Ageing modelling of seal bitumen binder

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ABSTRACT

Most current seal designs methods are based on the volumetric properties of materials and voids. In order to improve seal design, the possibility of introducing mechanistic principles into seal design was investigated. Introducing mechanistic concepts into seal design meant that principles such as elasticity and viscoelasticity could be used in terms of stress-strain to explain phenomena such as damage in the seal structure. Viscoelastic parameters of bituminous materials such as complex modulus (G^*) and phase angle (δ) are key elements in the understanding of performance, damage and failure of seal bituminous materials. Another major parameter that influences the performance, damage and failure of seals, is bitumen ageing.

This paper presents an ageing model developed based on the G^* master curve using recovered field-aged bitumens and fresh binder from the plant. Laboratory simulations of bitumen ageing (such as the Pressure Ageing Vessel (PAV) and weatherometre ageing (Q-sun ageing)) were included in this model.

An assessment of long term ageing was performed based on the model.

Keywords: Ageing, Complex Modulus, Master Curve, Bitumen.

1. INTRODUCTION

Most current seal designs methods are based on the volumetric properties of materials and voids. In order to improve seal design, the possibility of introducing mechanistic principles into seal design was investigated. Introducing mechanistic concepts into seal design meant that principles such as elasticity and viscoelasticity could be used in terms of stress-strain to explain phenomena such as damage in the seal structure. Viscoelastic parameters of bituminous materials such as complex modulus (G^*) and phase angle (δ) are key elements in the understanding of performance, damage and failure of seal bituminous materials. Another major parameter that influences the performance, damage and failure of seals, is bitumen ageing.

This paper presents an ageing model developed based on the G^* master curve using recovered field-aged bitumens and fresh binder from the plant. Laboratory simulations of bitumen ageing (such as the Pressure Ageing Vessel (PAV) and weatherometre ageing (Q-sun ageing)) were included in this model. The age of the two laboratory-aged bitumens were assessed based on the developed model.

The paper presents the development of the principles of the ageing model, assessment of the age of laboratory-aged bitumens using the model, discussion of the ageing mode and conclusions.

2. DEVELOPMENT PRINCIPLE OF AGEING MODEL

28 samples of 70/100 penetration grade bitumen (70/100) and 21 samples of elastomer modified bitumen for seal purpose (SE1) were recovered from different field-aged seals across South Africa. The recovering process followed is a combination of ASTM D1856 and TMH Method C7 (b) which uses AR benzene as solvent, and a centrifuging process for fines mineral separation [1-6]. These 49 aged bitumens were tested using the Dynamic Shear Rheometer (DSR). Data obtained from the DSR were modelled based on linear viscoelastic rheological master curves. The complex modulus (G*) master curve based on Prony series was used to develop the model. Both 70/100 and SE1 original bitumens formed part of the modelling. The original bitumens were tested and modelled in the "fresh" state (Unaged-Unconditioned) [7] and after laboratory simulations of bitumen ageing using the Pressure Ageing Vessel (PAV) [8] and weatherometre ageing (Q-sun ageing) [7, 9, 10]. Their respective ages were assessed based on the model.

The ageing was considered to be the stiffening of bitumen with time (stiffness represented by the complex modulus G*). The principle of development of the ageing model of a seal's bitumen is presented as follows:

1) All the recovered bitumens, fresh bitumens (Unaged-Unconditioned), and bitumens aged by PAV and Q-SUN methods were modelled using the Prony series method.
2) The G* values for each specific bitumen type were combined and presented in a unique graph as functions of reduced frequency. **FIGURE 1** represents the case of 70/100.
3) Three frequencies (i.e. 10 rad/s, 62.83 rad/s and 100 rad/s) were chosen as reference frequencies for the analysis of changing of G^* with time. These frequencies were selected in a range reported as the "common moving vehicle frequency range". It was reported that automobile frequency ranging from 1 to 16 Hz (6.28 to 100.5 rad/s) [11-13]. The choice of 62.83 rad/s (10 Hz) was justified by its relative middle position in the automobile frequency range.
4) G^* for each Prony series curve (at the three given frequencies) were presented graphically as a function of time. Through regression, the ageing model was obtained as a "power" type function (Eq. (1) and **FIGURE 2**). **FIGURE 2** presents the case of the seal's bitumen ageing model for the three reference frequencies for SE1 bitumen. The relationship between the modelled and Prony series G* in the ageing model is presented in **FIGURE 2**.

$$G^* = {G^*}_{t_0} + bt^c \qquad \textbf{(1)}$$

where

t is the age (time) of the seal's bitumen

${G^*}_{t_0}$ is the initial complex modulus of a seal's bitumen (complex modulus of the fresh bitumen)

G^* is the complex modulus of a seal's bitumen at time t

b and c are constants

Values of ${G^*}_{t_0}$, b and c, as well as the coefficient of determination (R^2), for 70/100 and SE1 bitumens for the three reference frequencies are shown in **TABLE 1**. ${G^*}_{t_0}$ is assumed to be constant for the purpose of simplification. In reality, all binders do not have the same initial modulus.

