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# A novel procedure for the evaluation of anti-rutting potential of asphalt binders

Asphalt binders play an important role in the rutting performance of road pavements, and therefore their characterization is crucial in preventing this type of distress. Several studies have been carried out to replace the  $G^*/\sin\delta$  Superpave criteria which was found to be inadequate to capture the anti-rutting potential of these materials. In this paper, a novel testing procedure combining single creep-recovery and multiple stress creep tests is proposed. Five asphalt binders of different type and origin were considered. For comparison purposes, two available standard methods, based on low shear viscosity and multiple stress creep recovery tests, were included in the study. Obtained experimental results indicated the effectiveness of the test method in highlighting fundamental material properties related to rutting, overcoming some of the drawbacks of existing standard protocols.

Keywords: rutting; asphalt binders; SBS; crumb rubber; creep-recovery

## 1 Introduction

One of the main distress types affecting asphalt pavements is rutting. Such a distress results from the accumulation of permanent deformation produced by repeated axle loads in asphalt-bound layers. Presence of ruts on pavement surfaces leads to a low level of comfort and safety, thus producing a decrease of overall road serviceability.

Several factors may influence the occurrence of rutting in asphalt concrete mixtures, including binder properties, aggregate physical characteristics and mixture volumetrics (Cooper *et al.* 1985; Monismith *et al.* 1985; Sousa *et al.* 1991). However, due to their temperature- and time-dependant behavior, asphalt binders play a major role in the development of rutting, especially at high in-service temperatures and under heavy and slow-moving vehicles (Delgadillo and Bahia 2010).

According to the approach originally proposed by the Superpave binder grading system, control of rutting performance is based on viscoelastic parameter  $G^*/\sin\delta$ , which at the maximum pavement design temperature should be compared with fixed limiting values both in the original and short-term aged state (Harrigan *et al.* 1994, Anderson *et al.* 1994). Nevertheless, several studies demonstrated the inadequacy of  $G^*/\sin\delta$  in evaluating the true anti-rutting potential of asphalt binders, especially in the case of polymer-modified products (Bahia *et al.* 2001; D'Angelo and Dongre 2002). As a consequence, different methods and criteria have been introduced by researchers to replace the Superpave parameter.

Sybilski (1994) proposed the use of the zero shear viscosity (ZSV) concept to characterize rutting properties of asphalt binders. ZSV is the value of viscosity exhibited by asphalt binders subjected to shear deformation as shear rate approaches zero. Experimental results obtained by Sybilski (1996) and Phillips and Robertus (1996) showed a good correlation between rutting performance of binders and that of corresponding asphalt mixtures. However, other authors questioned the use of the ZSV concept for those materials, such as highly polymer-modified binders, which behave as viscoelastic solids due to their cross-linked structure (Desmazes *et al.* 2002; Morea *et al.* 2010). In order to overcome these limitations, De Visscher and Vanelstraete (2009)

introduced the alternative concept of low shear viscosity (LSV).

With the purpose of simulating the intermittent nature of traffic loading, under NCHRP 9-10 project, Bahia *et al.* (2001) proposed the use of repeated creep recovery tests (RCRT) at high temperatures. The original NCHRP 9-10 test procedure required creep and recovery testing at a single stress level. Moving from the fact that materials like polymer-modified binders may exhibit a significant stress dependency, D'Angelo *et al.* (2007) improved the RCRT by defining a multiple stress creep recovery test method (MSCR).

Findings of the abovementioned studies led to the development of standard LSV (CEN/TS 15324 2008) and MSCR (AASHTO TP70-10 2010) test protocols which are currently used for the evaluation of rutting resistance of asphalt binders. Recent studies, however, revealed the existence of some drawbacks for both protocols. In the case of LSV, viscosity lines obtained for polymer-modified binders may show the absence of a plateau value, which implies that LSV cannot be determined as the viscosity continues to increase as shear rate decreases (Zoorob *et al.* 2012a). In the case of MSCR, the current protocol, which involves the application of 1 s loading followed by 9 s recovery, may not ensure full delayed elastic recovery for cross-linked materials such as binders modified with SBS polymers (Merusi and Giuliani 2011; Zoorob *et al.* 2012b).

More recently, Santagata *et al.* (2013) used a method consisting in single creep-recovery tests run at predefined loading and recovery times. Experimental results indicated the effectiveness of the proposed method in discriminating between the behavior of a wide set of polymer-modified binders and in capturing the effects caused by different factors related to modification, such as polymer type, composition, structure and dosage.

In the research work reported in this paper, a novel procedure involving single creep-recovery (SCR) tests combined with multiple stress creep (MSC) tests was used to evaluate the anti-rutting potential of five different asphalt binders. For comparison purposes, binders were also characterized by means of the abovementioned LSV and MSCR standard protocols. On the basis of obtained results, effectiveness of the different methods was analyzed and discussed.

## 2 Materials and equipment

Asphalt binders used in the experimental investigation were selected in order to cover a wide spectrum of visco-elastic properties, with the purpose of highlighting the effectiveness of different test methods in discriminating their performance characteristics.

The set of selected materials included:

- two neat bitumens (NA and NB) belonging to the same penetration grade (50-70) which were sampled from refineries operating on crudes of different origin and source;
- two polymer-modified binders (PMBS and PMBH) which were originated from base bitumen NB by adding a low and high percentage of styrene-butadiene-styrene co-polymer (SBS), respectively, according to the undisclosed processing scheme adopted by the plant which provided the material;

- one commercially available asphalt rubber (AR) containing 18% crumb rubber (by weight of base bitumen) derived from the grinding of end-of-life tyres.

All binders were investigated in short-term aged conditions after being subjected to the Rolling Thin Film Oven Test (RTFOT) in accordance with AASHTO T240 (2009).

