TOWARDS A PERFORMANCE RELATED SEAL DESIGN METHOD FOR BITUMEN AND MODIFIED ROAD SEAL BINDERS

by

Terence Ian Milne BSc (Eng) MSc (Eng) Pr Eng

Dissertation
Presented for the Degree of

Doctor of Philosophy (Engineering)

Promoter
Professor Kim J. Jenkins Pr Eng
University of Stellenbosch, South Africa

Co-Promoter
Associate Professor Ir Martinus F.C. van de Ven
Technical University Delft, Netherlands

University of Stellenbosch
December 2004

5.7.1.3   Test Trial Conclusions

On the basis of the linear calculations discussed here it is concluded the model will prove to give insight into seal behaviour and offers the following:

- Distinction between physical/chemical adhesion (IF-behaviour) and mechanical adhesion (grain shape);

- Enable better understanding of loss of adhesion and thus loss of stone, which is a prime cause of seal damage;

- To provide insight into stress and strain development in the binder;

- To explain various types of cohesive seal cracking; and

- Prediction of deformation in the binder resulting in stone rotation.

As a result of the above, insight into stresses in the stone/binder interface is obtained. This information might be of large importance in explaining adhesive seal cracking. This information will also give insight into bleeding which may be a result of temperature effects or penetration of stones into the binder as a result of viscous binder deformation.

Within the philosophy for the model discussed, future work into the prototype will include the addition of a base layer, to enable interaction between base and seal to accommodate punching of stones into the base.

In addition, realistic material models will have to be developed to further refine computational output the model provides.

Further development of the model is required to enable full expected lifecycle to be implemented and greater accuracy in parameters and behaviour characteristics.

5.7.2   Model Evolution

The numerical model evolved from the feasibility trials determined in 5.4 to the prototype test trials of 5.7.1, through elastic test phase where the integrity of the FEM mesh was tested, to the visco-elastic tests where a suitable numerical material model was decided upon. This section described the elastic and visco-elastic phases of the model evolution, culminating in the initial prototype model run.

The model runs in this evolution phase used a simplified load application, to reduce computational time, allowing attention to be focused on the FEM mesh and model parameters in an economical fashion.

5.7.2.1 Basic Traffic Loading

Traffic load for this evolution phase, involved a simulated tyre patch, with lateral (x), longitudinal (y) and vertical (z) stress, being applied. A time function allowing 10 loading and 10 unloading steps was applied, with the unloading step using the opposite direction lateral (y) stress, as a basic simulation of the effects of the more complex truck simulation described previously, and used for the prototype test runs. For the mesh and convergence tests, only the vertical (z) load was applied to ensure that the load was applied with correct signs, and that the loaded nodes could be checked.

5.7.2.2 Evolution of Load Application

- Filter method

Initially a filter was used to apply the simulated type contact patch to the seal stones through a node filter based on texture depth (load was applied to nodes at the specified depth below top of stone, with an **applied local direction stress** (force/unit area)).

CAPA FEM modelling programme uses local element axes for application of stress. This method is thus convenient for uniform loads, and where the elements surface orientation allow resulting forces to be applied in the desired direction as the intended wheel load.

The filter method was used to apply a load on multiple elements in an economic manner.

Figure 5.29 (a) and (b) shows a 2 mm filter (i.e. all elements 2 mm or less from top of stone) showing mesh behaviour under specified load. This model behaves as expected.

Figure 5.30 (a) and (b) shows the limitation of the filter method, where load applied to elements had direction change due to element local axes orientation, as the axes of the element surfaces rotated around the global axes.
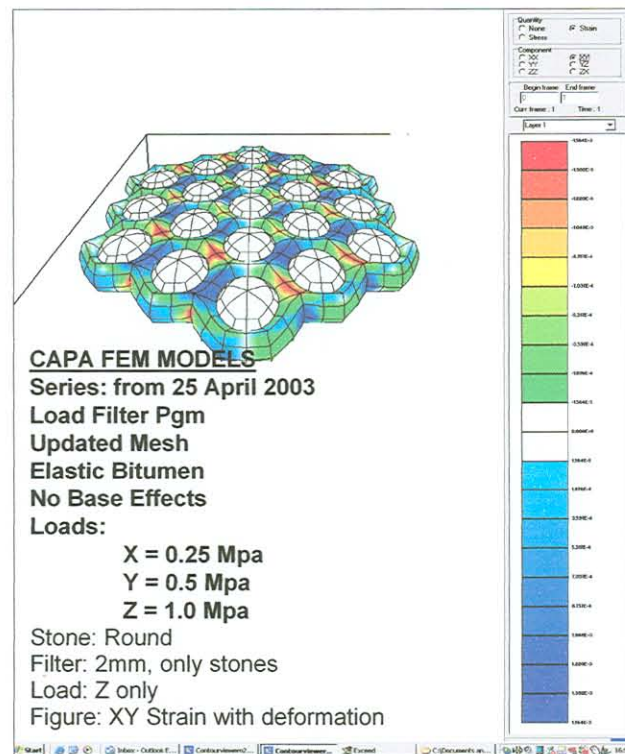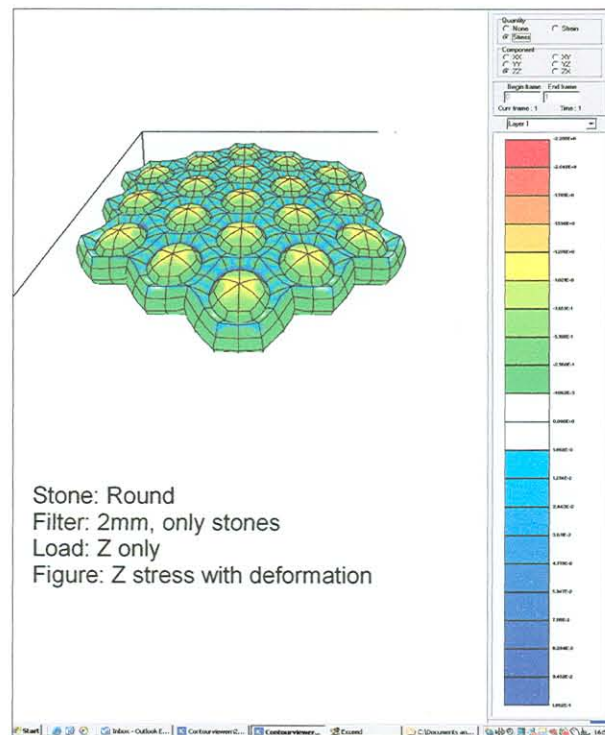
Figure 5.29 (a): Test Run: Load Filter within Limitations

Figure 5.29 (b): Test Run: Load Filter within Limitations

Stone: Round
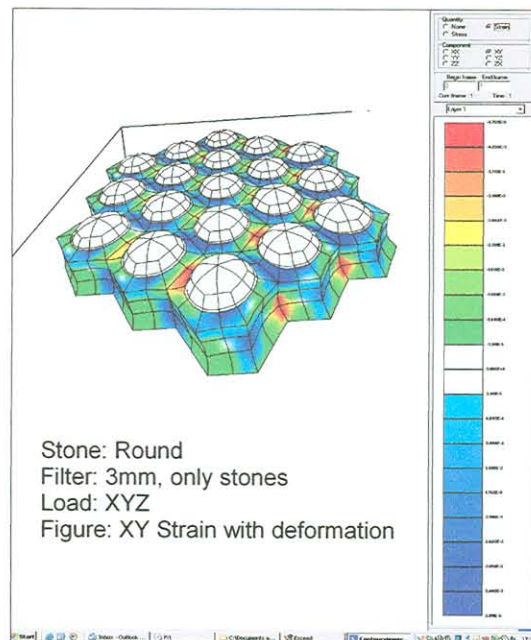Filter: 3mm, only stones
Load: XYZ
Figure: XY Strain with deformation

Figure 5.30 (a): Tensile Stresses in Bitumen Mesh: Load Direction Altered due to Stone Element Curvature (below a Certain Depth Below Top of Stone)
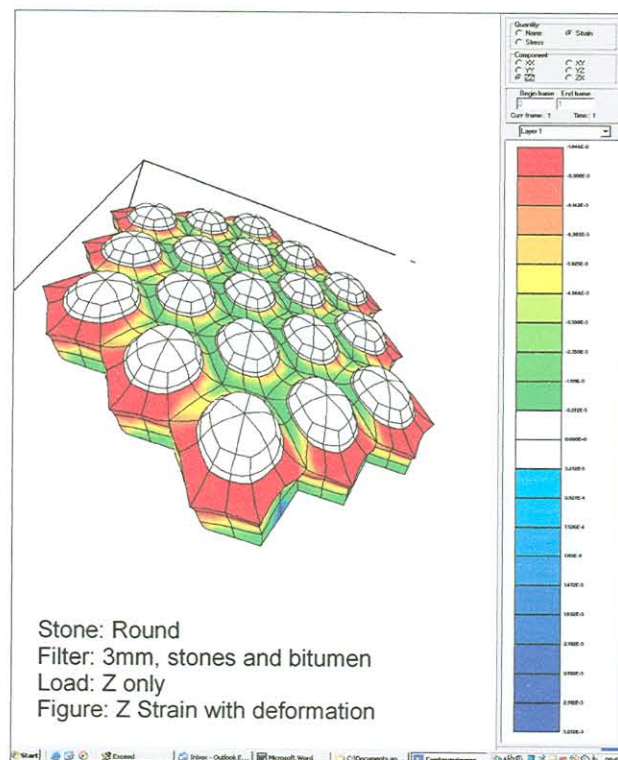

Stone: Round
Filter: 3mm, stones and bitumen
Load: Z only
Figure: Z Strain with deformation

Figure 5.30 (b): Load Filter Outside of Limitations

Figure 5.31 (a) shows a cross section and partial seal element, where load is applied to element surfaces, even internally through the filter method. This figure shows how the load is applied in opposite direction in the stones (blue = tension in stone), while the load desired is vertical (with only compressive forces).

Figure 5.31 (b) shows behaviour within the limitations, with compression in the stones, and tension in the binder as it is compressed under the stone and pulled apart between the stones.

- Nodal Method

    Nodal **forces** are applied in CAPA on global axes direction. A "sort" process was used to determine the nodes where the load should be applied (also based on "texture depth"), and the time load function as discussed in 5.5 used to apply load.
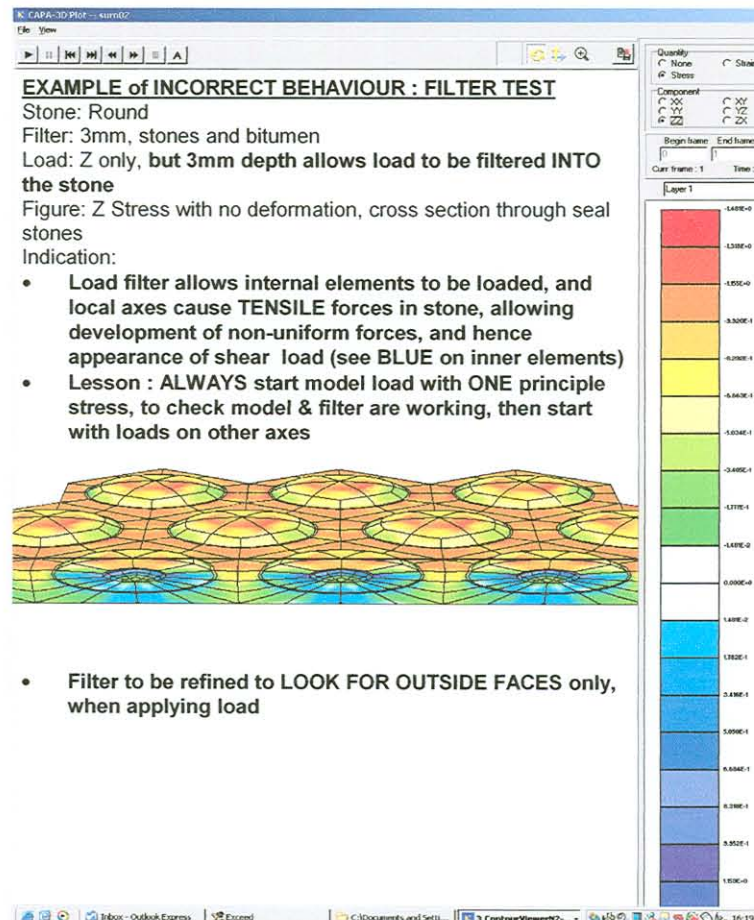

Figure 5.31 (a): Limitations of Load Filter

In the case illustrated in Figure 5.31 (a), the load filter was placed at a 3 mm depth below top of stone. There were nodes inside the stone at this depth that were also loaded at local axes direction, allowing tensile forces to be developed in the stone as the load direction changed, while the loads would be expected to be compressive in the seal stone under a vertical load.

Figure 5.31 (b): Within Limitation of Load Filter

Figure 5.32 is an example of nodal forces simulation of stresses. The mesh is seen to behave as expected: Compression under the stones, bulging bitumen between the stones.

Stone: Round

Filter: NO FILTER, Load force applied to Nodes (derived from stress X affected area)

Stress X = 0 Mpa

    Y = 0 Mpa

    Z = 1 Mpa

Figure: XY Strain, with displacement

Figure 5.32: Load applied to Nodes

### 5.7.2.3   Mesh Evolution

The meshes used comprised of 9 rows of stone in the longitudinal direction, the number of stones limited by the data storage and computational capacity of the computer. A central stone is available to be analysed free from edge effects.

Round and rough (random shaped) stones were used in the various meshes, as described in the trial runs (5.7.1).

5.7.2.4   Binder Material Evolution

The binder was first used as elastic, where the behaviour and integrity of the seal meshes were examined and refined. The visco-elastic bitumen material was only introduced once the loading method and mesh integrity were tested.

Figure 5.33 illustrates the seal stone rotation in the mesh, with the first visco-elastic binder trial run.
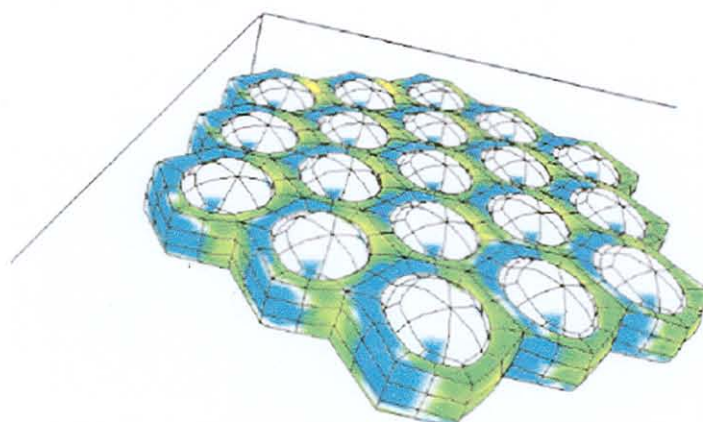
First Visco-Run

19 May 2003

SEAL

X = 0.25 Mpa

Y = 0.5 Mpa

Z = 1 Mpa

Applied in the Kasbergen point load to Nodes representing Area Load

Applied immediate, then static

Visco = 60 Gpas

Yield Stress = 0.1 Mpa

Reaction under load with Time

Shear Strain XY

Figure 5.33: Visco-elastic Run: Seal Stone Rotation at Peak Load

Figure 5.34 (a) and (b) shows the viscous effects of the bitumen, specifically at end of load cycle, where there is still strain (i.e. permanent or semi-permanent deformation) at the end of rest cycle.
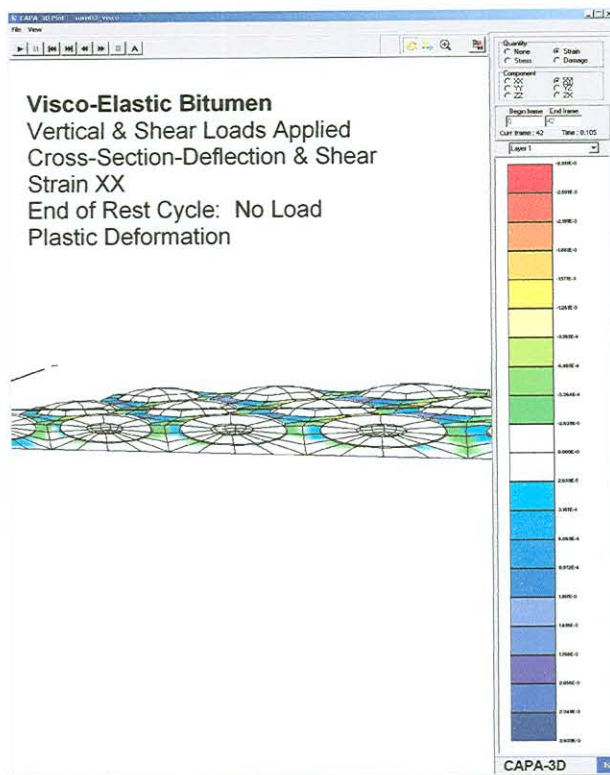
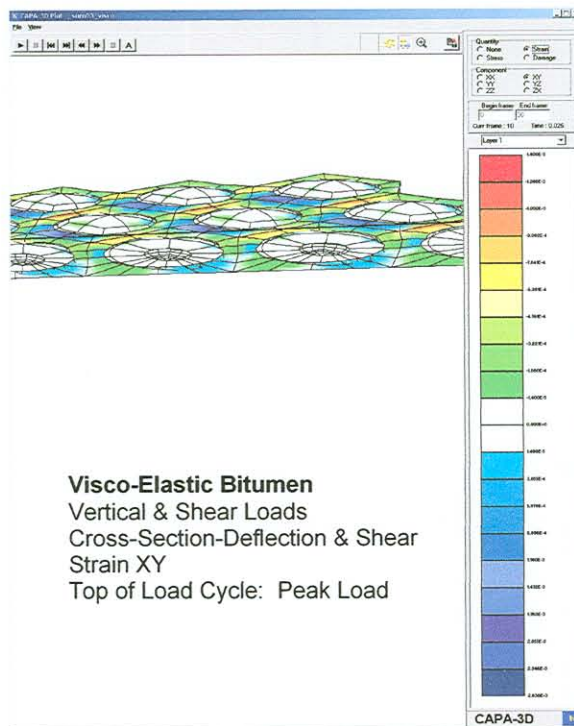**Figure 5.34 (a): Visco-Elastic Bitumen: Residual Strain**

Figure 5.34 (b): Visco-Elastic Bitumen: Peak Load

5.7.2.5 Model Output Test

The output data of CAPA is available, not only to enable the 3-D visual plots, but in terms of actual data for an identified node. Figure 5.35 reflects the displacement at top of the central stone, with displacement under a load, first applied with lateral stress in direction of wheel direction on loading phase, then reverse force (under driven wheel).

The data enables plots of stress and deflection. Figure 5.35 reflects the deflection in global x, y and z directions, for each load time step, for an **elastic binder** in this case.
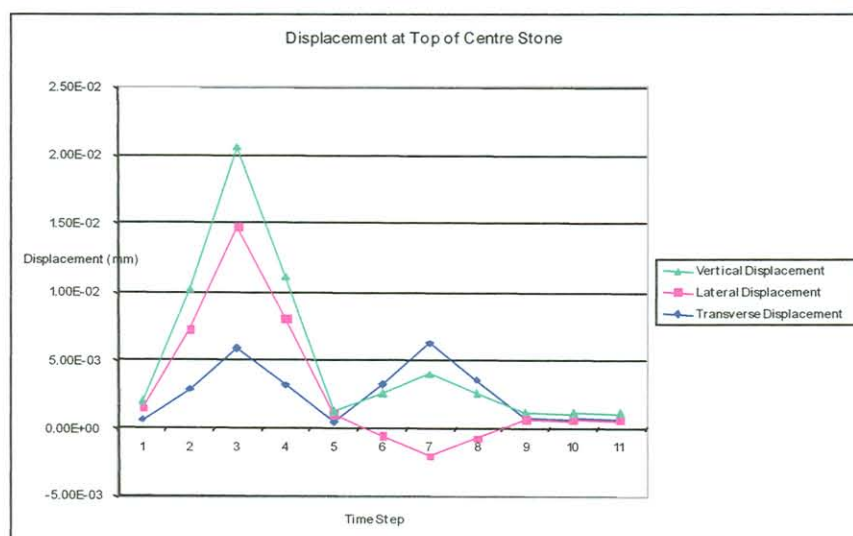
Figure 5.35: FEM Output: Example of Displacement

5.7.3 Model Test Plan: Model Parameters for Investigation

5.7.3.1 Model Input Parameters: Prototype Model Programme

TRH3 (CSRA, 1998) and Marais (1979) provide an indication of the parameters affecting seal performance. These references, and the results of the literature summary and evaluation of the assessment of surfacing seals during the empirical test phase, have been collated in the Matrix of Influences on Seals (Table 3.3).

The parameters affecting the seal performance have been prioritised. The binder emerges as the single most important contributor to seal behaviour, due to bitumen's temperature and load susceptible behaviour, and required material properties as the "active" element in the seal.

The sensitive prototype "test" or "critical" parameters identified for examination in the seal numerical model are summarised in the table 5.8 below, to enable assessment of the functioning of the numerical model.

Table 5.8: FEM Model Parameters for Examination

Seal Component	Parameter for Assessment	
	Physical	Model (Collop et al,, 2003)
	Pen Grade	$E_n\lambda_n$
	EVA	$E_n\lambda_n$
	SBS Radial	$E_n\lambda_n$
	SBS (Longitudinal)	$E_n\lambda_n$
	Application Rate	Parametised Thickness
	Shape	Round
		Random
Base Condition (Hardness)	Hard	$E_n\lambda_n$
	Softer	$E_n\lambda_n$
Environment (Temperature)	Binder	$E_n\lambda_n$
Traffic	Heavy/Light	Light
		Heavy

5.7.3.2 Prototype Simulation Programme

This project focused on the **development of a working numerical model prototype**. To this end, the Model Parameters for examination in this project were selected to focus on the assessment of the functioning of the model, i.e. to assess the functioning and capability of the model (refinement will take place under filter research projects).

To this end, the prototype test run parameters were selected to examine whether the model was able to show the differing behaviour of the seal with different parameters: geometric, material, environmental (temperature) and loading. The effect of moisture is not concluded at prototype stage. It is noted for completeness that a base is being developed, and there is the postulated possibility of including the effect of moisture in future development.

Table 5.9 shows the selected highest priority parameters, to allow assessment of:

- Effect of binder type

- Effect of stone shape

- Effect of interface characteristics

- Effect of temperature/environment

- Effect of traffic

These models' output will then be compared with the empirical results, to enable verification of the numerical prototype.

The assessment of the prototype model results will be made in terms of trends and indications of behaviour and not exact numbers, as the material parameters and base support, although based on the best available current data, still require further research under possible future projects. It is further emphasized that under this project the seal was placed on an elastic support layer, and NO EMBEDMENT of the seal stones in the base was modeled. (This is recommended for further research and development).

Table 5.9: FEM Prototype Simulations: Test Run Programme

SEAL COMPONENT	PARAMETER Physical	Model	1	2	5	6	9	10	11	12	13	14	3	4	7	8
Binder	Type															
	Pen Grade	$E_r A_r$	√	√	√	√	√	√	√	√	√					
	EVA	$E_n A_r$														
	SBS(R)	$E_n A_n$														
	SBS(L)	$E_n A_n$										√	√	√	√	√
	Application Rate	Parametised Thickness														
Aggregate	Shape	Round	√	√			√	√			√	√	√	√		
		Random			√	√			√	√					√	√
Interface	Extremes	E,A Bitumen	√		√		√	√			√	√	√		√	
		E,A Aggregate		√		√			√	√				√		√
Base Condition	Hardness															
	Hard	$E_r A_n$														
	Softer	$E_n A_r$														
Environment	Temperature	√ at 25degC														
	A Binder at 10 & 50deg C	$E_n A_n$					10	50	10	50						
Traffic	Heavy/Light	Light									√	√				
		Heavy	√	√	√	√	√	√	√	√			√	√	√	√

5.8 PROTOTYPE SIMULATIONS

The results of the prototype simulations are provided under this section in graphic format with discussion. Of note is that wherever practical the scale of the graphs is kept constant to allow ease of comparison. Appendix D reflects the 3-D plots of the meshes for the above FEM runs. The reporting is made under the heading of the parameter assessed.

