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ORIGINAL ARTICLE

The use of asphalt low shear viscosity to predict permanent deformation performance of asphalt concrete

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Abstract The permanent deformation performance of asphalt concrete is strongly dependent on the rheological properties of the asphalt binder. It has been recognized that the asphalt's low shear viscosity (LSV) characterizes the mixture's rutting resistance. At the same time, the pavement temperature is one of the main factors that significantly affect the mixture performance. In this work the rutting performance of mixtures prepared with the same aggregate gradation and different binders [conventional (C), multigrade (M) and polymer modified (PM) asphalts] were evaluated by using wheel tracking tests (WTT) performed at 50, 60, 70 and 80°C; in parallel, the LSV of asphalts were measured at the same temperatures. The relationship between the asphalt's LSV and rutting, to predict asphalt mixture performance, was discussed and a criterion to consider the effect of LSV is proposed.

Keywords Low shear viscosity (LSV) · Rutting · Asphalt concrete performance

1 Introduction

Rutting is a common pavement distress. It is characterized by deformation in the wheel path under traffic load. When a load is applied to an asphalt concrete a small but permanent deformation occurs. The accumulated deformations produce a rut depth that causes a lower level of comfort and hazardous conditions to traffic. Traffic densities, heavy loads, slow traffic and high temperatures are the main factors that contribute to this process.

The new specifications take the asphalt binder rheological properties related to permanent deformation, fatigue and cracking asphalt mixture performance. As permanent deformations are specifically related to a mixture flow problem, it is logical to select the asphalt binder from its rheological properties.

The different rheological behaviours of unmodified and modified asphalts must be taken into account when the concrete asphalt rutting performance is evaluated. At high pavement temperatures the response of conventional asphalts when resisting small shear stresses is like a Newtonian fluid, their behaviour is simple and their viscosity is independent of shear rate. In contrast, modified asphalt behaves like a pseudo plastic fluid in which the rheological response strongly depends on the shear rate; but for very low shear rates, the behaviour turns less complex and becomes similar to a Newtonian fluid. In this case the energy is dissipated until the flow resistance that the asphalt structure offers reaches a

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constant value. At this point the viscosity becomes independent of shear rates [7]. This viscosity is called zero shear viscosity (ZSV) and is a physical property of the asphalt. In this way conventional and modified asphalt are comparable.

The asphalt ZSV has been related with the mixture rutting performance in many cases. Sybilski [11] uses the ZSV to characterize the contribution of modified asphalt binders in rutting performance. In another work [12] a good relation between ZSV and rutting performance of mixtures prepared with different asphalts was found.

Phillips and Robertus [10] concluded that ZSV is the key quantity determining the binder contribution to permanent deformation in asphalt pavement rutting. De Visscher [4] consider that the ZSV is an indicator of two rutting related binder characteristics, the stiffness and the resistance to permanent deformations under long term loading.

Many experimental methods were used to measure ZSV: the frequency sweep test, the shear rate sweep test, the creep test at a constant stress until the asphalt reaches a steady state flow, and the multi creep test. Both the frequency and shear rate sweep tests represent the most practical methods. In the frequency sweep test, asphalt's complex viscosity is measured at different frequencies at a specific temperature in a dynamic shear rheometer (DSR).

De Visscher [4] found that some modified asphalts present very high complex viscosity gradients at low frequencies, and therefore, an unrealistically high value of ZSV can be obtained. To solve this problem the use of the complex viscosity at a very low frequency called low shear viscosity (LSV) is proposed.

In a previous work it was found that the frequency sweep and creep tests give comparable LSV and ZSV results, but the former appears to be an easier test method to perform [8].

Regarding the significance and application of the study, the CEN prEN 15324 [3] uses the LSV concept to calculate a viscosity at 0.0001 Hz from viscosity data obtained in a frequency sweep test. De Visscher and Vanelstraete [5] compared unmodified and modified asphalt LSV measured at 0.0001, 0.001 and 0.01 Hz with asphalt concrete rutting performances. A good relation between rutting performance and LSV measured at 0.001 and 0.01 Hz was found, while LSV taken at 0.0001 Hz overestimates the rutting potential of modified asphalts.

Otherwise CEN prEN 15324 is also used to calculate the temperature at which the asphalt binders present a viscosity of 2000 Pa.s. This equiviscous temperature, as it is called, is considered as a performance indicator for the partial contribution of the binder to the rutting resistance of asphalt mixture at elevated pavement temperatures. This viscosity limit was obtained from studies carried out by using the wheel tracking test (WTT) in modified asphalts mixtures. It was observed that rutting drastically increases for asphalt viscosities lower than 2000 Pa.s [6].

