Materials and Structures (2014) 47:683–692
DOI 10.1617/s11527-013-0088-3

ORIGINAL ARTICLE

Wheel tracking rutting performance estimation based on bitumen Low Shear Viscosity (LSV), loading and temperature conditions

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Received: 12 October 2012 / Accepted: 3 May 2013 / Published online: 15 May 2013

Abstract The development of new technologies and road pavement materials require the evaluation of the asphalt mixture performance. Rutting is one of the main modes of failure of asphalt mixtures; it is typically studied at the laboratory through the wheel tracking test (WTT). Weather and traffic conditions (temperature, loads) significantly affect the pavement rutting performance. The bitumen rheological properties also have a main role in mixture rutting response; they can adequately characterized by the bitumen Low Shear Viscosity (LSV). The estimation of rutting performance appears as a useful decision tool to optimize pavement design process. This paper studies the rutting performance of asphalts mixtures utilising the WTT. The specimens were tested at different temperatures and loading levels to simulate different climatic and traffic pavement conditions. A performance estimator was developed including temperature and traffic load on the pavement, and LSV of the binder as input data.

Keywords Rutting performance estimation · Low Shear Viscosity · Pavement temperature · Pavement load level · Asphalt concrete

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1 Introduction

Rutting is a permanent deformation of asphalt pavement in the traffic wheel path. Excessive permanent deformations compromise the comfort and safety of vehicles on the road. The mix proportions and materials properties (bitumen content, filler type, filler bitumen ratio, aggregate particle size distribution) affect the rutting behaviour of a mixture. The main variables that increase asphalt concrete rutting risk are: high temperature, excessive traffic load and poor quality of mixture materials.

The investigation of rutting is extended worldwide because it is a common road failure. Different researches have tried to explain the problem [1, 2]; some of them studied materials or technologies with the objective of minimize rutting [3, 4].

The bitumen properties have a main role in the rutting process of a mixture. Nowadays the rheological properties of binders are used to characterize the rutting behaviour of asphalt concretes. The Low Shear Viscosity (LSV) was found as an adequate parameter to characterize the contribution of different bitumens to mixture rutting performance [5, 6]. Other binder properties in addition to LSV have been found to characterize the effect of bitumen on rutting performance; the creep compliance obtained in the Multiple Stress Creep Recovery Test (MSCRT) is an example of them. This rheological property is a nonlinear measure on the bitumen behaviour and can be related to the different stress levels applied on pavements [7, 8].

New approaches like the Mechanistic-Empirical Pavement Design Guide (MEPDG) take into account the material properties and pavement conditions to which the mixture will be exposed, to predict the performance by means of models. The models have been developed to capture the effects of different factors on asphalt concrete performance [9]. For pavement engineers, a model can provide accurate information about the performance of asphalt concrete under realistic loading conditions, thus leading to a better assessment of the service life of a new pavement or the remaining life of an existing pavement. For materials engineers, the performance model founded on basic principles of mechanics provides relationships between material properties (chemical or mechanical) and model parameters, which can be used for the selection or design of better performing binders or mixtures [9].

The study and characterization of permanent deformations in a rational way have led to the development of laboratory test procedures that tried to reproduce the problem. The wheel tracking tests (WTT), in its different versions, is accepted world-wide as a test procedure that gives an indication of the asphalt mixture rutting resistance. Recent researches explore different testing alternatives for the WTT in order to find a better quantification of the rutting performance [10–12]. In addition, the WTT is used in laboratories to analyse the rutting performance behaviours while varying gradation and materials [13].

Asphalt pavements are exposed to different temperatures and loads depending on the geographic location and traffic conditions. The WTT is carried out at a standard temperature and load, not always representing the field conditions. Thus, it is interesting to estimate the WTT performance taking into account the conditions to which the asphalt mixture will be exposed in situ. Within certain limits considering well design mixtures; the bitumen type, the temperature and the service load appear as the main factors affecting the final rutting performance of a mixture.

Previous works [6, 14, 15] show that the bitumen LSV reflects the binder contribution in the mixture rutting performance. In [14] a lot of bitumens were studied including, three different conventional, multigrade, oxidized and three polymer modified bitumen (two different SBS and EVA). The LSV were measured at different temperatures and related with their WTT performance in the mixtures of different gradations.