Rheological measurements were carried out by means of a Physica MCR 302 Dynamic Shear Rheometer (DSR) from Anton Paar Inc., an air bearing stress-controlled device equipped with a permanent magnet synchronous drive (minimum torque = 0.1  $\mu$ Nm, torque resolution < 0.1  $\mu$ Nm) and an optical incremental encoder for measurement of angular rotation (resolution < 1  $\mu$ rad). The 25 mm parallel plates geometry was employed for testing with a 1.0 mm gap between the plates. The only exception was made in the case of the AR binder, for which the gap was increased to 1.5 mm to avoid wall effects due to the maximum crumb rubber particle size, equal to 0.8 mm (Mituri *et al.* 2011). At least two replicates were run for each measurement and average data were considered in the analysis.

Preliminary rheological tests were performed on asphalt binders in order to determine their high limiting performance-grade temperatures ( $T_{PG-H}$ ), corresponding to  $G^*/\sin\delta$  equal to 2.2 kPa. Obtained results are reported in Table 1.

Table 1. High limiting performance-grade temperatures of the asphalt binders

Binder Code	Description	$T_{PG-H}$ [°C] [ $G^*/\sin\delta = 2.2$ kPa]
NA	Neat	68.3
NB	Neat	66.0
PMBS	Modified with SBS (low polymer content)	70.5
PMBH	Modified with SBS (high polymer content)	81.7
AR	Modified with crumb rubber	101.5

### 3 LSV and MSCR testing

Characterization of asphalt binders based on the LSV concept was carried out in accordance with CEN/TS 15324 (2008), which requires tests to be performed in two subsequent steps.

The first step involved a temperature sweep carried out in 1°C increments at a frequency of 0.01 Hz and at a strain amplitude of 0.1. Temperature values varied over a range which depended on binder type: in particular, temperature ramps were imposed between 40 and 60°C for neat binders NA and NB, between 48 and 68°C for low polymer content modified binder PMBS, between 55 and 78°C for high polymer content modified binder PMB, and between 70 and 120°C for asphalt rubber AR. Resulting plots of complex viscosity  $\eta^*$  versus temperature in the semi-log scale are reported in Figure 1.

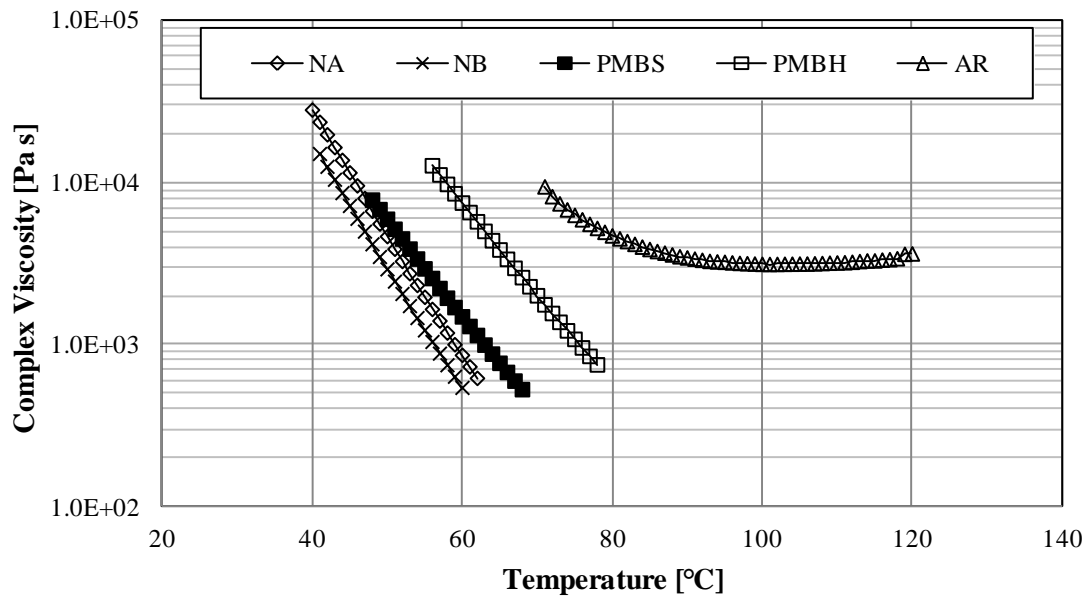


Figure 1. Complex viscosity obtained from temperature sweep tests (LSV protocol)

An almost linear trend was observed for neat (NA and NB) and SBS modified (PMBS and PMBH) binders, with complex viscosity values covering an interval that in all cases was coherent with that recommended by CEN/TS 15324. A completely different behaviour was exhibited by binder AR. In this case, three subsequent stages can be distinguished: an initial stage in which complex viscosity decreased with temperature, an intermediate stage (starting at around 90°C) during which complex viscosity remained approximately constant, and a final stage (starting at around 115°C) in which complex viscosity showed a slight increase with temperature. This evidence can be related to the fact that at increased temperatures the bond between crumb rubber particles and the bituminous matrix becomes very loose, due to the reduced viscosity of base bitumen. In such conditions, rheological properties of the bulk material are mainly governed by crumb rubber particles, showing a typical rubber-like response under oscillatory loading.

From the analysis of complex viscosity as a function of temperature, equiviscous temperatures (EVT1) corresponding to a predefined low shear viscosity value (LSV1) equal to 2,000 Pa·s were determined. The minimum LSV value of 2,000 Pa·s has been recommended to ensure a sufficient contribution of the binder to rutting resistance of asphalt concrete mixtures (De Visscher and Vanelstraete 2009). In the case of binder AR, over the temperature interval adopted for testing, complex viscosity values never fell below the reference threshold: this makes the determination of EVT1 impossible and reveals that the LSV standard protocol is not applicable for this type of material. Results obtained for the other binders are summarized in Table 2.