5.8.1   Binder Type

Due to computational time required per FEM run (the mesh having in excess of 16 000 nodes, under a load time function) the ability of the prototype model to differentiate between **binder type** was assessed by comparing two binders: "straight" penetration grade and a modified binder.   25 °C was decided upon for material parameter determination, as this is in the accepted zone of visco-elastic behaviour.   70/100 pen grade binder, and SBS modified (3 %) binder (longitudinal, as the geometry fits in with the longitudinal Burgers model, with the visco-elastic component on a single axis, in series).

The series of graphs demonstrating the behaviour of the different binder types are provided below, in terms of cumulative displacements under four truck passes.   The displacements of the top, central node of the central stone is provided for the comparison.

From Figure 5.37, when assessing the X-lateral displacement, the behaviour of the penetration grade and SBS modified binders are illustrated in terms of displacement at top of stone, elastic and permanent deformation after relaxation.   It is evident that the latex modified binder is still recovering at the end of the last rest period of 80 time steps of 0,007 sec, while the pen grade bitumen relaxation plot shows no further visco-elastic recovery.

Figures 5.36 (a) and (b) reflect the differing magnitudes and behaviour between the modified and straight pen grade binders, with the permanent or viscous displacement after the immediate passing of the second or "rear" truck wheel as plotted.   It is evident that the SBS modified bitumen viscous displacement follows a decreasing trend with successive loading cycles, tending to consolidate elastic behaviour, with better recovery of the viscous displacement over time.   Maximum displacement after truck passes is greater for the pen grade bitumen, while the visco-elastic recovery for the SBS modified binder is greater than that of the pen grade binder.
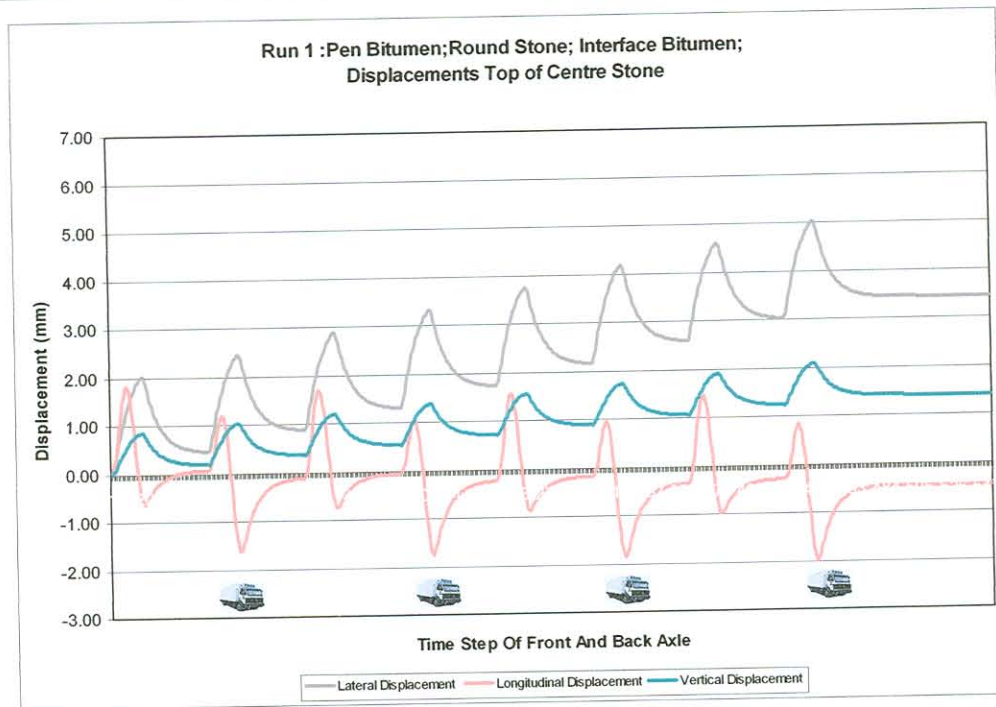
Figure 5.36 (a): Pen Grade Bitumen: Displacement under Sequential Loading: 25 °C
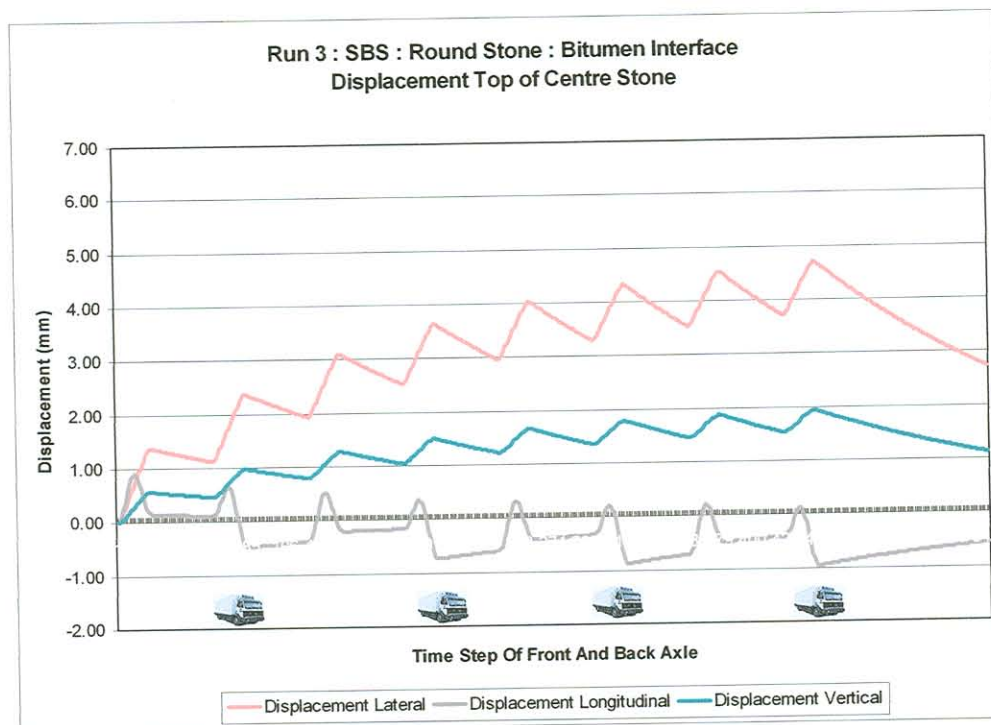

Figure 5.36 (b): SBS Modified Bitumen: Displacement under Sequential Loading: 25 °C
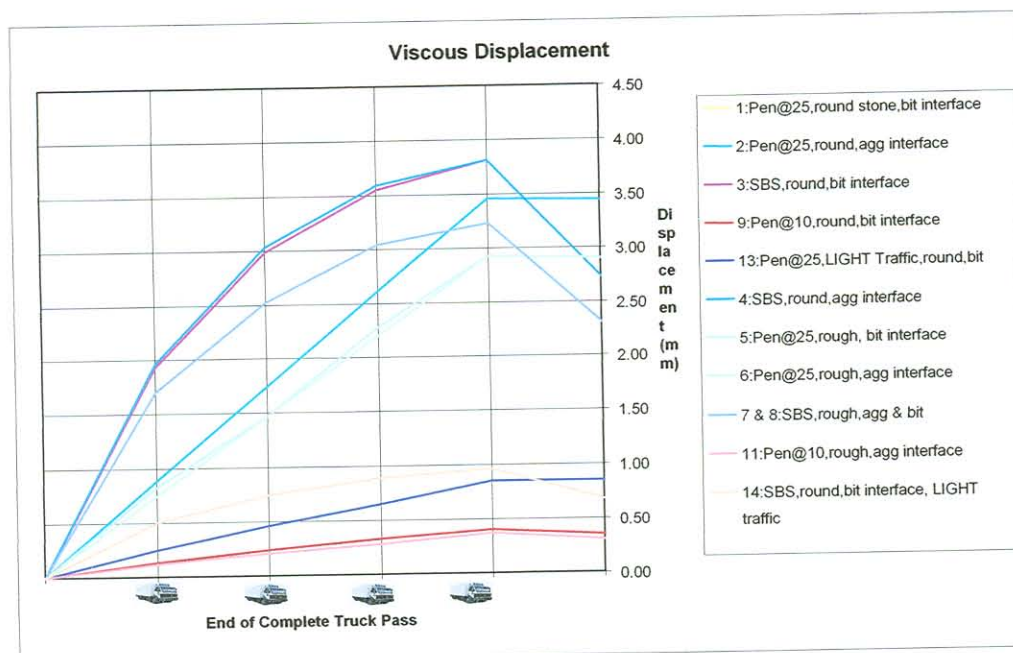
Figure 5.37: Viscous Displacement in X (Lateral) Direction after Load (excl 50 °C)

5.8.2   Interface Effects

The series of Figures 5.38 (a) to (f) and 5.36 (a) and (b) provide insight into the effect of interface stiffness in the model.

For round, or symmetrical stone for same bitumen type, the effect of interface is zero, as displacement follows the same trend and has the same values (shown by the plots 5.36 (a) and 5.38 (a) having the same shapes, 5.36 (b) and 5.38 (b) the same, 5.38 (c) and (f), 5.38 (d) and (e)). When considering interface with asymmetrical stones, there is also no evidence of difference in behaviour with changing interface stiffness.

Thus, when considering the behaviour parameter of displacement, the seal model makes no distinction between interface stiffness for same bitumen type and same stone shape, from examination of the above (Figures 5.36 (a), 5.38 (a) to (c)) four runs. Interface properties regarding the future adhesive characteristics should thus be focused on modelling adhesion and stone loss.
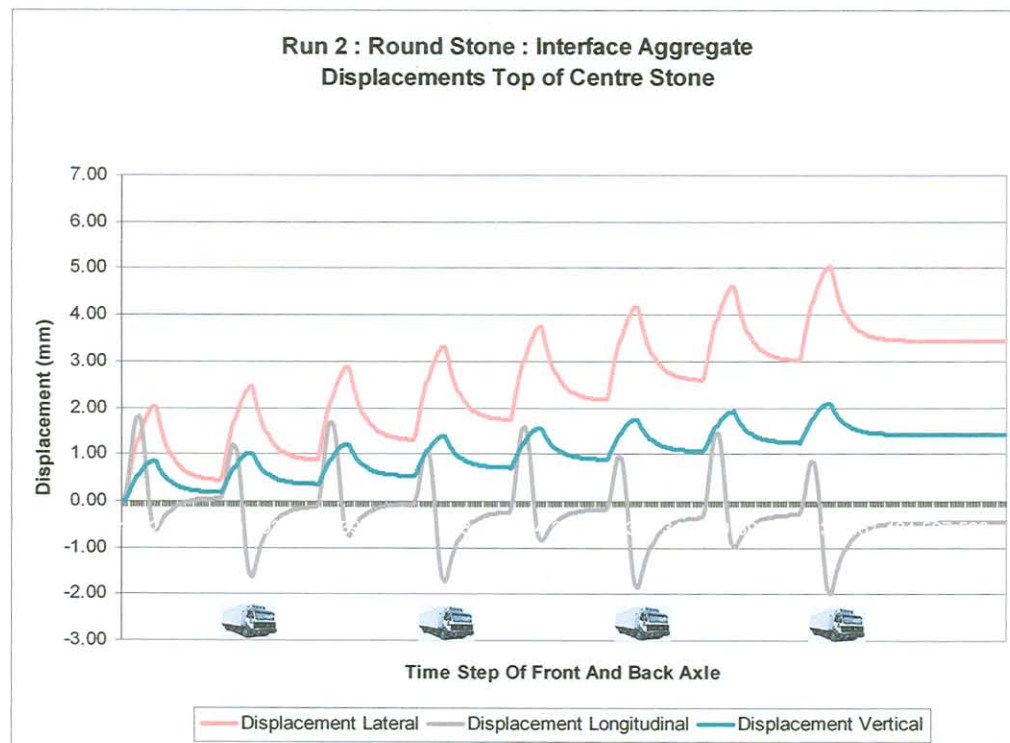
Figure 5.38 (a): Penetration Grade Bitumen at 25 °C: Displacement under Sequential Loading
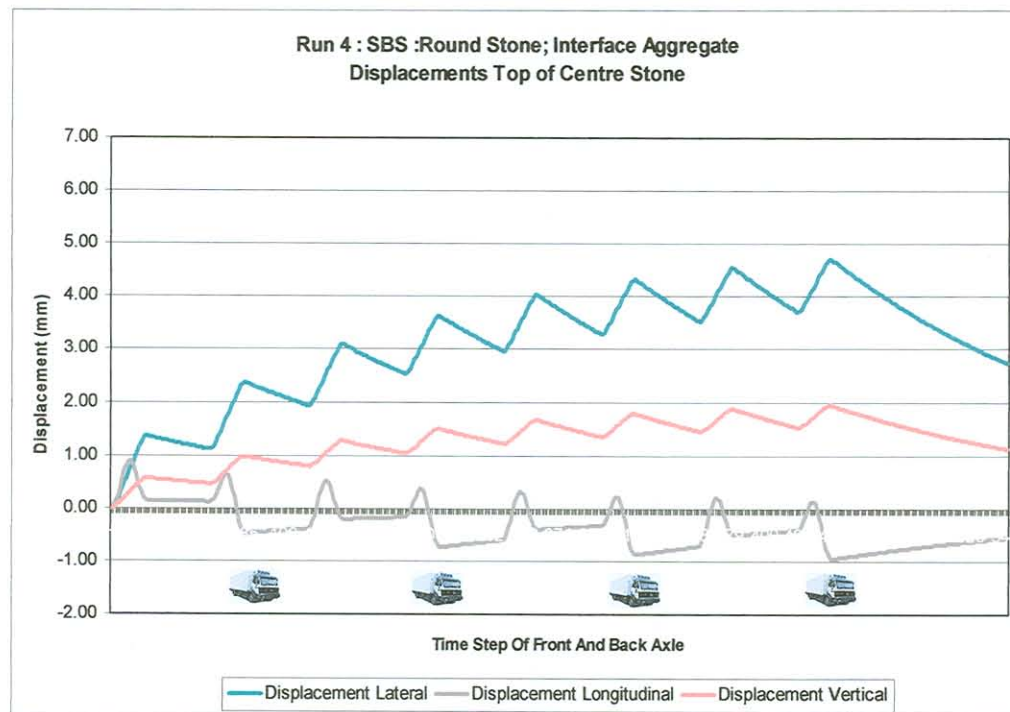
Figure 5.38 (b): SBS Modified Bitumen: Displacement under Sequential Loading
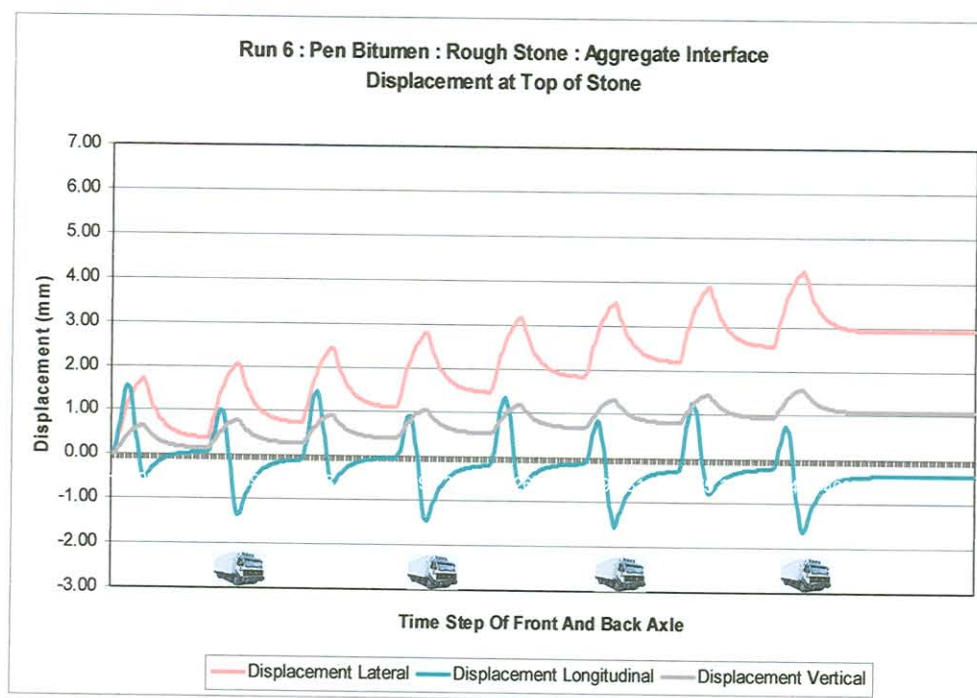
Figure 5.38 (c): Pen Bitumen: Rough Stone: Aggregate Interface: Displacement at Top of Stone
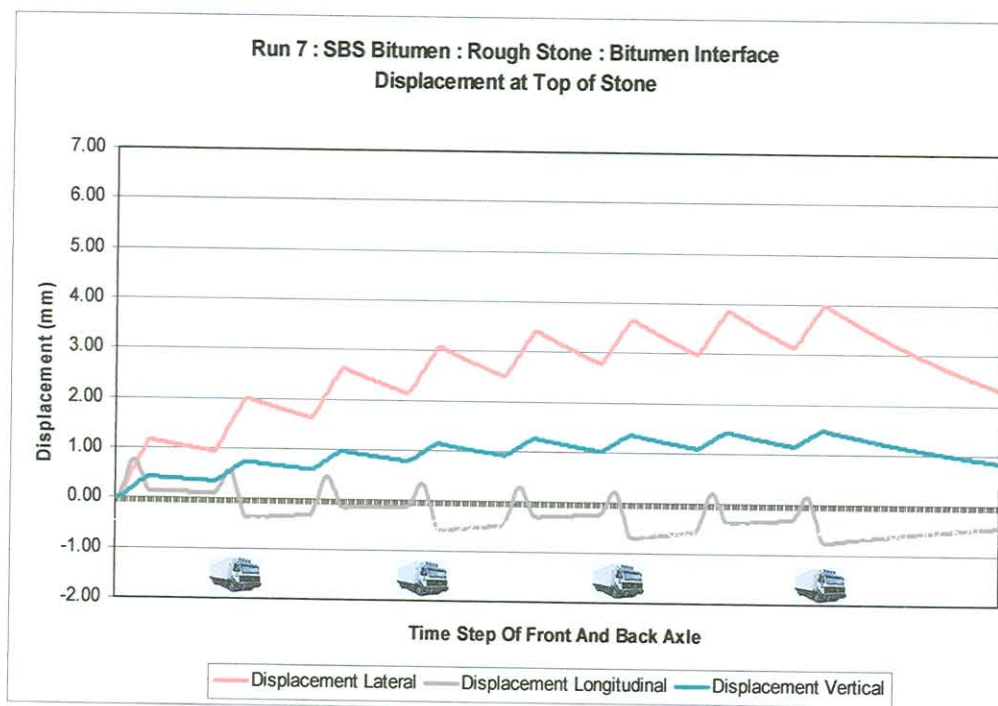
Figure 5.38 (d): SBS Bitumen: Rough Stone: Bitumen Interface: Displacement at Top of Stone
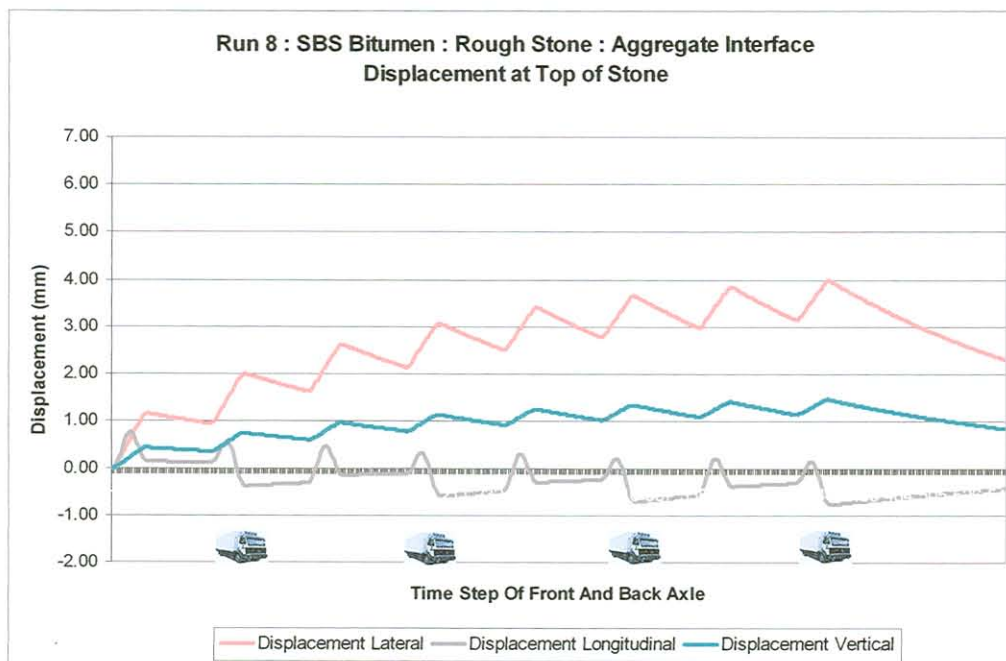
Figure 5.38 (e): SBS Bitumen: Rough Stone: Aggregate Interface: Displacement at Top of Stone
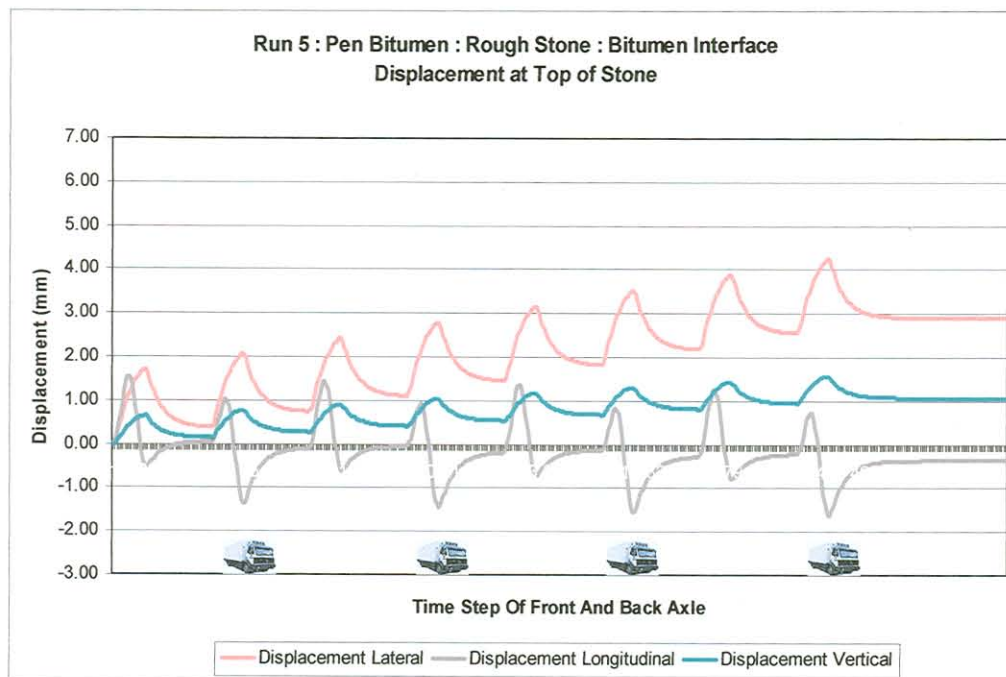
Figure 5.38 (f): Pen Bitumen: Rough Stone: Bitumen Interface: Displacement at Top of Stone

5.8.3   Temperature

Figures 5.39 (a) to (d), and Figure 5.36 (a) with Figure 5.37 refer.

