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**FUNDAMENTAL BINDER AND PRACTICAL ASPHALT MIXTURE EVALUATION OF SEALOFLEX**

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FUNDAMENTAL BINDER AND PRACTICAL ASPHALT MIXTURE EVALUATION OF SEALOFLEX

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Summary

Conventional bituminous materials have tended to perform satisfactorily in most highway pavement and airfield runway applications. However, in recent years, increased traffic levels, larger and heavier loads, new axle designs and increased tyre pressures have added to the already severe demands of load and environment on the pavement system. This has facilitated the need to enhance the properties of existing asphalt material. Bitumen modification, particular polymer modification to produce binders such as Sealoflex, offers one solution to overcome the deficiencies of bitumen and, thereby, improve the performance of asphalt mixtures.

The paper evaluates the relative performance of Sealoflex with regard to the two main modes of distress in asphalt pavements – permanent deformation and fatigue. The study makes use of fundamental rheological binder testing by means of dynamic shear rheometry, pavement performance prediction by means of the Strategic Highways Research Program (SHRP) binder parameters and the zero shear viscosity concept, and practical, mechanical asphalt mixture testing by means of the Nottingham Asphalt Tester (NAT). Analysis of the fundamental rheological data through to the permanent deformation and fatigue testing in the NAT all indicate an improved rutting and fatigue performance for Sealoflex compared to an unmodified penetration grade bitumen.

Introduction

A careful balance of binder properties is generally required to alleviate one mode of asphalt mixture distress without aggravating other modes, such as the use of a harder bitumen to alleviate rutting without aggravating fatigue. To this end, novel binders with improved rheological characteristics are continuously being developed. Sealoflex polymer modified bitumen (PMB) is one such product that has the ability to improve both the permanent deformation and fatigue deficiencies of conventional, unmodified bitumens.
This paper addresses two modes of asphalt mixture distress – permanent deformation (rutting) and fatigue cracking – and the relative performance of Sealoflex and a penetration grade bitumen in terms of these two distress modes. The focus of the paper is on the use of fundamental rheological testing of bitumen, pavement performance prediction methods and practical mechanical property testing of asphalt mixtures. The fundamental rheological testing has been undertaken by means of dynamic shear rheometry, the pavement performance prediction methods consist of the Superpave binder parameters for rutting and fatigue and the zero shear viscosity concept, and the mixture testing has been conducted with the Nottingham Asphalt Tester (NAT).

**Fundamental Rheological Testing of Binders**

Traditionally used specifications are based on measurements of viscosity, penetration, ductility and softening point temperature. These measurements are generally not sufficient to thoroughly describe the linear viscoelastic (LVE) and failure properties of bitumen needed to relate bitumen properties to mixture properties and to pavement performance. In order to relate binder properties to pavement performance it is necessary to undertake more fundamental testing of bitumen.

Bitumen is a thermoplastic, viscoelastic liquid that behaves as a glass-like elastic solid at low temperatures and/or rapid loading (short loading times – high loading frequencies) and as a viscous fluid at high temperatures and/or during slow loading (long loading times – low loading frequencies). The response of bitumen to stress is, therefore, dependent on both temperature and loading time and, consequently, the rheology of bitumen is defined by its stress-strain-time-temperature response. Based on these observations bitumen rheology can broadly be defined as the fundamental measurements associated with the flow and deformation characteristics of bitumen.

**Dynamic Shear Rheometer**

At present the most commonly used method of rheological testing of bitumen is by means of dynamic mechanical methods using oscillatory-type testing, generally conducted within the region of linear viscoelastic (LVE) response. These oscillatory tests are undertaken using Dynamic Shear Rheometers (DSRs) which apply oscillating shear stresses and strains to samples of bitumen sandwiched between parallel plates at different loading frequencies and temperatures [1].
The DSR tests reported in this paper were performed under the following test conditions:

- **Mode of loading:** Controlled-strain,
- **Temperatures:** 10, 15, 25, 35, 45, 55, 65 and 75°C,
- **Frequencies** 0.01, 0.015, 0.02, 0.05, 0.1, 0.15, 0.2, 0.5, 1, 1.5, 2, 5, 10, 15 Hz,
- **Strain amplitude:** Within LVE response (0.5 to 10%).

The rheological properties of the binders were measured in terms of complex (shear) modulus (stiffness), $G^*$, and phase angle (viscoelastic balance of rheological behaviour), $\delta$.