The prediction of mixture rutting performance under specific field conditions appears as a useful tool in the design process. This work explores the relationship between the mixture rutting behaviour, the pavement service conditions and the bitumen characteristics, represented by the LSV, based on WTT obtained at different temperatures and loading levels, to simulate diverse climatic and traffic conditions.

2 Experimental

2.1 Materials and mixtures

Three mixture gradations were selected for this work, a micro asphalt mixture (M-10), a Stone Mastic Asphalt (SMA-10) and a dense grade asphalt mixture (D-20). Two coarse aggregates (6–20 and 6–12 mm), two crushed sands (0–6 and 0–3 mm), hydraulic lime, filler and cellulose fibres were used. Table 1 shows the main characteristics of gradations studied and Fig. 1 the grading curves. The main mixture design properties are included in Table 2.

These types of mixtures are commonly used in Argentina as top surface on highways to bring safety and comfort. M-10 and SMA-10 are open grade mixtures with similar grading curves; however the inclusion of fibres and higher bitumen content in the SMA-10 turns this mixture different to M-10. In fact, the design of each mixture is different respect to optimal bitumen content. The D-20 is a coarse dense grade mixture design according to Marshall Method. It is important to mention that these mixtures are well proven designs used extensively in our laboratory.

Three bitumen binders currently used in Argentina, Conventional (C), Multigrade (M) and Polymer

Table 1 Aggregates gradations

Mixture proportions (%)	M-10	SMA-10	D-20
6–20 mm	–	–	40
6–12 mm	75	75	12
0–6 mm	–	–	45
0–3 mm	16	15.5	
Filler	8	8	2
Hydraulic lime	1	1	1
Cellulose fibres	–	0.5	–

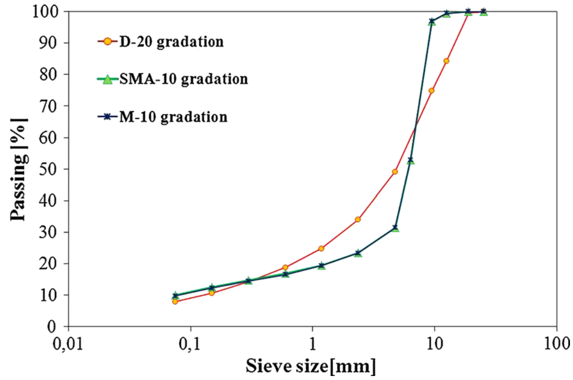

Fig. 1 Mixture gradation curves

Table 2 Main mixture design properties

Design properties	M-10	SMA-10	D-20
Optimal bitumen content (%)	5.3	6.0	5.0
Density (g/cm^3)	2.380	2.400	2.437
Air voids (%)	4.9	3.3	3.5

Modified (PM), were used in each gradation to make different asphalt mixtures. Table 3 presents the main bitumen characteristics including penetration, softening point (R & B), Brookfield viscosity at 60 °C, torsional recovery test results as well as their Performance Grades (PG) according to the [16]. Table 3 also shows the LSV of the bitumens at different temperatures between 50 and 80 °C. The LSV measurements were obtained by means of frequency sweep tests in a Dynamic Shear Rheometer (DSR). The Cross model was used to fit the complex viscosity data obtained and then the LSV was calculated at a frequency of 0.001 Hz, as recommended by [17].

These gradation and asphalt combinations represent a total of nine mixtures; they are identified as D-20 C, D-20 M, D-20 PM, M-10 C, M-10 M, M-10 PM, SMA-10 C, SMA-10 M and SMA-10 PM.

