MODELING OF THE VISCOELASTIC BEHAVIOR OF PAVING BITUMEN USING FRACTIONAL DERIVATIVES

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Key words: bitumen, fractional viscoelastic model, differential derivatives, experimental testing

Abstract. *The paving grade bitumen used in the production of asphalt mixtures for road construction is significantly able to affect the in-service performances of flexible road pavements. It has been proved that, when subjected to loading conditions comparable with most pavement operating conditions, bituminous binders behave as linear visco-elastic materials. The aim of this paper is to propose a model based on fractional differential equations which is able to describe the behavior of bituminous binders in the linear visco-elastic range.*

Shear creep testing and creep recovery testing were carried out over a range of temperatures and by applying a stress level which makes it possible to maintain the response of the studied bitumens within the linear visco-elastic region. It is shown that creep tests follow a power decay law, rather than an exponential one: it follows that the most appropriate operator for describing the constitutive law for bitumen is a fractional operator. The procedures used to determine the model's parameters from the experimental data are discussed.

1 INTRODUCTION

The paving grade bitumens used for producing asphalt mixtures for road construction are significantly able to affect the in-service performances of road pavements. In the last few decades, this has encouraged several studies aiming at defining models for appropriate description of the constitutive laws, in order to predict their mechanical response when subject to loading conditions that are representative of the real ones[1,2]. In particular, the linear visco-elastic (LVE) rheological properties of bitumens have been widely studied since it has been proved that, when subjected to loading conditions comparable with most pavement operating conditions, they behave as LVE materials[3].

In the past, different rheological models have been proposed to describe the LVE behavior of bitumen. One of the most used is Burgers' model[4] which is a composition of springs and dashpots. It follows that the corresponding constitutive law involves classical derivatives coming from the dashpots, and therefore the creep compliance and the relaxation modulus of this model is governed by an exponential decay law. On the other hand, all physical phenomena show a power decay law when the "distance" from the source increases, rather than an exponential decay. In particular for visco-elastic material like rubber, bitumen, polymers, concrete etc. the power law decay always fits experimental data. This behavior has been observed from the beginning of the 20th century[5,6]. From these observations Scott Blair[7] and many others recognize that by using fractional derivatives instead of the classical ones the viscoelastic behavior fits the experimental results very well. For this reason many research works have been addressed to frame the viscoelastic problem by means of fractional calculus, among them the most significant are Bagley[8], Schimdt[9], Spanos[10], Soczkiwicz[11], Podliubny[12], Lesueur[13]. In any case, visco-elastic behavior is usually introduced postulating that the constitutive law is governed by fractional derivatives with some parameters that are defined by fitting experimental data.

In this paper a sustematic (experimental) study on bitumes under various load and temperature conditions is performer, showing that for all the test performer the linearised Nutting equation fit quite well the experimental data in terms of creep compliance and/or relaxation modulus. Based on this observation, it is shown that the appropriate constitutive law for pure bitumens is the Riemann-Liouville fractional operator.

2 ROAD PAVING BITUMEN MODELING

Several studies are available for modeling the linear viscoelastic behaviour of bitumen. Lesueur[14] gives a comprehensive overview of those developed over the last decades, from the very first attempts.

Amongst the previously mentioned models, in what follows only a few will be described, namely the Generalized Burgers models and the proposed fractional model for bitumen.

2.1 Analogical models

Several analogical models made up of discrete elastic and viscous elements - normally a number of spring and dashpot elements arranged in series and parallel as studied, for example, by Flugge[15] - have been proposed and specified for both bitumen[16] and asphalt mixture behavior[17].

One of the most common is the generalization of the well-known Burgers model[4], which contains a Maxwell model in series with a certain number of Kelvin-Voigt models as depicted in Fig. 1.

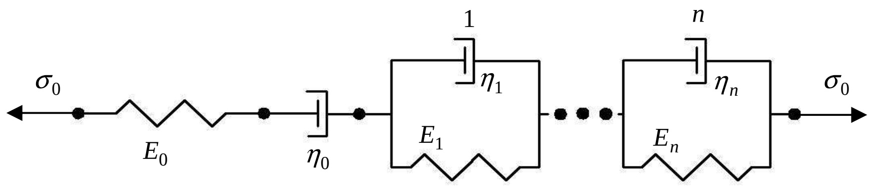

Figure 1. Representation of the Generalized Burgers model.

