CHARACTERIZATION OF DAMAGE BEHAVIOR IN MODIFIED BINDERS AT HIGH TEMPERATURES. MEASUREMENTS METHODOLOGIES AND RHEOMETRICAL ASPECTS

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ABSTRACT

In order to obtain bitumen mechanical properties really connected with the performance of pavements in the field, recent developments in rheological characterization have focused on the evaluation of damage behavior in asphalt binders. With high service temperature, when more frequent distress is identified by rutting, the damage behavior of binders can be described by separating delayed elastic phenomena from non-reversible deformation. On the basis of this concept, a creep approach was introduced by the NCHRP project 9-10 and a similar one is now under development by CEN TC336. The experimental investigation presented in this paper focuses on the application of these test methods to modified and unmodified binders, and aims at highlighting the different laboratory conditions and theoretical assumptions at the basis of the creep analysis. The viscous component of creep compliance and low-shear viscosity of binders were determined under several conditions in order to provide a quantitative evaluation of the influence of rheometrical aspects on the measurements. Furthermore different results of the experimental program carried out can provide an initial comparison between the static creep-recovery and the repeated creep test. The tests conducted can also provide different useful results for the development of the rheometrical technique and the assessment of the creep test as a tool for ranking modified binders on the basis of their performance.

Keywords: asphalt binders, damage behavior, permanent deformation, energy dissipation, repeated creep test, zero-shear viscosity.

1. INTRODUCTION

1.1 Background

There are different opinions about the contribution of binders to rutting resistance. Aggregate properties and mix design are very important but binders properties certainly play an important role in rutting resistance of asphalt pavements. This fact can be observed by analyzing the mitigation of rutting problems when modified binders are used (Bahia and Anderson, 1995). A correct interpretation of binders' role in resistance to rutting should thus be considered in order to attain a reliable pavement design. To reach this objective, the Superpave specification parameter G*/sinδ was identified by SHRP as the term for high temperature performance grading of asphalt binders. Although this term is still used, it was found inadequate for describing the real anti-rutting performance of binders with high delayed elasticity (Shenoy 2002, Bahia et al., 2001). It is generally recognized that this occurs because the SHRP parameter is connected with the partially reversible energy of binders and consequently it is not fully associated with pavement damage (Bahia et al., 2001). The concept of binder damage behavior was thus introduced as a correct way to separate reversible energy connected with delayed elastic phenomena from energy dissipated in viscous flow. In fact only the dissipated energy correlated with viscous flow can be associated with the non-reversible deformation (damage) of binders. On the basis of this concept, different rheometrical approaches based on creep analysis were thus developed for asphalt binders characterization by CEN TC336 (static creep) and during the NCHRP project 9-10 (repeated creep and recovery). Although these two test methods are based on similar theoretical concepts, the rheometrical conditions and the final specification parameters proposed for the standardization are different. Moreover the reliability in the case of modified binders and the influence of the test conditions on the results are not fully known.

1.2 Objectives

The experimental investigation presented in this paper was conducted by means of static shear measurements and aimed at pointing out the application of creep analysis for binder characterization also through a comparison with SHRP grading. The creep flow behavior of binders was analyzed by means of Burger's equation.

The objectives of the study were as follows:

- to further understand the theoretical concepts at the basis of damage behavior of asphalt binders in the case of high service temperatures.
- to determine the influence of rheometrical conditions on the results; to reach this objective, the viscous part of compliance and low-shear viscosity of binders was evaluated under different conditions to provide a quantitative evaluation of the influence of rheometrical aspects on the measurements.
- to provide a first comparison between the repeated creep approach, the static creep approach and the SHRP oscillatory analysis.

- to obtain results that can be useful for the development of the rheometrical technique and the assessment of the creep test as a tool for ranking modified binders on the basis of their performance.