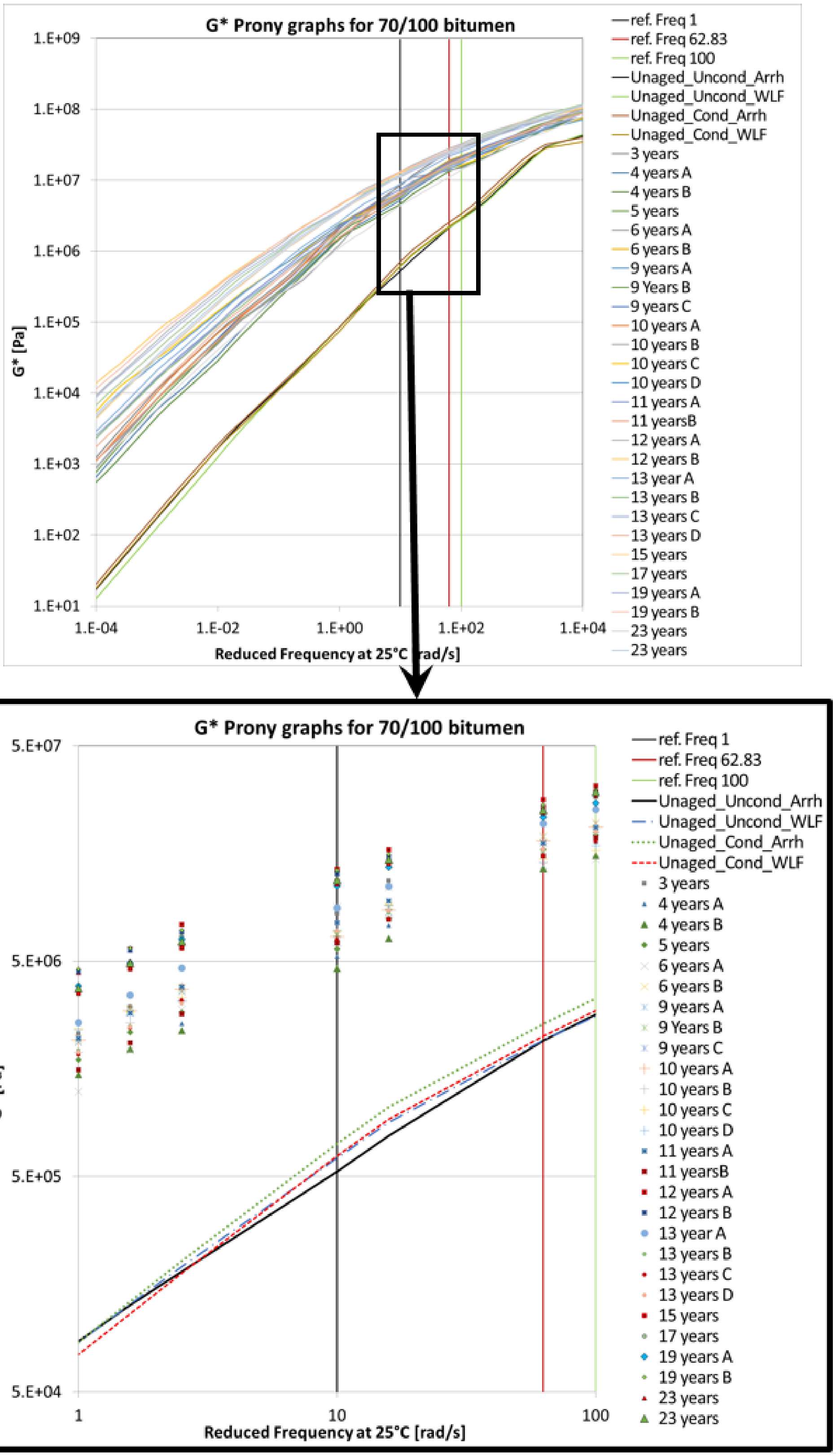

FIGURE 1: Combined Graph for all 70/100 G* Prony Series with magnification for reference frequencies