**Rheological Data Analysis**

The DSR rheological data for the penetration grade bitumen (Binder A) and the Sealoflex PMB (Binder B) are presented in the form of isochronal plots of complex modulus, $G^*$, and phase angle, $\delta$, in Figures 1 and 2. The isochronal plots in Figure 1 represent the rheological data measured in the DSR at a loading frequency of 0.02 Hz, while the isochronal plots in Figure 2 represent data at 1 Hz. The two figures clearly indicate not only the temperature but also the time dependency of the rheological behaviour of the two binders.

![Isocronal plots of complex modulus and phase angle for Binders A and B](image)

*Figure 1: Isochronal plot at 0.02 Hz for Binder A and Binder B*
The isochronal plots show that the Sealoflex PMB has a lower stiffness ($G^*$ value) at the lower end of the temperature domain but a higher stiffness at higher temperatures compared to the unmodified bitumen. This indicates the improved temperature susceptibility of the modified binder resulting in both increased flexibility at the lower temperatures and increased hardness at high temperatures for the Sealoflex PMB.

The phase angle, $\delta$, is generally considered to be more sensitive to the chemical structure and morphology of the binder and, therefore, more sensitive to the degree and type of modification of the bitumen than $G^*$ [2]. The phase angle isochronal plots in Figures 1 and 2 show the change in rheology with modification as a reduction in $\delta$ for the Sealoflex PMB and, therefore, an increased elastic behaviour compared to the unmodified bitumen. This decrease in phase angle occurs across the entire temperature domain of the plots, but is more significant at the higher temperatures were the unmodified binder becomes increasingly more viscous in nature.

The DSR rheological data has also been presented in the form of master curves of complex modulus, $G^*$, and phase angle, $\delta$, at a reference temperature of 25°C. The master curves have been produced by shifting the $G^*$ isotherms to produce a smooth continuous master curve in Figure 3. The shift factors, derived for the $G^*$ master curve, have then been used to shift the phase angle isotherms to produce the phase angle master curves in Figure 4.

The complex modulus master curve shows, in addition to an increase in stiffness at long loading times (low frequencies), a reduction in stiffness at high loading frequencies when compared to the rheological properties of the unmodified bitumen.
Using time-temperature equivalency this behaviour can be considered to be analogous to the increased stiffness at high temperatures and the decreased stiffness at low temperatures seen in the isochronal plots of Figures 1 and 2.

As with the isochronal plots, the phase angle master curve in Figure 4 shows the increased elastic behaviour of the Sealoflex PMB. The increase in elastic behaviour is particularly noticeable at low frequencies where the polymer is most dominant. Appreciating that rutting is primarily a viscous phenomenon and that the bitumen is responsible for the viscoelastic behaviour characteristic of the asphalt mixture, increasing the elastic component of the bitumen should reduce the viscous component and, thereby, result in a reduction in permanent strain.
The Black diagram in Figure 5 allows all the experimental data to be presented on a single plot without requiring the shifting of data. The Black diagram shows the increased elastic behaviour of the elastomeric Sealoflex PMB, which is particularly marked at the low complex modulus values found at high temperatures and/or long loading times where rutting has the potential to be most prevalent.
The combined fundamental rheological information obtained from the isochronal plots, master curves and Black diagram show the lower stiffness and increased flexibility of Sealoflex at low and intermediate temperatures and the increased stiffness and elastic behaviour at high temperatures. This indicates that the Sealoflex PMB should be able to provide modified asphalt mixtures with both improved low temperature thermal cracking and fatigue resistance as well as improved high temperature rutting resistance.

**Pavement Performance Prediction From Fundamental Binder Rheological Information**

*Strategic Highway Research Program Binder Specification*

The Strategic Highway Research Program (SHRP) was a highly focused, ambitious research effort which targeted four specific areas for intense study over the time frame from 1987 to 1993 [3]. Bitumen was one of the four study areas which culminated in the production of Superpave (Superior Performing Asphalt Pavements).

One of the major products of the SHRP asphalt research program was a performance-based asphalt binder specification which is applicable to both modified and unmodified bituminous binders, including binders with modifiers dispersed, dissolved or reacted with the base bitumen. A major objective of the asphalt research program was to identify and validate engineering properties that could be directly linked to the performance (the response to traffic and environmental loading) of bituminous binders.

The SHRP binder specifications, and the measurements upon which they are based, are designed to provide performance-related properties that can be related in a rational manner to pavement performance. The pavement distress modes that are considered in this paper are rutting, caused by inadequate shearing resistance in the asphalt mixture, and load associated fatigue cracking.