2. ENERGY DISSIPATION AND DAMAGE BEHAVIOR OF ASPHALT BINDERS AT HIGH SERVICE TEMPERATURE

During each cycle of traffic loading a certain amount of the work done to deform the surface layer is dissipated in viscous losses through heat, and the remainder is elastically stored (Bahia and Anderson, 1995). This elastic work is stored as potential energy within the structure of the viscoelastic body, while the work dissipated generates permanent deformation (Tschoegl, 1989). Energy dissipation in the viscoelastic body is termed damping or internal friction, and depends on material, temperature, frequency and loading mode (Dowling, 1999). Damage behavior of binders at high temperature and its role in pavement rutting mechanics derives from the determination of the total work of deformation ($\Delta W(t)$), or the mechanical energy absorbed per unit volume of material, as well as the amount of energy stored and the amount of energy dissipated (equation 1).

$$\Delta W(t) = \int_0^t \sigma \cdot \frac{d\varepsilon}{dt} \cdot dt = W_s(t) + W_d(t) \qquad \text{(Eq. 1)}$$

where σ is the stress applied, ε the consequent deformation, W_d is the dissipated energy and W_s is the stored energy, evaluated for a given mode of deformation up to time t. Stored energy and dissipated energy combine to make up the total deformation energy but only the dissipated energy is connected to irreversible deformation and therefore to binder damage at high temperatures.

2.1 Dissipated energy from reversible cyclic loading

During the development of the SHRP (Strategic Highway Research Program), pavement rutting was interpreted in terms of accumulation of permanent deformation due to the repeated application of traffic loading. According to this definition, damage in binders was considered as a consequence of a cyclic stress-controlled phenomenon (Bahia and Anderson, 1995). Consequently reversible cyclic shear analyses performed with Dynamic Shear Rheometer were proposed to characterize binder behavior. In such case a sinusoidal stress (or deformation) is applied on a viscoelastic material and the total dissipated work for damping effect per load cycle (ΔWc) can be calculated through equation 2 as the area of the hysteresis loop developed during each cyclic loading (figure 1):

$$\Delta Wc = \pi \cdot \sigma_0 \cdot \varepsilon_0 \cdot \sin\delta = \pi \cdot \sigma_0^2 \cdot \frac{\sin\delta}{G^*} \qquad \text{(Eq. 2)}$$

where σ_0 is the amplitude of the stress applied, ε_0 is the amplitude of the deformation, G* the complex modulus and δ is the phase angle of the material. As a consequence to this assumption, the contribution of binders in rutting resistance was correlated with the term G*/sinδ, connected with this total dissipated energy (Bahia and Anderson, 1995).

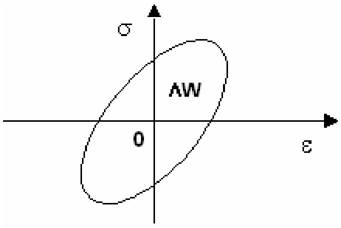


Figure 1. Hysteresis loop from cyclic loading.

Despite the fact that this approach can be considered correct for the characterization of unmodified binders, it is now generally recognized that it is not clear if all the dissipated energy defined by the area of the hysteresis loop from reversible cyclic loading is really associated with damage (Bahia *et al.*, 2001). It is in fact known that the dissipated energy determined by means of the reversible cyclic approach can be strongly affected by the delayed elastic behavior so, in the case of modified binders, part of this energy cannot really be associated with damping (W_V); on the contrary, it must be considered partially reversible (W_{DE}).

$$\Delta W_C = W_{DE} + W_V \qquad \text{(Eq. 3)}$$

This fact can be explained considering that the dissipated energy *Wc* from reversible cyclic loading is a function of phase angle δ. Hence, in the case of modified binders when the entity of delay in the response is influenced by its recoverable delayed elastic component, it can be observed that the phase angle is not a reliable parameter to predict permanent deformation. Moreover, it must be considered that in reversible cyclic loading, materials are forced back to their original conditions, while the rutting mechanism does not include any action intended to take back the material to its initial conditions. Consequently it clearly appears that in conditions typical of reversible loading it is not possible to have a correct theoretical correlation between test results and damage behavior of binders in pavement rutting.