2.2 Testing program

The performance of each asphalt mixtures were studied in the WTT at 50, 60, 70 and 80 °C with a load of 520 N. Rutting commonly occurs between 50 and 60 °C (usual high pavement temperature conditions) while temperatures of 70 and 80 °C were chosen to represent extreme climate conditions. It must be mentioned that the EN 13108-20

Table 3 Bitumen properties

Bitumen	C	M	PM
Modification	–	Multigrade	SBS
Argentinean standard type	CA-30	–	AM3-C
Penetration to 25 °C (dmm)	55	60	64
Softening point (°C)	51.8	58.3	95.5
Brookfield viscosity to 60 °C (Pa s)	297.6	1,224	–
Torsional recovery (%)	–	–	77.2
Performance grade (PG)	64–16	70–22	70–22
LSV (Pa s)			
50 °C	1012.4	3631.1	7669.9
60 °C	252.5	947.5	2459.3
70 °C	83.2	308.1	911.3
80 °C	34.3	120.5	383.1

allow to each European Community country to choose the WTT test temperature according to climate condition.

To consider the effect of traffic loading, additionally to standard load of 520 N, the WTT mixture performances with load levels of 700 and 900 N at 60 °C were studied. Considering a wheel imprint of 10 cm^2 the contact pressure produced for the different used loads results in 520, 700 and 900 kPa, approximately. These stresses are similar to the wheel contact pressures produced by a single axle of 8, 10.5 and 13 t, respectively, considering a simplified circular imprint of 15 cm on the pavement surface. The wheel print depends on tyre pressure and load; Bodin et al. [10] showed the importance of the wheel/slab contact conditions. Inputs to mechanistic design require the definition of the loaded area [18], here the wheel imprint simplifications give an approximation of the stress produced in WTT as well as in the pavement.

The 8 t is close to the legal maximum load in Argentina, while 10.5 and 13 t are legal maximum loads in other countries, and represent an overload in Argentina. The loads of 520, 700 and 900 N are the specified loads in the wheel tracking test standards BS 598 part 110, CEN 12697-22 and NLT 143, respectively.

In each asphalt mixture, twelve samples, 300 mm wide and 50 mm high, were cast. They were compacted up to the design Marshall density using roller compactor equipment [19]. The densities were controlled to verify a minimum of 98 % of the design density; then the specimens were tested in pairs at each of the temperature and load levels described.

2.3 Wheel tracking test (WTT)

The WTT device (see Fig. 2) follows the B.S. 598 part 110 [20] specifications. It consists in a loaded solid rubber wheel, 207 mm diameter and 47 mm wide, put over a mixture sample. The sample was placed in a plate capable to describe a simple harmonic motion (backward and forward) under the wheel with a frequency of 21 cycles per min (42 passes). The wheel travelled a distance of 230 mm over the mixture. A weighted cantilever arm was used to apply the load to the wheel. The equipment was hold in a chamber to allow maintaining the sample at test temperature. Under this condition rut depth was measured at the centre of sample at 1 min intervals through a LVDT during 120 min of test. The device software read the LVDT lecture each time a device sensor counted 42 wheel passes over the centre of mixture sample.

The rut depth collected data were fitted with the potential model as Eq. 1 indicates.

$$\varepsilon_p = a \cdot t^b \tag{1}$$

where ε_p is the permanent deformation data; t is the time; a and b is the model constants. The first ten data points collected were not taken into account because they significantly affect the fit.

The rutting performance was evaluated through the Rutting rate (Rr); this parameter represents the rate of change in rut depth determined over the last portion to the rut depth-time curve. It is calculated as Eq. 2 indicates where $D_{120\ \mathrm{min}}$ and $D_{105\ \mathrm{min}}$ are the deformations at 120 and 105 min, respectively.

$$\mathrm{Rr} = \frac{D_{120} - D_{105}}{15\,\mathrm{min}} \left[\frac{\mu\mathrm{m}}{\mathrm{min}}\right] \tag{2}$$

According to BS 598 part 110, 60 °C and 520 N are temperature and load standard conditions. In this work additional conditions were studied at other temperatures (50, 70 and 80 °C) and load levels (700 and 900 N). To change the load level was only necessary switch the weight in cantilever arm (see Fig. 3). The load level under the wheel was verified by means of a load cell.

The BS 598 part 110 equipment is similar to the actual specified in CEN 12697-22 as “small size device” distinguish between them the load level (520 instead of 700 N), test duration (120 min instead of 6.5 h) and the frequency of cycles (21 instead of 26.5 cycles/min).