When considering penetration grade bitumen through the temperature ranges, it is demonstrated that temperature has an effect in behaviour of bitumen, and the prototype model is able to reproduce this. The behaviour of the seal mesh in terms of displacement of top of middle stone reflects this. At the low 10 °C temperature (the brittle zone of bitumen) displacements are approximately 10 times smaller than the displacements at 25 °C (the elastic zone of bitumen). Displacements at 50 °C are again a factor 10 greater than the displacement at 25 °C. Of note is also the visco-elastic recovery of displacement.

At 25 °C displacement recovers elastically to an extent, while at 50 °C the penetration grade bitumen never recovers elastic or viscous displacements, where at 10 °there is still recovery of visco-elastic displacement of the end of the computed rest period.
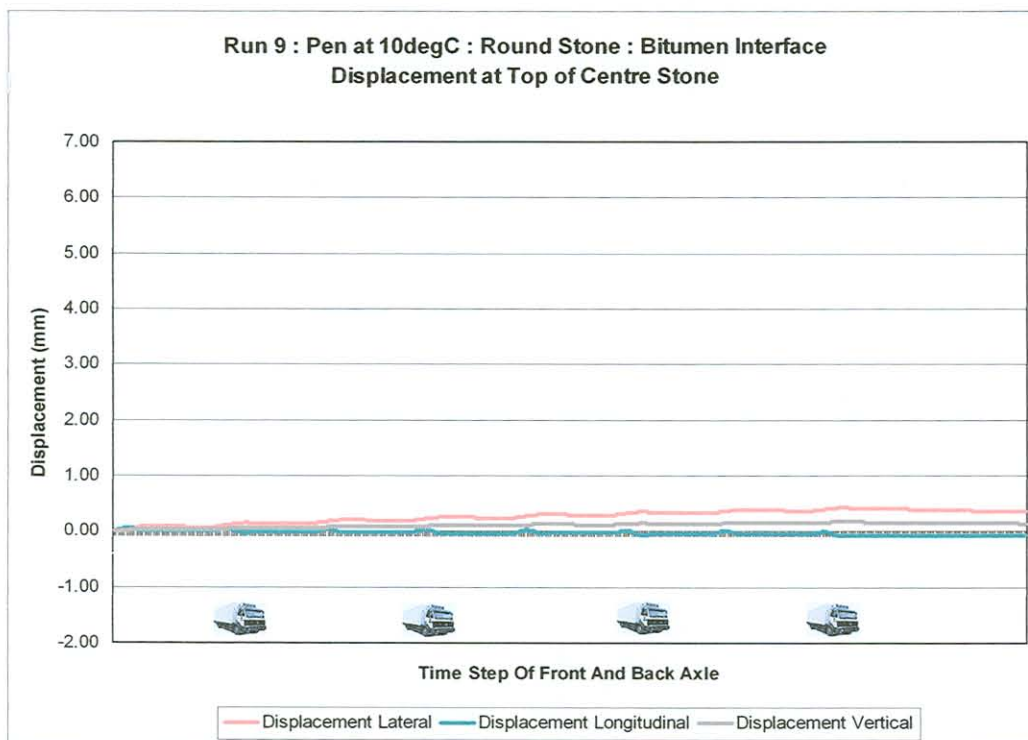
Figure 5.39 (a): Penetration Grade Bitumen at 10 °C: Round Stone: Displacement

Further examination of the behaviour of the seal mesh at high temperature was required, specifically regarding lateral displacement. The prototype mesh is comprised of the seal stone and bitumen. At high temperature (50 °C) the binder is approaching a viscous fluid. Thus under load, displacement is very high, especially the lateral displacement. The

nodes at the bottom of the mesh are fixed in all the planes. However, the bitumen is not able to restrain the stones at 50 °C under loading. The high displacement in the lateral direction at 50 °C becomes so large in the simulation that the geometry of the analytical FEM problem changed, leading to geometric instability.

At 10 °C and 25 °C the bitumen acts as a visco-elastic material where there is an elastic component active at these temperatures. Also the viscous component has a relatively high resistance to deformation. These binders thus show the relatively small displacements under loading, with the recovery of a large part of the initial displacement after unloading.

As indicated, at 50 °C the binder is a viscous material, where not only are the elastic components absent, but the viscosity is lower too. This binder acts as a fluid, where displacements build up as there is no elastic recovery, and there is very little resistance to displacement under the load. The conclusion is thus at 50 °C or higher, the bitumen will not contribute to resistance to deformation of the seal. An added contribution to the high displacements predicted by the model is the geometric instability brought about by the high displacements. Geometric non-linearity will have to be implemented into any future development of the model. This will contribute to the resolution of the computational problems related to the current constraints of geometric instability. Figures 5.39 (c) and (d) specifically illustrate the geometric instability of the model with binders of low viscosity (at high temperature).

The addition of a base material that allows plastic deformation (to enable seal stone embedment), a base mesh that accommodates seating of the stone in the mesh, and investigation in to the use of geometric non-linearity techniques in future models should address this problem. In essence, however, the prototype provides an indication of reality – stones under sideways load in a viscous fluid would display high displacements. However, the researcher should take note of the proposed development of the model.
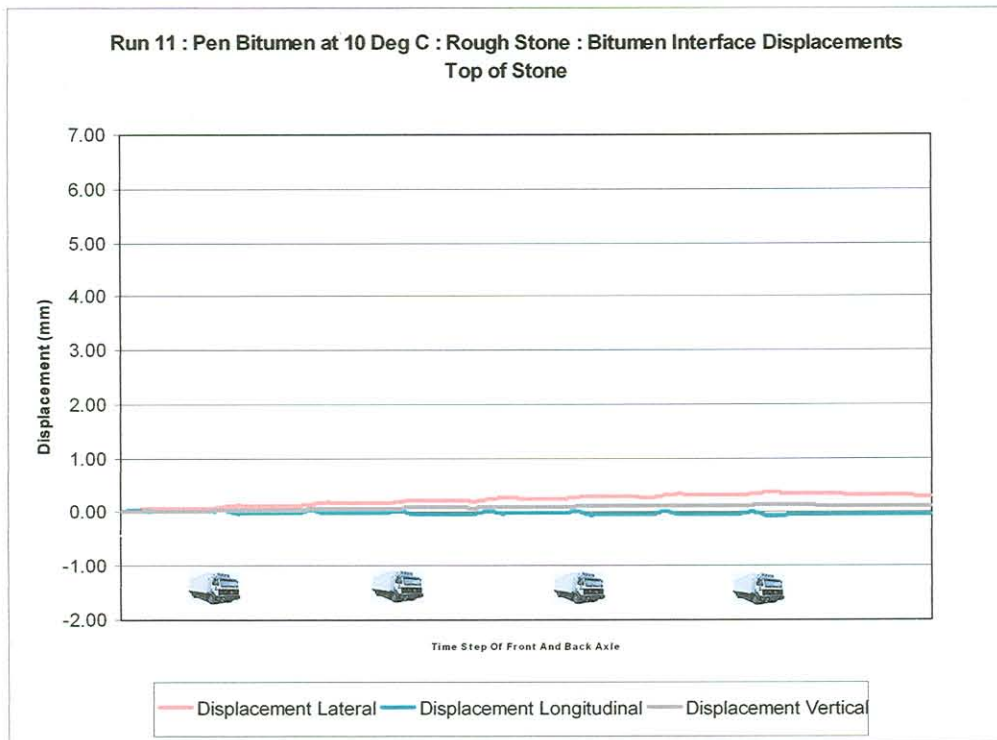
Figure 5.39 (b): Penetration Grade Bitumen at 10 °C: Rough Stone
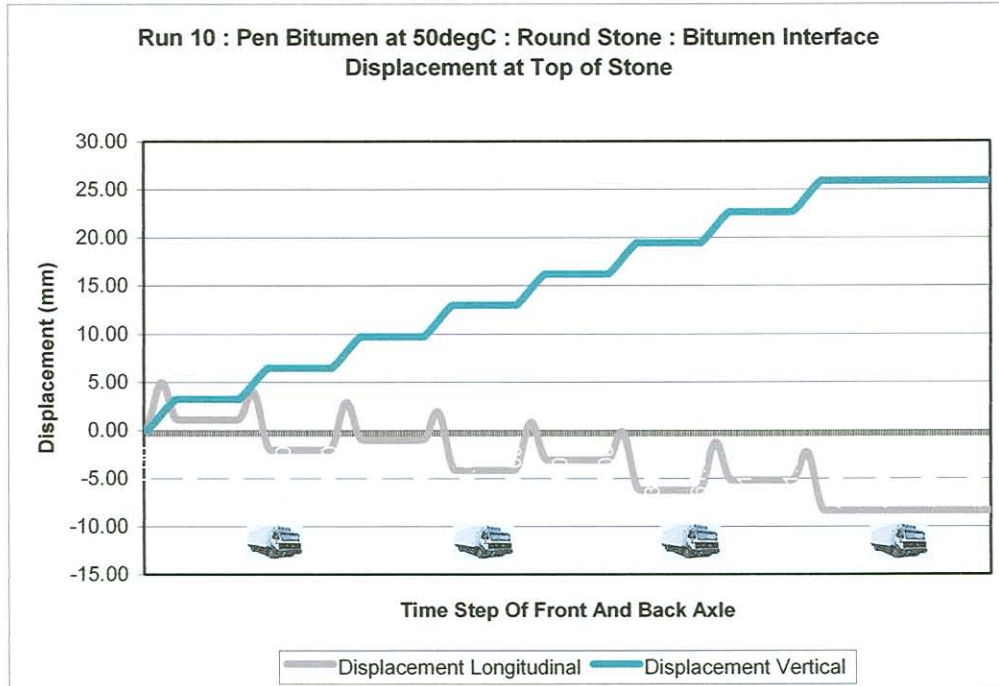
Figure 5.39 (c): Penetration Grade Bitumen at 50 °C: Round Stone
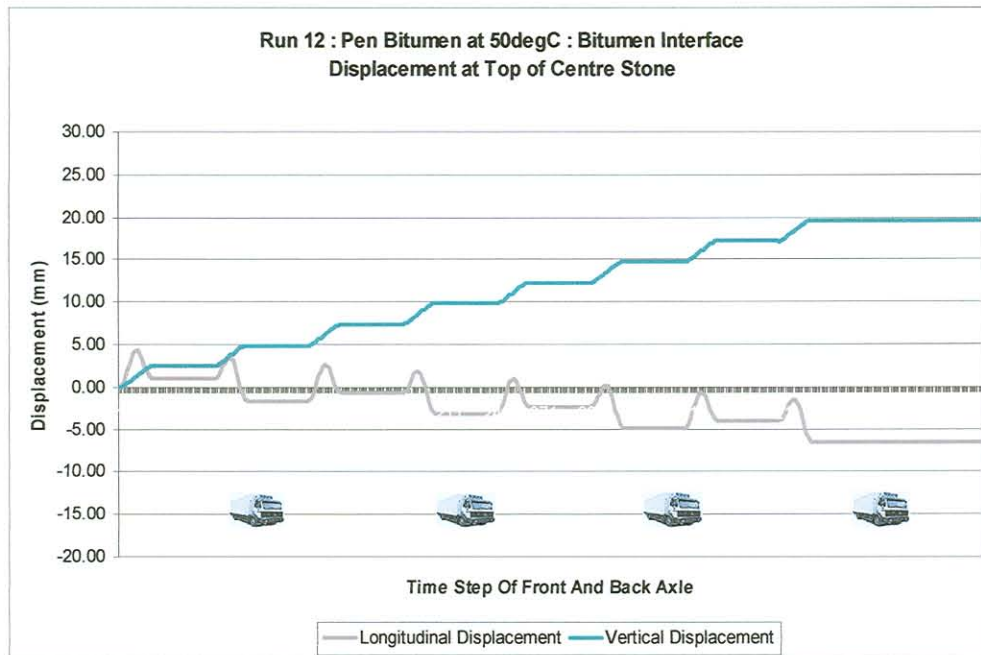
Figure 5.39 (d): Pen Bitumen at 50 ºC: Rough Stone Bitumen Interface: Displacement at Top of Centre Stone
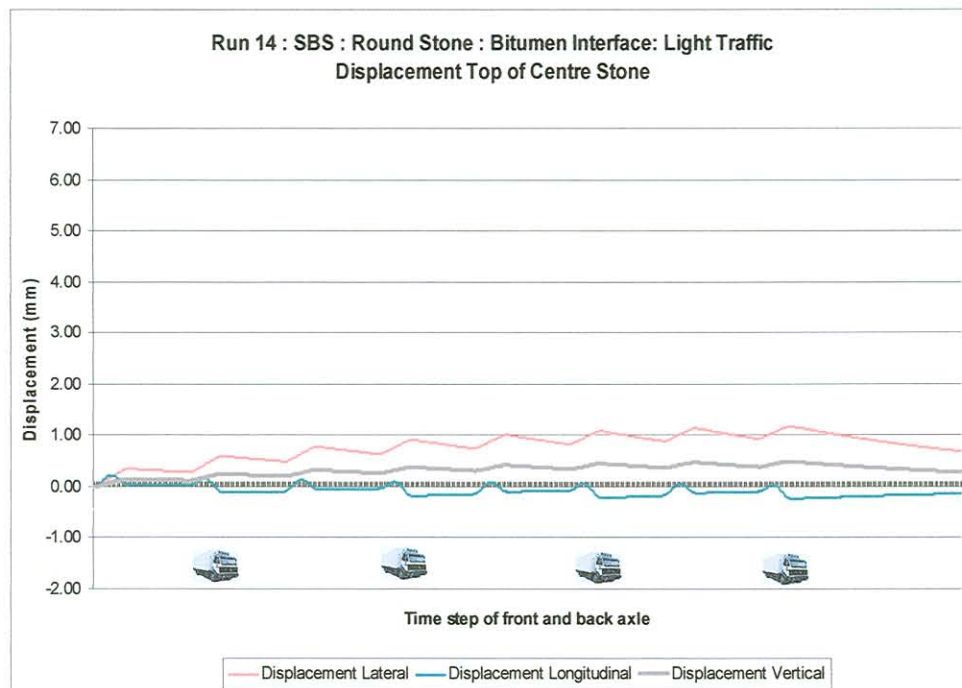
Figure 5.40 (a): SBS Bitumen: Round Stone: Bitumen Interface: Light Traffic Displacement at Top of Centre Stone at 25 ºC
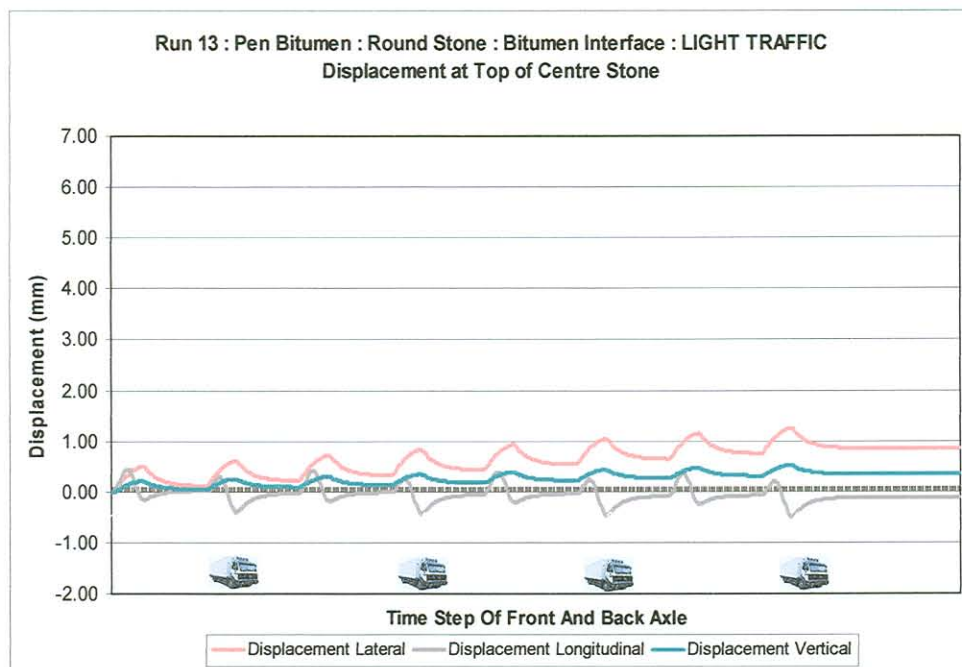
Figure 5.40 (b): Pen Bitumen: Round Stone: Bitumen Interface: Light Traffic Displacement at Top of Centre Stone at 25 ºC

5.8.4   Geometry

The smooth, "round" stone lies with ALD on the Z axis with a height of 6,0 mm, while the rough (randomly shaped) stone has height on Z axis of 6,275 mm.

Figures 5.36 (a), 5.36 (b), 5.38 (f) and 5.43 (a) demonstrate the displacements.

The amplitude of displacements under load is provided in Table 5.10 below:

Table 5.10: FEM Effect of Stone Geometry

Binder	Stone	ALD	X-Lateral Displacement at Top of Centre Stone Node 8606			
			Under First Wheel		Cumulative under Last Wheel	
			Displace-ment	% of ALD	Displace-ment	% o f ALD
Run 1: Pen @ 25 ºC	Round	6 mm	1,94 mm	32,3 %	4,96 mm	82,6 %
Run 5: Pen @ 25 ºC	Rough	6 mm	1,64 mm	27,3 %	4,18 mm	69,7 %
Run 3: SBS @ 25 ºC	Round	6,275 mm	1,35 mm	21,5 %	4,69 mm	74,7 %
Run 7: SBS @ 25 ºC	Rough	6,275 mm	1,15 mm	18,3 %	3,90 mm	62,2 %

From these results, it is evident that the rougher, less smooth, non-uniform stone rotates, or is displaced, less than the smooth stone, both in terms of displacement, and in terms of ratio to ALD.

The prototype model is thus able to differentiate behaviour on the basis of geometry of seal stone, and it is evident that the rougher stone is displaced less than the smooth stone, for the seal stone geometry with this model.

5.8.5 Traffic Load

The traffic induced stresses are analysed in the seal in terms of vehicle type (relative effect between heavy and light vehicles) and in terms of stress variation with load-time function.

5.8.5.1 Effect of Heavy and Light Vehicle Traffic on Imposed Stress

From Figures 5.36 (a) and (b), and 5.40 (a) and (b) (runs 1, 3, 5 and 7), and the CAPA data (summarised in Annexures B and C to Chapter 5), the lateral displacement, as an indicator of relative behaviour of the respective binders under wheel load, has been summarised in Table 5.11.

Table 5.11: Effect of Traffic Loading on Displacement

Binder	Stone	Traffic	X – Lateral Displacement (wheel on top of stone)	
			Under 1st Wheel	Under Trucks 4th Rear Wheel
			Displacement	Displacement
Run 1: Pen @ 25 °C	Round	Heavy	1,94 mm	4,96 mm
Run 3: SBS @ 25 °C	Round	Heavy	1,35 mm	4,69 mm
Run 13: Pen @ 25 °C	Round	Light	0,485 mm (25 % of Heavy)	1,23 mm (24,7 % of Heavy)
Run 14: SBS @ 25 °C	Round	Light	0,337 mm (24,96 % of Heavy)	1,17 mm (24,95 % of Heavy)

Through Table 5.11 it is clear that lateral displacement is directly proportional to the traffic loading at ratio heavy/light tyre pressure, for the prototype model time load functions.

The effect of vehicle type on imposed stress is able to be assessed when considering the CAPA output (Annexure B), as summarised under the 4th truck wheel.

Table 5.12: Effect of Traffic Loading on Imposed Stress under Stone (Node 4978 from Annexure B)

Binder	Stone	Traffic		Transferred Stress (4th Truck, Driven Wheel, wheel on top of stone)					
		Type	PI (kPa)	Lateral XX		Longitudinal YY		Vertical ZZ	
				Stress (MPa)	% of PI	Stress (MPa)	% of PI	Stress (MPa)	% of PI
1 Pen @ 25°C	Round	Heavy	800	-3,78	473 %	-3,80	475 %	-4,27	543 %
3 SBS @ 25°C	Round	Heavy	800	-3,83	479 %	-3,85	481 %	-4,32	540 %
13 Pen @ 25°C	Round	Light	200	-0,945	473 %	-0,951	475 %	-1,07	535 %
14 SBS @ 25°C	Round	Light	200	-0,957	479 %	-0,963	481 %	-1,08	540 %

'+': Tensile Stress

'-': Compressive Stress

From the assessment of normal stresses (given in Table 5.12) in the prototype mesh, it is evident that the stresses for each binder with same aggregate shape are of the same ratio to the applied tyre pressure. The damage to this binder would thus be expected to be in proportion to the ratio of contact stress: heavy and light traffic, assuming light motor vehicle time load functions are of similar shape, as used for this model.

The results of Table 5.12 show that the factor heavy vehicle to elv is dependent on tyre pressures, when purely considering the load imposed on the seal. The higher empirical damage factors as used in the seal design code (40:1 damage heavy to elv) (TRH3, CSRA, 1998) indicate that the support of the base effects seal performance, and that the base type and behaviour would also affect seal life. The empirical design factor to convert heavy to light vehicles is thus postulated to be a measure of ratio of tyre pressure and a factor of the base type (and **not only** seal or binder type). It is further postulated that the conversion of heavy vehicles to "elv's" will require transfer functions for different base types, and different damage types. The effect of moisture on the base will add further

complexity to the determination of the equivalency factor, and "expected wet heavy axles" may also require separate consideration. This is especially applicable to granular bases.

5.8.5.2   Induced Stress with Load Time Function

The Figures 5.41 (a) and (b) reflect the CAPA output for Run 1 (penetration grade bitumen at 25 ºC, heavy traffic) in terms of stresses transferred to the bitumen by the four truck passes. Figure 5.41 (a) reflects the stresses in the bitumen under the stone, and Figure 5.41 (b) reflects the stresses in the bitumen in front of the stone, just below the bitumen surface.

The stresses in the bitumen at the bottom of the stone reflect high compressive forces, under rolling and driven wheels throughout the cycle. The **maximum** lateral and longitudinal stresses are up to 600 % higher than inflation pressure Pi, while vertical stresses are up to 683 % higher than Pi. Maximum tensile stresses occur as the wheel rolls off the stone, and are up to 625 % (longitudinal and lateral) of tyre pressure.