The new laboratory test procedures, like WTT, tried to reproduce pavement conditions by studying and characterizing the asphalt rutting performance. The WTT measures the variation of permanent deformations of an asphalt concrete along a period of time under extreme temperature and load traffic conditions; however, in the field application, the pavement temperature and traffic loads are not always so extreme.

Summarizing, the asphalt concrete rutting performance is related to the binder rheological properties as well as the traffic and temperature conditions of the pavement; but for mixture design these variables are analyzed independently. In this work the rutting performance of asphalt concretes exposed to a temperature range between 50 and 80°C were studied through the WTT. Mixes were prepared with different types of asphalts and, at the same time the asphalt's LSV was measured along the same temperature range through the frequency sweep test method. The relationship between LSV and rutting performance of the asphalt mixtures is discussed.

2 Experimental

2.1 Materials

A typical dense grade asphalt mixture (D-20) was designed through the Marshall Method using granite aggregates from the province of Buenos Aires, Argentina. Figure 1 shows the mixture graduation. Three asphalt mixtures were made with asphalts currently used in Argentina, Conventional (C), Multigrade (M) and Polymer Modified (PM). Table 1 presents their main characteristics including penetration, softening point (R & B), Brookfield viscosity at 60°C, torsional recovery test results, as well as their

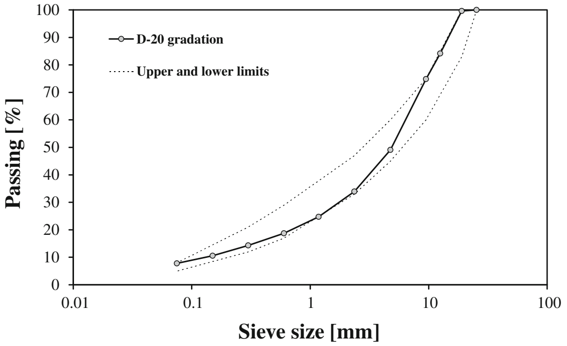

Fig. 1 Mixture gradation

Table 1 Asphalt binder properties (main program)

Asphalt binder	C	M	PM
Modification	–	Multigrade	SBS
Argentina standard type	CA-30	–	AM3-C
Penetration to 25°C (dmm)	55	60	64
Softening point (R & B) (°C)	51.8	58.3	95.5
Brookfield viscosity at 60°C (Pa.s)	297.6	1224	–
Torsional recovery (%)	–	–	77.2
PG[a]	64–16	70–22	70–22

[a] Performance grades (ASTM D 6373 1999)

Performance Grades (PG) according to the ASTM D 6373 standard [1]. The asphalt content was kept constant for all mixtures and these are identified by the type of asphalt binder used.

2.2 Testing program

In the main program, the asphalt mixture performance at different temperatures was studied within laboratory controlled conditions performing the WTT at 50, 60, 70 and 80°C. These temperatures were chosen because they represent the temperature range in which asphalt pavement permanent deformation occurs.

Eight samples, 300 mm wide and 50 mm high, were cast for each asphalt concrete and tested in pairs at each selected temperature. The specimens were compacted using roller compactor equipment [13]; with the same procedure and times for each of the samples. The densities were controlled to verify a minimum of 98% of the design density.

At the same time, the LSV of each original asphalt binder was measured at the same temperatures (50, 60, 70 and 80°C).

Based on these tests the relationship between rutting performance, temperature and the asphalt rheological properties (represented by the LSV) was studied and a prediction formula for mixture performance by LSV was obtained.

Finally to validate the obtained formula a complementary program was performed. Two other conventional asphalts (C1 and C2), two modified asphalts (M1 and M2) and oxidized asphalt (O) were chosen (see Table 2); and measurements of asphalt LSV and mixture rutting performance tests were done.

2.3 Test procedures

2.3.1 *Frequency sweep test*

A DSR Paar Physica SM-KP with a Rheolab MC-100 was used to evaluate the rheological behaviour of the asphalts. The equipment has a thermo stabilizer to allow the temperature to be set in a range from 0 to 90°C through a water recirculation system that surrounds the asphalt sample.