3 Results and discussion

Table 4 shows the Rr results from the WTT at the different load levels and temperatures studied. The mixtures are identified by gradation and type of binder. As was observed in previous works, Rr increase (worse rutting performance) as the temperature increase. Rr also increase when the load level increases as expected.

Fig. 2 Wheel tracking test (WTT) device

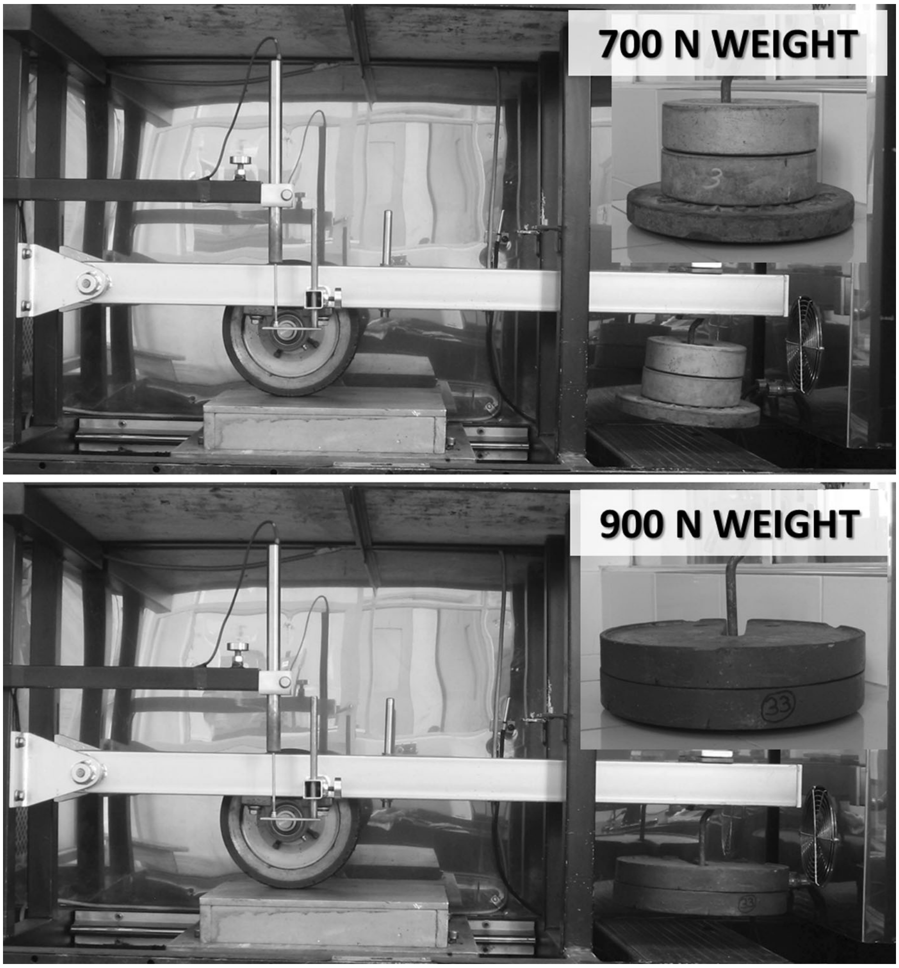

Fig. 3 Device arrangements for 700 and 900 N load levels

The Rr results obtained for the different gradations (D-20, M-10 and SMA-10) blended with a same bitumen (C, M or PM) tested at the standard temperature (60 °C) and load level (520 N) are comparable. Something similar can be observed in other test conditions, with the exception of tests carried out at 70 °C–520 N and 60 °C–700 N for C bitumen and 80 °C–520 N for M bitumen. These facts can be explained considering that at high temperatures (70 and 80 °C) the LSV of the bitumen decrease, see Table 3, and the differences in gradation play a major role in the rutting resistance. However these temperatures represent an extreme and not common condition. In the other hand the case of open grade mixture (M-10 and SMA-10) blended with C bitumen tested at 60 °C and 700 N; the low bitumen LSV were not enough to avoid the higher rutting of these mixture compare with D-20; however the open grade mixture are not design to be used with conventional bitumen. Nevertheless, these results reflect possible extreme condition and help to understand the rutting process.

