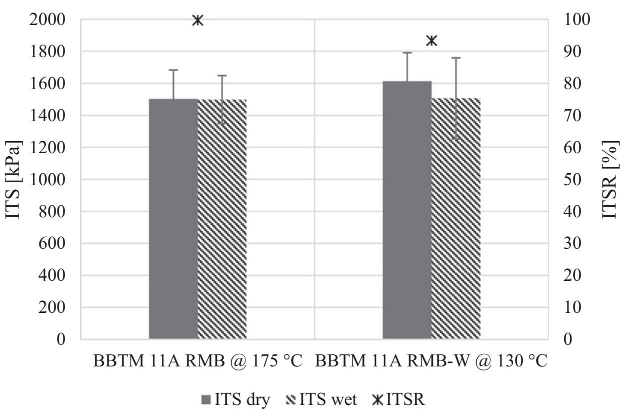

Fig. 6. Water sensitivity results of the asphalt mixtures.

Ratio (ITSR). Firstly, the ITS of both rubberised asphalt mixtures are adequate for this type of asphalt mixtures (BBTM 11A), usually manufactured with a PMB or a 50/70 penetration grade bitumen modified with a low tire crumb rubber content (maximum 5%) [33]). This fact reveals that is feasible to use a high tire crumb rubber content with a 70/100 penetration grade bitumen for this type of asphalt mixtures, and furthermore it is possible to reduce their manufacturing temperature 45 °C by introducing a warm mix additive and without compromising their ITS.

In terms of water sensitivity, the Spanish specification [29] for these type of asphalt mixtures requires the ITSR to be higher than 90% to be acceptable. This requirement is clearly met by both rubberised asphalt mixtures.

Fig. 7 shows the results of the wheel tracking test. It can be observed that rut depth (RD) and wheel track slope (WTS) are similar for the two asphalt mixtures tested, as well as the deformation curves obtained during the test. In the same way than for ITS, the

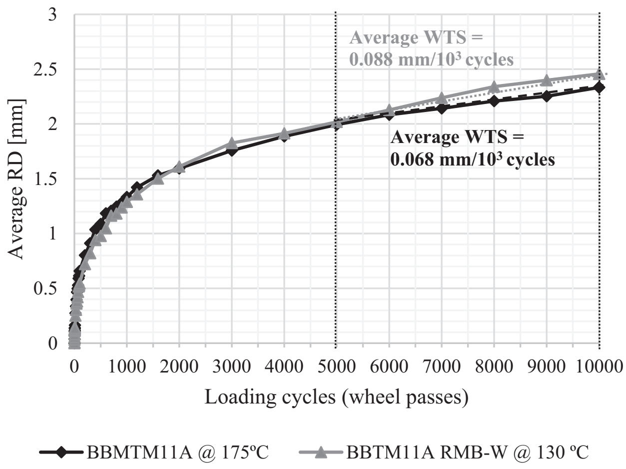

Fig. 7. Permanent deformation versus loading cycles in the wheel tracking test.

results of the RD of both show to be suitable compared to typical values for conventional BBTM 11A [33]. Moreover, the average RD of the warm mixture is only 5% higher than the hot rubberised mixture, having that the resistance to rutting of BBTM11A RMB-W manufactured at 130 °C is equivalent to that of the BBTM11A RMB manufactured at 175 °C. These results further support the viability of using a high amount of crumb rubber modified high-penetration grade bitumen for this type of asphalt mixture, and reduce the asphalt mixture manufacturing temperature to 130 °C, moving towards more sustainable solutions for pavements.

4. Conclusions

The aim of this study is to analyse the viability of manufacturing asphalt mixtures with highly modified rubber binders (20% rubber content) at warm temperatures (130 °C), without compromising their mechanical performance. To achieve this, modified binders and asphalt mixtures were produced using a high penetration binder (70/100) and two warm additives (a wax and a surfactant) that help to reduce manufacturing temperatures.