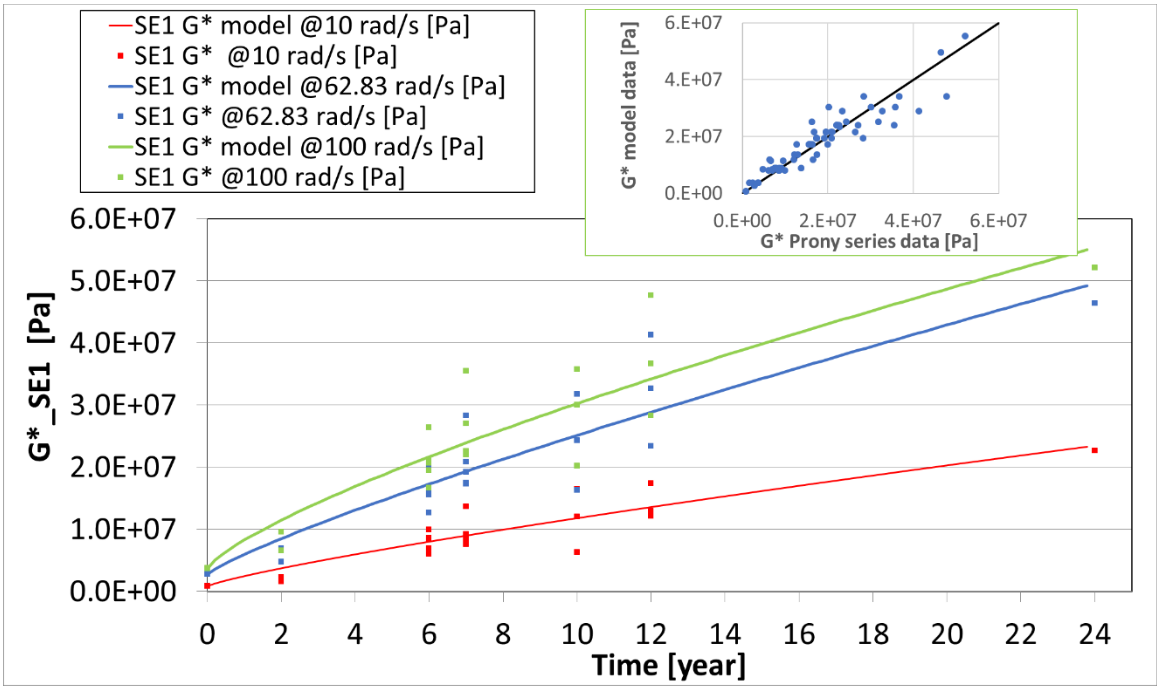

FIGURE 2: Relationship between G* and time for SE1 bitumen at three reference frequencies

TABLE 1: Values of constants of seal's bitumen ageing model for 70/100 and SE1

Type of bitumen	Frequency	10 rad/s	62.83 rad/s	100 rad/s
70/100	**G^*_{t0}**	5.28E+05	2.14E+06	2.83E+06
	b	8.78E+05	3.13E+06	3.49E+06
	c	0.859	0.674	0.688
	R^2	0.73	0.74	0.75
SE1	**G^*_{t0}**	8.13E+05	2.74E+06	3.63E+06
	b	1.63E+06	3.22E+06	4.64E+06
	c	0.828	0.843	0.759
	R^2	0.82	0.82	0.82

3. ASSESSMENT OF THE AGE OF LABORATORY AGED BITUMEN USING THE MODEL

G* values collected from bitumen aged in the laboratory by the PAV and Q-SUN methods [7-10] were plotted against the graph of the seal's bitumen ageing model. The aim was to assess the simulated ageing time on the field-aged model. G^* values for 70/100 and SE1 at the three reference frequencies are shown in **TABLE 2**. The estimation of aged time of PAV and Q-SUN bitumens using the ageing model of a seal's bitumen is between 0.6 and 5.7 years (**TABLE 3**). The Q-SUN method presents the highest ageing simulation of 5.7 years for 70/100 bitumen at 10 rad/s.