*SHRP binder rutting parameter*

Rutting in the upper pavement layers is caused by accumulated plastic deformation in the mixture that results from the repeated application of traffic loading. Although the rutting tendencies of a pavement are primarily influenced by aggregate and mixture properties, the properties of the binder also affect the rutting resistance of mixtures. This is particularly true for polymer modified bitumens (PMB’s), which have been shown to enhance the rutting resistance of pavements. In addition, rutting is more prevalent at elevated temperatures than at intermediate or low temperatures.
Based on these observations, a measurement of the non-recoverable deformation of the bitumen was established as the critical specification criterion for rutting resistance. This lead to the adoption of the inverse of the loss compliance, $1/J''$, which is numerically equivalent to the complex shear modulus divided by the phase angle, $G*/\sin\delta$ [4]. The loading frequency used in the specification was selected as 10 rad/sec (1.59 Hz), with higher values of $G*/\sin\delta$ indicating superior rutting resistance.

The SHRP rutting parameters for Binder A and Binder B (both after aging) are presented in Table 1. The parameters have been determined at a temperature of 40°C to coincide with the temperature of the NAT test for permanent deformation. In addition to the loading frequency of 10 rad/sec, a slower loading frequency of 0.02 Hz was included to accentuate the viscous behaviour and, therefore, the permanent deformation susceptibility of the binders.

### Table 1: SHRP rutting binder parameter at 40°C on RTFOT aged binders

<table>
<thead>
<tr>
<th>Binder</th>
<th>$G*/\sin\delta$ @ 0.02 Hz</th>
<th>$G*/\sin\delta$ @ 10 rad/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder A</td>
<td>3.5 kPa</td>
<td>162.3 kPa</td>
</tr>
<tr>
<td>Binder B</td>
<td>5.9 kPa</td>
<td>116.3 kPa</td>
</tr>
</tbody>
</table>

The greater $G*/\sin\delta$ value, at the lower frequency of 0.02 Hz, of the Sealoflex PMB indicates a predicted improved rutting performance for the binder. However, the $G*/\sin\delta$ values at 10 rad/sec show the opposite trend to that found at 0.02 Hz. The lower $G*/\sin\delta$ values of the Sealoflex PMB are a consequence of the lower stiffness, $G^*$, of the Sealoflex binder compared to Binder A at low temperatures and high loading frequencies.

The appropriateness of using the $G*/\sin\delta$ rutting parameter to predict the rutting performance of different binders at 40°C, and particularly at higher loading frequencies, is however questionable. This is due to the fact that this temperature is below the lowest test temperature of 45°C used by SHRP and could, therefore, have an effect on the sensitivity of the rutting parameter. The $G*/\sin\delta$ parameters were, therefore, also determined at a higher temperature of 55°C and presented in Table 2. As with the slower frequency of 0.02 Hz, the higher temperature was chosen to accentuate the viscous behaviour of the binders.

### Table 2: SHRP rutting binder parameter at 55°C on RTFOT aged binders

<table>
<thead>
<tr>
<th>Binder</th>
<th>$G*/\sin\delta$ @ 0.02 Hz</th>
<th>$G*/\sin\delta$ @ 10 rad/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder A</td>
<td>0.162 kPa</td>
<td>11.0 kPa</td>
</tr>
<tr>
<td>Binder B</td>
<td>0.597 kPa</td>
<td>14.3 kPa</td>
</tr>
</tbody>
</table>

At the higher temperature of 55°C, the Sealoflex PMB showed superior rutting performance at both frequencies as indicated by the higher $G*/\sin\delta$ values compared to the unmodified binder.
**SHRP binder fatigue parameter**

The fatigue parameter was chosen to reflect the energy dissipated per load cycle, which can be calculated as $G \times \sin \delta$ [4]. The specification prescribed a relationship whereby a reduction in $G \times \sin \delta$ at 10 rad/sec corresponds to improved fatigue resistance. Validation of the SHRP binder fatigue parameter with pavement performance has shown that, although the binder properties are important, pavement structural effects may be equally or more important [5]. The selection of appropriate specification criteria is further complicated by conflicting evidence regarding the effect of bitumen properties on fatigue performance.

The results of laboratory stress-controlled fatigue tests imply that stiffer binders are more resistant to fatigue cracking [6]. Conversely, laboratory strain-controlled fatigue testing implies that softer binders are more resistant to fatigue cracking [7,8].

Using the hypothesis that a reduction in $G \times \sin \delta$ will correspond to improved fatigue resistance, the fatigue parameters of the penetration grade bitumen and the Sealoflex PMB (both after aging) were calculated and presented in Table 3. The $G \times \sin \delta$ values in Table 3 indicate that the Sealoflex PMB should have far superior fatigue performance compared to Binder A.