As the rolling wheel rolls on to the stone, vertical tensile stress peaks at 80 % of the pressure as the stone is pushed forwards, and a vertical compressive stress of up to the 683 % of Pi as the stone rolls on to and over the stone.
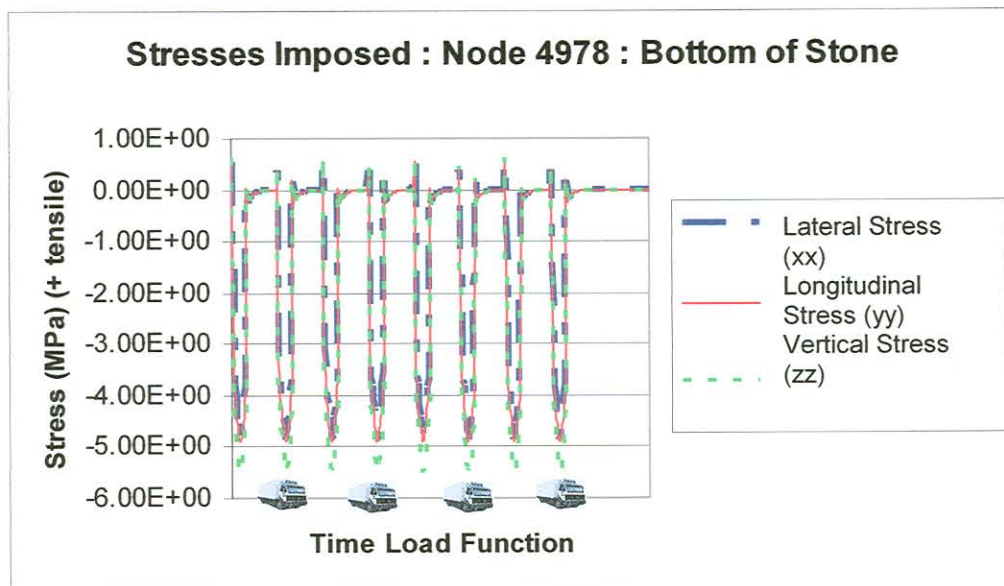
Figure 5.41 (a): Stresses Imposed on Run 1 Pen Grade Bitumen (bottom of stone) under 4 Truck Passes (Pi 800 kPa)
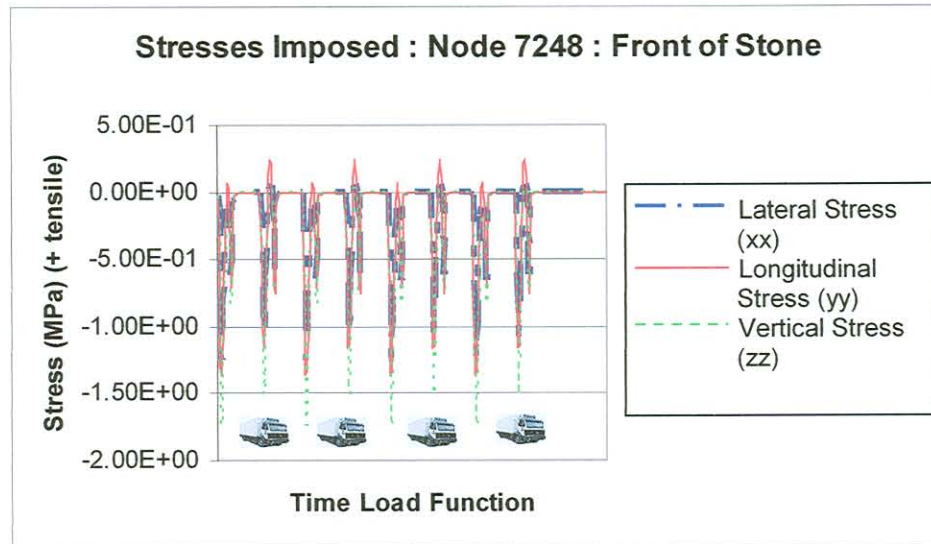
Figure 5.41 (b): Stresses Imposed on Run 1 Pen Grade Bitumen (front of stone) under 4 Truck Passes (Pi 800 kPa)

The stresses at the front of the stone reflect tensile stress as the driven tyre rolls on and off the stone, in the longitudinal direction, of up to 25 % of inflation pressure Pi. Vertical compressive stress peaks at approximately 220 % of Pi as the wheel reaches the mid cycle, while compressive longitudinal stresses peak at 155 % of Pi.

This type analysis, with further development of the model, will enable assessment of the order size of stress, both compressive and tensile, the seal binder is subjected to. This will allow focus on the further development of performance specifications for the binder, to enhance bitumen service properties.

5.9 MODEL INTERPRETATION AND UTILISATION

5.9.1 Focus Areas: Utilisation of Seal Prototype Numerical Model

As indicated in the previous section 5.7.3.2, a simulation programme was determined and executed to allow assessment of the prototype's ability to model differences in behaviour between the seal model parameters as:

- Binder type
- Stone shape/geometry
- Interface characteristics

- Temperature effects

- Traffic effects

This was successfully demonstrated in 5.8 above the prototype model has shown its ability to differentiate in behavioural terms between the different seal parameters, and at this stage not in absolute numerical terms due to the current available material parameters and geometry still requiring focused research and refinement under future projects. In line with the discussion of the basis of a prototype model under 5.3.4, the ultimate requirements of the model were postulated as:

- Prediction of serviceable life (in terms of traffic load)

- Assessment of seal performance under different materials components or types

- Assessment of the behaviour of the seal under different traffic loads

- Assessment of the effect of the environment (temperature especially)

Under Chapter 3, the failure parameters for determination were summarised. Table 5.13 collates the above focus areas with proposed determination possibilities:

Table 5.13: Prototype Numerical Seal Model Proposed Assessment of Results

Seal Failure Parameters (Chapter 3)		Prototype Model Assessment Output
Deformation	- Rotation	X and Y (lateral and longitudinal) displacement
	- Punching	Z (vertical) displacement
Cracking	- Brittle/cold	Strain at break
	- Fatigue/cohesive	Indication through assessment of stresses and strains
Adhesive failure		Interface stresses

The indication of the potential ability of the prototype model to accommodate the above, from the results of the FEM runs, is discussed in the sections below.

5.9.2 Deformation Assessment

Deformation assessment will assist in the determination of:

- Punching (using vertical displacement of the stone into the bitumen and base - Z or vertical displacement)

- Rotation of the stone (i.e. to ALD under construction or traffic) (using X or Y lateral and longitudinal displacement)

The prototype model demonstrates that for different binder types for which bituminous material parameters are available (although these require refinement), in behavioural terms, it is possible to model the difference in real seal behaviour.

The effect of binder type on stresses imposed on, and displacement of, seal stones was also examined in terms of the possibility of a higher stress required when comparing the high viscosity binders, due to the higher binder stiffness than a penetration grade bitumen. From assessment of Annexures B and C to Chapter 5, the following examples illustrate the difference in displacement of the stone and stresses for modified and straight binders.

Using an example of bitumens with differing binder characteristics:

At time $3,08.10^{-1}$ secs (4th **truck pass under driven wheel**)

- **Run 1, pen grade bitumen at 25 °C**

  - Displacement at bottom of central stone (node 4975)

    $U_Z = 2,09$ mm (downwards)

    Corresponding stress at the same wheel pass at adjacent bitumen (node 4978) is:

    $\sigma_{ZZ} = 4,27$ MPa (compressive)

  - Displacement on surface, in plane of wheel travel (Y) (node 7245)

    $U_Y = -1,59$ mm (in opposite direction to travel of driven wheel)

    Corresponding stress at adjacent bitumen (node 7248)

    $\sigma_{YY} = -4,93$ MPa (compressive)

- **Run 3 SBS modified bitumen at 25 °C**

  - Displacement at bottom of central stone (node 4975)

    $U_Z = 1,93$ mm

    Corresponding stress at adjacent bitumen (node 4970)

    $\sigma_{ZZ} = 4,32$ MPa compressive

- Displacement on surface in plane of wheel travel (Y) (node 7265)

U_Y = -0,702 mm (in opposite direction to wheel travel)

Corresponding stress at adjacent bitumen (node 7248)

σ_{YY} = 5,15 x 10^{-1} MPa (compressive)

From the above, the less viscous binder, namely the 80/100 pen, demonstrated higher displacements and lower stresses in the model.

The model is thus able to demonstrate the effects of stiffer binders in terms of improved behaviour (e.g. reduced displacement) and also give indirection of the added internal stresses required by the binder to perform as designers expect.

5.9.3 Fatigue Cracking

The Shell Bitumen Handbook (Green, 1991) provides a curve for determination of strain at break.
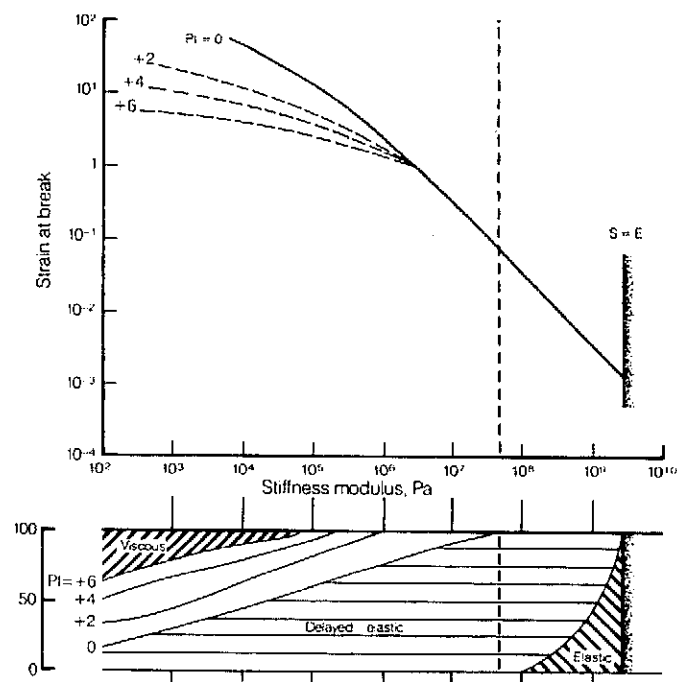
Figure 5.42: Bitumen Strain at Break as a Function of Stiffness Modulus and Penetration Index (Whiteoak, 1991, Shell)

With further development of the FEM Model, and fatigue relationships similar to the above figure, the use of the model to predict fatigue cracking is proposed, using the strain output of the model run results. However, principal strains will be required and not only strains on the X, Y and Z axes.

5.9.4 Adhesive Failure

The interface behaviour and characteristics of the FEM model will be a possible further research project, due to the complexity of the problem. This interface will be used to model adhesion in future. Stress and strain are already available on all the interface boundaries, but the actual ultimate parameters are required.

5.9.5 Brittle Failure

Failure criteria for the actual bitumens included in the prototype model, in terms of brittle failure, are not available. Trends using the Mohr type method of determining the stress strain combinations could possibly be used in determining seal binders that will be more likely to fail.

5.9.6 Summary of Behaviour of Seals in terms of Performance Criteria

Using the same format for the assessment of the performance tests (Table 4.10), and the provided performance criteria (Table 3.4), comparative results for the straight and modified binders are provided in Table 5.14 as summarised from the results in Annexure B.

Table 5.14: Seal Performance Parameters: Overall Performance

Node	Binder	Deformation (mm)			Cracking	Crushing	Adhesion
		Rotation		Punching	Fatigue		Max measured stresses (tensile)
		X	Y	Z			
4978 (bottom of stone)	80/100				No failure in load range	•	No tensile
	3 % SBS (L)				No failure in load range	•	No tensile
7248 (front of stone)	80/100				No failure in load range	•	0,243 MPa
	3 % SBS (L)				No failure in load range	•	0,283 MPa
8606 (top of stone)	80/100	2,1 sideways away from CL	-2 backwards	5 down			
	3 % SBS (L)	2 sideways away from CL	-1 backwards	4,8 down			

For the parameters and nodes chosen, it is summarised that the modified binder allows less deformation, with the expected increase in stress transferred through the binder. The demonstrated increased performance benefits of the modified binders can be modelled, with the advantage to the designer of assessing the increased demands from the bitumen for the greater performance.

5.10 CONCLUDING REMARKS: PROTOTYPE NUMERICAL SEAL MODEL

The prototype seal numerical model has demonstrated the ability of the use of mechanistic type analysis, specifically FEM, to model a surfacing seal.

5.10.1 Benefits of the Numerical Model

The benefits of the prototype numerical model as developed under this project are:

- Allows focus on the real issues relating to seal design:

    - where does the vehicle tyre travel (on stone, stone and bitumen)

    - shape of load time friction on a textured surface

    - influence of binder type

    - influence of stone geometry

    - identify failure mechanisms (at this stage only comparative performance)

    - allow refinement of influences matrix (Section 3) or sensitivity analysis of parameters the design should consider

    - contributes to the understanding of the behaviour of each seal component under traffic load

    - allows assessment of influence of temperature on the seal

5.10.2 Ultimate Model Output

From consideration of the behaviour of the seal in service, and the current successful implementation of the numerical prototype model, the aim of the ultimate output of the Numerical Model of Seal Performance should consider:

- Determine relative performance of each seal type in terms of:

    - Number of wheel load repetitions to:

        ➤ Stripping of stone, i.e. loss of adhesion

        ➤ Cracking of binder, i.e. loss of cohesion

        ➤ Crushing of stone

        ➤ Embedment of stone and flushing, i.e. penetration of stone into base (what texture depth is adequate)

> ➤ Rotation of stone, i.e. void loss and texture depth

- For each

  > ➤ Temperature regime

  > ➤ Binder type

  > ➤ Binder application rate

  > ➤ Base type

  > ➤ Seal aggregate size and shape

  > ➤ And age

However, for this project the prototype will be assessed in terms of its potential to enable, with further refinement, the above parameters to be effectively included and the model verified and/or calibrated.

REFERENCES

Airey GD, Dunhill ST, Collop AC, 2002, *"A Constructive Material Modelling Methodology for Asphalt Mixes"* (unpublished).

Collop AC, Khanzada S, 1999, *"Permanent Deformation in Idealised Bituminous Composites"*, 3rd European Symposium on Performance and Durability of Bituminous Materials and Hydraulic Stabilised Components, Leeds (UK).

Collop AC, Khanzada S, 2001, *"Permanent Deformation in Idealised 'Sand Asphalt' Bituminous Mixtures"*, International Journal of Road Materials and Pavement Design.

Collop AC, Scarpas A, Kasbergen C, De Bondt A, 2003, *"Development and Definite Element Implementation of a Stress Dependent Elasto-visco-plastic Constitutive Model with Damage for Asphalt"*, TRB 82nd Annual Meeting, Washington.

Committee of State Road Authorities, CSRA, 1996, *Technical recommendations for Highways 4 Structural Design of Interurban and Rural Road Pavements*, Department of Transport (RSA) for CSRA.

Committee of State Road Authorities, CSRA, 1996, *Technical Recommendations for Highways 14 Guidelines for Road Construction Materials*, Department of Transport (RSA).

Committee of State Road Authorities, CSRA, 1998, *Technical Recommendations for Highways 3 Surfacing Seals for Rural and Urban Roads and Compendium of Design Methods for Surfacing Seals using in RSA*, Department of Transport, RSA.

De Beer M, 1995, *Measurement of Tyre/Pavement Interface Stresses Under Moving Wheel Loads*, CSIR.

De Bondt AH, 1999, *Mechanische Aspecten van Rafeling in ZOAB*, VBW Asphalt 4.

Desai CS, 2002, *"Mechanic Pavement Analysis and Design using Unified Material and Computer Models"*, Proceeding of Symposium on 3D Element Modelling of Pavement Structures, Amsterdam.

Emery S, O'Connell J, 1999, *Development of a High Performance SBS Modified Binder for Production*, 7th Conference on Asphalt Pavements for Southern Africa, Zimbabwe.

Erkens SMJE, Liu X, Scarpas A, Molenaar AAA, Blauwendraad J, 2002, *"Asphalt Concrete Response: Experimental determination of finite element implementation* (unpublished).

Green G, 1991, *South African Shell Bitumen Handbook,* Shell South Africa.

Groenendijk J, 1998, *"Accelerated Testing and Surface Cracking of Asphaltic Concrete Pavements",* PhD Thesis, TU Delft.

Hagos ET, 2002, *"Characterisation of Polymer Modified Bitumen (PMB)",* Dienstweg en Waterbouwkunde, Netherlands.

Harichadran RS, Yeh M-S, TRR07, 1988, *Flexible Boundary in Finite − Element Analysis of Pavements,* Transportation Research Record 1207.

Huang YH, 2003, *"Pavement Analysis and Design",* Practice Hall, New Jersey.

Huurman M, Milne TI, Van de Ven MFC, Scarpas A, 2003, *Development of a Structural FEM for Road Surfacing Seals,* ICCES Conference.

Marais CM, 1979, *Advances in the Design and Application of Bituminous Materials in Road Construction,* University of Natal.

Maree JH, 1979, *Die Laboratoriumbepaling van die Elastiese Parameters, die Skuifsterkteparameters en die Gedrag onder Herhaalde Belasting van Klipslagkroonlaagmateriale: Toetsmetodes en Apparaatbeskrywing,* CSIR.

Milne TI, Van de Ven MFC, Jenkins KJ, Huurman M, Scarpas A, *"Road Surfacing Seal Design: Fundamental Modelling",* submitted to SAICE Journal, 2003.

Molenaar AAA, 2003, *Pavement Performance Evaluation and Rehabilitation Design,* MAIREPAV'03, Third international symposium on maintenance and rehabilitation of pavements and technological control. Guimaraes, Portugal.

Nazarian S, Boddapati KM, 1995, *Pavement − Falling Weight Deflectometer Interaction Using Dynamic Finite − Element Analysis.*

RD Cook, 1995, *"Finite Element Modelling for Stress Analysis",* John Wiley & Sons Inc.

Semmelink CJ, 1991, *Elastic Moduli of Untreated Road Building Materials as Determined with the DRTT K-Mould,* CSIR, South African Roads Board, Project Report 89/149.

Thyse HL, de Beer M, Rust FC, 1996, *Overview of the South African Mechanistic Pavement Design Analysis Method,* Divisional Publication DP-96/005, TRANSPORTEK, CSIR.

Woodside A.R., Wilson J., Guo Xin Liu, 1992, *The Distribution of Stresses at the Interface Between Tyre and Road and Their Effect on Surface Chippings,* 7th International Conference on Asphalt Pavements, Design and Performance, Volume 3, ISAP, Nottingham.

Woodside AR, Woodward WDH, Siegfried, c.1999, *The Determination of Dynamic Contact Stress,* APT Conference, Reno.

ANNEXURE A

TO CHAPTER 5

BURGERS MODEL PARAMETERS FOR FEM MODEL

Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

Determination of Burgers Model Parameters for FEM Model (reworked from Hagos)

Tr	20	C	Reference Temperature
T	10	C	Service Temperature

Material	PEN 70/100	EVA 3%	EVA 5%	EVA 7%	SBS (L)3%	SBS (L)5%	SBS (L)7%	SBS (R) 3%	SBS (R) 5%	SBS (R)7%
C1	11.78	12.02	11.12	15.61	10.55	11.35	12.22	12.47	14.03	11.25
C2	104.22	108.06	99.07	132.16	95.49	97.08	108.34	109.86	117.05	102.37
Alfa	17.79366199	16.81822408	17.71969614	18.9597388	17.142038	20.109403	17.483469	17.7316131	20.44572533	16.51687563

Properties at Tr=20C

Burgers Parameters	PEN 70/100	EVA 3%	EVA 5%	EVA 7%	SBS (L)3%	SBS (L)5%	SBS (L)7%	SBS (R) 3%	SBS (R) 5%	SBS (R) 7%
E1[Pa]	2.00E+08	2.00E+08	1.80E+08	1.50E+08	2.00E+08	1.00E+08	8.50E+07	1.50E+08	1.30E+08	1.00E+08
E2 [Pa]	1.50E+06	1.50E+06	6.50E+05	3.00E+05	8.00E+05	2.20E+05	2.00E+05	4.00E+06	5.00E+05	3.50E+05
n1[Pa.s]	3.00E+05	4.00E+05	9.00E+05	3.00E+06	7.00E+05	2.80E+06	6.00E+06	5.00E+05	1.60E+06	7.00E+06
n2 [Pa.s]	3.00E+04	2.50E+04	2.80E+04	3.50E+04	3.50E+04	6.00E+04	9.50E+04	3.00E+04	2.50E+04	4.50E+04

Properties at T=10C

Burgers Parameters	PEN 70/100	EVA 3%	EVA 5%	EVA 7%	SBS (L)3%	SBS (L)5%	SBS (L)7%	SBS (R) 3%	SBS (R) 5%	SBS (R) 7%
E1[Pa]	2.00E+08	2.00E+08	1.80E+08	1.50E+08	2.00E+08	1.00E+08	8.50E+07	1.50E+08	1.30E+08	1.00E+08
E2 [Pa]	1.50E+06	1.50E+06	6.50E+05	3.00E+05	8.00E+05	2.20E+05	2.00E+05	4.00E+06	5.00E+05	3.50E+05
n1[Pa.s]	5.34E+06	6.73E+06	1.59E+07	5.69E+07	1.20E+07	5.63E+07	8.74E+07	8.87E+06	3.27E+07	1.16E+08
n2 [Pa.s]	5.34E+05	4.20E+05	4.96E+05	6.64E+05	6.00E+05	1.21E+06	1.66E+06	5.32E+05	5.11E+05	7.43E+05

Factors for PMA

	PEN 70/100	EVA 3%	EVA 5%	EVA 7%	SBS (L)3%	SBS (L)5%	SBS (L)7%	SBS (R) 3%	SBS (R) 5%	SBS (R)7%
E1[-]	1	1	1	1	1	1	1	1	1	1
E2 [-](Decreased)	1									
n1[-]	1	7	7	7	7	7	7	14	14	14
n2 [-]	1	1.5	1.5	1.5	2.5	2.5	2.5	2	2	2

Corrected Properties at T=10C

Burgers Corrected	PEN 70/100	EVA 3%	EVA 5%	EVA 7%	SBS (L)3%	SBS (L)5%	SBS (L)7%	SBS (R) 3%	SBS (R) 5%	SBS (R)7%
E1[Pa]	2.00E+08	2.00E+08	1.80E+08	1.50E+08	2.00E+08	1.00E+08	8.50E+07	1.50E+08	1.30E+08	1.00E+08
E2 [Pa]	1.50E+06	3.00E+05	1.30E+05	6.00E+04	2.00E+05	5.50E+04	5.00E+04	3.64E+05	4.55E+04	3.18E+04
n1[Pa.s]	5.34E+06	4.71E+07	1.12E+08	3.98E+08	8.40E+07	3.94E+08	6.12E+08	1.24E+08	4.58E+08	1.62E+09
n2 [Pa.s]	5.34E+05	6.31E+05	7.44E+05	9.95E+05	1.50E+06	3.02E+06	4.15E+06	1.06E+06	1.02E+06	1.49E+06

| n1 Check | 1.0 | 8.8 | 20.9 | 74.6 | 15.7 | 73.8 | 114.6 | 23.3 | 85.8 | 303.2 |

T I Milne

7/26/2004

Determination of Burgers Model Parameters for FEM Model (reworked from Hagos)

Tr	20	C	Reference Temperature								
T	25	C	Service Temperature								

Material	PEN 70/100	EVA 3%	EVA 5%	EVA 7%	SBS (L)3%	SBS (L)5%	SBS (L)7%	SBS (R)3%	SBS (R)5%	SBS (R)7%
C1	11.78	12.02	11.12	15.61	10.55	11.35	12.22	12.47	14.03	11.25
C2	104.22	108.06	99.07	132.16	95.49	97.08	108.34	109.86	117.05	102.37
Alfa	0.288882663	0.294051802	0.292243063	0.26974695	0.2985879	0.278012	0.2890108	0.2865288	0.266216862	0.299302707

Properties at T=20C

Burgers Parameters	PEN 70/100	EVA 3%	EVA 5%	EVA 7%	SBS (L)3%	SBS (L)5%	SBS (L)7%	SBS (R)3%	SBS (R)5%	SBS (R)7%
E1[Pa]	2.00E+08	2.00E+08	1.80E+08	1.50E+08	2.00E+08	1.00E+08	8.50E+07	1.50E+08	1.30E+08	1.00E+08
E2 [Pa]	1.50E+06	1.50E+06	8.50E+05	3.00E+05	8.00E+05	2.20E+05	2.00E+05	4.00E+06	5.00E+05	3.50E+05
n1[Pa.s]	3.00E+05	4.00E+05	9.00E+05	3.00E+06	7.00E+05	2.80E+06	5.00E+06	5.00E+05	1.60E+06	7.00E+06
n2 [Pa.s]	3.00E+04	2.50E+04	2.80E+04	3.50E+04	3.50E+04	6.00E+04	9.50E+04	3.00E+04	2.50E+04	4.50E+04