TABLE 2: G* values for 70/100 and SE1 at the three reference frequencies

Type of bitumen	**Description of bitumen:** (type, conditioning, recovered position, rheological modelling type…)	**G* [Pa]**		
		at 10 rad/s	**at 62.83 rad/s**	**at 100 rad/s**
70/100	70/100 PAV_Uncond_Arrh	3.38E+06	7.65E+06	8.83E+06
	70/100 _1252_Q-Sun	4.42E+06	1.10E+07	1.40E+07
SE1	SE1 PAV_Uncond_Arrh	2.10E+06	6.06E+06	7.93E+06
	SE1 Q-SUN	1.83E+06	5.26E+06	6.84E+06

TABLE 3: Modelled aged time of PAV and Q-SUN for 70/100 and SE1 at the three reference frequencies

Type of bitumen	**Description of bitumen:** (type, conditioning, recovered position, rheological modelling type…)	**Modelled age time [year]**		
		at 10 rad/s	**at 62.83 rad/s**	**at 100 rad/s**
70/100	70/100 PAV aged_Uncond_Arrh	3.9	2.3	2.2
	70/100_1252_Q-Sun	5.7	4.7	5.4
SE1	SE1 PAV_Uncond_Arrh	0.8	1.0	0.9
	SE1 Q-SUN	0.6	0.8	0.6

The age for an average G* in the common moving vehicle frequency range was assessed and is presented in **TABLE 4**. The related graphs for 70/100 and SE1 are respectively presented in **FIGURE 3** and **FIGURE 4**.

TABLE 4: Data for average G* and estimated aged time for PAV and Q-SUN aged bitumen

	Seal's bitumen ageing model			**Average estimated aged time [year]**	
70/100	G^*_{t0}	b	c	70/100	70/100 _1252_Q-Sun
	1.83E+06	2.47E+06	0.71	2.8	5.3
SE1	G^*_{t0}	b	c	SE1	SE1 Q-SUN
	2.39E+06	3.15E+06	0.80	0.9	0.6

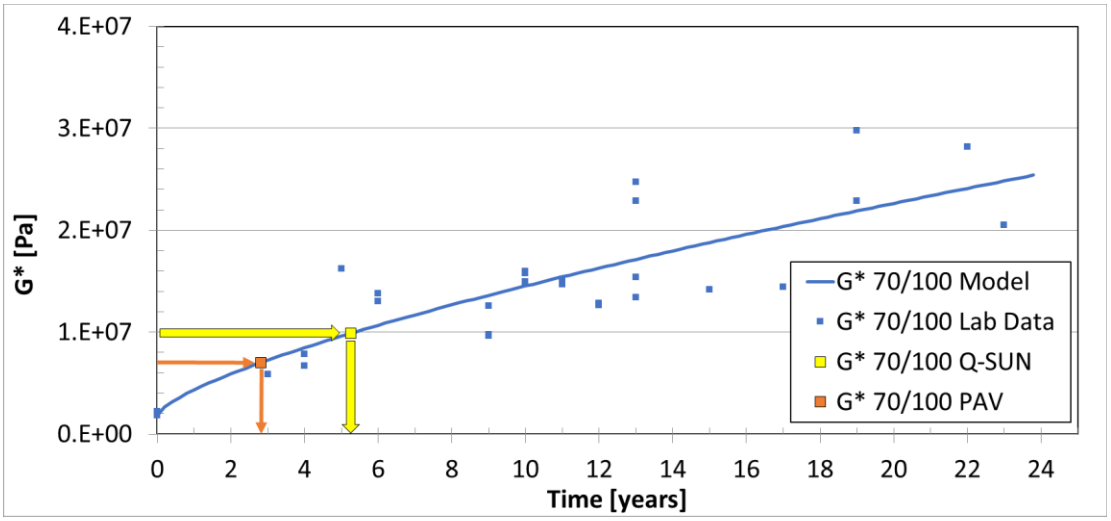

FIGURE 3: Graph of ageing model of 70/100 seal's bitumen based on average G* from the three reference frequencies