Let us suppose a constant stress is applied to the extremities of the mechanical model. Because of the equilibrium, the same stress is shared by each element, while the strains (and strain rates) are additive, giving:

$$\varepsilon(t) = \sigma_0 \left(\frac{1}{E_0} + \frac{t}{\eta_0} + \sum_{i=1}^{n} \frac{1}{E_i} \left(1 - e^{-\frac{t}{\tau_i}} \right) \right). \tag{1}$$

As can be seen, parameters are necessary for completely describing the Generalized Burgers model, namely E_0, η_0, Ei and τi=ηi/Ei (i=1,2,3), which are, respectively, the elastic modulus and the viscosity of the Maxwell element, and the elastic modulus and the relaxation time of the generic i-th Voigt element.

The strain per unit of applied stress provides the so-called creep compliance. From eq.(1) we recognize that the Generalized Burgers model provides an exponential decay of the creep compliance. This is not surprising because in this model spring and dashpot yield forces that are proportional to derivatives of zero-th order (spring) and first order (dashpot).

3 FRACTIONAL MODELS AND BACKGROUND

In this section it will be shown that from the creep test the fractional derivative constitutive law emerges in a natural way. The creep compliance function is the measured strain for a unit step applied stress $(\sigma(t) = \sigma_0 U(t);\ \ U(t) = 1, \forall\, t > 0;\ \ U(t) = 0,\ \forall\, t < 0)$. The impulse response function is then simply the time derivative of the creep compliance, that is $h(t) = \dot{J}(t)$. For a quiescent system at $t = 0$, the response in terms of strain may be written in the classical Duhamel form:

$$\varepsilon(t) = \int_0^t h(t-\tau)\, \sigma(\tau)\, d\tau \tag{2}$$

On the other hand, from experimental testing on bitumen the creep compliance function is very well fitted by the power law function

$$J(t) = At^{\alpha} \quad ; \quad \alpha > 0 \tag{3}$$

where the parameters A and α are properly selected by means of the best fitting procedure described in § 5. Substituting eq.(3) into eq.(2) it follows that

$$\varepsilon(t) = c_{\alpha}\left(I_{0+}^{\alpha}\sigma\right)(t) \tag{4}$$

where $\left(I_{0+}^{\alpha}\sigma\right)(t)$ is the Riemann-Liouville fractional integral defined as:

$$\left(I_{0+}^{\alpha} f\right)(t) = \frac{1}{\Gamma(\alpha)}\int_0^t \frac{f(t)}{(t-\tau)^{1-\alpha}}\, d\tau \tag{5}$$

$\Gamma(\cdot)$ being the Euler Gamma function. The coefficient c_{α} in eq.(4) is given as $c_{\alpha} = A\alpha\Gamma(\alpha)$.

From eq.(5) it may be easily recognized that for $\alpha = 1$ it follows that $\left(I_{0^+}^{1} f\right)(t) = \int_0^t f(\tau)\, d\tau$ and in the case of $\sigma(t) = \sigma_0 U(t)$ we get the solution of a pure fluid, in this case $\varepsilon(t) \propto t$. This behaviour has been observed in bitumen for high values of temperature as will be shown later on. Once the mathematical form of the creep compliance has been chosen as in eq.3, the relaxation modulus $E(t)$, which describes the stress history due to a constant unitary strain $\varepsilon(t) = U(t)$, may be obtained taking advantage of the linearity of the system.

Defining, therefore, the Laplace transform $L\left(f(t)\right)$ of a generic function $f(t)$ as

$$F(s) = L\left(f(t)\right) = \int_0^{\infty} e^{-st} f(t)\, dt \tag{6}$$

the well-known property

$$E(s)\, J(s) = s^{-2} \tag{7}$$

between the Laplace transform of the creep and relaxation function holds true.

Since $J(s) = As^{-(1+\alpha)}\alpha\Gamma(\alpha)$, then

$$E(t) = t^{-\alpha} \big/ \left(A\alpha\Gamma(\alpha)\,\Gamma(1-\alpha)\right) \tag{8}$$

which immediately makes it possible to find the relaxation modulus too, from a creep test.

It is interesting to note that the same result may be obtained by making use of the properties of the fractional calculus. In fact, thanks to the composition rule of the fractional calculus, eq.(4) may be rewritten as

$$\left(D_{0^+}^{\alpha}\varepsilon\right)(t) = c_{\alpha}\sigma(t) \tag{9}$$

where $\left(D_{0^+}^{\alpha}\varepsilon\right)(t)$ is the Riemann Liouville fractional derivative:

$$\left(D_{0^+}^{\alpha} f\right)(t) = \frac{1}{\Gamma(1-\alpha)}\frac{d}{dt}\int_0^t \frac{f(\tau)}{(t-\tau)^{\alpha}}\, d\tau \quad ; \quad 0 < \alpha < 1 \tag{10}$$

After some straightforward algebra, assuming $\varepsilon(t) = U(t)$, eq. (9) leads to the same result as that obtained in eq.(8).