Table 2 Asphalts properties (complementary program)

Asphalt binder	C1	C2	M1	M2	O
Modification	–	–	EVA	SBS	Oxidized
Argentina standard	CA-10	CA-20	AM2	AM3	
Penetration to 25°C (dmm)	89	60	64	64	17
Softening point (R & B) (°C)	47.4	54.2	69.2	95.5	65.7
Brookfield viscosity at 60°C (Pa.s)	147.2	256.0	270.4	–	2524
Torsional recovery (%)	–	–	67.2	77.2	–
PG	58–22	64–22	70–28	70–22	76–10

The frequency sweep test method was used to obtain the asphalts LSV. The frequency sweeps were done in a 10–80°C temperature range at 10°C steps. The Plate-plate configuration was used in all DSR tests. In the lower temperature range (10–30°C) an 8 mm diameter and 2 mm gap sample geometry was used. Meanwhile for the upper temperature range (40–80°C) a 25 mm diameter and 1 mm gap sample geometry was used. The frequency sweeps were done from 0.5 to 10 Hz and from 1 to 10 Hz for the lower and upper temperatures ranges, respectively. The frequency sweep test was done inside the linear viscoelastic region of the studied asphalts.

Master curves for reference temperatures of 50, 60, 70 and 80°C were built using the frequency-temperature superposition principle trough the frequency sweeps at different temperatures. The Cross model is used to fit the complex viscosity data, Eq. 1.

$$\eta' = \eta'_\infty + \frac{\eta'_0 - \eta'_\infty}{1 + (k \cdot f)^n} \tag{1}$$

where η', viscosity data; η'_0, ZSV; η'_∞, limiting viscosity; K and n, model constants; f, frequency in Hz. As recommended by De Visscher, the LSV was calculated at a frequency of 0.001 Hz for each reference temperature.

2.3.2 *WTT*

The WTT (B.S. 598 part 110 1996) was used to characterize the asphalt mixture rutting performance within laboratory controlled conditions. The device consists of a solid rubber wheel, of 207 mm diameter and 47 mm width, loaded with 520 ± 5 N. The loaded wheel describes a simple harmonic motion with a total travel distance of 230 mm and a frequency of 21 cycles per minute over a sample of asphalt concrete. Test samples were compacted to the design Marshall density. Rutting depth was measured in 1 min intervals by a LVDT over a period of 120 min. The collected data are fitted with the potential model, Eq. 2. The first ten data collected were not taken into account because they significantly affect the fit.

$$\varepsilon_p = a \cdot t^b \tag{2}$$

where ε_p, permanent deformation data; t, time; a and b, model constants. The rutting performance was evaluated through the Rutting rate (Rr); this parameter represents the rate of chance in rut depth determined over the last part to the rut depth-time curve. It is calculated as Eq. 3 indicates where $D_{120\text{min}}$ and $D_{105\text{min}}$ are the deformations at 120 and 105 min, respectively.

$$Rr = \frac{D_{120} - D_{105}}{15\ \text{min}}\left[\frac{\mu\text{m}}{\text{min}}\right] \tag{3}$$

3 Test results and discussion

3.1 The effect of temperature and asphalt LSV on rutting performance

The rutting performances of each asphalt mixture were studied in the WTT. Figure 2 shows a typical curve of permanent deformation versus time obtained in the WTT. A potential model (Eq. 2) was used to fit the collected data. After that the Rr was calculated (Eq. 3).

Table 3 shows the Rr results and the asphalt LSV obtained during the main program for mixtures tested at different temperatures. Table 3 also show the fit values obtained in the potential model (a and b, as well the corresponding R^2) for each mixture.

Figure 3 shows the variation of Rr with temperature for the three asphalt mixtures. As expected, it is clearly seen that the asphalt rutting performance decreases as the temperature increases and that the rutting susceptibility is higher for conventional asphalt mixture (C) than for M and PM mixtures.