Table 2. Equiviscous temperature values obtained from temperature sweep tests (LSV protocol)

Binder Code	EVT1 [°C] [ $\eta^* = 2.0 \text{ kPa}$ ]
NA	55.0
NB	52.3
PMBS	57.9
PMBH	70.3
AR	-

In the second step, as required by CEN/TS 15324, frequency sweeps were performed at a test temperature equal to EVT1 (different for each binder), imposing progressively lower shear rates corresponding to a frequency range comprised between 1 and 0.003 Hz. For the reasons explained above, binder AR was excluded from this part of the investigation. Obtained results are diagrammed in Figure. 2.

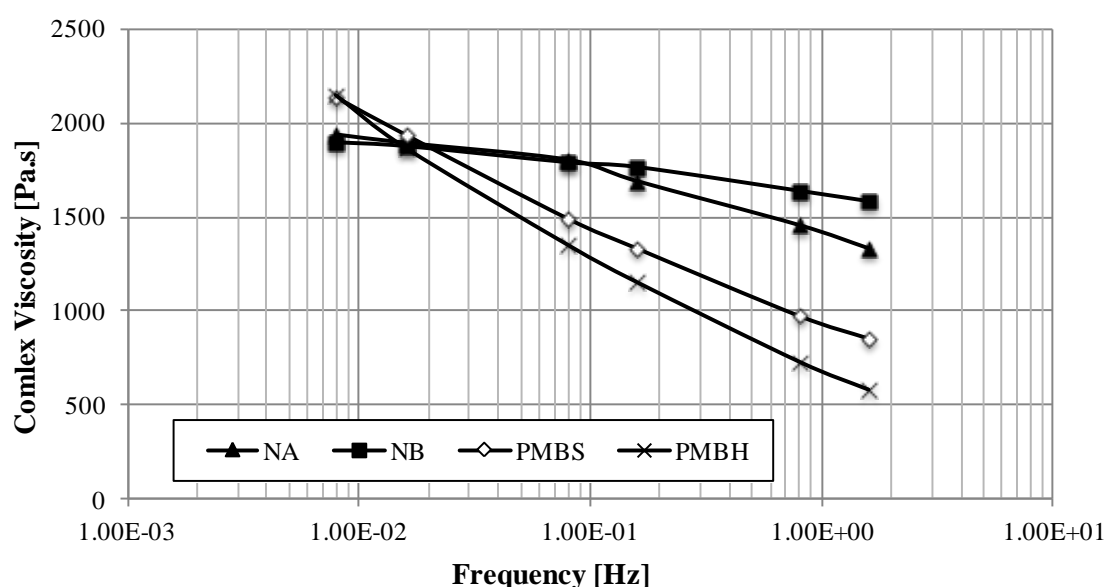


Figure 2. Complex viscosity obtained from frequency sweep tests (LSV protocol)

CEN/TS 15324 suggests the calculation of a second, more reliable, value of low shear viscosity (LSV2) by extrapolating frequency sweep data to 0.0001 Hz. The corresponding equiviscous temperature (EVT2) can be calculated by means of an adjustment factor  $\Delta T$ , which represents the increase in equiviscous temperature that would occur if the previous temperature sweep were carried out at 0.0001 Hz instead of 0.01 Hz. Results obtained for the four binders subjected to analysis are listed in Table 3.

Table 3. Equiviscous temperature and low shear viscosity values obtained from frequency sweep tests (LSV protocol)

Binder Code	LSV2 [Pa·s]	EVT2 [°C]
NA	2421	56.1
NB	2015	52.3
PMBS	3168	61.3
PMBH	3223	71.9

Coherently with the findings of other studies (Zoorob *et al.* 2012a; Zoorob *et al.* 2012b), data corresponding to neat binders showed the presence of a viscosity plateau and therefore led, by means of curve fitting, to the calculation of reliable low shear viscosity values which were slightly greater than the default value considered in the first step of the protocol. A small increase of equiviscous temperature was recorded for binder NA, while in the case of binder NB no variation was observed due to the fact that LSV2 and LSV1 were practically equal.

In the case of binders PMBS and PMBH, complex viscosity showed a monotonic increase with the decrease of loading frequency. In the absence of any plateau, this makes the extrapolation of viscosity to 0.0001 Hz not fully coherent with the low shear viscosity concept, confirming that the employed test protocol is not appropriate to characterize rutting properties of SBS polymer-modified binders.

MSCR tests were performed according to AASHTO TP 70-10 (2010), with 1 s creep loading and 9 s recovery at two different stress levels (equal to 0.1 and 3.2 kPa), applying 10 cycles for each stress value. Different temperature ranges were used depending on the type of material: 52-70°C for binders NA and NB, 52-76°C for binder PMBS, and 64-88°C for binders PMBH and AR. In all cases, a 6°C increment was adopted to pass from each measuring step to the following one.

Experimental data retrieved from MSCR tests were analyzed in order to determine non-recoverable creep compliances ( $J_{nr0.1}$  and  $J_{nr3.2}$ ), given by the average non-recovered strains occurring in the 10 creep and recovery cycles divided by the corresponding applied stress. Figure 3 shows non-recoverable compliance values plotted as a function of temperature for all asphalt binders considered in the study.