**Table 3: SHRP fatigue binder parameter at 20 °C on RTFOT aged binders**

<table>
<thead>
<tr>
<th>Binder</th>
<th>$G \times \sin \delta @ 10$ rad/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder A</td>
<td>3800 kPa</td>
</tr>
<tr>
<td>Binder B</td>
<td>900 kPa</td>
</tr>
</tbody>
</table>

**Zero Shear Viscosity Concept**

An alternative means of relating binder properties to asphalt pavement performance and particularly to permanent deformation (rutting) is the zero shear viscosity concept. The concept is based on the fact that the binder contribution to rutting arises solely from an irreversible, purely dissipative, permanent deformation process, describable at the continuum level by the viscosity of the material [9]. The zero shear viscosities for Binder A and Binder B are presented in Table 4 at the two temperatures used in Tables 1 and 2 with the SHRP rutting parameter.

**Table 4: Zero shear viscosity at 40 °C and 55 °C on unaged binders**

<table>
<thead>
<tr>
<th>Binder</th>
<th>$\eta_0 @ 40^\circ C$</th>
<th>$\eta_0 @ 55^\circ C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder A</td>
<td>13.6 kPa.s</td>
<td>0.6 kPa.s</td>
</tr>
<tr>
<td>Binder B</td>
<td>16.7 kPa.s</td>
<td>2.1 kPa.s</td>
</tr>
</tbody>
</table>

As with the SHRP rutting parameter at low frequencies, the Sealoflex PMB showed a higher viscosity and, therefore, a predicted greater permanent deformation performance than the unmodified binder.
Mechanical Property Testing of Asphalt Mixtures

The unmodified penetration grade bitumen and the Sealoflex PMB have been used to produce an unmodified (Mixture A) and modified (Mixture B) surfacing (wearing course) asphalt mixture. These two asphalt mixtures were then subjected to practical, mechanical testing using the Nottingham Asphalt Tester (NAT).

Nottingham Asphalt Tester

The Nottingham Asphalt Tester (NAT) was developed at the University of Nottingham in response to the need for rapid, economical test methods for the measurement of the mechanical properties of bituminous materials under repeated loading conditions [10]. It was designed to carry out tests on either 100 mm or 150 mm diameter specimens which could be produced either by moulding (compaction) in the laboratory or by coring from the pavement. The permanent deformation resistance of the unmodified and Sealoflex modified mixtures were determined by means of the repeated load axial test (RLAT), while the fatigue performance of the mixtures was determined by means of the indirect tensile fatigue test (ITFT).

The RLA tests were performed in accordance with the British Standards Draft for Development DD185 (1994) using the following test parameters:

- Test temperature: 40°C,
- Test duration: 7200 seconds (3600 cycles) with a load pattern 1 second loading on (load application period) followed by one second off (rest period),
- Axial stress: 100 kPa, and
- Conditioning load: 10 kPa for 600 seconds.

The permanent deformation performance of the asphalt mixtures was quantified by the ultimate percentage strain after 3600 cycles and by the rate of strain (microstrain per cycle) over the linear phase of the deformation response calculated by linear regression between 1800 and 3600 load cycles [11].

The ITFT tests were performed in accordance with the University of Nottingham fatigue testing protocol using the following test parameters:

- Test temperature: 20°C,
- Loading condition: Controlled-stress
- Loading rise-time: 120 milliseconds,
- Load pulse rate: 40 pulses/minute (1500 ms between pulses), and
- Failure indication: 9 mm vertical deformation.
Linear regression analysis of the ITFT results were undertaken to determine fatigue functions for the asphalt mixtures using the following relationship:

\[ N_f = a e^{b\varepsilon_0} \]

where:  
- \( N_f \) = fatigue life  
- \( \varepsilon_0 \) = initial tensile strain (microstrain)  
- \( a, b \) = experimentally determined coefficients

The fatigue performance of the asphalt mixtures was evaluated by using the following four fatigue parameters based on the fatigue functions obtained for the mixtures [12]:

- Strain @ \( 10^6 \) cycles (microstrain),  
- Cycles @ 100 microstrain,  
- Strain @ \( 5 \times 10^4 \) cycles (microstrain),  
- Cycles @ 200 microstrain.

**Permanent Deformation**

The RLAT results for the penetration grade asphalt mixture (Mixture A) and the Sealoflex asphalt mixture (Mixture B) are presented in Figure 6. The RLAT plot showing the accumulation of permanent strain for five Mixture A and four Mixture B test specimens indicates a superior resistance to permanent deformation for the Sealoflex modified mixture.