From experimental tests usually the load is kept constant for an assigned time $\bar{t}$ and for $t > \bar{t}$ it is then removed: the curve for $t > \bar{t}$ is termed as *recovery function*. In order to get the solution for $t \geq \bar{t}$ we may observe that, from eq.(4)

$$\varepsilon(t) = \frac{c_\alpha \sigma_0}{\Gamma(\alpha)} \int_0^t \frac{w(\tau; 0 \div \bar{t})}{(t-\tau)^{1-\alpha}} d\tau \tag{11}$$

where

$$w(t; 0 \div \bar{t}) = \begin{cases} 1; & \forall t : 0 \leq t \leq \bar{t} \\ 0; & elsewhere \end{cases} \tag{12}$$

it follows that

$$\varepsilon(t) = A\sigma_0 \left\{ t^\alpha - \left[U(t-\bar{t})(t-\bar{t}) \right]^\alpha \right\} \quad ; \quad \alpha > 0 \tag{13}$$

As a conclusion, it is possible to state that if the relaxation test or the creep test follows a linear behaviour and, at the same time, a power law function rather than an exponential one, then the appropriate constitutive law is governed by a Riemann-Liouville fractional derivative rather than a classical differential equation involving first order derivatives.

4 EXPERIMENTAL SETUP

In order to assess the validity of the proposed model in describing the creep behavior of pure bitumens, the experimental plan has been structured in two parts. first, two different binders have been selected based on physical characterization, then they have been subjected to shear creep testing and creep recovery testing performed with a Dynamic Shear Rheometer (DSR) over a range of temperatures and by applying a constant stress.

4.1 Conventional bitumen tests

For the purpose of this study, a preliminary characterization of the selected materials has been carried out by undertaking empirical physical tests such as penetration, softening point (in order to calculate the temperature susceptibility in terms of Penetration Index, PI) and ductility. Rotational viscosity measurements by using the DV-III Ultra Brookfield rheometer have also been taken. Based on the preliminary characterization, two pure bitumens having great differences in terms of physical properties (Table 1) were involved in this study; both of them were unmodified and supplied by different European manufacturers. The characteristics of the binders, as deduced from classical identification tests , are provided in Table 1, together with the corresponding specification.

		B1	B2
Penetration[18]	(dmm)	68.80	39.60
Softening Point[19]	(°C)	47.00	50.00
PI (Pfeiffer)[20]		-1.24	-1.70
Ductility[21]	(cm)	>100	>100

Table 1. Conventional properties of the selected bitumens

Rotational Viscosity RV [Pa·s]		
T	B1	B2
@100°C	1.9700	3.9800
@135°C	0.2533	0.4179
@160°C	0.0950	0.1369

Table 2. Rotational Viscosity of the selected bitumens at different temperatures

4.2 Rheological tests

The experimental verification of the proposed model was carried out by performing static creep and recovery tests on the studied material. All the test were performed with an Anton Paar Physica MCR 101 Dynamic Shear Rheometer (DSR) and related software Rheoplus 3.49.

4.2.1 Sample preparation

The preparation of the samples was done by heating up the original tin of each bitumen and then by filling 3 vials of 10 ml (one per test's repetition) for each binder. The direct pouring method, which ensures the highest repeatability[22], was therefore used to provide the bitumen samples to be tested with the DSR. Moreover, in order to minimize negative effects on samples, like oxidation, volatilization and prolonged exposure to air room temperature (even 30°C during testing period), each vial was heated up to perform the direct pouring, for only 4-5 minutes at 160°C and then it was topped and stored at a low temperature (5°C).