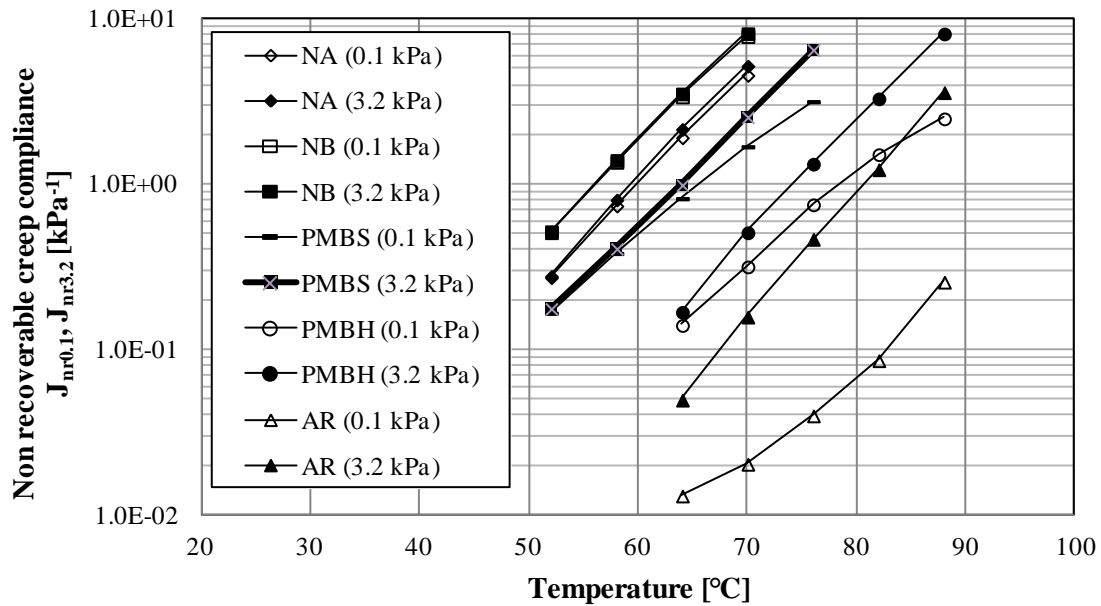


Figure 3. Non-recoverable creep compliance obtained from MSCR tests

As expected,  $J_{nr0.1}$  and  $J_{nr3.2}$  increased with temperature as a consequence of the combined effects of increased total strain (reduced creep stiffness) and increased relative amount of permanent component of total strain. Neat binders (NA and NB) exhibited a similar behaviour, with non-recoverable compliances which were distinctly higher than those of SBS modified binders (PMBS and PMBS) and asphalt rubber (AR). In addition, curves corresponding to 0.1 and 3.2 kPa overlapped almost perfectly, indicating both materials to be in their linear visco-elastic domain. By considering the modified binders, asphalt rubber AR was observed to show the highest rutting resistance combined with the most pronounced non-linear response at all temperatures, followed by PMBH and PMBS. For all modified materials, non-recoverable compliance values at 3.2 kPa always exceeded those obtained at 0.1 kPa.

An important aspect that must be taken into account in the use of  $J_{nr}$  for binder performance characterization is related to the fact that it is a mechanical parameter not univocally connected with non-reversible deformation (Merusi 2012). In fact,  $J_{nr}$  is determined on the basis of strains measured at the end of the recovery phase of each cycle, without distinguishing between different types of components. In other terms, if a delayed elastic component is present in measured strain at the end of the recovery phase, such a component affects the value of  $J_{nr}$ . This is clearly demonstrated by the example reported in Figure 4, in which shear strain values obtained for binder AR at a given temperature and stress level are plotted as a function of time.

It can be observed that no horizontal plateau was reached at the end of the unloading phase of each cycle, thus indicating that delayed elastic deformation was not completely recovered and that strain recorded at the end of each cycle was certainly affected by the residual strain recorded at the end of the previous ones. A similar response was obtained for other SBS modified binders at all test temperatures and stress levels considered in this study.



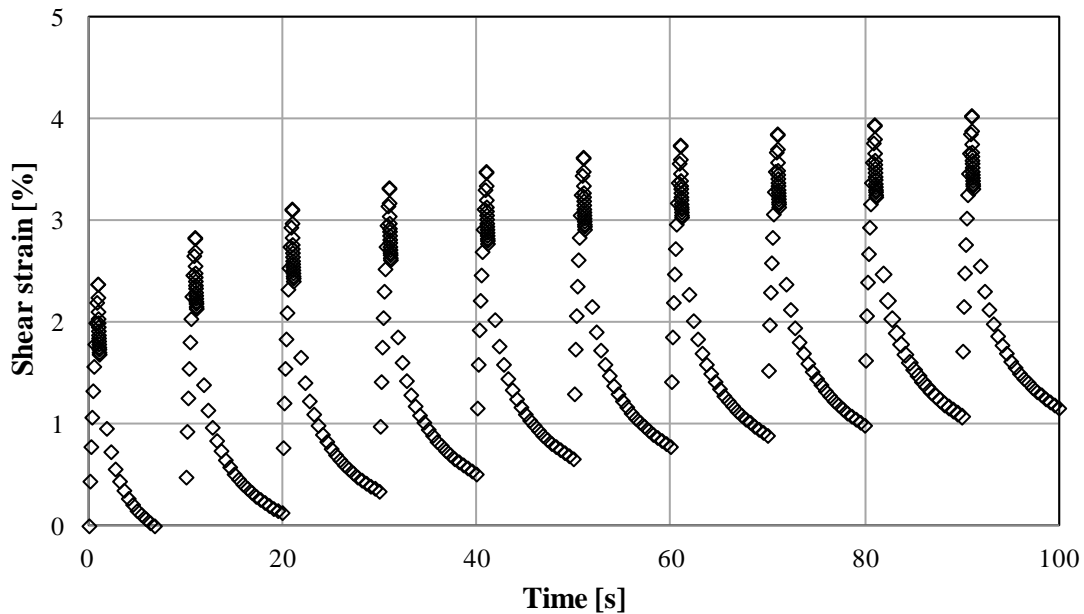


Figure 4. Typical results of a MSCR test (binder AR, 70°C, 0.1 kPa)

#### 4 SCR-MSR testing

The SCR-MSR testing procedure used in this study consists in single creep-recovery (SCR) tests combined with multiple stress creep (MSC) tests.