Nevertheless, if the Rr measurements (WTT) are represented as a function of the asphalt's LSV

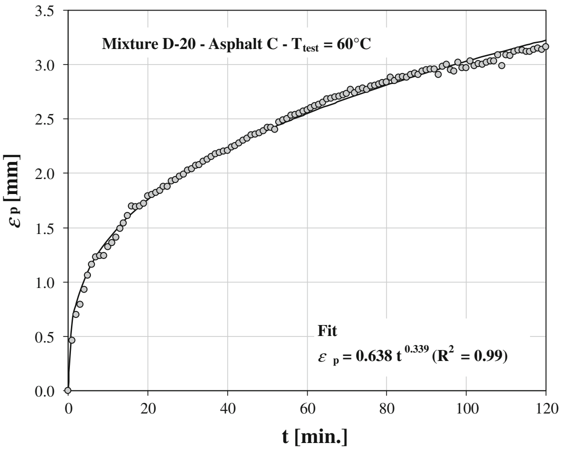

Fig. 2 Permanent deformations versus time curve

Table 3 Effect of temperature on LSV and *Rr*

Asphalt	T (°C)	LSV (Pa.s)	Fit values			*Rr* (µm/min)
			a	*b*	R^2	
C	50	1012.4	0.67	0.23	0.99	3.9
	60	252.5	0.64	0.34	0.99	9.6
	70	83.2	0.67	0.46	0.99	23.4
	80	34.3	–	–	–	–[a]
M	50	3631.1	0.25	0.25	0.91	2.4
	60	947.5	0.42	0.26	0.98	3.4
	70	308.1	0.65	0.29	0.99	6.7
	80	120.5	0.88	0.35	0.99	14.1
PM	50	7669.9	0.58	0.20	0.97	2.3
	60	2459.3	0.49	0.23	0.98	3.0
	70	911.3	0.45	0.26	0.98	3.5
	80	383.1	0.44	0.30	0.98	4.9

[a] Test cannot be carried out

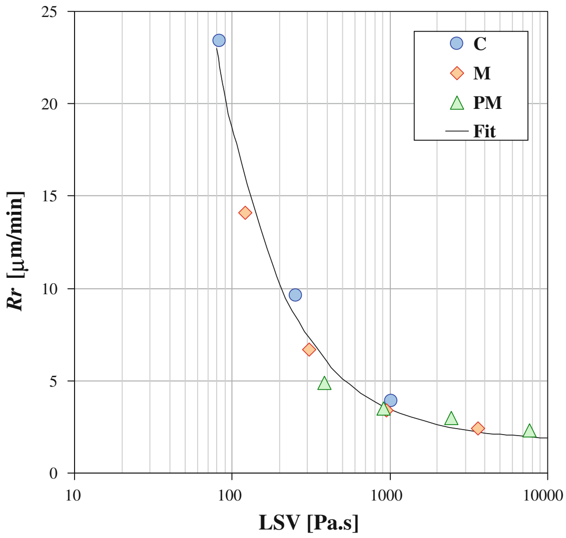

Fig. 4 Asphalt mixtures *Rr* versus asphalt LSV

determined at each test temperature, Fig. 4, all mixtures follow a similar tendency. In addition Fig. 4 shows that *Rr* drastically changes for low LSV values. With this dense grade asphalt mixture (D-20), considering all the temperatures range and the type of asphalts studied, strong changes in rutting resistance appear when the asphalt binder presents LSV values lower than 500 Pa.s.

In the standard CEN prEN 15324 a LSV value of 2000 Pa.s is used to calculate an equiviscous temperature. As was mention above, this viscosity limit was obtained in studies carried out by using the WTT in modified asphalts mixtures [6]. When considering this LSV as a limit in most cases test results fall outside, as a consequence this limit appears here as a rigorous threshold for practical applications.

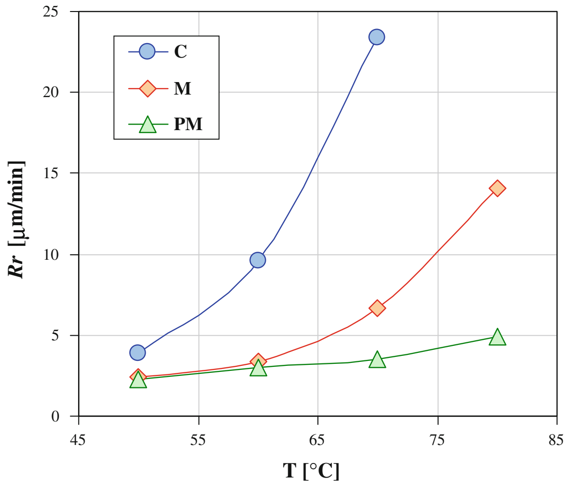

Fig. 3 *Rr* versus temperature relationship in concrete asphalts prepared with different binders

It is important to mention that in these experiences the LSV was measured in the asphalts in their original state. Measuring LSV on aged asphalts a higher threshold will be obtained. Then, both limits on original and aged asphalts, must be considered. This topic will be analyzed in a future work.