4.2.2 Linearity check and testing time estimation

In order not to move away from the LVE range, which ensures that the area where the basic laws of rheology are not exceeded[23], preliminary isothermal creep tests at different stress levels were performed. As is well known, the linearity stress limits of bituminous binders decreases with a decrease in shear modulus (increase in temperature)[24]. Based on this, linearity checks were performed by carrying out creep tests at the highest testing temperatures and then, by comparing the obtained creep compliance curves J(t), a stress level for the subsequent main creep tests was assessed. As a result, if the analysis is performed within the linear visco-elastic regime, the creep compliance is independent of the stress level and therefore J(t) curves have to present the same curvature[23]. If by increasing the stress level, those J(t) curves tend to deviate upwards, measurements were clearly taken under conditions outside the LVE range[23] (Fig. 2). In order to be sure that the stress level was not too low, the behavior at the lowest temperature have been investigated by checking that the minimum deformation was higher than 0.5%[25]. The above mentioned preliminary tests were also fundamental to choosing the right testing geometry for correctly performing the rheological tests. The SHRP project, indeed, prescribes using 8mm parallel plates only when the shear modulus is higher than 1×10^5 Pa[26]. Preliminary tests at the lowest temperature made it possible to use 25 mm parallel plates for all the experimental program.

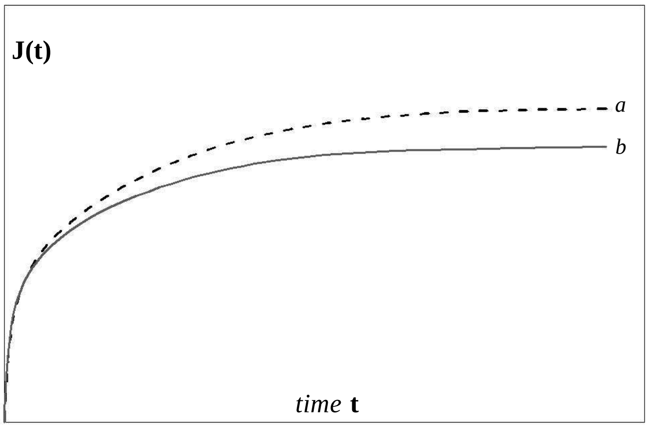

Figure 2. Linearity check: creep compliance curves J(t), a) in the LVE range, b) outside the LVE range with increased compliance

Therefore, the procedure followed for the linearity check provided a better knowledge of the different binders' behavior, giving a chance to establish the constant shear stress to be used in the creep tests, to select the right testing geometry and also to choose the necessary time length to correctly describe the creep phenomenon up to steady-state flow (Table 3). Steady-state flow occurs when the material shows a purely viscous behavior and during a creep test it is reached only when the shear rate, as well as the viscosity, approach a constant value. The creep time was therefore determined with a double check by firstly assessing when the registered shear rate proved to be constant for at least 10% of the total measured point[23] and then by verifying that the instantaneous viscosity of the binders was not increasing by more than 5% in the last fifteen minutes of testing[27].

BINDER	SHEAR STRESS (Pa)	TEMPERATURE (°C)	CREEP TIME (h)	RECOVERY TIME (h)
B1	10	20	1.5	3
		40	1.25	2.5
		60	1	2
B2	30	20	1.25	2.5
		40	1	2
		60	0.75	0.75

Table 3. Creep and recovery testing conditions

4.2.3 Creep and recovery tests

After establishing the linearity range for the binders studied, creep tests were performed for verifying the proposed model within the LVE range. All the creep tests were carried out by applying a constant shear stress level (10 Pa or 30 Pa, according to the bitumen to be tested) at the selected temperatures of 20, 40 and 60°C. Temperature was carefully controlled by pre-heating the plates at test temperature for 10 minutes and then by allowing the sample to equilibrate for 30 minutes before applying any stress. All the rheological tests were performed with a 25mm parallel plates and a gap of 1 mm.

Creep recovery test were performed just after the creep test by simply unloading the sample and registering the consequent deformations. In order to better describe the behavior of the binders, the time length of the unloading phase was set as double the loading phase. Moreover, in order to increase the reliability of the results, three repetitions of the tests were carried out for each combination of bitumen and temperature. Table 3 summarizes all the above described testing conditions, for both tests and for each binder.

5. COMPARISON AND CALIBRATION OF RESULTS

As previously mentioned, all types of material behaviour are usually schematized starting from spring and dashpot and then generalizing a number of both in parallel or in series.

In any case, from the simplest to the generalized one, the analytical formulation or briefly the constitutive law is typically governed by ordinary differential equations, whose solution in the case of the generalized Burgers model appears in the form of eq.1. It is worth noticing that even the simple Burgers model ($n = 1$) requires the evaluation of a minimum of four parameter. In this section, the numerical results will be discussed in detail. The aim of these tests is to show how the fractional model can perfectly fit the experimental curves, providing, through a small number of parameters, a straightforward interpretation of bitumen behaviour.