SCR tests were carried out at four temperatures (with 6°C increments between each one) at a single stress level, equal to 100 Pa. The basic assumption was made that the contribution of asphalt binders to rutting resistance of asphalt concrete mixtures can be described by separating delayed elastic deformation from viscous flow (Merusi and Giuliani 2011). As a consequence, the duration of creep and recovery phases of SCR tests was set in order to allow materials to reach steady-state flow under loading and to recover all delayed elastic deformation after load removal. Neat binders were expected to flow quite quickly in the temperature range selected for testing, whereas in the case of binders modified with crumb rubber or with a high dosage of SBS it was well known that steady-state conditions may be or may not be reached due to their rubber-like nature. In any case, very high creep and recovery times are generally required for these last types of materials. Following the experience of previous research works (Santagata *et al.* 2013; Baglieri 2004), test conditions adopted for each asphalt binder were those summarized in Table 4.

Table 4 also contains creep loading times adopted in MSC tests carried out at the same temperatures of SCR tests at two further stress levels, equal to 20 and 500 Pa. The use of multiple stresses was deemed necessary to evaluate the susceptibility of flow properties to stress variations, thus complementing the information retrieved from SCR data. Creep loading times of MSC tests were adjusted with respect to those adopted in SCR tests taking into account that the increase of applied stress may lead to a decrease of transition times from linear to non linear visco-elastic response (Delgadillo and Bahia 2010), thus influencing the time which is needed to reach steady-state conditions.

Table 4. Test conditions used in SCR-MSD tests

Binder Code	Temperature [°C]	SCR (Creep + Recovery)	MSD (Creep)	
		$\tau_0 = 100 \text{ Pa}$	$\tau_0 = 20 \text{ Pa}$	$\tau_0 = 500 \text{ Pa}$
NA	46	(60 + 60) s	100 s	12 s
	52	(10 + 10) s	16.7 s	2 s
	58	(3.5 + 3.5) s	5.0 s	1.5 s
	64	(1.65 + 1.65) s	4.0 s	1.0 s
NB	46	(60 + 60) s	100 s	12 s
	52	(10 + 10) s	16.7 s	2 s
	58	(3.5 + 3.5) s	5.0 s	1.5 s
	64	(1.65 + 1.65) s	4.0 s	1.0 s
PMBS	52	(600 + 1200) s	1000 s	120 s
	58	(100 + 200) s	167 s	20 s
	64	(33 + 66) s	55.0 s	3.5 s
	70	(16.5 + 33) s	44.0 s	2.0 s
PMB	58	(10,800 + 43,200) s	18,000 s	2160 s
	64	(1800 + 7200) s	3000 s	360 s
	70	(600 + 2400) s	1000 s	60 s
	76	(300 + 1200) s	800 s	40 s
AR	58	(10,800 + 43,200) s	18,000 s	2160 s
	64	(1800 + 7200) s	3000 s	360 s
	70	(600 + 2400) s	1000 s	60 s
	76	(300 + 1200) s	800 s	40 s

Figure 5 reports shear strain versus time curves derived from SCR tests carried out on the five asphalt binders at 64°C. As expected, creep time adopted for neat binders NA and NB was sufficient to allow them to flow as indicated by the constant slope of creep curves. An almost linear trend was also observed for the final portion of strain-time curves of modified binders PMBS, PMBH and AR, revealing for these materials

that quasi steady-state conditions were actually reached. Similar results were obtained at all other temperatures used for testing.

From the linear portion of creep curves, a creep compliance rate (CCR) was calculated as follows:

$$CCR = \frac{d\left(\frac{\gamma}{\tau_0}\right)}{dt} = \frac{dJ}{dt}$$

in which  $\gamma$  is shear strain,  $\tau_0$  is applied stress and  $J$  is creep compliance.

CCR represents a material property which does not depend upon time and that from a rheological point of view corresponds to the inverse of ZSV. As the ZSV, it provides a measure of the resistance to flow of asphalt binders and can thus be related to their aptitude to resist to permanent deformation under loading.