Properties at T=25C

Burgers Parameters	PEN 70/100	EVA 3%	EVA 5%	EVA 7%	SBS (L)3%	SBS (L)5%	SBS (L)7%	SBS (R)3%	SBS (R)5%	SBS (R)7%
E1[Pa]	2.00E+08	2.00E+08	1.80E+08	1.50E+08	2.00E+08	1.00E+08	8.50E+07	1.50E+08	1.30E+08	1.00E+08
E2 [Pa]	1.50E+06	1.50E+06	6.50E+05	3.00E+05	8.00E+05	2.20E+05	2.00E+05	4.00E+06	5.00E+05	3.50E+05
n1[Pa.s]	8.67E+04	1.18E+05	2.63E+05	8.09E+05	2.09E+05	7.78E+05	1.45E+06	1.43E+05	4.26E+05	2.10E+06
n2 [Pa.s]	8.67E+03	7.35E+03	8.18E+03	9.44E+03	1.05E+04	1.67E+04	2.75E+04	8.60E+03	6.66E+03	1.35E+04

Factors for PMA

	PEN 70/100	EVA 3%	EVA 5%	EVA 7%	SBS (L)3%	SBS (L)5%	SBS (L)7%	SBS (R)3%	SBS (R)5%	SBS (R)7%
E1[-]	1	1	1	1	1	1	1	1	1	1
E2 [-](Decreased)	1									
n1[-]	1	7	7	7	7	7	7	7	14	14
n2 [-]	1	1.5	1.5	1.5	2.5	2.5	2.5	2	2	2

Corrected Properties at T=25C

Burgers Corrected	PEN 70/100	EVA 3%	EVA 5%	EVA 7%	SBS (L)3%	SBS (L)5%	SBS (L)7%	SBS (R)3%	SBS (R)5%	SBS (R)7%
E1[Pa]	2.00E+08	2.00E+08	1.80E+08	1.50E+08	2.00E+08	1.00E+08	8.50E+07	1.50E+08	1.30E+08	1.00E+08
E2 [Pa]	1.50E+06	3.00E+05	1.30E+05	6.00E+04	2.00E+05	5.50E+04	5.00E+04	3.64E+05	4.55E+04	3.18E+04
n1[Pa.s]	8.67E+04	8.23E+05	1.84E+06	5.66E+06	1.46E+06	5.45E+06	1.01E+07	2.01E+06	5.96E+06	2.93E+07
n2 [Pa.s]	8.67E+03	1.10E+04	1.23E+04	1.42E+04	2.61E+04	4.17E+04	6.86E+04	1.72E+04	1.33E+04	2.69E+04
n1 Check	1.0	9.5	21.2	65.4	16.9	62.9	116.7	23.1	68.8	338.4

Determination of Burgers Model Parameters for FEM Model (reworked from Hagos)

Tr	20	C	Reference Temperature
T	50	C	Service Temperature

Material	PEN 70/100	EVA 3%	EVA 5%	EVA 7%	SBS (L)3%	SBS (L)5%	SBS (L)7%	SBS (R)3%	SBS (R)5%	SBS (R)7%
C1	11.78	12.02	11.12	15.61	10.55	11.35	12.22	12.47	14.03	11.25
C2	104.22	108.06	99.07	132.16	95.49	97.08	108.34	109.86	117.05	102.37
Alfa	0.002328142	0.002443949	0.002602292	0.00129453	0.0030053	0.0020921	0.0022388	0.00211438	0.001373119	0.002820516

Properties at Tr=20C

Burgers Parameters	PEN 70/100	EVA 3%	EVA 5%	EVA 7%	SBS (L)3%	SBS (L)5%	SBS (L)7%	SBS (R)3%	SBS (R)5%	SBS (R)7%
E1[Pa]	2.00E+08	2.00E+08	1.80E+08	1.50E+08	2.00E+08	1.00E+08	8.50E+07	1.50E+08	1.30E+08	1.00E+08
E2 [Pa]	1.50E+06	1.50E+06	6.50E+05	3.00E+05	8.00E+05	2.20E+05	2.00E+05	4.00E+06	5.00E+05	3.50E+05
n1[Pa.s]	3.00E+05	4.00E+05	9.00E+05	3.00E+06	7.00E+05	2.80E+06	5.00E+06	5.00E+05	1.60E+06	7.00E+06
n2 [Pa.s]	3.00E+04	2.50E+04	2.80E+04	3.50E+04	3.50E+04	6.00E+04	9.50E+04	3.00E+04	2.50E+04	4.50E+04

Properties at T=50C

Burgers Parameters	PEN 70/100	EVA 3%	EVA 5%	EVA 7%	SBS (L)3%	SBS (L)5%	SBS (L)7%	SBS (R)3%	SBS (R)5%	SBS (R)7%
E1[Pa]	2.00E+08	2.00E+08	1.80E+08	1.50E+08	2.00E+08	1.00E+08	8.50E+07	1.50E+08	1.30E+08	1.00E+08
E2 [Pa]	1.50E+06	1.50E+06	6.50E+05	3.00E+05	8.00E+05	2.20E+05	2.00E+05	4.00E+06	5.00E+05	3.50E+05
n1[Pa.s]	6.98E+02	9.78E+02	2.34E+03	3.88E+03	2.10E+03	5.86E+03	1.12E+04	1.06E+03	2.20E+03	1.97E+04
n2 [Pa.s]	6.98E+01	6.11E+01	7.29E+01	4.53E+01	1.05E+02	1.26E+02	2.13E+02	6.34E+01	3.43E+01	1.27E+02

Factors for PMA

	PEN 70/100	EVA 3%	EVA 5%	EVA 7%	SBS (L)3%	SBS (L)5%	SBS (L)7%	SBS (R)3%	SBS (R)5%	SBS (R)7%
E1[-]	1		1	1	1	1	1	1	1	1
E2 [-](Decreased)	1		7	7	7	7	7	14	14	14
n1[-]	1		1.5	1.5	1.5	2.5	2.5	2	2	2
n2 [-]	1		1	1	1	1	1	1	1	1

Corrected Properties at T=50C

Burgers Corrected	PEN 70/100	EVA 3%	EVA 5%	EVA 7%	SBS (L)3%	SBS (L)5%	SBS (L)7%	SBS (R)3%	SBS (R)5%	SBS (R)7%
E1[Pa]	2.00E+08	2.00E+08	1.80E+08	1.50E+08	2.00E+08	1.00E+08	8.50E+07	1.50E+08	1.30E+08	1.00E+08
E2 [Pa]	1.50E+06	3.00E+05	1.30E+05	6.00E+04	2.00E+05	5.50E+04	5.00E+04	3.64E+05	4.55E+04	3.18E+04
n1[Pa.s]	6.98E+02	6.84E+03	1.64E+04	2.72E+04	1.47E+04	4.10E+04	7.84E+04	1.48E+04	3.08E+04	2.76E+05
n2 [Pa.s]	6.98E+01	9.16E+01	1.09E+02	6.80E+01	2.63E+02	3.14E+02	5.32E+02	1.27E+02	6.87E+01	2.54E+02
n1 Check	1.0	9.8	23.5	38.9	21.1	58.7	112.2	21.2	44.0	395.8

T I Milne

7/26/2004

ANNEXURE B

TO CHAPTER 5

STRESSES AND STRAINS

Node 8606   Node 7245 YY Stone   Node 7248YY Bitumen

Node 4975 Stone   Node 4978 Bitumen
Node 4981 Bitumen   Node 4982 Bitumen
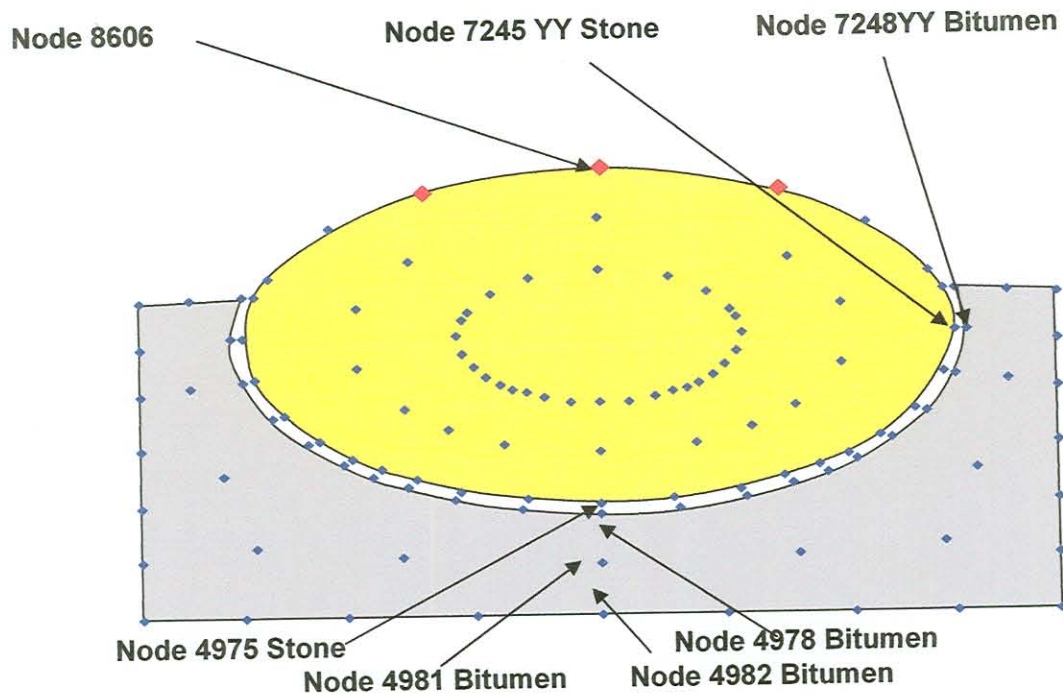
Figure 5.45: Nodes for Output Analysis: Cross-Section of Central Stone in Direction of Travel Seal FEM Mesh

Conventions:

- Stress and strain

    '+' tensile

    '-' compressive

- Displacement

    '+ in direction of increasing axis values
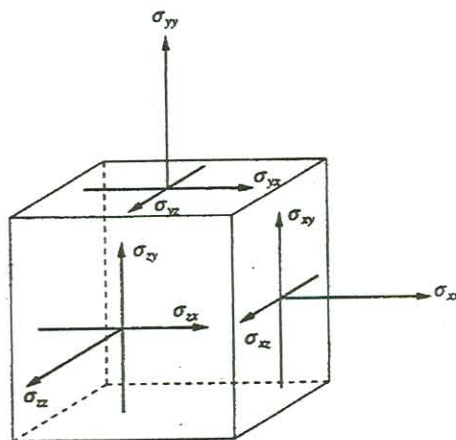
    '-' in direction of decreasing axis values

$$\sigma_{yy}$$

Figure 5.46: Stress Components in a Three-dimensional Continuum

NUMERICAL MODEL

STRESSES AND STRAINS AT SPECIFIC NODES

RUN NO	RUN	DESCRIPTION	TIME	MAT	NODE	STRESS XX	STRESS YY	STRESS ZZ	SHEAR XY	SHEAR XZ	SHEAR YZ	STRESS (+MAX)	STRESS (-MAX)	STRAIN (+MAX)	STRAIN (-MAX)
1	PEN	roundpenviscbitint	1.40E-02	3	4978	-3.83E+00	-3.85E+00	-4.32E+00	5.36E-04	3.91E-01	-2.99E-01				
1	PEN	roundpenviscbitint	2.98E-01	3	4978	-3.78E+00	-3.80E+00	-4.27E+00	-2.73E-04	-4.05E-01	-2.99E-01				
1	PEN	roundpenviscbitint	2.98E-01	3	4978	-4.07E+00	-4.10E+00	-4.61E+00	-1.72E-04	-5.04E-01	-3.09E-01				
1	PEN	roundpenviscbitint	3.08E-01	3	4978	-3.78E+00	-3.80E+00	-4.27E+00	5.08E-04	6.15E-01	-2.98E-01				
1	PEN	roundpenviscbitint	3.15E-01	3	4978	-1.03E-01	-1.04E-01	-1.18E-01	4.25E-06	1.04E-02	-6.75E-03				
1	PEN	roundpenviscbitint	5.39E-02	3	4978							9.01E-01 (YZ)			
1	PEN	roundpenviscbitint	5.04E-02	3	4978								-5.53E+00 (ZZ)	9.91E-01 (YZ)	-1.73E+00 (ZX)
1	PEN	roundpenviscbitint	3.09E-01	3	4978										
2	PEN	roundpenviscagint	1.40E-02	3	4978	-3.83E+00	-3.85E+00	-4.32E+00	5.37E-04	3.91E-01	-2.99E-01				
2	PEN	roundpenviscagint	2.98E-01	3	4978	-3.84E+00	-3.86E+00	-4.34E+00	-2.79E-04	-4.06E-01	-3.00E-01				
2	PEN	roundpenviscagint	2.98E-01	3	4978	-4.06E+00	-4.08E+00	-4.59E+00	-1.69E-04	-5.05E-01	-3.09E-01				
2	PEN	roundpenviscagint	3.08E-01	3	4978	-3.77E+00	-3.80E+00	-4.26E+00	5.10E-04	6.14E-01	-2.98E-01				
2	PEN	roundpenviscagint	3.15E-01	3	4978	-9.44E-02	-9.49E-02	-1.06E-01	5.28E-06	1.04E-02	-6.72E-03				
2	PEN	roundpenviscagint	5.39E-02	3	4978							9.02E-01 (YZ)			
2	PEN	roundpenviscagint	5.04E-02	3	4978								-5.53E+00 (ZZ)	9.92E-01 (YZ)	-1.73E+00 (ZX)
2	PEN	roundpenviscagint	3.09E-01	3	4978										
3	SBS	roundsbsviscbitint	1.40E-02	3	4978	-3.87E+00	-3.90E+00	-4.38E+00	5.69E-04	4.17E-01	-3.03E-01				
3	SBS	roundsbsviscbitint	2.98E-01	3	4978	-4.04E+00	-4.06E+00	-4.56E+00	-2.60E-04	-4.29E-01	-3.17E-01				
3	SBS	roundsbsviscbitint	2.98E-01	3	4978	-4.27E+00	-4.29E+00	-4.83E+00	-1.47E-04	-5.32E-01	-3.26E-01				
3	SBS	roundsbsviscbitint	3.08E-01	3	4978	-3.83E+00	-3.85E+00	-4.32E+00	5.66E-04	8.44E-01	-3.03E-01				
3	SBS	roundsbsviscbitint	3.15E-01	3	4978	-7.45E-04	-7.84E-04	-6.72E-04	-5.94E-07	1.66E-04	-5.68E-05				
3	SBS	roundsbsviscbitint	5.39E-02	3	4978							9.57E-01 (YZ)			
3	SBS	roundsbsviscbitint	5.04E-02	3	4978								-5.72E+00 (ZZ)	4.79E-01 (YZ)	-1.83E+00 (ZX)
3	SBS	roundsbsviscbitint	3.10E-01	3	4978										
3	SBS	roundsbsviscbitint	3.09E-01	3	4978										
4	SBS	roundsbsviscagint	1.40E-02	3	4978	-3.86E+00	-3.88E+00	-4.36E+00	5.73E-04	4.16E-01	-3.03E-01				
4	SBS	roundsbsviscagint	2.98E-01	3	4978	-4.07E+00	-4.10E+00	-4.61E+00	-2.70E-04	-4.29E-01	-3.18E-01				

Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

RUN NO	RUN	DESCRIPTION	TIME	MAT	NODE	STRESS XX	STRESS YY	STRESS ZZ	SHEAR XY	SHEAR XZ	SHEAR YZ	STRESS (+MAX)	STRESS (-MAX)	STRAIN (+MAX)	STRAIN (-MAX)
4	SBS	roundsbsviscaggint	2.98E-01	3	4978	-4.28E+00	-4.31E+00	-4.84E+00	-1.45E-04	-5.33E-01	-3.27E-01				
4	SBS	roundsbsviscaggint	3.08E-01	3	4978	-3.81E+00	-3.83E+00	-4.30E+00	5.70E-04	6.42E-01	-3.03E-01				
4	SBS	roundsbsviscaggint	3.15E-01	3	4978	-1.52E-04	-1.51E-04	-1.59E-04	-1.66E-07	-1.71E-07	1.25E-06				
4	SBS	roundsbsviscaggint	5.39E-02	3	4978							8.58E-01			
4	SBS	roundsbsviscaggint	5.04E-02	3	4978							YZ			
4	SBS	roundsbsviscaggint	3.10E-01	3	4978								-5.73E+00	4.80E-01	ZX
4	SBS	roundsbsviscaggint	3.09E-01	3	4978								ZZ	YZ	-1.63E+00
5	PEN	roughpenviscbitint	1.40E-02	3	4978	-3.81E+00	-3.74E+00	-4.17E+00	1.55E-02	3.93E-01	-3.22E-01				
5	PEN	roughpenviscbitint	2.98E-01	3	4978	-4.45E+00	-4.46E+00	-4.82E+00	-4.11E-02	-4.35E-01	-3.10E-01				
5	PEN	roughpenviscbitint	2.98E-01	3	4978	-4.75E+00	-4.77E+00	-5.14E+00	-4.84E-02	-5.43E-01	-3.19E-01				
5	PEN	roughpenviscbitint	3.08E-01	3	4978	-3.57E+00	-3.48E+00	-3.93E+00	3.12E-02	6.26E-01	-3.24E-01				
5	PEN	roughpenviscbitint	3.15E-01	3	4978	-8.84E-02	-8.70E-02	-9.77E-02	4.77E-04	1.00E-02	-7.17E-03				
5	PEN	roughpenviscbitint	5.39E-02	3	4978							9.17E-01			
5	PEN	roughpenviscbitint	7.00E-03	3	4978							YZ			
5	PEN	roughpenviscbitint	3.09E-01	3	4978								-5.87E+00	9.18E-01	ZX
5	PEN	roughpenviscbitint	3.09E-01	3	4978								ZZ	YZ	-1.84E+00
6	PEN	roughpenviscaggint	1.40E-02	3	4978	-3.81E+00	-3.74E+00	-4.17E+00	1.55E-02	3.93E-01	-3.22E-01				
6	PEN	roughpenviscaggint	2.98E-01	3	4978	-4.46E+00	-4.47E+00	-4.82E+00	-4.12E-02	-4.36E-01	-3.10E-01				
6	PEN	roughpenviscaggint	2.98E-01	3	4978	-4.75E+00	-4.77E+00	-5.13E+00	-4.84E-02	-5.43E-01	-3.19E-01				
6	PEN	roughpenviscaggint	3.08E-01	3	4978	-3.57E+00	-3.48E+00	-3.93E+00	3.11E-02	6.26E-01	-3.24E-01				
6	PEN	roughpenviscaggint	3.15E-01	3	4978	-8.77E-02	-8.60E-02	-9.60E-02	4.63E-04	1.01E-02	-7.10E-03				
6	PEN	roughpenviscaggint	5.39E-02	3	4978							9.17E-01			
6	PEN	roughpenviscaggint	7.00E-03	3	4978							YZ			
6	PEN	roughpenviscaggint	3.09E-01	3	4978								-5.87E+00	9.18E-01	ZX
6	PEN	roughpenviscaggint	3.09E-01	3	4978								ZZ	YZ	-1.84E+00
7	SBS	roughsbsviscbitint	1.40E-02	3	4978	-3.81E+00	-3.74E+00	-4.18E+00	1.71E-02	4.18E-01	-3.26E-01				
7	SBS	roughsbsviscbitint	2.98E-01	3	4978	-4.74E+00	-4.75E+00	-5.12E+00	-4.37E-02	-4.60E-01	-3.30E-01				
7	SBS	roughsbsviscbitint	2.98E-01	3	4978	-5.03E+00	-5.05E+00	-5.46E+00	-5.11E-02	-5.72E-01	-3.37E-01				
7	SBS	roughsbsviscbitint	3.06E-01	3	4978	-3.58E+00	-3.49E+00	-3.95E+00	3.30E-02	6.55E-01	-3.30E-01				
7	SBS	roughsbsviscbitint	3.15E-01	3	4978	1.07E-04	1.02E-04	1.10E-04	2.07E-06	-1.19E-05	1.24E-05				
7	SBS	roughsbsviscbitint	5.39E-02	3	4978							9.74E-01			

Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

RUN NO	RUN	DESCRIPTION	TIME	MAT	NODE	STRESS XX	STRESS YY	STRESS ZZ	SHEAR XY	SHEAR XZ	SHEAR YZ	STRESS (+MAX)	STRESS (-MAX)	STRAIN (+MAX)	STRAIN (-MAX)
7	SBS	roughsbsviscblitint	7.00E-03	3	4978							YZ	-6.12E+00 ZZ		
7	SBS	roughsbsviscblitint	3.10E-01	3	4978									3.95E-01 YZ	
7	SBS	roughsbsviscblitint	3.09E-01	3	4978	-3.82E+00	-3.75E+00	-4.19E+00	1.71E-02	4.19E-01	-3.26E-01				-1.72E+00 ZX
8	SBS	roughsbsviscaggint	1.40E-02	3	4978	-4.73E+00	-4.74E+00	-5.12E+00	-4.35E-02	-4.61E-01	-3.30E-01				
8	SBS	roughsbsviscaggint	2.98E-01	3	4978	-5.02E+00	-5.04E+00	-5.43E+00	-5.11E-02	-5.73E-01	-3.37E-01				
8	SBS	roughsbsviscaggint	2.98E-01	3	4978	-3.60E+00	-3.50E+00	-3.96E+00	3.30E-02	6.55E-01	-3.29E-01				
8	SBS	roughsbsviscaggint	3.06E-01	3	4978	-3.62E-05	-3.76E-05	-3.05E-05	-1.78E-08	-6.54E-06	4.84E-06				
8	SBS	roughsbsviscaggint	5.39E-02	3	4978							9.75E-01			
8	SBS	roughsbsviscaggint	7.00E-03	3	4978							YZ	-6.10E+00 ZZ		
8	SBS	roughsbsviscaggint	3.10E-01	3	4978									3.95E-01 YZ	
8	SBS	roughsbsviscaggint	3.09E-01	3	4978										-1.72E+00 ZX
9	PEN	roundpenat10viscbi tint	1.40E-02	3	4978	-3.92E+00	-3.95E+00	-4.44E+00	5.62E-04	4.10E-01	-3.00E-01				
9	PEN	roundpenat10viscbi tint	2.98E-01	3	4978	-3.80E+00	-3.61E+00	-4.00E+00	-2.78E-04	-4.23E-01	-3.13E-01				
9	PEN	roundpenat10viscbi tint	2.98E-01	3	4978	-3.84E+00	-3.85E+00	-4.29E+00	-1.60E-04	-5.27E-01	-3.21E-01				
9	PEN	roundpenat10viscbi tint	3.06E-01	3	4978	-3.88E+00	-3.91E+00	-4.40E+00	5.43E-04	6.36E-01	-3.00E-01				
9	PEN	roundpenat10viscbi tint	3.15E-01	3	4978	-1.56E-01	-1.60E-01	-1.89E-01	2.61E-06	2.30E-03	-3.42E-03				
9	PEN	roundpenat10viscbi tint	5.39E-02	3	4978							9.45E-01			
9	PEN	roundpenat10viscbi tint	1.35E-01	3	4978							YZ	-5.41E+00 ZZ		
9	PEN	roundpenat10viscbi tint	3.08E-01	3	4978									3.91E-02 YZ	-1.51E-01 ZX
10	PEN	roundpenat50viscbi tin	1.40E-02	3	4978	-5.43E-01	-5.46E-01	-6.14E-01	1.12E-04	4.96E-02	-4.23E-02				
10	PEN	roundpenat50viscbi tin	2.98E-01	3	4978	-8.05E-01	-8.10E-01	-9.12E-01	-1.66E-04	-6.98E-02	-4.80E-02				
10	PEN	roundpenat50viscbi tin	3.06E-01	3	4978	-5.33E-01	-5.37E-01	-6.03E-01	1.12E-04	8.01E-02	-4.21E-02				
10	PEN	roundpenat50viscbi tin	3.15E-01	3	4978	2.28E-02	2.25E-02	2.45E-02	2.39E-05	-4.81E-04	3.01E-04				
10	PEN	roundpenat50viscbi tin	5.74E-02	3	4978							6.14E-01			
10	PEN	roundpenat50viscbi tin	4.41E-02	3	4978							ZZ	-1.05E+00 ZZ		
10	PEN	roundpenat50viscbi tin	3.11E-01	3	4978										
11	PEN	roughpenat10viscbi	1.40E-02	3	4978	-3.91E+00	-3.83E+00	-4.29E+00	1.70E-02	4.16E-01	-3.24E-01			4.09E+00 YZ	
11	PEN	roughpenat10viscbi	2.98E-01	3	4978	-4.69E+00	-4.69E+00	-5.05E+00	-4.22E-02	-4.52E-01	-3.23E-01				-2.11E+01 ZX

Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

RUN NO	RUN	DESCRIPTION	TIME	MAT	NODE	STRESS XX	STRESS YY	STRESS ZZ	SHEAR XY	SHEAR XZ	SHEAR YZ	STRESS (+MAX)	STRESS (-MAX)	STRAIN (+MAX)	STRAIN (-MAX)
11	PEN	roughpenat10viscbi	2.98E-01	3	4978	-4.99E+00	-5.01E+00	-5.38E+00	-4.98E-02	-5.63E-01	-3.31E-01				
11	PEN	roughpenat10viscbi	3.08E-01	3	4978	-3.67E+00	-3.58E+00	-4.05E+00	3.29E-02	6.51E-01	-3.27E-01				
11	PEN	roughpenat10viscbi	3.15E-01	3	4978	4.28E-02	4.07E-02	4.22E-02	-6.46E-04	-3.56E-03	-4.03E-03				
11	PEN	roughpenat10vIscbl	5.39E-02	3	4978							9.74E-01			
11	PEN	roughpenat10viscbi	7.00E-03	3	4978							YZ	-6.15E+00		
11	PEN	roughpenat10viscbi	3.08E-01	3	4978								ZZ	3.17E-02 / YZ	-1.60E-01 / ZX
12	PEN	roughpenat50viscbitin	1.40E-02	3	4978	-5.37E-01	-5.28E-01	-5.86E-01	1.79E-03	4.96E-02	-4.54E-02				
12	PEN	roughpenat50viscbitin	2.98E-01	3	4978	-9.02E-01	-9.05E-01	-9.83E-01	-6.95E-03	-7.72E-02	-5.09E-02				
12	PEN	roughpenat50viscbitin	2.98E-01	3	4978	-5.84E-01	-5.87E-01	-6.27E-01	-7.61E-03	-8.59E-02	-4.64E-02				
12	PEN	roughpenat50viscbitin	3.08E-01	3	4978	-5.01E-01	-4.86E-01	-5.51E-01	3.94E-03	8.13E-02	-4.57E-02				
12	PEN	roughpenat50viscbitin	3.15E-01	3	4978	3.58E-02	3.57E-02	3.95E-02	-3.91E-05	-5.72E-04	3.52E-04				
12	PEN	roughpenat50viscbitin	5.74E-02	3	4978							4.79E-01			
12	PEN	roughpenat50viscbitin	2.10E-03	3	4978							ZZ	-1.06E+00		
12	PEN	roughpenat50viscbitin	3.12E-01	3	4978								ZZ	2.89E+00	
12	PEN	roughpenat50viscbitin	3.11E-01	3	4978									YZ	-2.23E+01 / ZX
13	PEN	roundpenviscbitinfill	1.40E-02	3	4978	-9.57E-01	-9.62E-01	-1.08E+00	1.34E-04	9.78E-02	-7.48E-02				
13	PEN	roundpenviscbitinfill	2.98E-01	3	4978	-9.47E-01	-9.52E-01	-1.07E+00	-8.89E-05	-1.01E-01	-7.50E-02				
13	PEN	roundpenviscbitinfill	2.98E-01	3	4978	-1.02E+00	-1.03E+00	-1.15E+00	-4.44E-05	-1.26E-01	-7.73E-02				
13	PEN	roundpenviscbitinfill	3.08E-01	3	4978	-9.45E-01	-9.51E-01	-1.07E+00	1.32E-04	1.54E-01	-7.47E-02				
13	PEN	roundpenviscbitinfill	3.15E-01	3	4978	-2.63E-02	-2.65E-02	-3.01E-02	4.05E-06	2.65E-03	-1.81E-03				
13	PEN	roundpenviscbitinfill	5.39E-02	3	4978							2.25E-01			
13	PEN	roundpenviscbitinfill	1.34E-01	3	4978							YZ	-1.38E+00		
13	PEN	roundpenviscbitinfill	3.09E-01	3	4978								ZZ	2.47E-01 / YZ	-4.30E-01 / ZX
14	SBS	roundsbsviscbitint	1.40E-02	3	4978	-9.69E-01	-9.75E-01	-1.09E+00	1.42E-04	1.04E-01	-7.58E-02				
14	SBS	roundsbsviscbitint	2.98E-01	3	4978	-1.01E+00	-1.02E+00	-1.14E+00	-8.53E-05	-1.07E-01	-7.93E-02				
14	SBS	roundsbsviscbitint	2.98E-01	3	4978	-1.07E+00	-1.07E+00	-1.21E+00	-3.72E-05	-1.33E-01	-8.15E-02				
14	SBS	roundsbsviscbitint	3.08E-01	3	4978	-9.57E-01	-9.63E-01	-1.08E+00	1.42E-04	1.61E-01	-7.58E-02				
14	SBS	roundsbsviscbitint	3.15E-01	3	4978	-2.06E-04	-2.18E-04	-1.92E-04	-1.02E-07	4.26E-05	-1.76E-05				
14	SBS	roundsbsviscbitint	5.39E-02	3	4978							2.39E-01			

Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

RUN NO	RUN	DESCRIPTION	TIME	MAT	NODE	STRESS XX	STRESS YY	STRESS ZZ	SHEAR XY	SHEAR XZ	SHEAR YZ	STRESS (+MAX)	STRESS (-MAX)	STRAIN (+MAX)	STRAIN (-MAX)
14	SBS	roundsbsviscbitint	2.18E-01	3	4978							YZ	-1.43E+00		
14	SBS	roundsbsviscbitint	3.10E-01	3	4978								ZZ	1.20E-01	ZX
14	SBS	roundsbsviscbitint	3.09E-01	3	4978									YZ	-4.06E-01

Note:

(1) PEN: Penetration grade binder

(2) SBS: 3 % SBS (longitudinal) modified bitumen binder

(3) Material 3: Bitumen

(4) Material 1: Stone

Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

RUN NO	RUN	DESCRIPTION	TIME	MAT	NODE	STRESS XX	STRESS YY	STRESS ZZ	SHEAR XY	SHEAR XZ	SHEAR YZ	STRESS (+MAX)	STRESS (-MAX)	STRAIN (+MAX)	STRAIN (-MAX)
1	PEN	roundpenviscbitint	1.40E-02	3	7248	-5.57E-01	-6.20E-01	-7.26E-01	-5.16E-02	-1.41E-01	7.83E-02				
1	PEN	roundpenviscbitint	2.98E-01	3	7248	-1.05E+00	-1.16E+00	-1.46E+00	-8.85E-02	-3.16E-01	1.72E-01				
1	PEN	roundpenviscbitint	2.98E-01	3	7248	-1.08E+00	-1.15E+00	-1.51E+00	-9.25E-02	-3.33E-01	1.89E-01				
1	PEN	roundpenviscbitint	3.09E-01	3	7248	-4.28E-01	-4.93E-01	-5.34E-01	-4.24E-02	-9.31E-02	5.01E-02				
1	PEN	roundpenviscbitint	3.15E-01	3	7248	-1.00E-02	-9.66E-03	-1.32E-02	-1.15E-03	-2.39E-03	1.50E-03				
1	PEN	roundpenviscbitint	3.05E-01	3	7248							2.43E-01			
1	PEN	roundpenviscbitint	2.56E-01	3	7248							(YY)	-1.74E+00		
1	PEN	roundpenviscbitint	3.03E-01	3	7248								(ZZ)	7.01E-01	
1	PEN	roundpenviscbitint	3.02E-01	3	7248									(ZX)	-1.08E+00
2	PEN	roundpenviscaggint	1.40E-02	3	7248	-5.66E-01	-6.19E-01	-7.25E-01	-5.12E-02	-1.40E-01	7.82E-02				(YZ)
2	PEN	roundpenviscaggint	2.98E-01	3	7248	-1.05E+00	-1.16E+00	-1.45E+00	-8.78E-02	-3.12E-01	1.70E-01				
2	PEN	roundpenviscaggint	2.98E-01	3	7248	-1.08E+00	-1.15E+00	-1.51E+00	-9.22E-02	-3.33E-01	1.89E-01				
2	PEN	roundpenviscaggint	3.08E-01	3	7248	-4.25E-01	-4.92E-01	-5.33E-01	-4.20E-02	-9.31E-02	5.02E-02				
2	PEN	roundpenviscaggint	3.15E-01	3	7248	-9.95E-03	-9.58E-03	-1.35E-02	-1.19E-03	-2.96E-03	1.91E-03				
2	PEN	roundpenviscaggint	3.05E-01	3	7248							2.42E-01			
2	PEN	roundpenviscaggint	2.56E-01	3	7248							(YY)	-1.74E+00		
2	PEN	roundpenviscaggint	3.03E-01	3	7248								(ZZ)	6.99E-01	
3	SBS	roundsbsviscbitint	1.40E-02	3	7248	-5.69E-01	-6.40E-01	-7.37E-01	-5.18E-02	-1.40E-01	7.63E-02			(ZX)	-5.36E-01
3	SBS	roundsbsviscbitint	2.98E-01	3	7248	-1.12E+00	-1.23E+00	-1.54E+00	-9.34E-02	-3.34E-01	1.84E-01				(ZZ)
3	SBS	roundsbsviscbitint	2.98E-01	3	7248	-1.14E+00	-1.21E+00	-1.59E+00	-9.75E-02	-3.54E-01	2.01E-01				
3	SBS	roundsbsviscbitint	3.08E-01	3	7248	-4.39E-01	-5.15E-01	-5.45E-01	-4.25E-02	-9.17E-02	4.78E-02				
3	SBS	roundsbsviscbitint	3.15E-01	3	7248	-2.22E-04	-2.97E-04	-1.02E-04	3.55E-05	1.00E-04	-5.99E-05				
3	SBS	roundsbsviscbitint	3.05E-01	3	7248	0.00E+00						2.83E-01			
3	SBS	roundsbsviscbitint	2.56E-01	3	7248	0.00E+00						(YY)	-1.84E+00		
3	SBS	roundsbsviscbitint	2.67E-01	3	7248	0.00E+00							(YY)	8.46E-01	
4	SBS	roundsbsviscaggint	1.40E-02	3	7248	-5.65E-01	-6.36E-01	-7.35E-01	-5.13E-02	-1.40E-01	7.65E-02			(ZX)	-9.92E-01
4	SBS	roundsbsviscaggint	2.98E-01	3	7248	-1.12E+00	-1.23E+00	-1.54E+00	-9.28E-02	-3.30E-01	1.80E-01				(YZ)
4	SBS	roundsbsviscaggint	2.98E-01	3	7248	-1.14E+00	-1.22E+00	-1.59E+00	-9.72E-02	-3.52E-01	1.99E-01				
4	SBS	roundsbsviscaggint	3.08E-01	3	7248	-4.34E-01	-5.10E-01	-5.40E-01	-4.19E-02	-9.18E-02	4.81E-02				
4	SBS	roundsbsviscaggint	3.15E-01	3	7248	-2.23E-05	-2.45E-05	-4.37E-05	-8.18E-06	-1.36E-05	6.83E-06				

Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

RUN NO	RUN	DESCRIPTION	TIME	MAT	NODE	STRESS XX	STRESS YY	STRESS ZZ	SHEAR XY	SHEAR XZ	SHEAR YZ	STRESS (+MAX)	STRESS (-MAX)	STRAIN (+MAX)	STRAIN (-MAX)
4	SBS	roundsbsviscagglnt	3.05E-01	3	7248							2.80E-01		6.45E-01	
4	SBS	roundsbsviscagglnt	2.56E-01	3	7248							(YY)	-1.84E+00	(ZX)	(YZ)
4	SBS	roundsbsviscagglnt	2.67E-01	3	7248								(ZZ)		-9.92E-01
5	PEN	roughpenviscbtlnt	1.40E-02	3	7248	-9.85E-01	-1.08E+00	-1.13E+00	-4.92E-02	-7.99E-02	-1.64E-02				
5	PEN	roughpenviscbtlnt	2.98E-01	3	7248	-1.45E+00	-1.55E+00	-1.78E+00	-8.34E-02	-1.39E-01	2.90E-03				
5	PEN	roughpenviscbtlnt	2.99E-01	3	7248	-1.47E+00	-1.54E+00	-1.82E+00	-8.30E-02	-1.37E-01	1.04E-02				
5	PEN	roughpenviscbtlnt	3.08E-01	3	7248	-8.68E-01	-9.72E-01	-9.66E-01	-4.18E-02	-6.64E-02	-2.42E-02				
5	PEN	roughpenviscbtlnt	3.15E-01	3	7248	-2.04E-02	-2.15E-02	-2.32E-02	-8.86E-04	-1.28E-03	-2.66E-04				
5	PEN	roughpenviscbtlnt	7.00E-03	3	7248							3.64E-02			-4.38E-01
5	PEN	roughpenviscbtlnt	2.56E-01	3	7248							(ZX)	-2.04E+00	1.32E-01	(ZZ)
5	PEN	roughpenviscbtlnt	3.01E-01	3	7248								(ZZ)	(XX)	
5	PEN	roughpenviscbtlnt	3.02E-01	3	7248										
6	PEN	roughpenviscagglnt	1.40E-02	3	7248	-9.85E-01	-1.08E+00	-1.13E+00	-4.91E-02	-7.99E-02	-1.65E-02				
6	PEN	roughpenviscagglnt	2.98E-01	3	7248	-1.45E+00	-1.55E+00	-1.78E+00	-8.30E-02	-1.39E-01	2.66E-03				
6	PEN	roughpenviscagglnt	2.99E-01	3	7248	-1.47E+00	-1.54E+00	-1.82E+00	-8.31E-02	-1.38E-01	1.03E-02				
6	PEN	roughpenviscagglnt	3.08E-01	3	7248	-8.68E-01	-9.72E-01	-9.66E-01	-4.17E-02	-6.64E-02	-2.43E-02				
6	PEN	roughpenviscagglnt	3.15E-01	3	7248	-2.03E-02	-2.14E-02	-2.33E-02	-9.47E-04	-1.42E-03	-2.72E-04				
6	PEN	roughpenviscagglnt	7.00E-03	3	7248							3.65E-02			-4.38E-01
6	PEN	roughpenviscagglnt	2.56E-01	3	7248							(ZX)	-2.04E+00	1.32E-01	(ZZ)
6	PEN	roughpenviscagglnt	2.59E-01	3	7248								(ZZ)	(XX)	
6	PEN	roughpenviscagglnt	3.02E-01	3	7248										
7	SBS	roughsbsviscbtlnt	1.40E-02	3	7248	-1.00E+00	-1.10E+00	-1.15E+00	-5.00E-02	-8.16E-02	-1.79E-02				
7	SBS	roughsbsviscbtlnt	2.98E-01	3	7248	-1.54E+00	-1.84E+00	-1.89E+00	-8.80E-02	-1.46E-01	2.73E-03				
7	SBS	roughsbsviscbtlnt	2.99E-01	3	7248	-1.55E+00	-1.83E+00	-1.92E+00	-8.79E-02	-1.45E-01	1.13E-02				
7	SBS	roughsbsviscbtlnt	3.08E-01	3	7248	-8.88E-01	-9.97E-01	-9.84E-01	-4.25E-02	-6.81E-02	-2.58E-02				
7	SBS	roughsbsviscbtlnt	3.15E-01	3	7248	-8.32E-05	-7.78E-05	-1.07E-04	-6.17E-06	-3.61E-06	1.91E-06				
7	SBS	roughsbsviscbtlnt	2.59E-01	3	7248							3.83E-02			-4.01E-01
7	SBS	roughsbsviscbtlnt	2.56E-01	3	7248							(ZX)	-2.15E+00	1.19E-01	XX
7	SBS	roughsbsviscbtlnt	3.02E-01	3	7248								(ZZ)	XX	
7	SBS	roughsbsviscbtlnt	3.05E-01	3	7248										

Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

RUN NO	RUN	DESCRIPTION	TIME	MAT	NODE	STRESS XX	STRESS YY	STRESS ZZ	SHEAR XY	SHEAR XZ	SHEAR YZ	STRESS (+MAX)	STRESS (-MAX)	STRAIN (+MAX)	STRAIN (-MAX)
8	SBS	roughsbsviscaggint	1.40E-02	3	7248	-1.00E+00	-1.10E+00	-1.15E+00	-5.00E-02	-8.16E-02	-1.82E-02				ZZ
8	SBS	roughsbsviscaggint	2.99E-01	3	7248	-1.54E+00	-1.64E+00	-1.89E+00	-8.77E-02	-1.46E-01	2.83E-03				ZZ
8	SBS	roughsbsviscaggint	2.99E-01	3	7248	-1.56E+00	-1.63E+00	-1.92E+00	-8.78E-02	-1.46E-01	1.11E-02				
8	SBS	roughsbsviscaggint	3.08E-01	3	7248	-8.89E-01	-9.97E-01	-9.83E-01	-4.25E-02	-6.81E-02	-2.62E-02				
8	SBS	roughsbsviscaggint	3.15E-01	3	7248	-6.08E-05	-6.43E-05	-7.69E-05	-4.79E-06	-4.86E-06	-1.52E-06				
8	SBS	roughsbsviscaggint	2.59E-01	3	7248							3.86E-02			
8	SBS	roughsbsviscaggint	2.66E-01	3	7248							(ZX)	-2.15E+00		
8	SBS	roughsbsviscaggint	3.02E-01	3	7248									1.19E-01	
8	SBS	roughsbsviscaggint	3.05E-01	3	7248								(ZZ)	XX	-4.02E-01
9	PEN	roundpenat10viscbit Int	1.40E-02	3	7248	-5.60E-01	-8.32E-01	-7.39E-01	-6.01E-02	-1.34E-01	7.02E-02				ZZ
9	PEN	roundpenat10viscbit Int	2.98E-01	3	7248	-1.23E+00	-1.35E+00	-1.73E+00	-1.27E-01	-3.65E-01	1.93E-01				
9	PEN	roundpenat10viscbit Int	2.98E-01	3	7248	-1.25E+00	-1.31E+00	-1.76E+00	-1.25E-01	-3.77E-01	2.14E-01				
9	PEN	roundpenat10viscbit Int	3.08E-01	3	7248	-4.33E-01	-5.10E-01	-5.51E-01	-5.16E-02	-8.57E-02	4.09E-02				
9	PEN	roundpenat10viscbit Int	3.15E-01	3	7248	7.32E-03	3.93E-03	1.93E-02	5.57E-03	2.65E-03	-1.38E-03				
9	PEN	roundpenat10viscbit Int	5.25E-02	3	7248							3.58E-01			
9	PEN	roundpenat10viscbit Int	2.56E-01	3	7248							(ZX)	-2.03E+00		
9	PEN	roundpenat10viscbit Int	3.02E-01	3	7248								(ZZ)	8.09E-02 XX	-9.38E-02
10	PEN	roundpenat50viscbit In	1.40E-02	3	7248	-9.03E-02	-1.03E-01	-1.17E-01	-7.54E-03	-2.19E-02	1.16E-02				ZZ
10	PEN	roundpenat50viscbit In	2.98E-01	3	7248	-1.52E-01	-1.69E-01	-2.28E-01	-1.85E-02	-5.47E-02	3.07E-02				
10	PEN	roundpenat50viscbit In	2.98E-01	3	7248	-1.74E-01	-1.79E-01	-2.30E-01	-1.08E-02	-4.74E-02	2.71E-02				
10	PEN	roundpenat50viscbit In	3.08E-01	3	7248	-7.39E-02	-8.83E-02	-9.17E-02	-6.24E-03	-1.53E-02	7.42E-03				
10	PEN	roundpenat50viscbit In	3.15E-01	3	7248	-4.82E-03	-4.80E-03	-2.61E-03	8.04E-04	9.66E-04	-7.46E-04				
10	PEN	roundpenat50viscbit In	5.25E-02	3	7248							4.09E-02			
10	PEN	roundpenat50viscbit In	8.75E-02	3	7248							YY	-2.78E-01		
10	PEN	roundpenat50viscbit In	3.09E-01	3	7248								(ZZ)	8.57E+00	
10	PEN	roundpenat50viscbit In	3.11E-01	3	7248									ZX	-1.32E+01
11	PEN	roughpenat10viscbl	1.40E-02	3	7248	-1.01E+00	-1.11E+00	-1.14E+00	-4.83E-02	-9.06E-02	-2.12E-02				YZ
11	PEN	roughpenat10viscbl	2.99E-01	3	7248	-1.54E+00	-1.62E+00	-1.91E+00	-9.50E-02	-1.52E-01	1.01E-02				
11	PEN	roughpenat10viscbl	2.98E-01	3	7248	-1.56E+00	-1.60E+00	-1.95E+00	-9.48E-02	-1.52E-01	1.81E-02				