2.2 Dissipated energy from creep loading

Recent experiments have shown that the inadequacy of reversible cyclic loading in characterization of dissipated energy also occurs with asphalt mixes. A study carried out on different asphalt mixes demonstrated that the dissipated energy from the hysteresis loop is far greater than the dissipated creep strain energy predicted from the measured viscous response of the materials (Kim *et al.*, 2006). Therefore, in order to obtain mechanical properties of asphalt binders really connected with their damage behavior at high temperatures, the dissipated energy must still be considered as the correct concept, but a reliable approach should be based on creep analysis. In this case the material is not forced back to its initial conditions and Burger’s model (equation 4) describes experimental data well, allowing a separation of the non-reversible component of the response (J_v) from the elastic and delayed elastic ones (J_e, J_{de}). In equation 4, G_0, G_1, η_0 and η_1 are the four parameters of the model and t is the time.

$$J(t) = J_e + J_{de} + J_v = \frac{1}{G_0} + \frac{1}{G_1}\left(1 - e^{-t\frac{G_1}{\eta_1}}\right) + \frac{1}{\eta_0}t \qquad \text{(Eq. 4)}$$

3. EXPERIMENTAL PROGRAM

3.1 Materials and samples preparation

In accordance with the aims of the investigation presented, the materials selected for the experimental tests include seven bituminous binders, two unmodified binders and five modified binders with radial SBS (Styrene-Butadiene-Styrene) polymer. Their conventional properties and G*/sinδ at 60°C and 10 rad/s are shown in table 1.

Table 1. Materials selected for the investigation and their conventional properties.

Binder	Penetration [dmm]	$T_{r\&b}$ [°C]	G* @ 60°C f = 10 rad/s [Pa]	δ @ 60°C f = 10 rad/s [deg]	G*/sin δ@ 60°C f = 10 rad/s [Pa]
T1	58	48.8	3485	87.6	3488
T2	76	47.2	2013	85.9	2018
SBS1	-	-	4359	76.5	4482
SBS2	30	86.0	12660	66.3	13826
SBS3	56	57.5	5136	74.1	5340
SBS4	62	96.5	4376	62.3	4942
SBS5	41	61.6	9210	71.5	9712

The samples preparation was referred to EN 12594. In the case of SBS modified binders, special attention was paid to the thermal history and storage conditions of the test samples. It is in fact known that the results of this kind of rheological analysis are strongly affected by the test samples storage time at room temperature and by the temperature at which materials are reheated before pouring the test samples (Soenen *et al.*, 2006). So SBS modified binder samples were homogenized after reheating at a temperature of 160°C, and the storage at room temperature was limited to 5 minutes after pouring the test samples.

3.2 Equipment

The tests were carried out by means of a Dynamic Shear Rheometer (DSR). The temperature during the tests was controlled by means of a Peltier conditioning cell. An air-operating suspension system guaranteed a significant reduction in the friction between the moving parts of the rheometer. This allowed great precision of the measurements even for a very low shear rate. The measurement system selected is represented by the double plate configuration with a 25 mm diameter and a 2.0 mm gap. The test temperature was set at 60°C with a maximum admitted deviation of +0.01°C from the selected temperature during the whole experiment. Before each test the samples were subjected to a 30-minute thermal conditioning period.

3.3 Organization of the experimental investigation and testing procedures

The introduction of creep analysis in the mechanical characterization of asphalt binders has led to new specifications parameters based on two different rheometrical approaches, i.e. a repeated creep test and a static creep test. Consequently, the experimental program here presented is composed of two phases.

- Phase 1. Repeated creep test (Bahia *et al*. 2001, Delgadillo *et al.*, 2006).
  The repeated creep test was developed in the United States during the NCHRP project 9-10. Several repeated cycles of creep and recovery are performed by means of a DSR in static mode. The parameter selected for the specification is the viscous component of the creep stiffness (Gv), determined by fitting experimental data with Burger's model (eq. 4). With respect to equation 4, Gv is identified by the inverse of the viscous compliance Jv = t/η_0. Testing procedures in this phase were referred to NCHRP protocol; details about the test parameters are reported in table 2.

- Phase 2. Static creep test (Desmazes *et al.*, 2000, CENTC336, 2005).
  A single cycle of a static creep is performed by means of a DSR. The parameter selected for the specification is the zero-shear viscosity (ZSV, η_0), or the viscosity determined when a steady state of flow within the Newtonian region (very low shear rate) is reached. So, in this phase the testing procedures were based on the verification of two different theoretical conditions:

  1. Creep time condition: $t \to \infty$.
  The creep time must be elevated in order to allow the exhaustion of delayed elastic phenomena, thus allowing to reach a steady-state of flow ($d\gamma/dt \to$ cost).