In order to get the two fundamental parameters of the fractional model in Eq.13, namely the amplitude factor A and the exponent α, also known as fractional order, a best fitting procedure over the different samples for each experimental setup, was implemented through the software Wolfram MATHEMATICA 6.0, by using the entire strain history. In this way, the variability of the experimental results was taken into account even considering the limited number of repetitions (for each bitumen and for each temperature, a minimum of three samples was tested).

As an example, in Fig. 3a a creep test for a bitumen B1 is depicted at a temperature T =20°C. From a close observation of this Fig. 3a it is clear that the experimental results are well-fitted by a power law (continuous thick line) as in Eq. 13, having A=0.7x10-5 $(\text{Pa s}^{a})^{-1}$ and α=0.637. It should be noticed that this pair of parameters makes it possible the fitting of both creep and relaxation phases.

As expected, when increasing the temperature (Fig.3b and Fig.3c), a more viscous behavior arises and the best fitting procedure produces α=1.

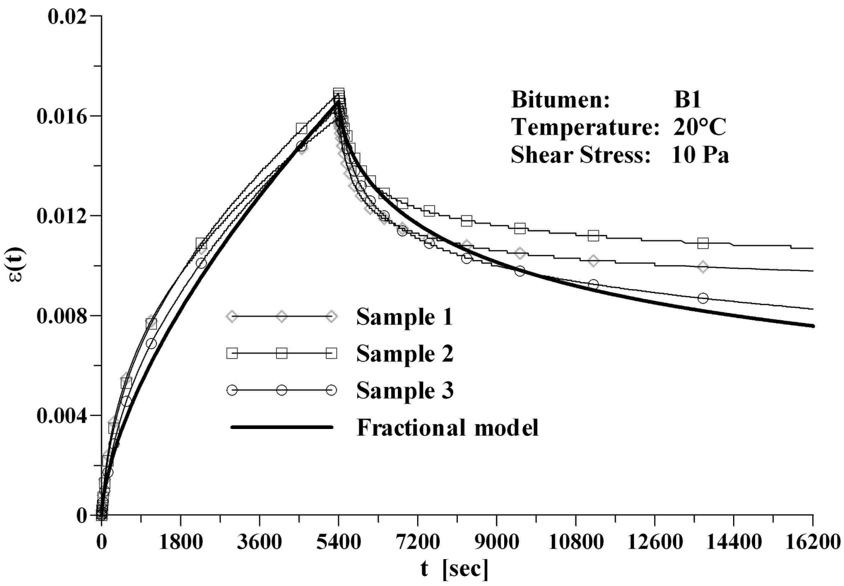

Figure 3a. Creep test for bitumen B1 at T =20°C.

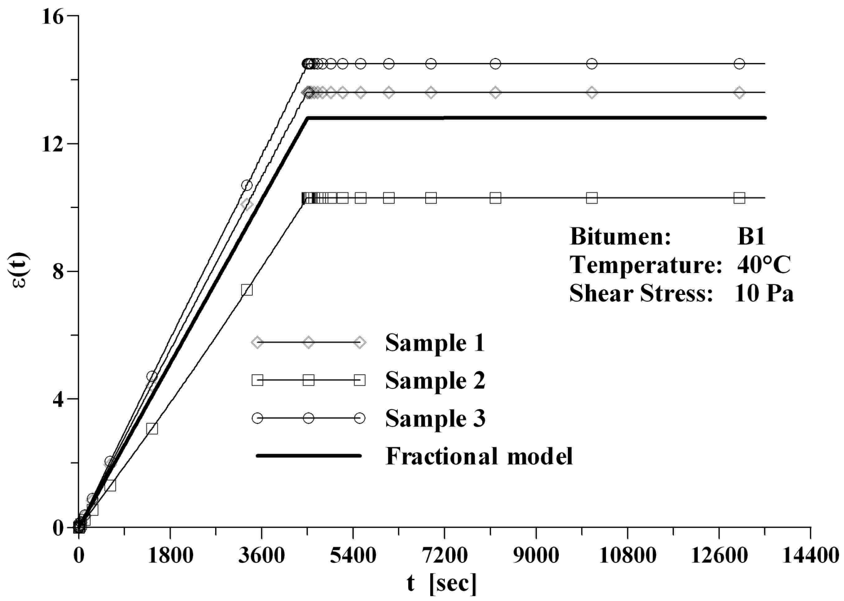

Figure 3b. Creep test for bitumen B1 at T =40°C.