![Figure 6: RLAT axial strain versus number of load cycles for Mixture A and Mixture B](image-url)
The RLAT parameters for the two asphalt mixtures are presented in Table 5. Of the two parameters, the mean strain rate can be considered to be a more reliable measure of the rutting performance of the asphalt mixtures as this parameter, unlike the ultimate strain, is independent of the initial strain experienced during the RLAT. Included in the table are the SHRP binder rutting parameter and the zero shear viscosity determined at the same temperature (40°C) as that used in the RLAT.

**Table 5: RLAT, SHRP rutting and zero shear viscosity parameters for Mixture A and Mixture B**

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Ultimate Strain Microstrain</th>
<th>Mean Strain Rate microstrain/cycle</th>
<th>G*/sinδ @ 0.02 Hz (kPa)</th>
<th>η₀ kPa.s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixture A</td>
<td>16666</td>
<td>1.73</td>
<td>3.5</td>
<td>13.6</td>
</tr>
<tr>
<td>Mixture B</td>
<td>6772</td>
<td>0.18</td>
<td>5.9</td>
<td>16.7</td>
</tr>
</tbody>
</table>

The results in Table 5 confirm the superior rutting resistance of the Sealoflex modified asphalt mixture as predicted by the fundamental DSR tests. However, both the SHRP rutting parameter and the zero shear viscosity parameter underestimate the relative increase in rutting resistance from the unmodified mixture to the modified mixture.

One possible reason for the G*/sinδ rutting parameter indicating a lower magnitude of rutting improvement compared to the actual asphalt mixture improvement is that the DSR and RLA tests were conducted at 40°C. This temperature is below the lowest test temperature of 45°C used by SHRP and could, therefore, have an effect on the sensitivity of the rutting parameter.

**Fatigue Resistance**

The fatigue functions, together with the raw fatigue data, for the Sealoflex modified and unmodified asphalt mixtures are presented in Figure 7.
The fatigue equation can also be written in a linear form by taking logarithms, such that the fatigue equation becomes:

$$\log N_f = \log a - b \log \varepsilon_o$$

The fatigue functions determined by linear regression and presented in Figure 7 are:

- Mixture A:  $$\log N_f = 12.83 - 3.78 \log \varepsilon_o \quad R^2 = 0.95$$
- Mixture B:  $$\log N_f = 18.43 - 5.35 \log \varepsilon_o \quad R^2 = 0.96$$

The fatigue parameters for the two mixtures, together with the SHRP binder fatigue parameter, are presented in Table 6.

**Table 6: ITFT and SHRP binder fatigue parameters for Mixture A and Mixture B**

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Strain @ 10⁸ Cycles (µε)</th>
<th>Cycles @ 100 microstrain</th>
<th>Strain @ 5x10⁸ Cycles (µε)</th>
<th>Cycles @ 200 Microstrain</th>
<th>G*sinδ kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixture A</td>
<td>64</td>
<td>1.86 x 10⁷</td>
<td>142</td>
<td>1.36 x 10⁴</td>
<td>3800</td>
</tr>
<tr>
<td>Mixture B</td>
<td>211</td>
<td>5.37 x 10⁷</td>
<td>369</td>
<td>1.32 x 10⁶</td>
<td>900</td>
</tr>
</tbody>
</table>

The fatigue functions in Figure 7 and the fatigue parameters in Table 6 confirm the superior fatigue performance of the Sealoflex modified asphalt mixture compared to Mixture A, as predicted by the fundamental DSR tests and the SHRP fatigue parameter.
Conclusions

The combination of fundamental rheological binder testing, pavement performance prediction parameters and practical mechanical property asphalt mixture testing has shown the improved performance of the Sealoflex PMB compared to an unmodified penetration grade bitumen.

Analysis of the fundamental rheological parameters of complex modulus and phase angle indicated the improved temperature susceptibility of Sealoflex compared to a penetration grade bitumen. The rheological data also indicated the increased high temperature stiffness, low temperature flexibility and elastic behaviour of the polymer modified bitumen. These factors indicated that the Sealoflex PMB should provide modified asphalt mixtures with improved fatigue resistance and high temperature rutting resistance. In turn, the SHRP rutting and fatigue parameters, as well as the zero shear viscosity parameter, have predicted superior rutting and fatigue performance for the Sealoflex PMB. Finally, mechanical property testing of the permanent deformation and fatigue characteristics of a Sealoflex modified asphalt mixture and an unmodified mixture has confirmed the superior performance of Sealoflex.
References