  2. Stress condition: $\tau_0 \to 0$.
  Rheological measurement must be carried out within the Newtonian region of flow in order to verify that the steady state reached is independent of shear rate.

  When conditions 1 and 2 are verified:

$$\tau = \tau_0 \to 0\,, \quad t \to \infty \quad \Rightarrow \frac{d\gamma}{dt} \to 0 \qquad \text{(Eq. 5)}$$

  On the basis of conditions 1 and 2, the test parameters for the static creep and recovery tests were selected as shown in table 2.

Table 2. Test parameters.

Test	Temperature [°C]	Shear stress [Pa]	Creep time	Recovery time	Number of cycles
Repeated creep	60	10÷300	1 s	9 s	17
Static creep & recovery	60	10÷300	1÷4 hours	4÷12 hours	1

4. RESULTS AND ANALYSIS

4.1 Repeated creep test

The results of repeated creep tests can be expressed, as reported in table 3, in terms of the viscous component of shear stiffness (Gv) and accumulated strain after 17 cycles (γ_{acc}).

The Gv values reported in table 3 were determined by fitting the experimental data of cycle 17 with Burger’s equation. The last cycle was chosen in order to avoid the influence due to the transient phenomena registered during the first cycles of loading. As well as experimental data, the accumulated strain after 17 cycles is reported as result of the application of equation 6, where Gv is the viscous modulus determined as explained above, n is the number of load repetitions, and τ the applied stress.

$$\gamma_{acc} = \frac{\tau}{G_v} \cdot n = \frac{\tau \cdot t}{\eta_0} \cdot n \qquad \text{(Eq. 6)}$$

Table 3. Repeated creep test – results.

Stress level	**τ = 10 Pa**			**τ = 300 Pa**		
Binder	**Gv** [Pa]	**γacc (fitting)** [%]	**γacc (experimental)** [%]	**Gv** [Pa]	**γacc (fitting)** [%]	**γacc (experimental)** [%]
T1	365	46.57	44.12	345	1478.26	1449.38
T2	211	80.57	80.59	203	2512.31	2447.72
SBS1	667	25.48	8.46	680	750.00	236.18
SBS2	3238	5.25	0.39	3253	156.78	16.73
SBS3	833	20.41	13.47	855	596.49	362.94
SBS4	1678	10.13	0.17	1650	309.09	4.75
SBS5	1605	10.59	5.07	1610	316.77	204.65

The Gv values obtained are similar for both stress levels used (10 and 300 Pa), so the linear viscoelastic conditions required seem to be achieved. However, some inconsistencies can be observed. When unmodified binders were tested, the accumulated strain from the experimental data and from equation 6 yields similar values, and there exists a good correlation between these values and the Gv obtained by fitting. This is not true in the case of the modified binders, when different observations can be reported as follows.

1. The viscous component of the creep stiffness (Gv) determined by fitting repeated creep data is generally not correlated with the experimental accumulated strain (γ_{acc}). Binders SBS4 and SBS5 have very similar Gv values, yet show very different residual strain at the end of the recovery phase (table 3, figure 2).
2. Accumulated strain from experimental and fitting data do not have similar values, and $\gamma_{acc\ (fitting)} > \gamma_{acc\ (experimental)}$.

Observations 1 and 2 can be explained by assuming that the Gv values obtained by fitting are indeed not related to the viscous response of the modified binders because of the very reduced loading time. Moreover in the case of modified bitumen, experimental data show the presence of non-linearity in strain accumulation, thus the Gv value changes with the number of cycle (figure 3).

As a consequence of the observations reported above, one should consider that the anti-rutting potential defined by Gv from repeated creep loading is measured only with respect to binder stiffness whilst the strain recovery due to elastic response is not completely considered. A more correct approach might thus be identified expressing results in terms of experimental accumulated strain.