As it is known, the asphalt binder rheological properties as well as the test temperature affect the mixture rutting performance. These tests confirm that the rutting behaviour varies with the type of asphalt binder at a given temperature and also changes with test temperature for the same asphalt binder (Fig. 3). The relationship between rutting performance, rheological properties (LSV) and temperature could be of interest in practice.

Usually the standards fix the temperature at which the test is to be carried out. In the WTT, 60°C is selected, which represents one of the highest temperatures that occur in asphalts pavements. According to the kind of binder, some asphalt mixtures cannot present an acceptable rutting behaviour at this temperature; but they can behave efficiently at lower temperatures.

By plotting the LSV versus temperature curves, Fig. 5, the temperature at which each asphalt binder present a LSV of 500 Pa.s can be obtained (T_{500}).

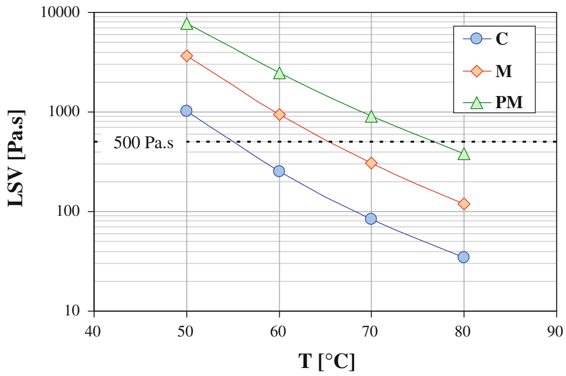

Fig. 5 Asphalt LSV versus temperature

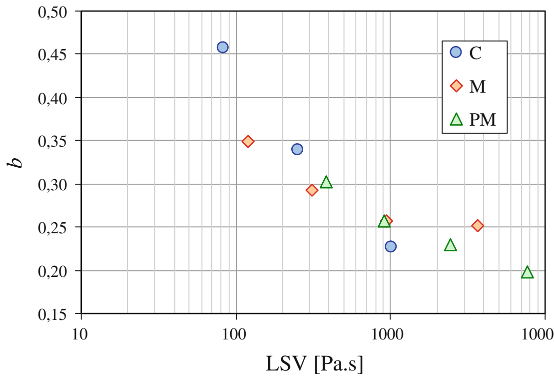

Fig. 6 Parameter *b* versus LSV

This temperature can be associated with the maximum pavement temperature at which each asphalt mixture can be submitted without compromising its rutting resistance. In this case values of T_{500} equal to 54.8, 65.5, and 76.8°C are obtained for C, M and PM asphalts, respectively. This fact is in accordance with the higher thermal susceptibility of the C asphalt mixture compared with the M or PM asphalt mixtures.

As was observed in Fig. 4 the asphalt mixtures follow a single curve when the *Rr* is represented as a function of the asphalt LSV. An *Rr*–LSV relationship was obtained fitting the data by a non lineal regression as Eq. 4 indicates.

$$Rr = 1.755 + \frac{1698.35}{\text{LSV}} \quad \left(R^2 = 0.98\right) \tag{4}$$

The relation *Rr*–LSV can be used to estimate the asphalt rutting resistance at different temperatures only if the asphalt's LSV at these temperatures is known. This appears to be a good way to select and optimize the asphalt binder during the mix design in accordance to the environmental conditions of the asphalt pavement in the field.

It must be considered that this relationship was analyzed for a particular dense grade asphalt mixture (D-20). Other asphalt mixtures such as Micro and Stone Mastic Asphalts (SMA) made with the same asphalt binders showed different rutting responses. The relationship between temperatures and the asphalt's LSV will be analyzed in a future work to observe if these mixtures show behaviour similar to the D-20 mixture.

As a final comment it must be mentioned that the parameter *b* (Eq. 2) should also be used instead of *Rr* to evaluate the rutting performance of asphalt mixtures, leading to similar conclusions (see Fig. 6). However, as the different standards of WTT (BS 598 [2], UNE 12697-22 [14], NLT 173 [9]) calculate a value of rutting rate as a result. Then, the use of the parameter *Rr* was preferred here to evaluate the rutting performance of asphalt mixtures.

3.2 Experimental validation

To validate the obtained relationship (Eq. 4) asphalt mixtures of similar characteristics (D-20) were prepared using other binders: two conventional asphalts (C1, C2), two modified asphalts (M1, M2) and oxidized asphalt (O). Mixtures are identified in accordance to the binder used.