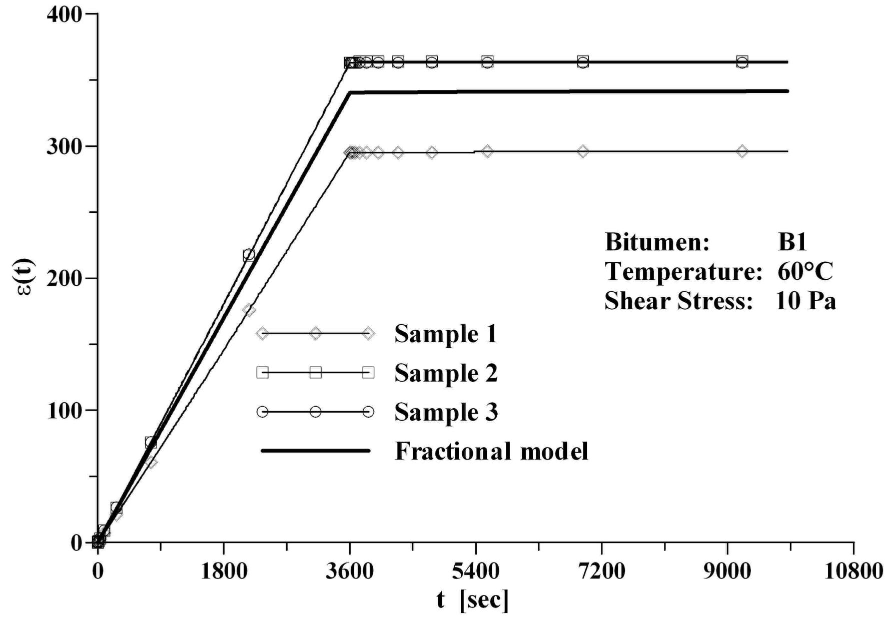

Figure 3c. Creep test for bitumen B1 at T =60°C.

The same remarks may be extended to the bitumen B2 by observing Fig. 4a,b,c. In particular, over the range of the testing temperatures, B2 shows prevalent viscous behavior. At 20°C, the best fitting procedure produces, in fact, α=0.979.

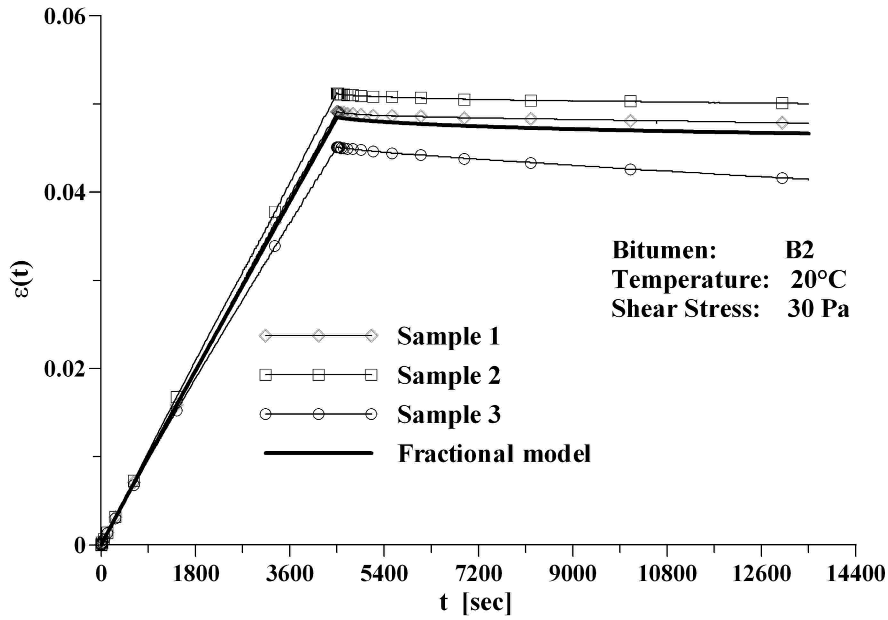

Figure 4a. Creep test for bitumen B2 at T =20°C.