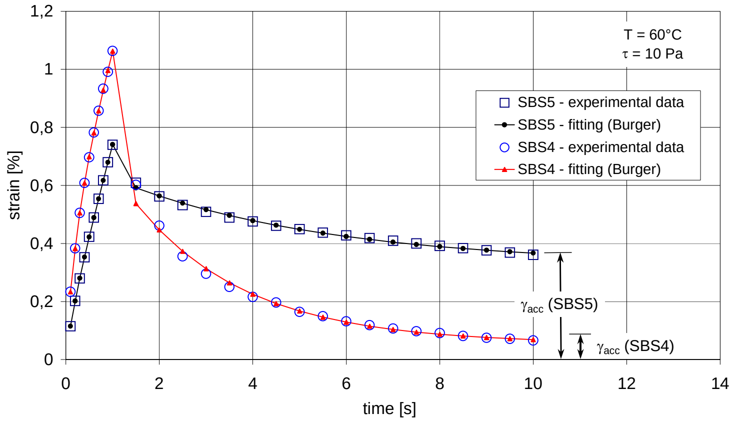


Figure 2. Experimental data and fitting – single cycle (SBS4 and SBS5).

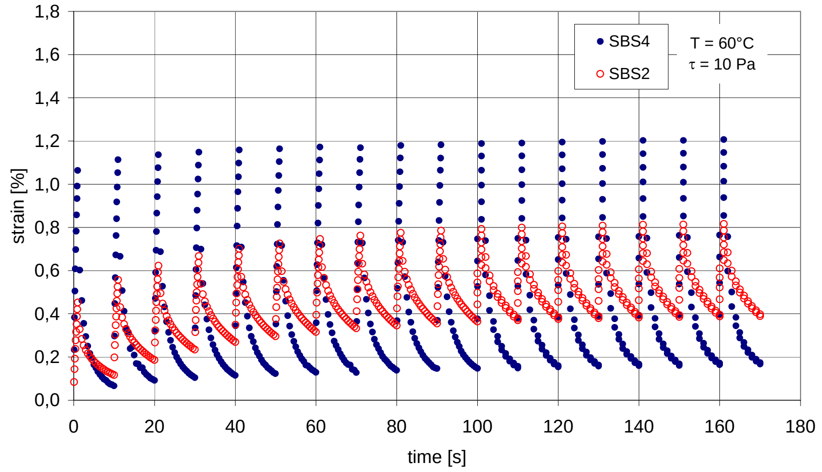
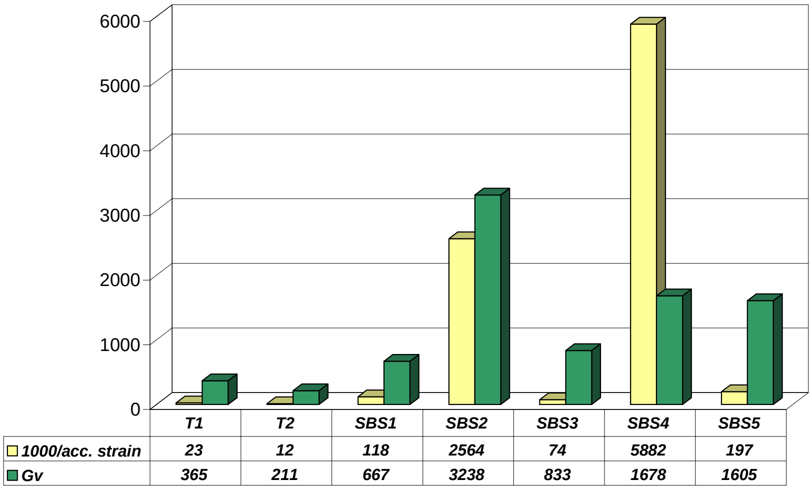


Figure 3. Comparison between repeated creep test on binders SBS2 and SBS4.

Figure 4 shows a comparison between the use of Gv and the inverse of the experimental accumulated strain for ranking tested binders. Binders SBS4 and SBS5 have similar ranking with respect to Gv (green line), but different ranking with respect to the experimental accumulated strain (yellow line). At the same time, inconsistency in the definition of the performance of binder SBS2 is shown. It appears to be better than binder SBS4 if the reference parameter is Gv, but the opposite occurs if the parameter selected is the inverse of the experimental accumulated strain (figures 3, 4).