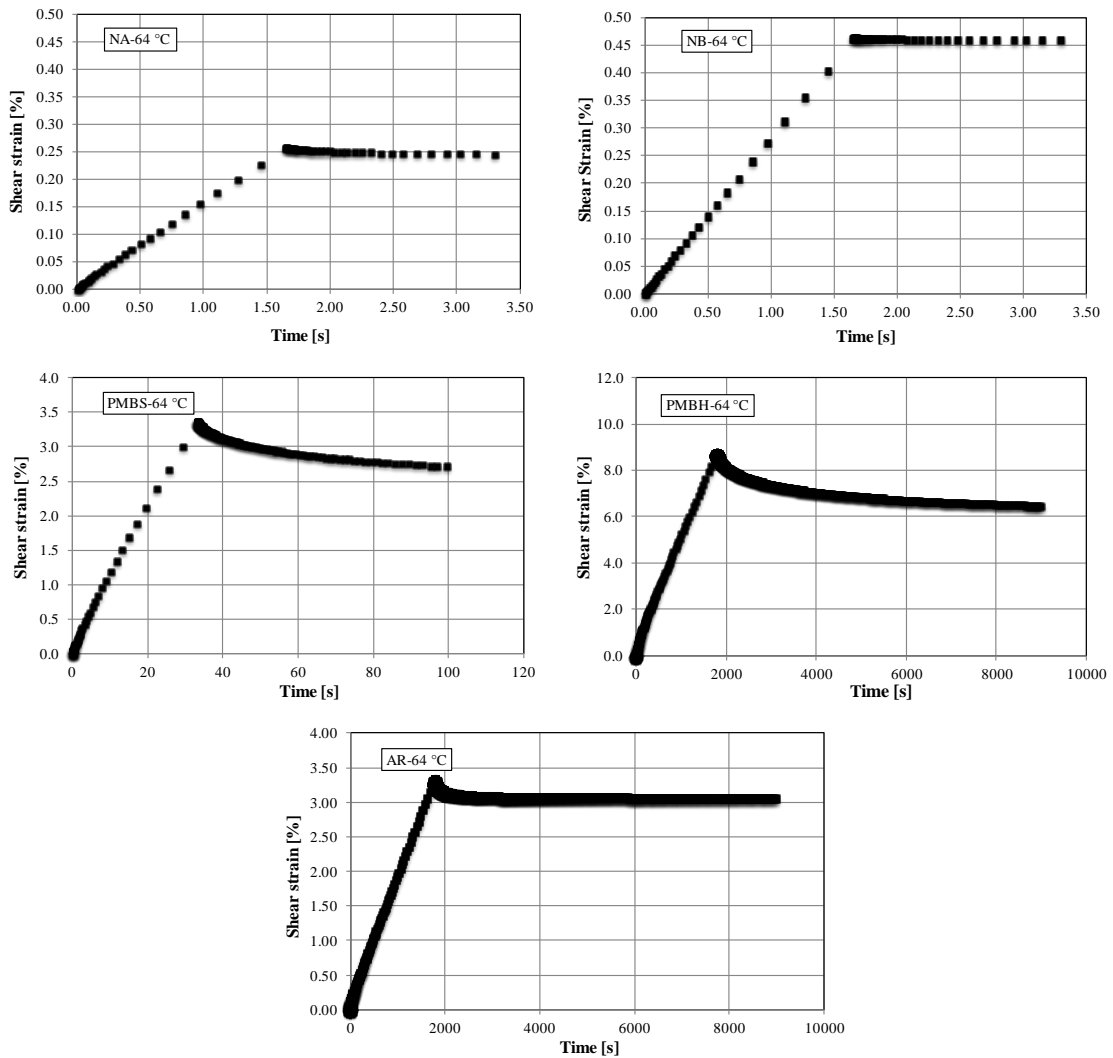


Figure 5. Shear strain versus time curves obtained from SCR tests carried out at 64°C

In Figure 6 values of CCR are plotted as a function of temperature. A linear relationship in the semi-log scale was found for all materials and coherently with

expectations CCR increased with temperature. A significant gap in creep response between neat binders (NA and NB) and highly modified binders (PMBH and AR) was highlighted, with the second ones being considerably stiffer than the first ones. The modified binder with low SBS content (PMBS) showed an intermediate response which was, however, more close to that of neat binders. A clear distinction was also made when comparing the two highly modified binders, with AR exhibiting a greater resistance to flow than PMBH over the whole temperature range.

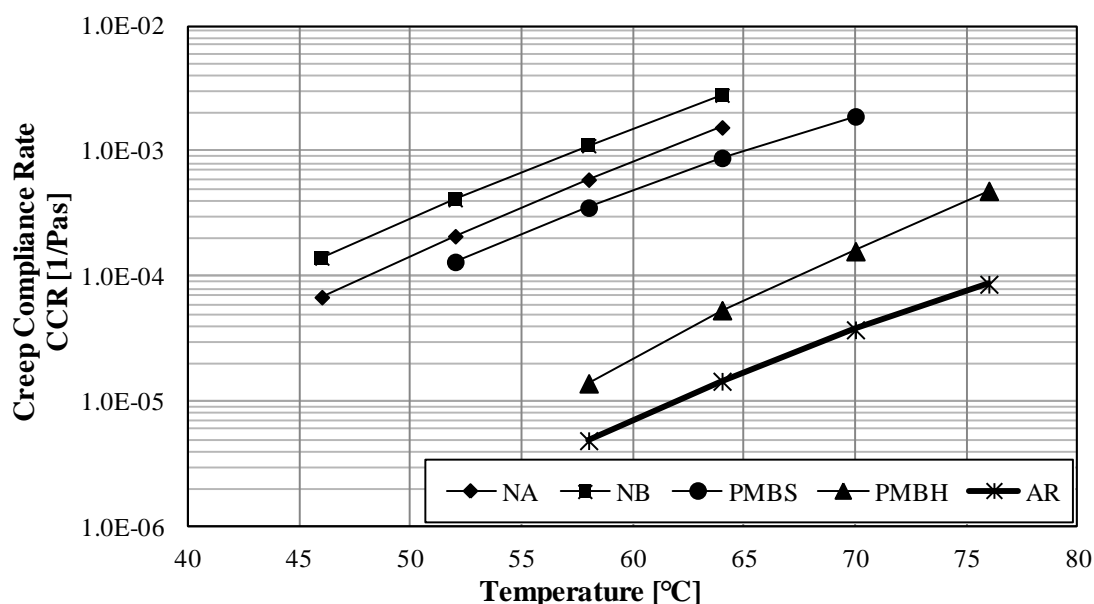


Figure 6. Creep compliance rates obtained from SCR tests

One of the main advantages offered by creep-recovery tests is that they allow permanent and delayed elastic components of accumulated strain to be directly measured. From the data recorded in the recovery phase, permanent compliance ( $J_P$ ) and delayed compliance ( $J_D$ ) were determined. The first one was calculated by dividing residual strain at the end of the recovery phase by applied stress; the second one is given by the difference between total compliance  $J_{TOT}$  at the end of the creep phase and permanent compliance  $J_P$ . A further parameter was also determined, given by the ratio between  $J_P$  and creep time  $t_C$ . Such a parameter represents the inverse of ZSV derived from the residual strain of the recovery phase (Desmazes *et al.* 2002). Obtained results are summarized in Table 5.