Rutting rate values were obtained by WTT (Rr_{measured}), tests were performed at 50 and 60°C for C1 and C2, at 50, 60 and 70°C for M1 and only at 60°C in the case of M2 and O mixtures. Meanwhile, measurements of the asphalt's LSV at the same temperatures were taken for each binder.

Rutting rate was estimated using Eq. 4 ($Rr_{\text{estimated}}$). Table 4 shows the experimental LSV and Rr_{measured} test results and the calculated values of $Rr_{\text{estimated}}$. In the last column of Table 4 it is possible to see the error between estimated and measured rutting values.

Figure 7 plots the WTT rutting rate measurements (Rr_{measured}) versus the estimated values ($Rr_{\text{estimated}}$). All values are very close to the equality line showing the aptness of this proposal to estimate long term deformation behaviour in concrete asphalt mixtures.

Table 4 Experimental test results and calculated values (complementary program)

Asphalt	Experimental data			Calculated data	
	T test (°C)	LSV (Pa.s)	Rr_{measured} (μm/min)	$Rr_{\text{estimated}}$ (μm/min)	e^{a} (%)
C1	50	554.1	5.5	4.8	12.4
	60	163.8	12.4	12.1	2.2
C2	50	1024.1	3.5	3.4	2.5
	60	346.3	6.7	6.7	0.6
M1	50	3534.4	2.3	2.2	2.8
	60	595.0	3.7	4.6	24.6
	70	147.7	10.4	13.3	27.4
M2	60	2642.1	2.7	2.4	11.2
O	60	1106.4	2.8	3.3	17.5

[a] $e = 100 \cdot |1 - (Rr_{\text{estimated}}/Rr_{\text{measured}})|$

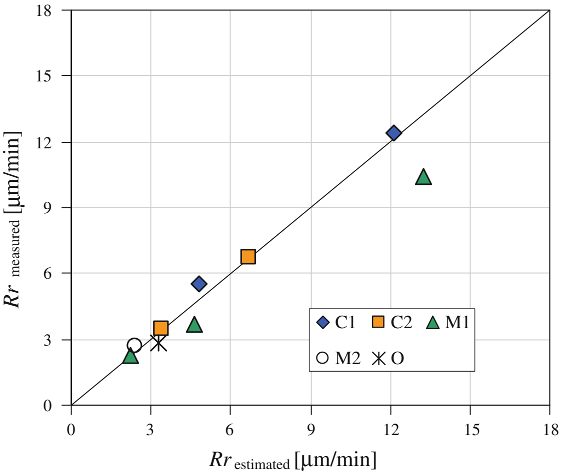

Fig. 7 *Rr* measured in WTT versus *Rr* estimated

4 Conclusions

The effects of temperature on the rutting performance of concrete asphalts elaborated with different asphalt binders were studied through the WTT. To consider the effect of the type of binder, particularly the rheological properties, the asphalt LSVs were measured at different temperatures using the frequency sweep test method. The main conclusions are indicated as follows.

As expected the rutting rate (*Rr*) depends on the type of asphalt binders and a lower performance takes place as the temperature increases. The *Rr* thermal susceptibility was higher for the Conventional asphalts followed by Multigrade and Polymer Modified asphalts.

For a same mixture graduation the *Rr* performance versus asphalt's LSV follow a similar behaviour beyond the used asphalt binder.

The asphalt mixture study showed drastic changes in rutting resistance when the original asphalt binder achieved LSV values lower than 500 Pa.s for all the temperature range and asphalts studied here. For these asphalt mixture this viscosity appears as a limit to the partial contribution of the asphalt binder to the rutting resistance. Based on this viscosity level, maximum temperatures for each asphalt binders can be defined; below which the asphalt mixture rutting resistance is acceptable.

An *Rr*–LSV relation was obtained for the study dense grade asphalt mixtures prepared with different asphalt binders. This can be used to estimate the asphalt rutting resistance at different temperatures only if the asphalt's LSV, at these temperatures, is known.

The relation *Rr*–LSV appears to be a good way to select and optimize the asphalt binder in accordance to the environmental conditions of the asphalt pavement.

The proposed procedure appears to be a practical tool to estimate the effect of a change in the binder on the asphalt concrete rutting performance.

The relation with temperatures and the asphalt's LSV will be analyzed in a future work to observe if other asphalt mixtures show a similar behaviour to dense mixture studied.

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