Given the results presented, the rheological characterisation showed that the high penetration bitumen with crumb rubber and additives present a more elastic behaviour and higher complex modulus than the SBS modified binder. This allowed reducing the concern of using a high penetration binder, which would have a high viscous behaviour and low complex modulus, modified with crumb rubber. In terms of production, it can be concluded that the high penetration binder provided adequate workability to be used for the manufacture of a highly crumb rubber modified asphalt mixture at 150 °C, displaying no compromise in mechanical performance. Meanwhile, for the reduction of the manufacturing temperature (130 °C), warm-mix additives are needed. The additives studied helped to obtain the correct workability for the asphalt mixtures, displaying a suitable behaviour in terms of stiffness, plastic deformations and particle loss.

Among the additives used in this study, the wax was found to particularly improve the cohesion of the rubberised mixture and exhibited adequate indirect tensile strength, water sensitivity and resistance to rutting; therefore, suitable to be used in wearing courses.

As a result, it can be said that the use of high penetration bitumen and additives allowed the reduction of the manufacturing temperature of the rubberised asphalt mixtures by 45 °C, without adversely affecting mechanical performance. Further work is needed to analyse other mechanical properties, such as thermal cracking, and study more additives and dosages. The implementation of these asphalt mixtures would reduce the energy consumption, costs and GHG emissions related to the manufacturing and application of high rubber modified asphalt mixtures, and improve the health and safety conditions for workers, by reducing hazardous production fumes. In this sense, performing the sustainability assessment of this technology to quantify such benefits will be crucial.

CRediT authorship contribution statement

Miguel Sol-Sánchez: Conceptualization, Methodology, Investigation, Project administration, Writing - review & editing. **Ana Jiménez del Barco Carrión:** Writing - original draft, Visualization, Investigation, Formal analysis. **Ana Hidalgo-Arroyo:** Investigation, Formal analysis. **Fernando Moreno-Navarro:** Conceptualization, Methodology, Writing - review & editing, Funding acquisition, Supervision. **Leticia Saiz:** Resources, Supervision. **María del Carmen Rubio-Gámez:** Writing - review & editing, Funding acquisition, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] G.D. Airey, (2002) 'Use of Black Diagrams to Identify Inconsistencies in Rheological Data Use of Black Diagrams to Identify Inconsistencies in Rheological Data', Road Mater. Pavement Des. 3(4), pp. 403–424. Available at: http://www.tandfonline.com/doi/abs/10.1080/14680629.2002.9689933.

[2] C.K. Akisetty, S.J. Lee, S.N. Amirkhanian, High temperature properties of rubberized binders containing warm asphalt additives, Constr. Build. Mater. 23 (1) (2009) 565–573, https://doi.org/10.1016/j.conbuildmat.2007.10.010.

[3] J.M. Bermejo-Muñoz, J. Gallego-Medina, L. Saiz-Rodríguez, Guía para la fabricación de betunes con polvo de neumático, Signus Ecovalor, Madrid, 2014.

[4] T. Blankendaal, P. Schuur, H. Voordijk, Reducing the environmental impact of concrete and asphalt: A scenario approach, J. Clean. Prod. 66 (2014) 27–36, https://doi.org/10.1016/j.jclepro.2013.10.012.

[5] L. Brasileiro, F. Moreno-Navarro, R. Tauste-Martínez, J. Matos, M.D.C. Rubio-Gámez, Reclaimed polymers as asphalt binder modifiers for more sustainable roads: A Review, Sustainability 11 (3) (2019) 646.

[6] CEDEX, Manual de Empleo de Caucho de NFU en Mezlcas Bituminosas, Ministerio de Fomento Ministerio de Medio Ambiente, Spain, 2007.

[7] T. Chen, T. Ma, X. Huang, Y. Guan, Z. Zhang, F. Tang, The performance of hot-recycling asphalt binder containing crumb rubber modified asphalt based on physiochemical and rheological measurements, Constr. Build. Mater. 226 (2019) 83–93.

[8] J. D'Angelo, et al. (2008) Warm-Mix Asphalt: European Practice. Washington, D.C. (US). Available at: http://international.fhwa.dot.gov/pubs/pl08007/pl08007.pdf.