RUN NO	RUN	DESCRIPTION	TIME	MAT	NODE	STRESS XX	STRESS YY	STRESS ZZ	SHEAR XY	SHEAR XZ	SHEAR YZ	STRESS (+MAX)	STRESS (-MAX)	STRAIN (+MAX)	STRAIN (-MAX)
11	PEN	roughpenat10viscbi	3.08E-01	3	7248	-8.89E-01	-1.01E+00	-9.75E-01	-4.07E-02	-8.72E-02	-2.92E-02				
11	PEN	roughpenat10viscbi	3.15E-01	3	7248	-2.45E-04	-1.78E-03	1.32E-03	1.51E-03	9.86E-04	-2.80E-04				
11	PEN	roughpenat10viscbi	1.75E-01	3	7248							4.18E-02			
11	PEN	roughpenat10viscbi	2.56E-01	3	7248							(ZX)	-2.18E+00		
11	PEN	roughpenat10viscbi	3.00E-01	3	7248								(ZZ)	1.11E-02	
11	PEN	roughpenat10viscbi	3.02E-01	3	7248									XX	-3.78E-02
12	PEN	roughpenat50viscbit in	1.40E-02	3	7248	-1.53E-01	-1.69E-01	-1.76E-01	-7.59E-03	-1.28E-02	-2.63E-03				ZZ
12	PEN	roughpenat50viscbit in	2.98E-01	3	7248	-2.18E-01	-2.33E-01	-2.77E-01	-1.60E-02	-2.17E-02	1.44E-04				
12	PEN	roughpenat50viscbit in	2.98E-01	3	7248	-2.28E-01	-2.35E-01	-2.77E-01	-1.01E-02	-2.03E-02	2.64E-03				
12	PEN	roughpenat50viscbit in	3.08E-01	3	7248	-1.39E-01	-1.57E-01	-1.65E-01	-8.63E-03	-1.11E-02	-3.88E-03				
12	PEN	roughpenat50viscbit in	3.15E-01	3	7248	-4.21E-03	-4.38E-03	-2.85E-03	5.65E-04	-6.30E-05	4.52E-05				
12	PEN	roughpenat50viscbit in	5.81E-02	3	7248							3.01E-02			
12	PEN	roughpenat50viscbit in	8.75E-02	3	7248							XX	-3.24E-01		
12	PEN	roughpenat50viscbit in	3.11E-01	3	7248								(ZZ)	1.57E+00	
12	PEN	roughpenat50viscbit in	3.09E-01	3	7248									XX	-5.31E+00
13	PEN	roundpenviscbitinili g	1.40E-02	3	7248	-1.39E-01	-1.55E-01	-1.82E-01	-1.29E-02	-3.51E-02	1.98E-02				ZZ
13	PEN	roundpenviscbitinili	2.98E-01	3	7248	-2.64E-01	-2.90E-01	-3.64E-01	-2.21E-02	-7.87E-02	4.31E-02				
13	PEN	roundpenviscbitinili g	2.98E-01	3	7248	-2.71E-01	-2.87E-01	-3.77E-01	-2.31E-02	-8.31E-02	4.71E-02				
13	PEN	roundpenviscbitinili g	3.08E-01	3	7248	-1.07E-01	-1.23E-01	-1.34E-01	-1.08E-02	-2.32E-02	1.25E-02				
13	PEN	roundpenviscbitinili	3.15E-01	3	7248	-2.57E-03	-2.45E-03	-3.29E-03	-2.69E-04	-5.74E-04	3.72E-04				
13	PEN	roundpenviscbitinili	3.05E-01	3	7248							6.06E-02			
13	PEN	roundpenviscbitinili g	8.82E-02	3	7248							YY	-4.36E-01		
13	PEN	roundpenviscbitinili	3.03E-01	3	7248								(ZZ)	1.75E-01	
13	PEN	roundpenviscbitinili g	3.02E-01	3	7248									ZX	-2.69E-01
14	SBS	roundsbsviscbitint	1.40E-02	3	7248	-1.42E-01	-1.60E-01	-1.84E-01	-1.29E-02	-3.49E-02	1.91E-02				YZ
14	SBS	roundsbsviscbitint	2.98E-01	3	7248	-2.79E-01	-3.07E-01	-3.85E-01	-2.33E-02	-8.36E-02	4.59E-02				
14	SBS	roundsbsviscbitint	2.98E-01	3	7248	-2.86E-01	-3.04E-01	-3.98E-01	-2.44E-02	-8.84E-02	5.02E-02				
14	SBS	roundsbsviscbitint	3.08E-01	3	7248	-1.10E-01	-1.29E-01	-1.36E-01	-1.06E-02	-2.29E-02	1.19E-02				

Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

RUN NO	RUN	DESCRIPTION	TIME	MAT	NODE	STRESS XX	STRESS YY	STRESS ZZ	SHEAR XY	SHEAR XZ	SHEAR YZ	STRESS (+MAX)	STRESS (-MAX)	STRAIN (+MAX)	STRAIN (-MAX)
14	SBS	roundsbsviscbitint	3.15E-01	3	7248	-5.70E-05	-7.49E-05	-2.51E-05	9.44E-06	2.56E-05	-1.51E-05				
14	SBS	roundsbsviscbitint	3.05E-01	3	7248							7.06E-02		1.61E-01	
14	SBS	roundsbsviscbitint	2.56E-01	3	7248							YY	-4.60E-01	ZX	YZ
14	SBS	roundsbsviscbitint	2.67E-01	3	7248								(ZZ)		-2.48E-01

ANNEXURE C

TO CHAPTER 5

DISPLACEMENTS

RUN NO	RUN	DESCRIPTION	TIME	NODE	DISPLACEMENT X	DISPLACEMENT Y	DISPLACEMENT Z
1	PEN	roundpenviscbitint	1.40E-02	7245	1.42E+00	-4.51E-01	4.51E-01
1	PEN	roundpenviscbitint	2.98E-01	7245	2.44E+00	3.28E-02	9.73E-01
1	PEN	roundpenviscbitint	2.98E-01	7245	2.56E+00	1.99E-01	1.06E+00
1	PEN	roundpenviscbitint	3.08E-01	7245	3.56E+00	-1.59E+00	9.82E-01
1	PEN	roundpenviscbitint	3.15E-01	7245	2.89E+00	-9.09E-01	8.70E-01
2	PEN	roundpenviscaggint	1.40E-02	7245	1.42E+00	-4.51E-01	4.51E-01
2	PEN	roundpenviscaggint	2.98E-01	7245	2.56E+00	1.99E-01	1.06E+00
2	PEN	roundpenviscaggint	2.99E-01	7245	2.68E+00	3.75E-01	1.16E+00
2	PEN	roundpenviscaggint	3.08E-01	7245	3.56E+00	-1.59E+00	9.82E-01
2	PEN	roundpenviscaggint	3.15E-01	7245	2.89E+00	-9.09E-01	8.70E-01
3	SBS	roundsbsviscbitint	1.40E-02	7245	9.03E-01	1.89E-01	4.20E-01
3	SBS	roundsbsviscbitint	2.98E-01	7245	2.70E+00	-2.31E-01	9.99E-01
3	SBS	roundsbsviscbitint	2.98E-01	7245	2.74E+00	-1.62E-01	1.03E+00
3	SBS	roundsbsviscbitint	3.08E-01	7245	3.30E+00	-7.02E-01	1.12E+00
3	SBS	roundsbsviscbitint	3.15E-01	7245	3.21E+00	-7.73E-01	1.05E+00
4	SBS	roundsbsviscaggint	1.40E-02	7245	9.03E-01	1.90E-01	4.19E-01
4	SBS	roundsbsviscaggint	2.98E-01	7245	2.70E+00	-2.31E-01	9.97E-01
4	SBS	roundsbsviscaggint	2.98E-01	7245	2.74E+00	-1.63E-01	1.03E+00
4	SBS	roundsbsviscaggint	3.08E-01	7245	3.30E+00	-7.01E-01	1.12E+00
4	SBS	roundsbsviscaggint	3.15E-01	7245	3.21E+00	-7.73E-01	1.05E+00
5	PEN	roughpenviscbitint	1.40E-02	7245	1.20E+00	-3.84E-01	3.39E-01
5	PEN	roughpenviscbitint	2.98E-01	7245	2.06E+00	4.53E-02	7.11E-01
5	PEN	roughpenviscbitint	2.98E-01	7245	2.17E+00	1.92E-01	7.74E-01
5	PEN	roughpenviscbitint	3.08E-01	7245	3.00E+00	-1.38E+00	7.56E-01
5	PEN	roughpenviscbitint	3.15E-01	7245	2.44E+00	-7.81E-01	6.66E-01
6	PEN	roughpenviscaggint	1.40E-02	7245	1.20E+00	-3.85E-01	3.40E-01
6	PEN	roughpenviscaggint	2.98E-01	7245	2.06E+00	4.47E-02	7.11E-01
6	PEN	roughpenviscaggint	2.98E-01	7245	2.17E+00	1.92E-01	7.74E-01
6	PEN	roughpenviscaggint	3.08E-01	7245	3.00E+00	-1.38E+00	7.57E-01
6	PEN	roughpenviscaggint	3.15E-01	7245	2.44E+00	-7.81E-01	6.66E-01
7	SBS	roughsbsviscbitint	1.40E-02	7245	7.65E-01	1.76E-01	3.01E-01
7	SBS	roughsbsviscbitint	2.98E-01	7245	2.29E+00	-1.84E-01	7.40E-01
7	SBS	roughsbsviscbitint	2.98E-01	7245	2.32E+00	-1.23E-01	7.63E-01
7	SBS	roughsbsviscbitint	3.08E-01	7245	2.79E+00	-5.93E-01	8.39E-01
7	SBS	roughsbsviscbitint	3.15E-01	7245	2.71E+00	-6.59E-01	7.91E-01
8	SBS	roughsbsviscaggint	1.40E-02	7245	7.64E-01	1.76E-01	3.02E-01
8	SBS	roughsbsviscaggint	2.98E-01	7245	2.29E+00	-1.85E-01	7.40E-01
8	SBS	roughsbsviscaggint	2.98E-01	7245	2.32E+00	-1.24E-01	7.63E-01
8	SBS	roughsbsviscaggint	3.08E-01	7245	2.79E+00	-5.94E-01	8.40E-01
8	SBS	roughsbsviscaggint	3.15E-01	7245	2.71E+00	-6.59E-01	7.91E-01
9	PEN	roundpenat10viscbitint	1.40E-02	7245	5.84E-02	1.47E-03	2.45E-02
9	PEN	roundpenat10viscbitint	2.98E-01	7245	2.74E-01	-1.55E-02	1.04E-01
9	PEN	roundpenat10viscbitint	2.98E-01	7245	2.76E-01	-9.34E-03	1.07E-01
9	PEN	roundpenat10viscbitint	3.08E-01	7245	3.10E-01	-6.61E-02	1.05E-01
9	PEN	roundpenat10viscbitint	3.15E-01	7245	3.00E-01	-5.57E-02	1.02E-01
10	PEN	roundpenat50viscbitin	1.40E-02	7245	5.21E+00	1.18E+00	2.44E+00
10	PEN	roundpenat50viscbitin	2.98E-01	7245	3.97E+01	-3.72E+00	1.45E+01

RUN NO	RUN	DESCRIPTION	TIME	NODE	DISPLACEMENT X	DISPLACEMENT Y	DISPLACEMENT Z
10	PEN	roundpenat50viscbitin	2.98E-01	7245	4.00E+01	-3.33E+00	1.48E+01
10	PEN	roundpenat50viscbitin	3.08E-01	7245	4.42E+01	-6.53E+00	1.56E+01
10	PEN	roundpenat50viscbitin	3.15E-01	7245	4.45E+01	-7.02E+00	1.56E+01
11	PEN	roughpenat10viscbi	1.40E-02	7245	4.95E-02	2.13E-03	1.68E-02
11	PEN	roughpenat10viscbi	2.98E-01	7245	2.31E-01	-1.16E-02	7.65E-02
11	PEN	roughpenat10viscbi	2.98E-01	7245	2.34E-01	-6.19E-03	7.85E-02
11	PEN	roughpenat10viscbi	3.08E-01	7245	2.62E-01	-5.56E-02	7.75E-02
11	PEN	roughpenat10viscbi	3.15E-01	7245	2.53E-01	-4.67E-02	7.64E-02
12	PEN	roughpenat50viscbitin	1.40E-02	7245	4.41E+00	1.09E+00	1.76E+00
12	PEN	roughpenat50viscbitin	2.98E-01	7245	3.35E+01	-2.99E+00	1.08E+01
12	PEN	roughpenat50viscbitin	2.98E-01	7245	3.38E+01	-2.64E+00	1.10E+01
12	PEN	roughpenat50viscbitin	3.08E-01	7245	3.73E+01	-5.43E+00	1.17E+01
12	PEN	roughpenat50viscbitin	3.15E-01	7245	3.76E+01	-5.86E+00	1.16E+01
13	PEN	roundpenviscbitintlig	1.40E-02	7245	3.55E-01	-1.13E-01	1.13E-01
13	PEN	roundpenviscbitintlig	2.98E-01	7245	6.06E-01	8.84E-03	2.42E-01
13	PEN	roundpenviscbitintlig	2.98E-01	7245	6.37E-01	5.02E-02	2.65E-01
13	PEN	roundpenviscbitintlig	3.08E-01	7245	8.84E-01	-3.96E-01	2.44E-01
13	PEN	roundpenviscbitintlig	3.15E-01	7245	7.18E-01	-2.26E-01	2.16E-01
14	SBS	roundsbsviscbitint	1.40E-02	7245	2.26E-01	4.74E-02	1.05E-01
14	SBS	roundsbsviscbitint	2.98E-01	7245	6.76E-01	-5.77E-02	2.50E-01
14	SBS	roundsbsviscbitint	2.98E-01	7245	6.86E-01	-4.06E-02	2.58E-01
14	SBS	roundsbsviscbitint	3.08E-01	7245	8.25E-01	-1.75E-01	2.80E-01
14	SBS	roundsbsviscbitint	3.15E-01	7245	8.03E-01	-1.93E-01	2.62E-01

RUN NO	RUN	DESCRIPTION	TIME	NODE	DISPLACEMENT X	DISPLACEMENT Y	DISPLACEMENT Z
1	PEN	roundpenviscbitint	1.40E-02	8606	2.01E+00	-5.34E-01	8.43E-01
1	PEN	roundpenviscbitint	2.98E-01	8606	3.49E+00	5.79E-02	1.42E+00
1	PEN	roundpenviscbitint	2.98E-01	8606	3.66E+00	2.54E-01	1.49E+00
1	PEN	roundpenviscbitint	3.08E-01	8606	5.03E+00	-1.89E+00	2.09E+00
1	PEN	roundpenviscbitint	3.15E-01	8606	4.06E+00	-1.09E+00	1.66E+00
2	PEN	roundpenviscaggint	1.40E-02	8606	2.01E+00	-5.33E-01	8.42E-01
2	PEN	roundpenviscaggint	2.98E-01	8606	3.49E+00	5.72E-02	1.42E+00
2	PEN	roundpenviscaggint	2.98E-01	8606	3.66E+00	2.54E-01	1.49E+00
2	PEN	roundpenviscaggint	3.08E-01	8606	5.03E+00	-1.89E+00	2.08E+00
2	PEN	roundpenviscaggint	3.15E-01	8606	4.06E+00	-1.09E+00	1.66E+00
3	SBS	roundsbsviscbitint	1.40E-02	8606	1.29E+00	2.31E-01	5.40E-01
3	SBS	roundsbsviscbitint	2.98E-01	8606	3.83E+00	-2.68E-01	1.57E+00
3	SBS	roundsbsviscbitint	2.98E-01	8606	3.89E+00	-1.87E-01	1.59E+00
3	SBS	roundsbsviscbitint	3.08E-01	8606	4.67E+00	-8.29E-01	1.94E+00
3	SBS	roundsbsviscbitint	3.15E-01	8606	4.53E+00	-9.21E-01	1.86E+00
4	SBS	roundsbsviscaggint	1.40E-02	8606	1.29E+00	2.31E-01	5.38E-01
4	SBS	roundsbsviscaggint	2.98E-01	8606	3.83E+00	-2.69E-01	1.57E+00
4	SBS	roundsbsviscaggint	2.98E-01	8606	3.89E+00	-1.87E-01	1.59E+00
4	SBS	roundsbsviscaggint	3.08E-01	8606	4.67E+00	-8.28E-01	1.93E+00
4	SBS	roundsbsviscaggint	3.15E-01	8606	4.53E+00	-9.21E-01	1.86E+00
5	PEN	roughpenviscbitint	1.40E-02	8606	1.70E+00	-4.38E-01	6.38E-01
5	PEN	roughpenviscbitint	2.98E-01	8606	2.95E+00	6.85E-02	1.08E+00
5	PEN	roughpenviscbitint	2.98E-01	8606	3.10E+00	2.37E-01	1.13E+00
5	PEN	roughpenviscbitint	3.08E-01	8606	4.24E+00	-1.57E+00	1.58E+00
5	PEN	roughpenviscbitint	3.15E-01	8606	3.43E+00	-8.90E-01	1.26E+00
6	PEN	roughpenviscaggint	1.40E-02	8606	1.70E+00	-4.37E-01	6.37E-01
6	PEN	roughpenviscaggint	2.98E-01	8606	2.95E+00	6.85E-02	1.08E+00
6	PEN	roughpenviscaggint	2.98E-01	8606	3.10E+00	2.37E-01	1.13E+00
6	PEN	roughpenviscaggint	3.08E-01	8606	4.24E+00	-1.56E+00	1.58E+00
6	PEN	roughpenviscaggint	3.15E-01	8606	3.43E+00	-8.90E-01	1.26E+00
7	SBS	roughsbsviscbitint	1.40E-02	8606	1.09E+00	2.05E-01	4.09E-01
7	SBS	roughsbsviscbitint	2.98E-01	8606	3.24E+00	-2.01E-01	1.19E+00
7	SBS	roughsbsviscbitint	2.98E-01	8606	3.29E+00	-1.31E-01	1.21E+00
7	SBS	roughsbsviscbitint	3.08E-01	8606	3.95E+00	-6.70E-01	1.47E+00
7	SBS	roughsbsviscbitint	3.15E-01	8606	3.82E+00	-7.47E-01	1.41E+00
8	SBS	roughsbsviscaggint	1.40E-02	8606	1.09E+00	2.06E-01	4.08E-01
8	SBS	roughsbsviscaggint	2.98E-01	8606	3.24E+00	-2.01E-01	1.19E+00
8	SBS	roughsbsviscaggint	2.98E-01	8606	3.29E+00	-1.31E-01	1.21E+00
8	SBS	roughsbsviscaggint	3.08E-01	8606	3.95E+00	-6.69E-01	1.47E+00
8	SBS	roughsbsviscaggint	3.15E-01	8606	3.82E+00	-7.47E-01	1.41E+00
9	PEN	roundpenat10viscbitint	1.40E-02	8606	8.34E-02	1.68E-03	3.58E-02
9	PEN	roundpenat10viscbitint	2.98E-01	8606	3.87E-01	-1.77E-02	1.60E-01
9	PEN	roundpenat10viscbitint	2.98E-01	8606	3.91E-01	-1.03E-02	1.62E-01
9	PEN	roundpenat10viscbitint	3.08E-01	8606	4.39E-01	-7.89E-02	1.82E-01
9	PEN	roundpenat10viscbitint	3.15E-01	8606	4.23E-01	-6.62E-02	1.74E-01
10	PEN	roundpenat50viscbitin	1.40E-02	8606	7.45E+00	1.44E+00	3.10E+00

RUN NO	RUN	DESCRIPTION	TIME	NODE	DISPLACEMENT X	DISPLACEMENT Y	DISPLACEMENT Z
10	PEN	roundpenat50viscbitin	2.98E-01	8606	5.61E+01	-4.37E+00	2.31E+01
10	PEN	roundpenat50viscbitin	2.98E-01	8606	5.65E+01	-3.91E+00	2.32E+01
10	PEN	roundpenat50viscbitin	3.08E-01	8606	6.24E+01	-7.72E+00	2.58E+01
10	PEN	roundpenat50viscbitin	3.15E-01	8606	6.28E+01	-8.34E+00	2.59E+01
11	PEN	roughpenat10viscbi	1.40E-02	8606	7.10E-02	1.98E-03	2.68E-02
11	PEN	roughpenat10viscbi	2.98E-01	8606	3.28E-01	-1.24E-02	1.21E-01
11	PEN	roughpenat10viscbi	2.98E-01	8606	3.31E-01	-6.11E-03	1.22E-01
11	PEN	roughpenat10viscbi	3.08E-01	8606	3.71E-01	-6.37E-02	1.38E-01
11	PEN	roughpenat10viscbi	3.15E-01	8606	3.58E-01	-5.32E-02	1.32E-01
12	PEN	roughpenat50viscbitin	1.40E-02	8606	6.31E+00	1.27E+00	2.35E+00
12	PEN	roughpenat50viscbitin	2.98E-01	8606	4.74E+01	-3.30E+00	1.75E+01
12	PEN	roughpenat50viscbitin	2.98E-01	8606	4.78E+01	-2.90E+00	1.76E+01
12	PEN	roughpenat50viscbitin	3.08E-01	8606	5.28E+01	-6.09E+00	1.95E+01
12	PEN	roughpenat50viscbitin	3.15E-01	8606	5.31E+01	-6.61E+00	1.96E+01
13	PEN	roundpenviscbitintlig	1.40E-02	8606	5.03E-01	-1.34E-01	2.11E-01
13	PEN	roundpenviscbitintlig	2.98E-01	8606	8.66E-01	1.52E-02	3.53E-01
13	PEN	roundpenviscbitintlig	2.98E-01	8606	9.10E-01	6.43E-02	3.71E-01
13	PEN	roundpenviscbitintlig	3.08E-01	8606	1.25E+00	-4.71E-01	5.19E-01
13	PEN	roundpenviscbitintlig	3.15E-01	8606	1.01E+00	-2.70E-01	4.13E-01
14	SBS	roundsbsviscbitint	1.40E-02	8606	3.23E-01	5.77E-02	1.35E-01
14	SBS	roundsbsviscbitint	2.98E-01	8606	9.57E-01	-6.71E-02	3.93E-01
14	SBS	roundsbsviscbitint	2.98E-01	8606	9.71E-01	-4.66E-02	3.98E-01
14	SBS	roundsbsviscbitint	3.08E-01	8606	1.17E+00	-2.07E-01	4.84E-01
14	SBS	roundsbsviscbitint	3.15E-01	8606	1.13E+00	-2.30E-01	4.66E-01

RUN NO	RUN	DESCRIPTION	TIME	NODE	DISPLACEMENT X	DISPLACEMENT Y	DISPLACEMENT Z
1	PEN	roundpenviscbitint	1.40E-02	4975	1.05E+00	-3.95E-01	8.43E-01
1	PEN	roundpenviscbitint	2.98E-01	4975	1.83E+00	3.42E-02	1.42E+00
1	PEN	roundpenviscbitint	2.98E-01	4975	1.92E+00	1.80E-01	1.49E+00
1	PEN	roundpenviscbitint	3.08E-01	4975	2.64E+00	-1.40E+00	2.09E+00
1	PEN	roundpenviscbitint	3.15E-01	4975	2.13E+00	-8.03E-01	1.66E+00
2	PEN	roundpenviscbitint	1.40E-02	4975	1.05E+00	-3.95E-01	8.41E-01
2	PEN	roundpenviscbitint	2.98E-01	4975	1.83E+00	3.41E-02	1.42E+00
2	PEN	roundpenviscbitint	2.98E-01	4975	1.92E+00	1.79E-01	1.49E+00
2	PEN	roundpenviscbitint	3.08E-01	4975	2.64E+00	-1.40E+00	2.08E+00
2	PEN	roundpenviscbitint	3.15E-01	4975	2.13E+00	-8.03E-01	1.66E+00
3	SBS	roundsbsviscbitint	1.40E-02	4975	6.77E-01	1.69E-01	5.40E-01
3	SBS	roundsbsviscbitint	2.98E-01	4975	2.01E+00	-2.02E-01	1.57E+00
3	SBS	roundsbsviscbitint	2.98E-01	4975	2.04E+00	-1.42E-01	1.59E+00
3	SBS	roundsbsviscbitint	3.08E-01	4975	2.45E+00	-6.17E-01	1.93E+00
3	SBS	roundsbsviscbitint	3.15E-01	4975	2.38E+00	-6.82E-01	1.86E+00
4	SBS	roundsbsviscaggint	1.40E-02	4975	6.77E-01	1.69E-01	5.38E-01
4	SBS	roundsbsviscaggint	2.98E-01	4975	2.01E+00	-2.02E-01	1.57E+00
4	SBS	roundsbsviscaggint	2.98E-01	4975	2.04E+00	-1.42E-01	1.59E+00
4	SBS	roundsbsviscaggint	3.08E-01	4975	2.45E+00	-6.16E-01	1.93E+00
4	SBS	roundsbsviscaggint	3.15E-01	4975	2.38E+00	-6.82E-01	1.86E+00
5	PEN	roughpenviscbitint.	1.40E-02	4975	8.63E-01	-3.41E-01	6.38E-01
5	PEN	roughpenviscbitint.	2.98E-01	4978	1.51E+00	5.26E-02	1.08E+00
5	PEN	roughpenviscbitint.	2.98E-01	4978	1.59E+00	1.84E-01	1.13E+00
5	PEN	roughpenviscbitint.	3.08E-01	4978	2.16E+00	-1.23E+00	1.58E+00
5	PEN	roughpenviscbitint.	3.15E-01	4978	1.75E+00	-7.02E-01	1.26E+00
6	PEN	roughpenviscaggint.	1.40E-02	4975	8.64E-01	-3.42E-01	6.37E-01
6	PEN	roughpenviscaggint.	2.98E-01	4975	1.51E+00	5.19E-02	1.08E+00
6	PEN	roughpenviscaggint.	2.98E-01	4975	1.59E+00	1.84E-01	1.13E+00
6	PEN	roughpenviscaggint.	3.08E-01	4975	2.16E+00	-1.23E+00	1.58E+00
6	PEN	roughpenviscaggint.	3.15E-01	4975	1.75E+00	-7.02E-01	1.26E+00
7	SBS	roughsbsviscbitint.	1.40E-02	4975	5.58E-01	1.64E-01	4.09E-01
7	SBS	roughsbsviscbitint.	2.98E-01	4978	1.66E+00	-1.59E-01	1.19E+00
7	SBS	roughsbsviscbitint.	2.98E-01	4978	1.68E+00	-1.04E-01	1.21E+00
7	SBS	roughsbsviscbitint.	3.08E-01	4978	2.01E+00	-5.26E-01	1.47E+00
7	SBS	roughsbsviscbitint.	3.15E-01	4978	1.95E+00	-5.89E-01	1.41E+00
8	SBS	roughsbsviscaggint.	1.40E-02	4975	5.59E-01	1.63E-01	4.08E-01
8	SBS	roughsbsviscaggint.	2.98E-01	4978	1.66E+00	-1.59E-01	1.19E+00
8	SBS	roughsbsviscaggint.	2.98E-01	4978	1.68E+00	-1.05E-01	1.21E+00
8	SBS	roughsbsviscaggint.	3.08E-01	4978	2.01E+00	-5.27E-01	1.46E+00
8	SBS	roughsbsviscaggint.	3.15E-01	4978	1.95E+00	-5.89E-01	1.41E+00
9	PEN	roundpenat10viscbitint	1.40E-02	4975	4.34E-02	1.54E-03	3.55E-02
9	PEN	roundpenat10viscbitint	2.98E-01	4978	2.03E-01	-1.37E-02	1.57E-01
9	PEN	roundpenat10viscbitint	2.98E-01	4978	2.05E-01	-8.39E-03	1.59E-01
9	PEN	roundpenat10viscbitint	3.08E-01	4978	2.30E-01	-5.79E-02	1.79E-01
9	PEN	roundpenat10viscbitint	3.15E-01	4978	2.22E-01	-4.91E-02	1.74E-01
10	PEN	roundpenat50viscbitin	1.40E-02	4975	3.91E+00	1.05E+00	3.10E+00