	T1	T2	SBS1	SBS2	SBS3	SBS4	SBS5
🟨 *1000/acc. strain*	*23*	*12*	*118*	*2564*	*74*	*5882*	*197*
🟩 *Gv*	*365*	*211*	*667*	*3238*	*833*	*1678*	*1605*

Figure 4. Binders ranking with respect to Gv and γ_{acc} (experimental).

4.2 Static creep and recovery test

The static creep test as proposed by CEN TC336 aims at evaluating the zero-shear viscosity (ZSV, η_0) of asphalt binders. With respect to Burger’s model presented above, it can be observed that zero-shear viscosity can be identified by the parameter η_0. This leads to think that there exists a close correlation between this method and the repeated creep, but in this case the rheometrical conditions are different: a single cycle of load is performed and the creep time becomes longer than 1 hour. When the measurement verifies this time condition and the stress applied is internal to the Newtonian region of flow, only the viscous compliance ($J_v = t/\eta_0$) increases, according to the theoretical equation of Burger’s model (eq. 4). Hence the zero-shear viscosity of the material can be well represented by parameter η_0 of Burger’s model, and can consequently be determined by the slope of the compliance curve (equation 8, 9).

$$t \to \infty \quad \Rightarrow \quad \frac{dJ(t)}{dt} \to \frac{dJv}{dt} = \frac{1}{\eta_0} \qquad \text{(Eq. 8)}$$

$$\eta_0 = \Delta t / \Delta J \quad [\text{Pa}\cdot\text{s}] \qquad \text{(Eq. 9)}$$

In equation 9 Δt represents a time interval expressed in seconds (s) and ΔJ is the difference between the compliance modulus measured at the end of the creep phase and the one measured at the start of the Δt interval. In the present research a recovery phase was performed too, because another way for calculating a η_0 value is related to the analysis of the recovery curve. Assumptions on the basis of the theory of linear viscoelasticity allow to consider that the permanent residual deformation (γ_r) registered at the end of the recovery phase is the same as the viscous deformation (γ_v) occurring during the creep phase (Phillips and Robertus, 1996). Thus the parameter η_0 can be also calculated as follows:

$$t \to \infty \qquad \Rightarrow \gamma_r \to \gamma_v \, , \qquad \eta_0 = \frac{\sigma_0 \cdot t_{creep}}{\gamma_r} \qquad \text{(Eq. 10)}$$

where σ_0 and t_{creep} are the stress and the time relative to the creep phase respectively, while γ_r is the permanent residual deformation at the end of the recovery phase.

Table 4. Static creep and recovery test – results.

Stress level	**τ = 10 Pa**		**τ = 100 Pa**		**τ = 300 Pa**	
Binder	**η_0 (slope)** [Pa]	**η_0 (recovery)** [Pa]	**η_0 (slope)** [Pa]	**η_0 (recovery)** [Pa]	**η_0 (slope)** [Pa]	**η_0 (recovery)** [Pa]
T1	339	340	342	342	344	343
T2	200	202	204	203	219	219
SBS1	2383	1558	582	625	513	522
SBS2	2253380	2813824	2310655	1718674	2272727	2368317
SBS3	4727	4201	1656	1583	1421	1486
SBS4	3639304	4807532	3071672	2773076	2532358	2870527
SBS5	3413	3199	2911	3166	1990	2144