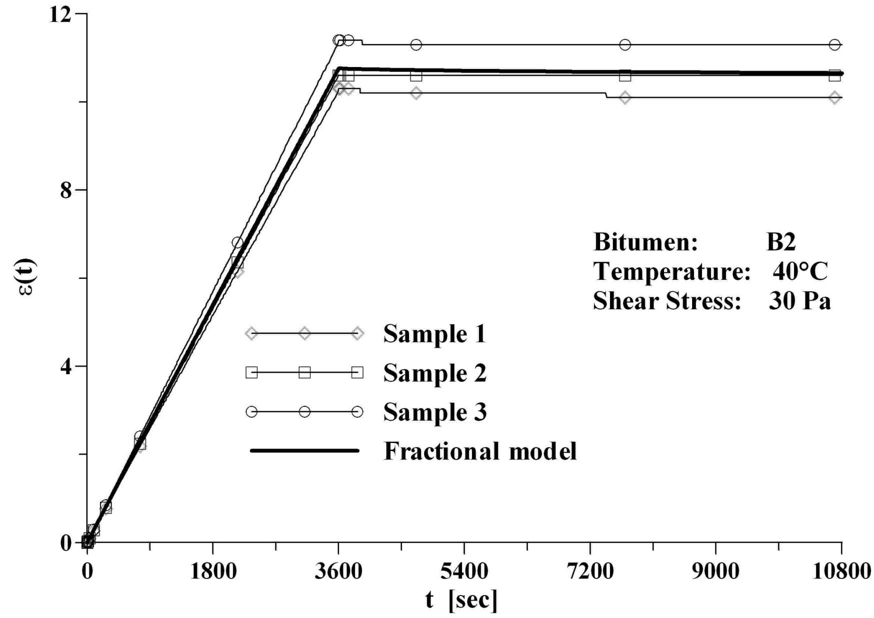

Figure 4b. Creep test for bitumen B2 at T =40°C.

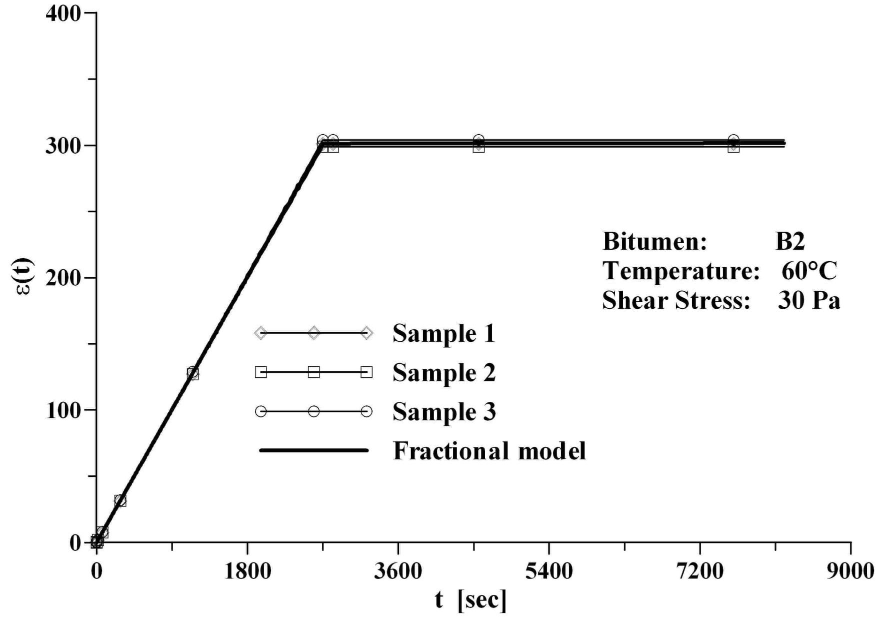

Figure 4c. Creep test for bitumen B2 at T =60°C.

These considerations may be better summarized by means of the curves given in Fig. 5a and 5b. In fact, from Fig. 5a it can be easily observed that the amplitude coefficient A exponentially increases at high temperature levels for both bitumens B1 and B2. This is quite normal since at high temperatures the bitumen, as it usually happens, experiences huge deformations. It is interesting to notice that the fractional order α, when varying the temperature, provides an exhaustive description of the visco-elastic behavior of the tested bitumens.

Looking at Fig. 5b and Fig. 3b,3c,4b,4c, one may affirm immediately that both B1 and B2, from 40°C to 60°C behave like perfectly viscous fluids (α=1). On the other hand at 20°C, B1 (see Fig. 5b and Fig. 3a,4a) shows a deeper visco-elastic behavior than that shown by B2. In this sense, the parameter α can be considered as an index of the degree of viscosity.