[9] X. Ding, T. Ma, W. Zhang, D. Zhang, Experimental study of stable crumb rubber asphalt and asphalt mixture, Constr. Build. Mater. 157 (2017) 975–981.

[10] X. Ding, L. Chen, T. Ma, H. Ma, G. Linhao, T. Chen, Y. Ma, Laboratory investigation of the recycled asphalt concrete with stable crumb rubber asphalt binder, *Constr. Build. Mater.* 203 (2019) 552–557.

[11] EN 12697-12 (2018) Bituminous mixtures. Test methods. Determination of the water sensitivity of bituminous specimens. European Standards. doi: 10.3141/2127-15.

[12] EN 12697-17 (2017) Bituminous mixtures. Test methods. Particle loss of porous asphalt specimens. European Standards.

[13] EN 12697-22 (2003) Bituminous mixtures. Test methods for hot mix asphalt. Wheel tracking. European Standards.

[14] EN 12697-25 (2016) Bituminous mixtures. Test methods. Cyclic compression test. European Standards.

[15] EN 12697-26 (2018) Bituminous mixtures. Test methods. Stiffness. European Standards.

[16] J. Gallego, A.M. Rodríguez-Alloza, F. Giuliani, (2016) 'Black curves and creep behaviour of crumb rubber modified binders containing warm mix asphalt additives', Mechanics of Time-Dependent Materials. Springer Science +Business Media Dordrecht, 20(3), pp. 389–403. doi: 10.1007/s11043-016-9300-5.

[17] Guo, et al. (2019) 'Study of the Mechanical Properties of Rubber Asphalt by Molecular Dynamics Simulation', J. Mol. Model. 25, 365. https://doi.org/10.1007/s00894-019-4250-x.

[18] Guo, et al. (2020) 'Evaluation of the compatibility between rubber and asphalt based on molecular dynamics simulation', Front. Struct. Civ. Eng. 14(2), pp. 435-445. https://doi.org/10.1007/s11709-019-0603-x.

[19] S. Huang, Rubber concentrations on rheology of aged, J. Mater. Civ. Eng. 20 (3) (2008) 221–229.

[20] Industry4Europe (2019) A long-term strategy for Europe's industrial future. From words to action. Industry4Europe Joint Paper. November 2019.

[21] A. Jiménez Barco-Carrión et al., Comparison of the effect of recycled crumb rubber and polymer concentration on the performance of binders for asphalt mixtures, Mater. Constr. 66 (323) (2016), https://doi.org/10.3989/mc.2016.08815.

[22] K.E. Kaloush, (2014) 'Asphalt rubber: Performance tests and pavement design issues', Construction and Building Materials. Elsevier Ltd, 67(PART B), pp. 258–264. doi: 10.1016/j.conbuildmat.2014.03.020.

[23] A.V. Kataware, D. Singh, Dynamic mechanical analysis of crumb rubber modified asphalt binder containing warm mix additives, Int. J. Pave. Eng. 20 (9) (2017) 1044–1054, https://doi.org/10.1080/10298436.2017.1380806.

[24] H. Kim et al., Performance properties of CRM binders with wax warm additives, Constr. Build. Mater. 66 (2014) 356–360, https://doi.org/10.1016/j.conbuildmat.2014.05.052.

[25] H.H. Kim, S.J. Lee, Effect of crumb rubber on viscosity of rubberized asphalt binders containing wax additives, Constr. Build. Mater. 95 (2015) 65–73, https://doi.org/10.1016/j.conbuildmat.2015.07.066.

[26] S.-J. Lee, C.K. Akisetty, S.N. Amirkhanian, The effect of crumb rubber modifier (CRM) on the performance properties of rubberized binders in HMA pavements, Constr. Build. Mater. 22 (7) (2008) 1368–1376, https://doi.org/10.1016/j.conbuildmat.2007.04.010.