In Morea et al. [15] the WTT rutting performances of D-20, M-10 and SMA-10 mixtures at different temperatures were studied. A clear relationship between the Rr and the bitumen LSV measured at the same temperatures that WTT were carried out (reflect bitumen's temperature dependency) was found. In that work, drastic increases in Rr were observed when the original bitumen LSV was lower than 500 Pa s. Figure 4 shows this Rr–LSV relationship where an Rr value of 5.2 μm/min was obtained for LSV = 500 Pa s. In this figure the different mixtures were fitted all together; it can be thing that M-10 mixtures follow a different tendency for LSV

Table 4 Wheel tracking test (WTT) results

Mixture	T (°C)	L (N)	Rr (μm/min)	Mixture	T (°C)	L (N)	Rr (μm/min)	Mixture	T (°C)	L (N)	Rr (μm/min)
D-20 C	50	520	3.9	M-10 C	50	520	4.2	SMA-10 C	50	520	3.4
	60	520	9.6		60	520	14.8		60	520	11.2
	70	520	23.4		70	520	37.9		70	520	24.0
	80	520	–*		80	520	–*		80	520	–*
	60	700	14.8		60	700	24.4		60	700	23.9
	60	900	40.2		60	900	–*		60	900	–*
D-20 M	50	520	2.4	M-10 M	50	520	1.8	SMA-10 M	50	520	2.1
	60	520	3.4		60	520	3.2		60	520	3.3
	70	520	6.7		70	520	10.4		70	520	8.4
	80	520	14.1		80	520	30.0		80	520	16.7
	60	700	4.3		60	700	5.2		60	700	4.8
	60	900	7.1		60	900	6.0		60	900	7.8
D-20 PM	50	520	2.3	M-10 PM	50	520	1.4	SMA-10 PM	50	520	1.8
	60	520	3.0		60	520	1.8		60	520	1.9
	70	520	3.5		70	520	2.6		70	520	3.0
	80	520	4.9		80	520	4.1		80	520	3.8
	60	700	3.0		60	700	2.0		60	700	1.9
	60	900	4.1		60	900	3.2		60	900	2.9

* Not measured

values below 300 Pa s when the rutting performance is poor and it is related with the high temperatures studied (70 and 80 °C). To simplify and considering that the use of different trends not gives a major improvement on the analysis of poor mixture performance in this region (below 300 Pa s) it was adopted a single fit for all mixtures studied.

In the previous work [15], the load level of the WTT was 520 N for all samples tested. Figure 5 shows the obtained Rr results tested here for load levels of 700 and 900 N as a function of the binder LSV at the same temperature (60 °C), as well as the Rr–LSV relationship for 520 N. It can be observed, even with few results, how the LSV limit shifts to a higher LSV value (around 1,000 Pa s) at the point when drastic changes in Rr results occur. In addition, the figure shows that the Rr value associated with an LSV of 1,000 Pa s for these load levels is close to 5 μm/min. From these results the Rr value of 5 μm/min seem to be a point of inflexion for rutting performance.

Regarding the estimation of rutting performance and considering that the temperature (T) and load (L) conditions in the field have an influence on the final rutting performance of the mixture, and that the LSV has a direct effect on rutting resistance and characterizes the bitumen type, it was analyzed the influence of these variables on the rutting rate (Rr).

The final rutting can be thought as the sum of effects of each individual variable. The Rr can be defined as Eq. 3 indicates, the temperature of 60 °C and load level of 520 N were considered as reference values (T_0 and L_0, respectively) because they are the standard values of the WTT in BS 598 part 110. The LSV for each binder type was taken at 60 °C to characterize the effect of the bitumen in the mixtures.

$$\log(\mathrm{Rr}) = k + z \cdot \log(\mathrm{LSV}_{60\,^\circ\mathrm{C}}) + C_\mathrm{T} \cdot \log(T) + C_\mathrm{L} \cdot \log(L) \quad (3)$$

Equation 3 can be rewritten as Eq. 4 indicates.

$$\mathrm{Rr} = k \cdot \mathrm{LSV}^{z}_{60\,^\circ\mathrm{C}} \cdot \left(\frac{T}{T_0}\right)^{C_\mathrm{T}} \cdot \left(\frac{L}{L_0}\right)^{C_\mathrm{L}} \quad (4)$$