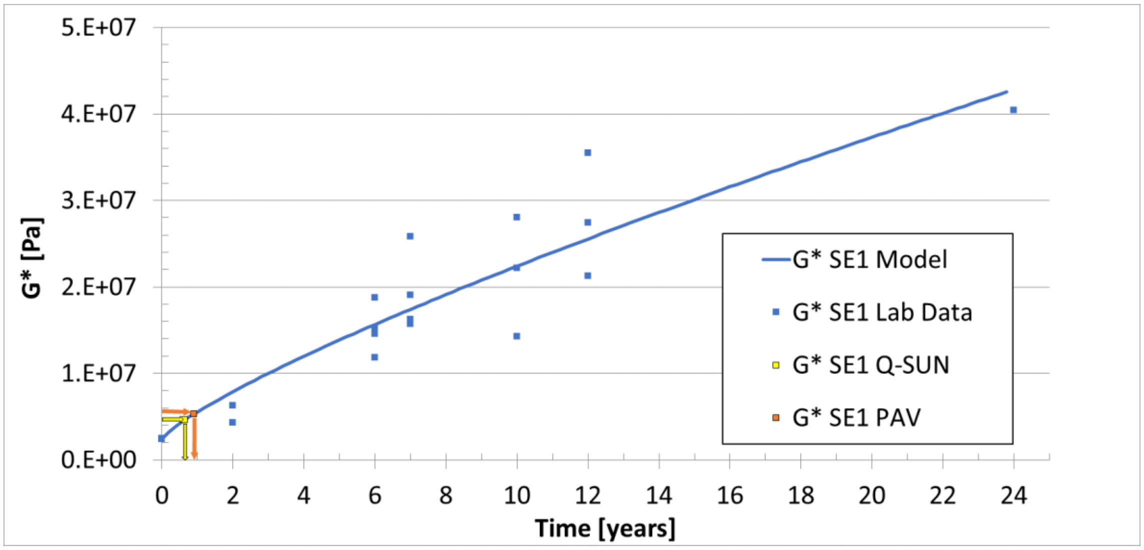

FIGURE 4: Graph of ageing model of SE1 seal's bitumen based on average G* from the three reference frequencies

4. DISCUSSION OF THE AGEING MODEL AND RECOMMENDATION

Although it was reported that the visco-elastic solid behaviour of modified binders cannot be modelled with some materials after ageing has occurred [14], the ageing model of a seal's bitumen developed appears to fit for both 70/100 and SE1 (R^2 of 0.7 and 0.8 respectively as presented in **TABLE 1**) This model can be considered as a good attempt at a field-ageing simulation. R^2 represent the relative spread of data which is expected due to the high variability linked to the field environment conditions. Thus, the effect of different variabilities on this modelling attempt should be noted. One of these variabilities is the change of bitumen consistency/stiffness due to possible treatments undergone by the seal during its field exposure such as rejuvenation, bitumen-recovery process in the laboratory, differences in initial complex modulus, change in ageing rate for different binders, and the gradient of field ageing with the thickness of the seal.

The ageing time simulations of the two laboratory ageing methods adopted (PAV and Q-SUN) were assessed based on the ageing model developed. From this assessment, the following appears:

- On average, the PAV-aged bitumen simulates less than three years of 70/100 seal's bitumen;
- The Q-SUN simulates on average just above five years for 70/100 seal's bitumen ageing, and
- The simulation of SE1 ageing was found to be less than one year for both the PAV and Q-SUN methods. In this particular case, the PAV ageing time (0.9 years) is slightly higher than the Q-SUN ageing time (0.6 years).

A detailed investigation into the ageing model of both non-modified and modified bitumen is recommended. This investigation could compare laboratory ageing methods (Q-SUN and the PAV method) with field-aged binder recovered by a method that minimises the change in bitumen properties. The recovery process of bitumen requires more investigation which can be based on research reported in literature such as works performed by the Western Research Institute (WRI) [15]. In this regard, it was reported that mechanical methods of bitumen recovery (e.g. using centrifugal forces) appear to be promising compared with chemical methods [16, 17].

5. CONCLUSION

An ageing model was developed, which involved the rheological modelling of 49 bitumens (70/100 and SE1) recovered from "field-aged" seals for four different types of bitumen used in South African seals. This ageing model, based on the relative stiffening of the complex modulus (G^*) with time, was analysed for 70/100 and SE1 bitumens at three reference frequencies (10 rad/s, 62.83 rad/s and 100 rad/s). The ageing model of a seal's bitumen appears to fit for both 70/100 and SE1. This "power" type model function, referred to as the "ageing model of a seal's bitumen", can be considered as a good attempt at a field ageing simulation. It should be noted that the unaged condition of bitumen (characterised by the initial complex modulus) was from the laboratory binder and did not represent the actual field materials. This is important as all binders after ageing eventually end at about the same stiffness, but they start at very different initial complex modulus.

The effect of different variabilities that could affect the model should be noted. One of these variabilities is the change of bitumen consistency/stiffness due to possible field treatment and the laboratory bitumen-recovery process. It was found that the Q-SUN method simulated higher field ageing than the PAV method in the case of 70/100, unlike the Q-SUN method which simulated less field ageing than the PAV method. Although the outcome from the ageing model appears to be conclusive, further investigation into laboratory ageing is required to refine the relationship with field ageing.

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