As specified above, both CCR and  $J_P/t_C$  can be used to estimate ZSV on the basis of strain data obtained from creep-recovery tests, leading to the same results. This is true if steady-state conditions are reached during the loading phase and a complete recovery of delayed elastic deformation is achieved at the end of the unloading phase. If these conditions are not satisfied, CCR and  $J_P/t_C$  are not consistent between each other. In the diagram shown in Figure 7, CCR values are compared with the corresponding  $J_P/t_C$  values obtained for all asphalt binders and test conditions used in the investigation. It can be noticed that all data points are close to the equality line, indicating a substantial equivalency between the two parameters. This confirms the adequacy of

creep and recovery times adopted for testing and the validity of CCR (or  $J_P/t_C$ ) to be used as a reliable indicator for the evaluation of materials' resistance to flow.

Table 5.  $J_P$ ,  $J_P/t_C$  and  $J_D$  values obtained from SCR tests

<b>Binder Code</b>	<b>Temperature [°C]</b>	<b><math>J_P</math> [Pa<sup>-1</sup>]</b>	<b><math>J_P/t_C</math> [Pa<sup>-1</sup>·s<sup>-1</sup>]</b>	<b><math>J_D</math> [Pa<sup>-1</sup>]</b>
NA	46	4.11E-03	6.85E-05	1.52E-04
	52	2.07E-03	2.07E-04	1.14E-04
	58	1.97E-03	5.90E-04	1.05E-04
	64	2.54E-03	1.54E-03	1.05E-04
NB	46	8.45E-03	1.41E-04	4.58E-05
	52	4.11E-03	4.11E-04	3.80E-05
	58	3.71E-03	1.11E-03	3.07E-05
	64	4.63E-03	2.81E-03	9.00E-06
PMBS	52	7.60E-02	1.27E-04	1.06E-02
	58	3.24E-02	3.24E-04	7.09E-03
	64	2.71E-02	8.21E-04	6.44E-03
	70	3.01E-02	1.82E-03	7.08E-03
PMBH	58	1.44E-01	1.34E-05	3.01E-02
	64	8.33E-02	4.63E-05	2.29E-02
	70	8.30E-02	1.38E-04	1.50E-02
	76	1.38E-01	4.60E-04	1.01E-02
AR	58	6.37E-02	5.90E-06	2.97E-03
	64	2.59E-02	1.44E-05	2.70E-03
	70	2.11E-02	3.51E-05	2.71E-03
	76	2.44E-02	8.12E-05	2.73E-03

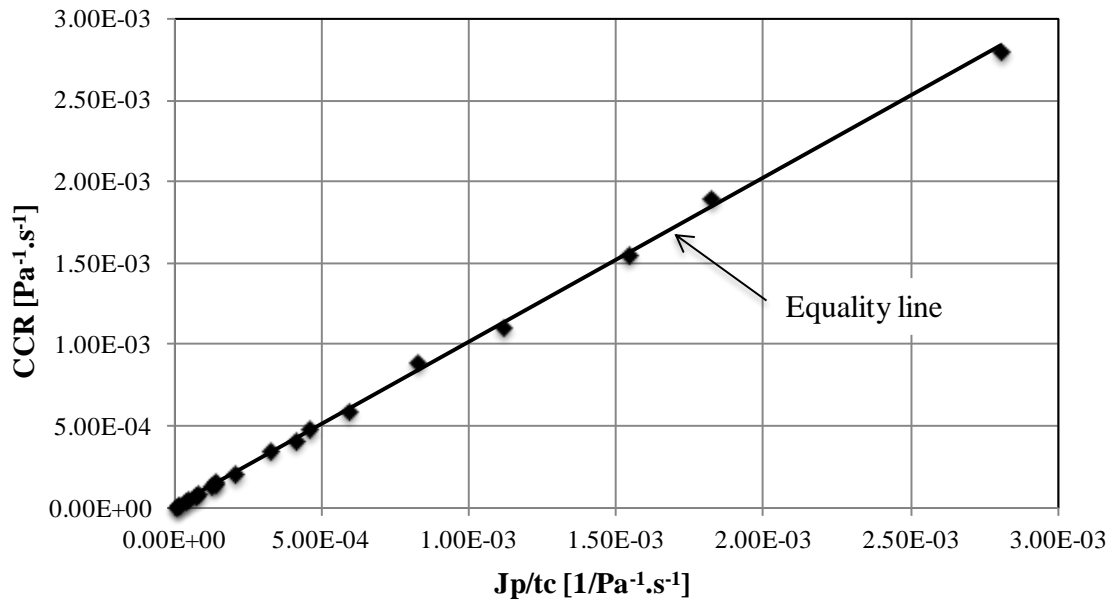


Figure 7. Comparison between CCR and  $J_p/t_c$  for all materials and test conditions

Further considerations can be drawn from the analysis of delayed compliance  $J_D$ . This parameter provides a measure of the capability of asphalt binders to recover accumulated deformation and it can be combined with CCR for the overall evaluation of rutting potential. As expected, a significant difference in delayed elastic strain was observed between binders NA, NB and PMBS on one side, and binders PMBH and AR on the other one. In addition,  $J_D$  values of binders PMBH were significantly higher than those of binder AR at any given temperature. From such an evidence it can be inferred that modification with crumb rubber results in a higher stiffening effect but also in a lower degree of elasticity when compared to modification with a high percentage of SBS polymer. This may be probably due to an enhanced networking contribution provided by SBS, related to the formation of a cross-linked elastomeric structure within the bituminous matrix.

As in the case of SCR tests, data retrieved from MSC tests carried out with applied stresses equal to 20 and 500 Pa were processed to calculate the CCR parameter. Obtained results plotted as a function of temperature are reported in Figure 8, together with those derived from the loading phase of SCR tests (stress equal to 100 Pa).