Where Rr is the rutting rate in μm/min; $\mathrm{LSV}_{60\,^\circ\mathrm{C}}$ is the Low Shear Viscosity of the binder at 60 °C in Pa s; T is temperature in °C; L is the load level in N, and k, z, C_T and C_L are adjustment parameters. It can be seen that the terms of temperature and load were redefined

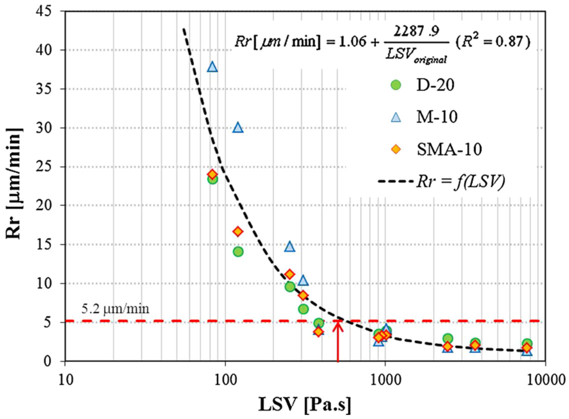

Fig. 4 Rr–binder LSV relationship for load level of 520 N. From Morea et al. [15]

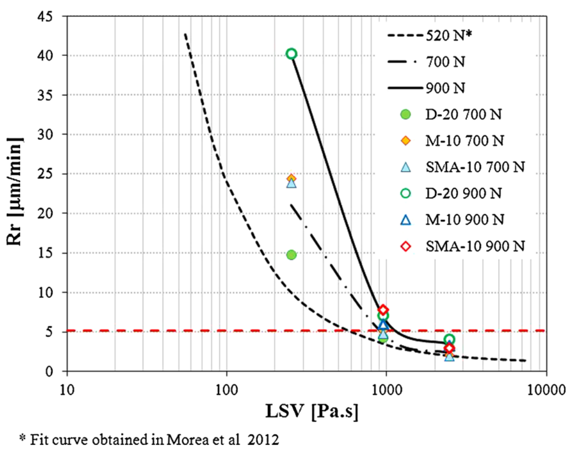

Fig. 5 Rr–LSV relationship for different load levels

considering the reference values of the standard WTT, T_0 and L_0. The results from the WTT were used to adjust the parameters of Eq. 4 by multiple regressions using statistical software; a good adjustment was established as indicated in Eq. 5.

$$\mathrm{Rr}[\mu m/\mathrm{min}] = 1,153 \cdot \mathrm{LSV}_{60}^{-0.82} \cdot \left(\frac{T}{T_0}\right)^{3.91} \cdot \left(\frac{L}{L_0}\right)^{1.04} \quad (R^2 = 0.86) \tag{5}$$

Figure 6 shows the estimated Rr values versus the experimental results obtained from the WTT. Different trend relations can be seen between estimated and measured values before and after Rr = 5 µm/min, which was previously found as an inflexion point in rutting behaviour. Based on this observation, the Rr results were fitted in two separate groups: those below and those above the 5 µm/min, generating Eqs. 6 and