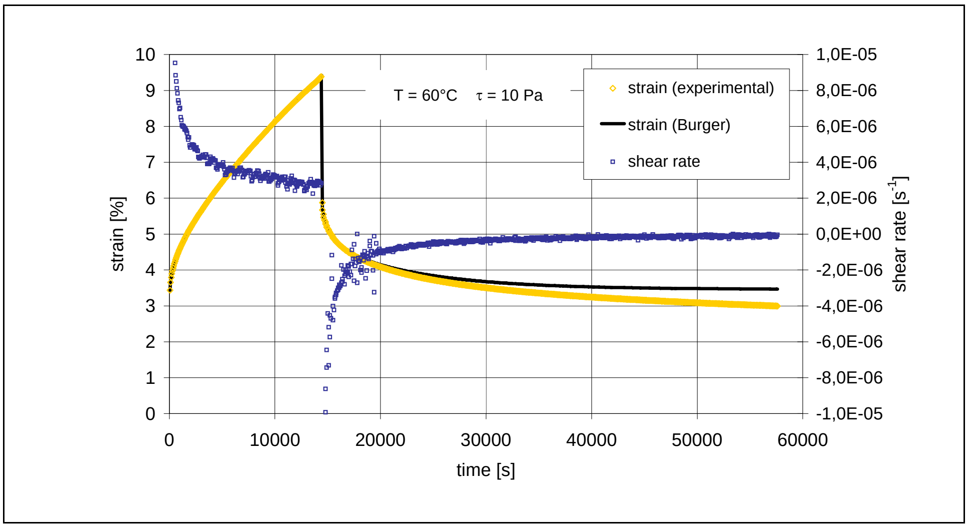


Figure 5. Strain and shear rate in static creep and recovery test (SBS4).

As already shown for the repeated creep test, even in the static creep and recovery test no problem appears for either of the unmodified binders T1 and T2. On the contrary, when the modified binders were tested, different values of η_0 were determined for the same binder. In these cases different effects related to the choice of rheometrical conditions were observed.

1. In the case of binders with a significant delayed elastic response, the increase in J(t) measured after 4 hours at 60°C is probably not due only to the viscous flow. This fact can be explained by observing that the maximum creep time selected (4 hours) does not allow the asymptotical stabilization of the shear rate in the creep phase for all binders (figure 5). On the contrary, as the viscosity measured during the creep phase can represent the effective resistance to permanent deformation, the shear rate should reach a constant value. With reference to the mathematical form of Burger's model (equation 4), only when this condition arises can one consider the equivalences expressed by equations 8 and 9 valid.
2. η_0 determined with regard to the non-recovered strain yields different values if compared to that determined by the slope of the compliance curve. This fact can be explained by observing that in some cases the shear rate is still different from zero even after 12-hour (43,200 s) recovery. Figure 5 shows the shifting occurring between the experimental strain and Burger's fitting curve due to the non-stabilization of the experimental shear rate.
3. Non-Newtonian typical phenomena arise for some binders (table 4) and a reduction in η_0 occurs with the increasing level of the shear stress applied.

4.3 Binder performance specification by creep approaches and SHRP oscillatory analysis

On the basis of the analysis conducted and the theoretical concepts exposed, it emerges that the damage behavior of asphalt binders can be characterized by means of different performance indicators. An initial comparison between the performance indicators resulting from the tests method presented above and the SHRP G*/sinδ is therefore proposed. In the present analysis it has been assumed that damage behavior of asphalt binders at high temperatures can be interpreted in terms of non-reversible deformation accumulated as a consequence of energy dissipation. Hence, the parameter used for the comparison here proposed is the experimental accumulated strain measured by the repeated creep with a 10 Pa stress level.

The results of the comparison are shown in figure 6 and table 5, where the correlations between accumulated strain γ_{acc} and G*/sinδ, Gv from repeated creep and η_0 from static creep are reported. In all three cases a power law ($y=a\cdot x^n$) was used for the regression.

Table 5. Regression parameters.

Performance indicator	a	n	R^2
G*/sinδ	7201	-0.1857	0.4495
Gv (repeated creep)	1612	-0.3661	0.7895
η_0 (static creep)	194836	-1.6941	0.9597

The poor value of coefficient R^2 obtained for G*/sinδ is indicative of the unreliability of the cyclic reversible test in the characterization of modified binders at high service temperatures. Moreover, it is very important to observe that exponent n in this case is close to zero. As consequence of this fact it can be observed (figure 6) that binders with very different accumulated strain have similar G*/sinδ values. This confirms the unreliability of G*/sinδ.

The results of the applications of creep approaches show a significant improvement quantified by the values obtained for R^2 and n. With respect to Gv it can be observed that the regression parameters obtained are good but a better result is obtained when the accumulated strain is plotted versus the η_0 values from static creep test. This fact confirms the observations reported above about the importance of the creep time for a correct evaluation of parameters correlated with the non-reversible deformation of binders. In particular it has been shown that in order to obtain a parameter (viscosity or modulus) really connected with the accumulation of permanent deformation, a mechanical test with a long creep time is required.