It can be noticed that for neat binders NA and NB, the curves corresponding to different stress levels overlap almost perfectly, indicating the materials to be in their linear visco-elastic domain. In the case of binders PMBS and PMBH, only the curves corresponding to the lower stress amplitudes (20 and 100 Pa) coincide and can be clearly distinguished from that obtained at 500 Pa. This implies that the materials undergo a transition from the linear to the non-linear region when passing from 100 to 500 Pa. Finally, binder AR exhibited a remarkable stress sensitivity. In fact, for this material three different curves can be identified, showing that CCR values increase with stress level at any given temperature. Furthermore, stress sensitivity appears to be more pronounced at the lowest temperature considered in the study (58°C) as indicated by the increased gap between 20 and 100 Pa curves. This may have a great impact on actual

field performance of the material if subjected to very heavy loads.

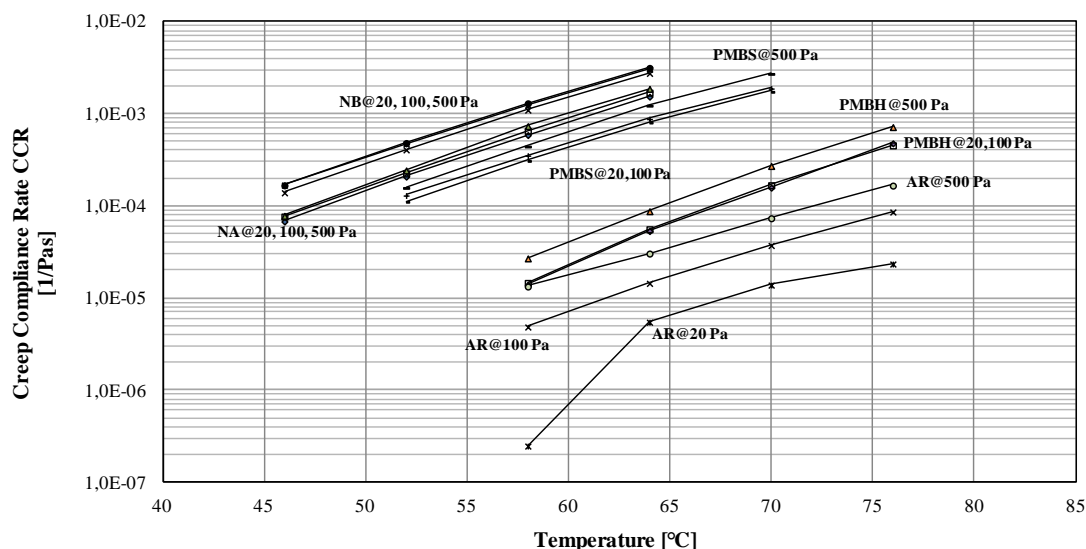


Figure 8. Creep compliance rates obtained from MSC and SCR tests

## 5 Summary and conclusions

In the experimental study described in this paper, a novel procedure based on the combined use of single creep-recovery and multiple stress creep (SCR-MSC) tests was used to evaluate the anti-rutting potential of five different asphalt binders. For comparison purposes, two existing standard methods, based on Low-Shear Viscosity (LSV) and Multiple Stress Creep Recovery (MSCR) tests, were also used. The main conclusions drawn from the investigation are indicated in the following.

The LSV test protocol was found to be not applicable to asphalt rubber. For this material, complex viscosity values gathered from temperature sweep tests were always higher than the recommended threshold of 2 kPa, making the determination of equiviscous temperature EVT1 impossible. In the case of the SBS polymer-modified binders, complex viscosity measured by means of frequency sweep tests showed a monotonic increase as loading frequency decreased, leading to unrealistic values of viscosity extrapolated at very low shear rates. These findings confirmed that the LSV concept can be used for neat asphalt binders, but is not adequate to characterize rutting properties of polymer or crumb rubber modified binders.

On the basis of MSCR test data, asphalt rubber showed a superior rutting resistance, as indicated by the lowest values of non-recoverable compliance ( $J_{nr}$ ) exhibited over the whole investigated temperature range. In terms of ranking, asphalt rubber was followed by the polymer-modified binder with high SBS content, by the one with lower SBS dosage and by the two neat bitumens. However, in the case of the first two binders, it was demonstrated that 1 s creep loading and 9 s recovery currently adopted by the standard protocol were not sufficient to allow materials to flow and to recover all delayed elastic deformation. As a consequence, strain recorded at the end of each cycle was affected by residual strain recorded at the end of the previous ones, thus

influencing final values of  $J_{nr}$ .

A creep compliance rate (CCR) was introduced by analysing strain - creep time curves determined from SCR-MSR tests. CCR represents a rheological parameter which is not dependant upon time and corresponds to the inverse of ZSV. It can be used as a reliable indicator for the evaluation of the potential rutting resistance of binders. Analysis of obtained results revealed a significant gap in creep response between highly modified binders and the other materials. A clear distinction could also be made when comparing asphalt rubber with the SBS modified binder, the former being stiffer than the latter.

By comparing CCR curves obtained at different stress levels, asphalt rubber proved to exhibit a remarkable stress sensitivity, with creep rate increasing as the applied stress increased. In the case of polymer-modified binders, changes in creep response were observed only when passing from 100 to 500 Pa, whereas both neat bitumens were in their linear domain.

Delayed compliance  $J_D$  was also considered to evaluate the rutting potential of binders. Also in this case, a significant gap was observed between highly modified binders and the remaining ones. In addition,  $J_D$  values were significantly higher for the SBS polymer-modified binder in comparison with asphalt rubber, indicating a higher degree of delayed elasticity provided by the elastomer.

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