[27] T. Ma et al., Laboratory Investigation of Crumb Rubber Modified Asphalt Binder and Mixtures with Warm-Mix Additives, Int. J. Civ. Eng. 15 (2) (2017) 185–194, https://doi.org/10.1007/s40999-016-0040-3.

[28] T. Ma et al., Property characterization of asphalt binders and mixtures modified by different crumb rubbers, J. Mater. Civ. Eng. 29 (7) (2017) 04017036.

[29] Ministerio de Fomento (2014) Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes. Parte 5 Firmes y Pavimentos. Spain.

[30] F. Moreno-Navarro et al., Analysis of the influence of binder properties on the mechanical response of bituminous mixtures, Int. J. Pavement Eng. 8436 (September) (2015) 1–10, https://doi.org/10.1080/10298436.2015.1057138.

[31] F. Moreno-Navarro, M. Sol-Sánchez, M.C. Rubio-Gámez, Reuse of deconstructed tires as anti-reflective cracking mat systems in asphalt pavements, Constr. Build. Mater. 53 (2014) 182–189, https://doi.org/10.1016/j.conbuildmat.2013.11.101.

[32] F. Moreno-Navarro, M. Sol-Sánchez, M.C. Rubio-Gámez, The effect of polymer modified binders on the long-term performance of bituminous mixtures: The influence of temperature, Mater. Des. 78 (2015) 5–11, https://doi.org/10.1016/j.matdes.2015.04.018.

[33] F. Moreno et al., The effect of crumb rubber modifier on the resistance of asphalt mixes to plastic deformation, Mater. Des 47 (2013) 274–280, https://doi.org/10.1016/j.matdes.2012.12.022.

[34] F. Moreno Navarro, M.C. Rubio Gámez, Influence of Crumb Rubber on the Indirect Tensile Strength and Stiffness Modulus of Hot Bituminous Mixes, J. Mater. Civ. Eng. 24 (6) (2012) 715–724, https://doi.org/10.1061/(ASCE)MT.1943-5533.

[35] F.J. Navarro et al., Influence of crumb rubber concentration on the rheological behavior of a crumb rubber modified bitumen, Energy Fuels 19 (5) (2005) 1984–1990, https://doi.org/10.1021/ef049699a.

[36] J.R.M. Oliveira et al., Use of a warm mix asphalt additive to reduce the production temperatures and to improve the performance of asphalt rubber mixtures, J. Clean. Prod. 41 (2013) 15–22, https://doi.org/10.1016/j.jclepro.2012.09.047.

[37] S.K. Palit, K.S. Reddy, B.B. Pandey, Laboratory evaluation of crumb rubber modified asphalt mixes, J. Mater. Civ. Eng. 16 (1) (2004) 45–53, https://doi.org/10.1061/(ASCE)0899-1561(2004)16:1(45).

[38] D. Lo Presti, Recycled tyre rubber modified bitumens for road asphalt mixtures: A literature review, Constr. Build. Mater. 49 (2013) 863–881, https://doi.org/10.1016/j.conbuildmat.2013.09.007.

[39] D. Lo Presti, M.A. Izquierdo, Jiménez del Barco, A. Carrión, Towards storage-stable high-content recycled tyre rubber modified bitumen, Constr. Build. Mater. 172 (2018), https://doi.org/10.1016/j.conbuildmat.2018.03.226.

[40] A.M. Rodríguez-Alloza et al., High and low temperature properties of crumb rubber modified binders containing warm mix asphalt additives, Constr. Build. Mater. 53 (2014) 460–466, https://doi.org/10.1016/j.conbuildmat.2013.12.026.

[41] A.M. Rodríguez-Alloza, J. Gallego, Mechanical performance of asphalt rubber mixtures with warm mix asphalt additives, Mater. Struct./Mater. Constr. 50 (2) (2017), https://doi.org/10.1617/s11527-017-1020-z.

[42] A.M. Rodríguez-Alloza, J. Gallego, I. Pérez, Study of the effect of four warm mix asphalt additives on bitumen modified with 15% crumb rubber, Constr. Build. Mater. 43 (2013) 300–308, https://doi.org/10.1016/j.conbuildmat.2013.02.025.