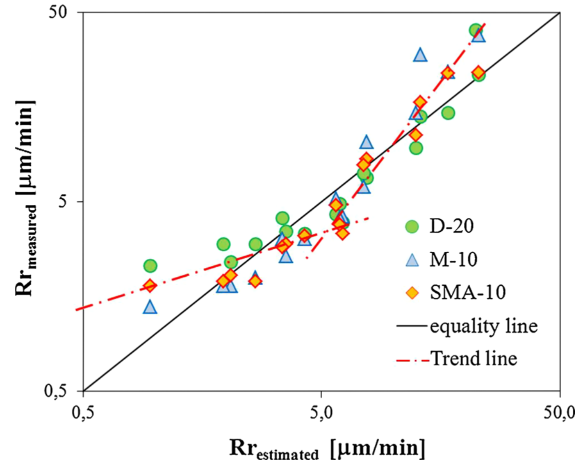

Fig. 6 Rr estimated by Eq. 5 versus experimental results

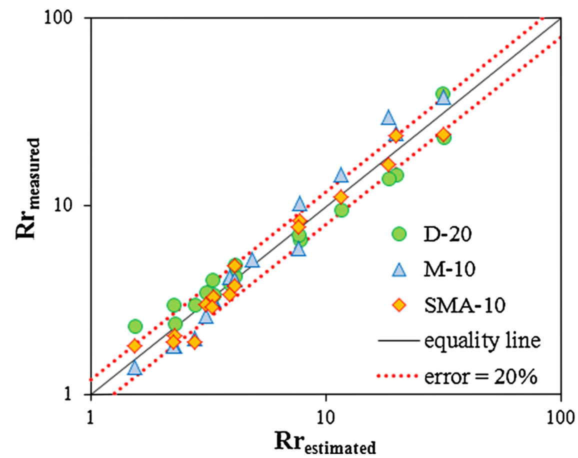

Fig. 7 Rr estimated by Eq. 6 or 7 versus Rr measured

7. The adjustment is regular, but a clear improvement in Rr prediction can be observed in Fig. 7 where 90 % of the results fall within the 20 % error region (±20 % of equality line value).

$$\mathrm{Rr}[\mu m/\mathrm{min}] = 4,034 \cdot \mathrm{LSV}_{60}^{-1.05} \cdot \left(\frac{T}{T_0}\right)^{6.53} \cdot \left(\frac{L}{L_0}\right)^{1.81} \quad (R^2 = 0.81) \tag{6}$$

$$\mathrm{Rr}[\mu m/\mathrm{min}] = 56\,\mathrm{LSV}_{60}^{-0.41} \cdot \left(\frac{T}{T_0}\right)^{2.08} \cdot \left(\frac{L}{L_0}\right)^{0.69} \quad (R^2 = 0.71) \tag{7}$$

To determine which equation to use when predicting rutting, the bitumen LSV at a specific pavement

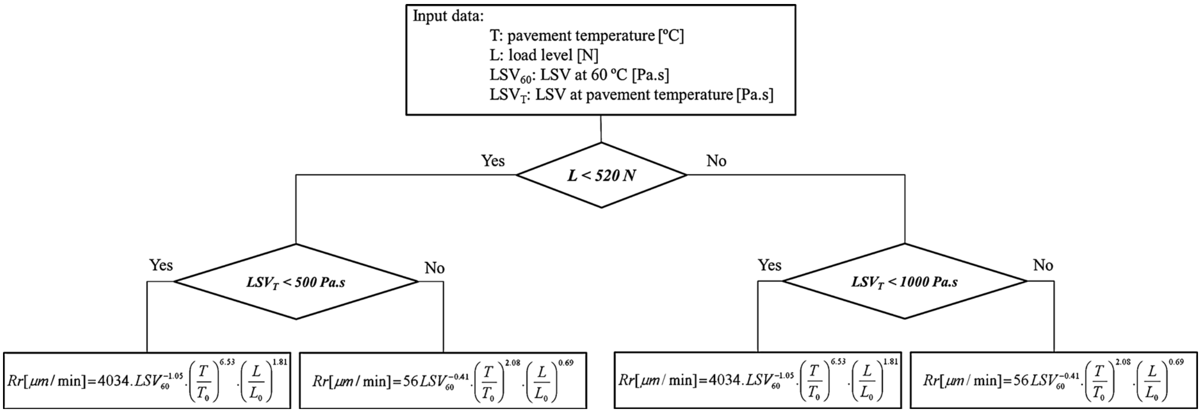

Fig. 8 Flow chart to use the equations to estimate Rr

temperature and load level must be established. It was previously shown that load level changes affect the LSV threshold at which rutting performance changes significantly. For a load level up to 520 N, if the original LSV of the binder is lower than 500 Pa s, Eq. 6 should be used, otherwise use Eq. 7. For load levels higher than 520 N, if the bitumen LSV is lower than 1,000 Pa s, Eq. 6 should be used, otherwise use Eq. 7. Figure 8 shows a flow chart with the selection process to predict Rr.