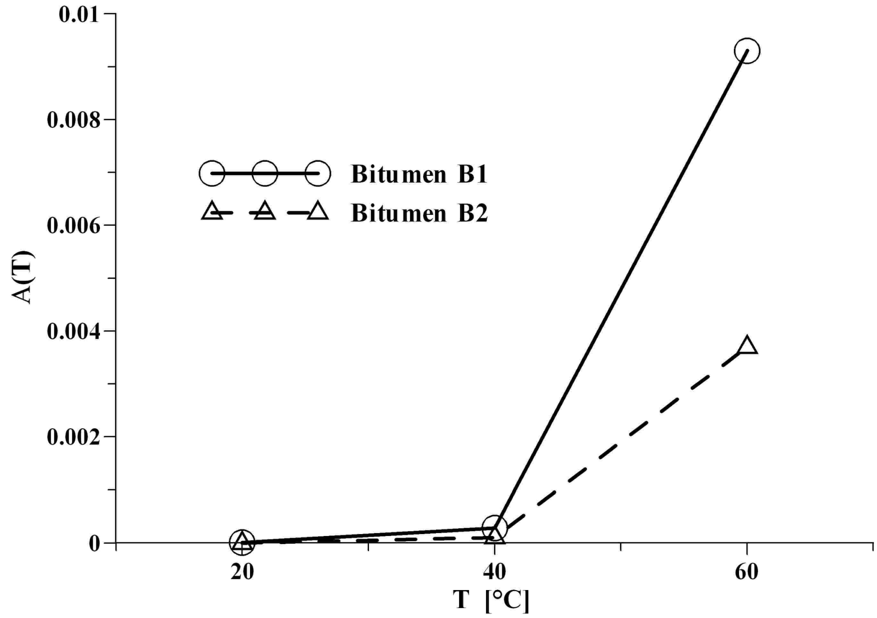

Figure 5a. Variation of the parameter A obtained with the testing temperature

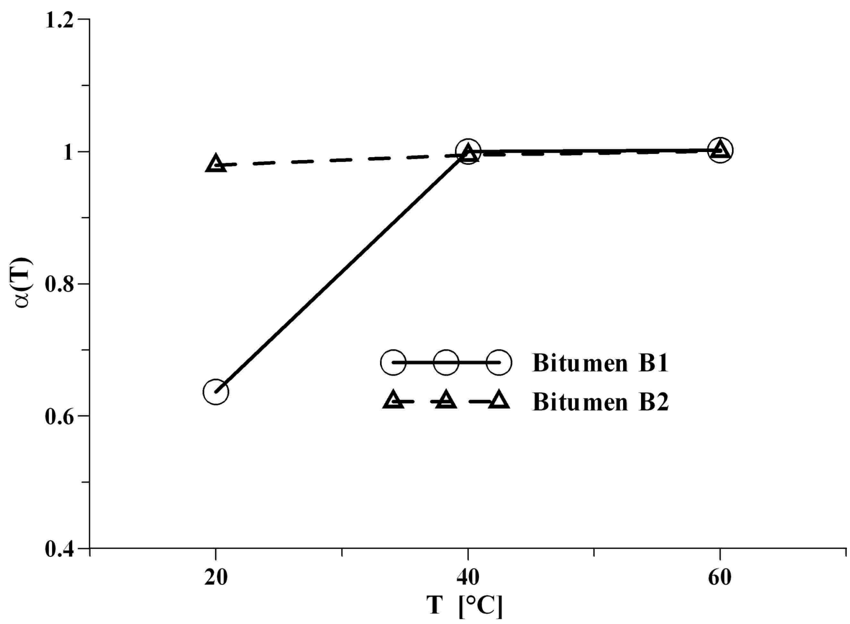

Figure 5b. Variation of the parameter α obtained with the testing temperature

6. CONCLUSION AND FUTURE DEVELOPMENTS

The fractional derivative model here proposed proves to be a good model for fitting both the experimental creep and recovery phases for the tested bitumens. The small number of parameters makes it possible to associate a clear physical meaning with all of them. The amplitude factor A rules the amount of strain, while the fractional order α can be assumed as a viscosity degree index.

Based on the preliminary validation of the model proposed in this paper, it is possible to foresee some interesting future developments such as:

i. widening the testing conditions for modified bitumens (with polymers and/or waste materials);
ii. generalizing the proposed model to multi-fractional derivatives models;
iii. taking into consideration the chemical composition of the bitumen, also considering a different order of the fractal model proposed.

On the basis of what has been discussed, it is clear that is necessary to have a fraction power law as the kernel into the Duhamell integral, which in turn leads to considering fractional derivatives instead of ordinary ones inside the constitutive law.

This important conclusion indicates that in order to accurately capture the behavior of visco-elastic material like road paving bitumen, it is appropriate to use fractional derivatives and that the fractional calculus should be implemented to get the right solution of these equations.

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