[43] M.C. Rubio et al., Warm mix asphalt: An overview, J. Clean. Prod. 24 (2012) 76–84, https://doi.org/10.1016/j.jclepro.2011.11.053.

[44] M.D.C. Rubio et al., Comparative analysis of emissions from the manufacture and use of hot and half-warm mix asphalt, J. Clean. Prod. 41 (2013) 1–6, https://doi.org/10.1016/j.jclepro.2012.09.036.

[45] B. Rymer et al., Tire/pavement noise intensity testing in Europe: The NITE study and its relationship to ongoing caltrans quiet pavement activities, J. Assoc. Asphalt Paving Technol. Proc. Technical Sessions (2005) 1107–1159.

[46] A. Sharma, B.K. Lee, Energy savings and reduction of CO2 emission using Ca (OH)2 incorporated zeolite as an additive for warm and hot mix asphalt production, Energy 136 (2017) 142–150, https://doi.org/10.1016/j.energy.2016.03.085.

[47] M. Sol-Sánchez, F. Moreno-Navarro, M.C. Rubio-Gámez, The use of deconstructed tires as elastic elements in railway tracks, Materials 7 (8) (2014) 5903–5919, https://doi.org/10.3390/ma7085903.

[48] A. Subhy, D. Lo Presti, G. Airey, Rubberised bitumen manufacturing assisted by rheological measurements, Road Mater. Pave. Des. 17 (2) (2016) 290–310, https://doi.org/10.1080/14680629.2015.1079549.

[49] H. Wang et al., Effect of warm mixture asphalt (WMA) additives on high failure temperature properties for crumb rubber modified (CRM) binders, Constr. Build. Mater. 35 (2012) 281–288, https://doi.org/10.1016/j.conbuildmat.2012.04.004.

[50] H. Wang et al., Review of warm mix rubberized asphalt concrete: Towards a sustainable paving technology, J. Clean. Prod. 177 (2018) 302–314, https://doi.org/10.1016/j.jclepro.2017.12.245.

[51] Y. Wen et al., The engineering, economic, and environmental performance of terminal blend rubberized asphalt binders with wax-based warm mix additives, J. Clean. Prod. 184 (2018) 985–1001, https://doi.org/10.1016/j.jclepro.2018.03.011.

[52] X. Yang et al., Environmental and mechanical performance of crumb rubber modified warm mix asphalt using Evotherm, J. Clean. Prod. 159 (2017) 346–358, https://doi.org/10.1016/j.jclepro.2017.04.168.

[53] X. Yang et al., Emission analysis of recycled tire rubber modified asphalt in hot and warm mix conditions, J. Hazard. Mater. 365 (2019) 942–951, https://doi.org/10.1016/j.jhazmat.2018.11.080.

[54] H. Yu et al., Optimization of preparation procedure of liquid warm mix additive modified asphalt rubber, J. Clean. Prod. 141 (2017) 336–345, https://doi.org/10.1016/j.jclepro.2016.09.043.

[55] H. Yu et al., Workability and mechanical property characterization of asphalt rubber mixtures modified with various warm mix asphalt additives, Constr. Build. Mater. 175 (2018) 392–401, https://doi.org/10.1016/j.conbuildmat.2018.04.218.

[56] X. Yu, Z. Leng, T. Wei, Investigation of the rheological modification mechanism of warm-mix additives on crumb-rubber-modified asphalt, J. Mater. Civ. Eng. 26 (2) (2014) 312–319, https://doi.org/10.1061/(ASCE)MT.1943-5533.0000808.

[57] J. Zhu, T. Ma, Z. Dong, Evaluation of optimum mixing conditions for rubberized asphalt mixture containing reclaimed asphalt pavement, Constr. Build. Mater. 234 (2020) 117426.

[58] H. Ziari, M. Naghavi, R. Imaninasab, Performance evaluation of rubberised asphalt mixes containing WMA additives, Int. J. Pavement Eng. 19 (7) (2018) 623–629, https://doi.org/10.1080/10298436.2016.1199874.