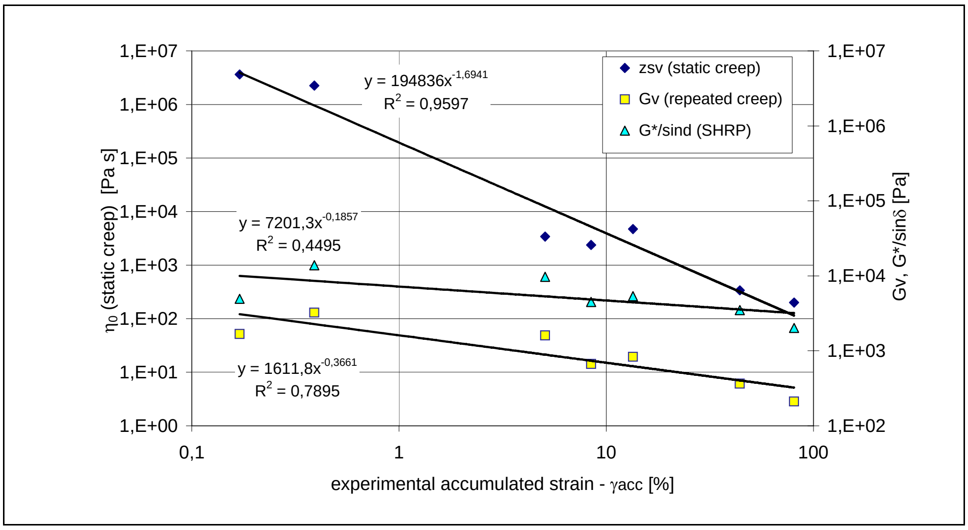


Figure 6. Relation between G*/sinδ, Gv, η_0 and γ_{acc} from repeated creep test.

5. CONCLUSIONS

With reference to the objectives of the investigation carried out, the main conclusions can be identified as follows:

1. The performance characterization of modified asphalt binders at high service temperatures should occur by means of a correct definition of the damage behavior. In this context it does not seem possible to leave aside the consideration about energy dissipation in the different test conditions.
2. Regarding the repeated creep test.
   - The rheometrical approach can be successfully applied to both unmodified and modified binders.
   - When $\tau < 300$ Pa the stress levels does not influence the results because it has been shown that the linear viscoelastic conditions are verified for all the binders tested.
   - The Gv value does not generally agree with the accumulated strain registered. This fact can be explained by observing that the 1s creep time does not allow a reliable evaluation of the viscous response. This fact is also shown by the difference registered between the accumulated strain from fitting and from experimental data.
   - The use of Gv as a specification parameter does not generally provide results correlated with the experimental accumulated strain (γ_{acc}). In the case of modified binders with high delayed elastic response, the Gv value determined by fitting data with 1 s loading time is not associated with the viscous response only.
3. Regarding the static creep and recovery test.
   - The time consumption is higher than in the repeated creep test but the recovery phase can be excluded because it has been shown that the η_0 calculated from the

recovery data is not too different from the one determined by the slope of the load curve.
- It has been highlighted that a 4-hour creep time is probably not sufficient for some modified binders. In these cases a longer creep time is required in order to obtain a less approximated η_0 value.
- The influence of the stress level is different for each kind of binder. However, in order to obtain reasonable approximations, 10 Pa stress can be used.
- The viscous modulus (Gv) from repeated creep tests and η_0 from static creep tests yield similar results only in the case of unmodified binders. This result is in accordance with the conclusions of a previous experiment (De Wisscher *et al.*, 2004).

4. If the accumulated strain is assumed as a measurement of damage behavior of asphalt binders at high temperatures, the regression data obtained (table 5) confirm that the energy dissipation from the cyclic loading approach is not correlated with the actual damage of the binders. This fact denotes the unreliability of the SHRP parameter in ranking modified binders. Considering the two creep approaches analyzed, it must be observed that the static creep and recovery is extremely time-consuming, but the results obtained correlate better with the non-reversible deformation.

Thanks to the observations reported, it can be stated that a correct approach to the characterization of damage behavior of bituminous binders at high temperatures can take place by analyzing the response to static load but it is necessary to understand the extension of the Newtonian range, and the creep time must generally be longer than 4 hours.

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