Establishing 1,000 Pa s as the LSV limit to decide which equation to use would be simpler. However, the Rr of mixtures with bitumen LSVs between 500 and 1,000 Pa s tested in the WTT with 520 N would be predicted with Eq. 6, which is associated with an Rr higher than 5 μm/min. The problem that arises is that these mixtures have observed performances lower than 5 μm/min. In consequence, considering 1,000 Pa s as the only limit to predict mixture performance underestimates the rutting performance of pavements with loads of less than 520 N.

Regarding rutting estimation, further studies must be done considering varying the bitumen content in the mixture, filler influence and measure of real contact pressure condition (in WTT and pavements) on several mixture. It is important to mention that aggregate gradation and air void content can have a significant role in rutting performance. Nevertheless, poor aggregate selection is more a design problem and air void rutting issues can be associated to poor asphalt compaction during placement. The three mix designs tested in this work have varied characteristics, but each one is well proven, eliminating gradation as a significant contributor to rutting. The major influences on rutting observed in this work were consequences of binder properties, temperature and loading. The different gradations or air void contents did not have an influence on the Rr–LSV relationship. To summarize, the development of proposed equations appears as a tool to predict the influence of temperature and loading (while considering a specific binder) on the WTT rutting behaviour of an asphalt mixture with a proper gradation design. However, this tool does not address the issues that can contribute to rutting when placing the asphalt in the field, such as poor compaction.

4 Conclusions

The performances of several asphalts mixtures at different temperatures (50, 60, 70 and 80 °C) and load levels (520, 700 and 900 N) were studied through the wheel tracking test (WTT). Three types of mixture gradations (dense, micro and SMA) blended with Conventional, Multigrade or Polymer Modified bitumen were studied. The Low Shear Viscosity (LSV) of original bitumen was also considered in order to relate the bitumen characteristics with the rutting behaviour. The main conclusions are indicated as follows.

As expected, the rutting performance of the mixtures in the WTT measured by means of the rutting rate (Rr) was worse (higher Rr) as the temperature and load level increase.

A rutting rate (Rr) of 5 μm/min seems to be a threshold value representing the point, related to the LSV of the binder, at which a sudden increase in rutting occurred.

While for the load level of 520 N a LSV of 500 Pa s for the original bitumens was found as a threshold in which drastic changes in rutting occurred, the LSV limit for the load levels of 700 and 900 N was 1,000 Pa s.

Based on the studied mixtures analyzed a rutting estimator for the WTT was obtained using the temperature and load level on the pavement and the bitumen LSV as input data. This is represented by the following equations:

$$\mathrm{Rr}[\mu\mathrm{m/min}] = 4,034 \cdot \mathrm{LSV}_{60}^{-1.05} \cdot \left(\frac{T}{T_0}\right)^{6.53} \cdot \left(\frac{L}{L_0}\right)^{1.81} \left.\begin{matrix} \text{If } L \leq 520\,\mathrm{N} \text{ and LSV} < 500\,\mathrm{Pa\,s} \\ \text{or } L > 520\,\mathrm{N} \text{ and LSV} < 1,000\,\mathrm{Pa\,s} \end{matrix}\right\}$$

$$\mathrm{Rr}[\mu\mathrm{m/min}] = 56\,\mathrm{LSV}_{60}^{-0.41} \cdot \left(\frac{T}{T_0}\right)^{2.08} \cdot \left(\frac{L}{L_0}\right)^{0.69} \left.\begin{matrix} \text{If } L \leq 520\,\mathrm{N} \text{ and LSV} > 500\,\mathrm{Pa\,s} \\ \text{or } L > 520\,\mathrm{N} \text{ and LSV} > 1,000\,\mathrm{Pa\,s} \end{matrix}\right\}$$

The determination of which equation to be used depends on the load level and the bitumen LSV taken at the temperature at which the performance will be estimated.

The estimation method proposed could be a tool to assess into the design process of asphalt mixture considering the possible field conditions to be exposing the mixture in the pavement and the variation in the bitumen properties with the aim to obtain an acceptable rutting performance of the mixtures. This is an ongoing research and further studies must be done to establish an accurate estimation method.

Acknowledgments The authors thank Claudio Veloso, Jorge Coacci, Norberto Amarillo and Javier Batic for their collaboration in the development of the experimental works.

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