RUN NO	RUN	DESCRIPTION	TIME	NODE	DISPLACEMENT X	DISPLACEMENT Y	DISPLACEMENT Z
10	PEN	roundpenat50viscbitin	2.98E-01	4975	2.94E+01	-3.27E+00	2.31E+01
10	PEN	roundpenat50viscbitin	2.98E-01	4975	2.97E+01	-2.93E+00	2.32E+01
10	PEN	roundpenat50viscbitin	3.08E-01	4975	3.28E+01	-5.75E+00	2.58E+01
10	PEN	roundpenat50viscbitin	3.15E-01	4975	3.30E+01	-6.19E+00	2.59E+01
11	PEN	roughpenat10viscbi	1.40E-02	4975	3.54E-02	2.51E-03	2.65E-02
11	PEN	roughpenat10viscbi	2.98E-01	4975	1.67E-01	-9.94E-03	1.21E-01
11	PEN	roughpenat10viscbi	2.98E-01	4975	1.69E-01	-5.09E-03	1.22E-01
11	PEN	roughpenat10viscbi	3.08E-01	4975	1.88E-01	-4.89E-02	1.37E-01
11	PEN	roughpenat10viscbi	3.15E-01	4975	1.82E-01	-4.13E-02	1.32E-01
12	PEN	roughpenat50viscbitin	1.40E-02	4975	3.23E+00	1.01E+00	2.35E+00
12	PEN	roughpenat50viscbitin	2.98E-01	4975	2.42E+01	-2.61E+00	1.75E+01
12	PEN	roughpenat50viscbitin	2.98E-01	4975	2.44E+01	-2.29E+00	1.76E+01
12	PEN	roughpenat50viscbitin	3.08E-01	4975	2.70E+01	-4.80E+00	1.95E+01
12	PEN	roughpenat50viscbitin	3.15E-01	4975	2.71E+01	-5.21E+00	1.96E+01
13	PEN	roundpenviscbitintlig	1.40E-02	4975	2.63E-01	-9.87E-02	2.11E-01
13	PEN	roundpenviscbitintlig	2.98E-01	4975	4.55E-01	9.13E-03	3.53E-01
13	PEN	roundpenviscbitintlig	2.98E-01	4975	4.77E-01	4.54E-02	3.70E-01
13	PEN	roundpenviscbitintlig	3.08E-01	4975	6.56E-01	-3.49E-01	5.19E-01
13	PEN	roundpenviscbitintlig	3.15E-01	4975	5.29E-01	-2.00E-01	4.13E-01
14	SBS	roundsbsviscbitint	1.40E-02	4975	1.69E-01	4.23E-02	1.35E-01
14	SBS	roundsbsviscbitint	2.98E-01	4975	5.02E-01	-5.05E-02	3.93E-01
14	SBS	roundsbsviscbitint	2.98E-01	4975	5.10E-01	-3.54E-02	3.98E-01
14	SBS	roundsbsviscbitint	3.08E-01	4975	6.13E-01	-1.54E-01	4.84E-01
14	SBS	roundsbsviscbitint	3.15E-01	4975	5.94E-01	-1.71E-01	4.66E-01

6. SYNTHESIS

This project has seen the development of two aids towards assessing the comparative performance of bitumen and modified bitumen seal binders: the performance testing, and the prototype numerical model. Both aids have indicated that the comparative performance of different seal types can be made for differing materials, traffic, pavement and environmental conditions. In this chapter the findings of the two research methods are consolidated, for synthesis of the two modelling disciplines (performance and numerical) and to allow validation of the functioning of the numerical model.

6.1 CONSOLIDATION OF COMMON PRIORITISATED SEAL INFLUENCES

From consideration of Chapter 3 (specifically Tables 3.3 and 3.4), and Chapters 4 and 5, a summary of the critical parameters examined for each of the research components, the performance tests and prototype numerical model are provided. Table 6.1 has been compiled as a means of facilitating consolidation of the two streams of the research project.

Table 6.1: Consolidation of Prioritised Seal Influences as Examined

Prioritised Influence (ref Table 3.3)	Effect of Influence Examined	
	Performance Tests	Prototype Numerical Model
▓▓▓▓▓▓▓▓▓▓▓▓	√	√
▓▓▓▓▓▓▓▓▓▓▓▓	√	
▓▓▓▓▓▓▓▓▓▓▓▓		√
Temperature (of binder)	√	√
Pavement condition/substrate	√	
Moisture/climate	√	
Voids in seal		
Curing/hardening/ageing/adhesion	√	
Interlock		
Traffic type		√
Geometry (gradient)		

In terms of the objective of the project: "Towards a performance based seal design method", the performance criteria examined by the two models are summarised in Table 6.2.

Table 6.2: Consolidation of Examined Common Seal Performance Criteria

Seal Performance Criteria		Effect of Influence Examined	
		Performance Model	Prototype Numerical Model
Deformation	- rotation	√	√ (X, Y)
	- punching	√	√ (limited: Z)
Cracking	- fatigue/cohesive		√
	- brittle	•	Mohr type – future project
Adhesion		√	Interface – future project

• No cracking evident

The respective Chapters (4 and 5) discuss the research findings. When looking to consolidation, and to verify the common items to each of the influences and performance criteria examined, the performance model and prototype numerical model are as given in Table 6.3 below.

Table 6.3: Common Parameters: Performance Tests and Prototype Numerical Model

Type of Parameter	Parameter	
Failure criteria	Deformation	- rotation
		- punching
Influencing parameter	▓▓▓▓▓▓▓▓▓▓▓▓▓▓▓▓	
	Temperature of binder	

Using the above common items, validation of the prototype numerical model behaviour will be discussed.

6.2 VALIDATION OF FUNCTIONALITY THROUGH COMMON PERFORMANCE RATINGS

Validation of functionality in the scope of this project is the "establishment of correctness of the seal model behaviour by examination or demonstration". As such, in terms of the above definition, validation of the prototype numerical seal model will be made by

examination of the common parameters measured by both performance tests and prototype numerical model.

6.2.1 Trends

As indicated in Chapter 5, the prototype numerical model has been developed using available material parameters and behaviour models, and the FEM mesh is being developed for future work outside of the project to accommodate a base layer to support the seal. Validation of the mode behaviour will be undertaken in terms of assessing the ability of the prototype numerical model to indicate seal behaviour **trends** as demonstrated under the performance tests, and not in terms of absolute numbers or values.

The performance parameters thus used is:
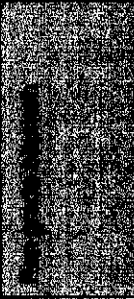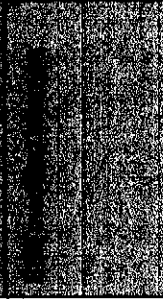
Deformation (in the X axis as this is the axis of maximum displacement under the current prototype numerical model)

The variables to be used for the verification are:

Binder type   -   pen grade bitumen and 3 % SBS modified binder

Temperature   -   in the ranges 10 °C, 25 °C, 50 °C

The validation data is summarized in Table 6.4 using results from Section 5.9 and 5.5

Table 6.4: Validation of Prototype Numerical Model by Examination of Performance Test Results

Influence	Factor	Failure Criteria: Displacement	
		Performance Testing (ref Chapter 4, Annexure A)	Prototype Numerical Model (ref Chapter 5)
Temperature with pen grade binder	10 °C	Less embedment Less rotation	Displacement (X) 10 x smaller than at 25 °C
	25 °C	Slight stone loss More rotation than at 10 °C, on average Less rotation than 50 °C (X and Y)	Displacement 10 x less than at 50 °C, 10 x more than at 10 °C
	50 °C	Slightly more rotation (Y)* More embedment than 10 °C (Z)	Displacements x 10 larger than 25 °C, no elastic recovery after wheel pass in relaxation period
Binder type @ 25 °C		More rotation towards ALD (X or Y) Similar embedment as SBS modified binder	Displacement larger in X direction (Figure 5.36 (a)) than SBS. Only immediate elastic recovery after last truck passes. No further recovery after rest period.
		Less rotation to ALD than pen grade bitumen Similar embedment as pen grade bitumen	Displacements (X) slightly less than (Figure 5.36 (b)) pen grade bitumen, but much higher ultimate visco-elastic recovery (to ± 50 % of max displacement after rest period after 4th truck)

* (X displacement excessive due to geometric instability)

From Table 6.4 the trends reflected by each component, the performance test and prototype numerical model, show that for the failure examined (i.e. displacement) the prototype numerical model performed as demonstrated under the performance tests. Due to the differing geometry of the road seal and mesh and the limitations of available materials parameters, statistical assessment is not possible. The model is verified in terms of examination of trends.

The prototype numerical model and new seal performance test are thus proposed as the basis for assessment trial towards a performance related road seal design method.

6.2.2 Value Ranges

In order to determine value ranges in the prototype numerical model for differing behaviour, the above trend examination is extended.

From 6.1.1 numerical model value ranges will be validated through the common performance criteria. The criteria examined are:

- Rotation (using X and Y displacement) (direction of travel)

- Punching (using Z displacement)

The influencing parameters examined in common are:

- Binder type

- Temperature

Table 6.5: Synthesis of Test Results: FEM Value Ranges

Run	Binder	Temperature	Punching	Rotation	
			Performance Test Rating (0 – good; 3-worst)	**Performance Test Rating (0 – good; 3-worst)**	
			Model U_Z	Model U_X	U_Y
1	Pen	25 °C	0 – 1	0 – 3	
			1,42 mm	3,44 mm	-0,46 mm
3	SBS	25 °C	0 – 1	0 – 1	
			1,13 mm	2,75 mm	-0,553 mm
9	Pen	10 °C	0	0	
			0,147 mm	0,357 mm	-0,056 mm
10	Pen	50 °C	1	3	
			25,9 mm*	62,8 mm*	-8,34 mm*

* Model geometrically unstable in these conditions, but trend is valid.

Note:

(1)   Model displacement at end of rest period (from Figures 5.41, 5.43, 5.44 and 5.45).

(2)   Performance test results from Annexure A to Chapter 4.

By using this protocol, comparative assessment of different binders can be made using the numerical behavioural model, and the displacement ranges for good – bad performance.

6.3   SYNTHESIS OF PERFORMANCE ASSESSMENT AND PREDICTION

The performance criteria to which seal behaviour are to be assessed has been discussed in Chapter 3, summarised in Figure 3.1. In terms of direct comparison between the experimental performance testing, where the modelled seals were constructed and tested in an environment simulating that of a full scale service environment (i.e. the real thing), and the numerical behavioural model, the numerical model would have to be complete and simulate all aspects of reality.

This project has initiated the prototype numerical behavioural model, that under the project constraints, the development protocol was focussed on the critical aspects: model FEM framework (seal mesh), and the most critical controllable factors: stone (geometry), and bitumen, and the critical non-controllable factors: traffic and environment (temperature).

Synthesis of the overall results of each of the models types should thus be undertaken in terms of **trends**, where induction of the success of the numerical nodes performance can be judged when compared against the performance tests. Figure 6.1 reflects this process.

The trends displayed by the performance testing and numerical behavioural models are the same for the areas of common examination. In terms of synthesis, through the two types of performance modelling it is possible for the designer to obtain an assessment of the performance of each seal **design** or type by using both tools, as all influencing factors can be examined, and performance assessed, even at this prototype stage of numerical modelling.

Figure 6.6: Synthesis of Seal Performance Modelling

Influencing factors	SINGLE SEAL				Numerical behavioural model	Perfor-mance testing
	Performance criteria					
	Deformation	Cracking	Adhesion	Aggregate (crushing)		

- Deformation decreased as stone got rougher (less round)

- Adhesion increased with modification

- With increased binder flushing increased

- With increased binder adhesion increased in moisture
- Adhesion reduced with adding of moisture
- With increased temperature, crushing increased as stones were able to rotate against each other

- No cracking observed or calculated

Influencing factors

Non-controllable
- Environmental
  - Moisture
  - Temperature
- Traffic

Performance testing and numerical behavioural model

- Modified binders improve performance in terms of reducing deformation at same service temperatures
- Deformation increases for same binder types as traffic increases
- Deformation increases for same binder types as temperature increases

REFERENCES

Committee of State Road Authorities, CSRA, 1998, *Technical Recommendations for Highways 3 Surfacing Seals for Rural and Urban Roads and Compendium of Design Methods for Surfacing Seals using in RSA*, Department of Transport, RSA.

7. CONCLUSION AND RECOMMENDATIONS

This project has as its stated aim contributed to the development of a performance related seal design method for bitumen and modified seal binders. To achieve the objectives, the project was undertaken in five phases, as summarised in Figure 1.2.

Phase 1, the literature review, was undertaken to provide the foundation of knowledge from which to launch the research process. During this phase the factors influencing the seal and seal surfaces performance were examined. The status quo of seal design methods was assessed, and the basis of current seal design determined.

Phase 2 was the needs assessment, and determination of influencing factors that had to be considered in the performance test protocols and numerical model development, and the critical parameters the seal performance and model behaviour would be assessed against.

Phase 3 was the development of the experimental design for the performance testing and model research methods, and Phase 4 the actual performance testing and development of the numerical behavioural model.

Phase 5 is the synthesis of the two modelling types (performance testing and numerical modelling) and the conclusion of the research project including recommendations for further research.

7.1 THE OVERALL CONCLUDING REMARKS

In Chapter 3, the performance criteria for seal performance examination were determined, as were the influencing factors on seal performance. In Chapter 4 the performance testing was reported. Arising from these chapters, the overall concluding remarks in context of the total project are:

- The defining function of the seal: To provide a durable, skid resistant surface, to protect the pavement layer from the abrasive traffic faces and to provide a waterproof cover, was fulfilled by the seals investigated in the performance tests.

- The modification of binders was shown to improve performance, both in the cold and hot extremes, and in moisture. However, at average service conditions (i.e. ambient temperature, moisture, traffic) straight binders also performed well.

- Each binder type has unique performance characteristics, and the different binders perform differently in each service environment. Designers should select a specific binder for a specific functional need or service environment.

- Assumptions such as the "mat behaviour" of the modified binders, and ability of seal stone to resist rotation or punching in modified binders, should be carefully examined under each service condition during the design process. The empirical assumption that modified binders allow increased binder application rate, should be examined, especially for hot service environments.

- The MMLS3 based seal performance testing provides a tool where each unique seal can be assessed in a modelled service environment to provide greater confidence when using the current empirical, volumetric based seal design methods.

Chapter 5 reported the development of a numerical behaviour model of seal performance. The model relied on the further development of the CAPA FEM program. The ability of FEM to model seals at micro-mechanic level was demonstrated, and a functioning prototype model (validated within available parameters) was developed. The benefits of the model are summarised as:

- Enabling desktop assessment of comparative seal performance for different seal designs and service environments.

- Creating awareness of the limits of our current knowledge in terms of transfer of the load onto a textured seal surface, and in terms of the damage incurred by heavy vehicles in relation to elv's.

- Provides insight into the effect of different binder types on the performance criteria, and assessing the effect of better service performance in terms of added demands to the binder on modified binders.

- Identification of failure mechanisms and the performance behaviour of the seal, at micro-mechanic level.

7.2   TOWARDS A PERFORMANCE RELATED SEAL DESIGN METHOD

The contribution of this project to the Science of Engineering is towards a performance related seal design method in two aspects:

- The development of a new performance test protocol for road seals.

   The development and implementation of the MMLS3 based seal performance test provides value to the practitioner in the terms of an additional design tool. Using this tool enables the behaviour of different road seals to be assessed in the field or laboratory, prior to construction.

The MMLS3 based test is also available for assessment of the contribution of the seal in terms of pavement serviceable life (where the effect of different seal types can be examined in terms of protection of the base layer).

A supplementary seal performance test method was developed using the Hamburg type wheel tracker, as an additional seal assessment tool.

The different seal types were assessed in terms of performance, and a performance based ranking system using visual assessment techniques was developed. The influences (external and controllable) were assessed, and an "expert" system developed where the sensitivity of each seal system to the influences can be assessed by the designer.

- The development of a seal numerical behavioural prototype model.

The numerical method FEM model was developed as a foundation for further research and refinement, and use in practice as a future design tool. The model is able to differentiate in terms of behaviour between the different binder types and temperature regimes, and load application.

In addition, the development process has enabled identification and ratification of the unknowns and assumptions relating to seal behaviour and empirical design, especially in the macro-micro conversion of loads and material parameters.

The complexity and magnitude of imposed stresses on the seal, and the assessment of the effect of rolling and driven wheels and tyre imposed forces, has highlighted the reaction of the different seal types under load. The model has also given insight in to the actual behaviour and reaction of seals at micro-mechanic level (i.e. reaction of the individual seal stone and its binder) under traffic.

The synthesis of performance testing and numerical model has enabled functional validation assessment of the processes, and provided applied scientific tools for further development by academic research and practical applications.

7.3   RECOMMENDED FURTHER RESEARCH

7.3.1   Seal Performance Modelling

From the assessment of seal performance, the design guide and findings, the following research is recommended:

- Further MMLS3 testing focusing on the aspects that will enhance validation of the future developments of the numerical model:

  o Seal aggregate applied with no contact between stones (this seal design will in effect not be used in practice, but the stone and binder behaviour will assist in the validation of the numerical model behaviour).

  o Utilising the enhanced capacity of the MMLS3 to include the moisture regime (careful consideration of the base behaviour when wet, will have to be made when assessing only the seal reaction). Consideration of the development of an equivalency factor for "wet axles" and the inclusion of this in the assessment of design life is recommended.

  o Testing of the seal on different base types, with different wheel loads and tyre pressures, to provide insight in to the determination of heavy-to-light vehicle factoring, for refinement of the design assumptions (currently the TRH3 design code assumes a factor 40 to 1 heavy to light vehicle).

  o Further consideration of the effect of volume of binder as compared with actual binder characteristics, when examining the different seal type's performance.

- Further examination on different base types (softness) of the assumed "mat behaviour" of the modified binders especially above softening point ($T_{R\&B}$).

- Examination of cracking of the binder.

- Examination of the inclusion of an MMLS3 based performance test protocol in the seal design code.

- Further development of the Texture Indication Meter, with possible application in industry.

7.3.2 Numerical Model

Due to the fact that the prototype numerical seal model has only now been initiated, there still remains research regarding the refinement of the model:

- Specific bitumen material parameters (enhancing the current Burgers model visco-elastic parameters).

- The addition of a base material that allows plastic deformation (to enable seal stone embedment), and a base mesh that accommodates seating of the stone in the

mesh. The addition of the base would also address the geometric instability of the seal at high binder temperatures.

- The modeling of punching, cracking, and the examination of the heavy vehicle to elv equivalency factor and transfer functions.

- Further examination of the load functions of a rolling wheel on a textured surface

- The function and role of the interface to allow assessment of the possibility of stripping, stone loss.

- Further assessment in a Materials Testing System of fatigue relationships for cracking, and the determination of the adhesive yield stress for stone loss.

- Assessment and determination of algorithms and numerical behaviour models to allow for the computation of permanent deformation damage in both binder and base.

- Effect of interlock between stones, and the numerical mechanisms of modelling friction due to contact.

- The inclusion of shear (including turning and braking behaviour) on the modelled wheel load functions.

Through the examination of the above research areas, the further movement towards a performance related seal design method would be enhanced.

7.3.3 Seal Design Concepts

Arising from the research, there are concepts that require further consideration:

- The concept or terminology of "voids" in the seal could be reconsidered. The concept of "Texture" or texture depth should perhaps be the evolution of Hanson's basing seal design on "voids". It is postulated that voids refer to unfilled volumes between or in the seal binder and aggregate, below the surface of the seal binder.

- Further awareness of the need to examine design traffic determination, from the possibilities of estimating the number and damage of "wet" axles, to the vehicle equivalency and transfer functions (heavy to elv).

- Further enhancing the design of seals in consideration of the unique benefits of each of the binder types for traffic and environmental conditions.

- Utilisation of theavailable research tools (MMLS3, Numerical FEM modeling) to enhance the current empirical design methods.

LIST OF APPENDICES

LIST OF FIGURES

LIST OF TABLES

APPENDIX A

SUPPORTING LITERATURE AND ANALYSIS

A1   INTRODUCTION

Through the course of this project, supporting literature was examined to contribute to a deeper understanding of the specific seal components, the seal's behaviour and its role in the road industry.

The supporting literature summation and analysis of aspects of subjects not directly focused on the development of the performance testing, or prototype numerical seal model, yet of relevance to the overall understanding of the subject, are provided under this appendix, both for completeness and ease of reference production,

A2   BINDER: BITUMEN

A2.1   SCOPE

Supplementary information that may enhance the general understanding of the behaviour of bitumen is provided under this section.

A2.2   PRODUCTION OF BITUMEN

The production methods affect the fractioning and behaviour of bitumen, and as such are of importance to understanding the behaviour of the different binder types.

A2.2.1   Source of Bitumen

Bitumen occurs naturally ("native bitumen") in many parts of the world, but the majority are small deposits, and are primarily of local significance. The most widely used native bitumen (generally referred to as asphaltite) has been named *gilsonite*, and is in a fairly pure state. The largest deposit of gilsonite occurs in Utah, United States (Hoiberg, 1965). Other native bitumens are *manjak*, occurring in the West Indies, Cuba, Mexico, USA, Argentina, Columbia, Israel, Esthonia and Germany, and *grahamite*.

Less pure deposits contain a high proportion of pure bitumen, but also a proportion of mineral matter. Predominant in this group is the Trinidad "pitch lake", discovered in 1595 by Sir Walter Raleigh. From 1878 (Marais, 1979) this Trinidad Lake asphalt was utilised as an asphalt, where the asphalt was cut into blocks, with water and excess organic material being removed. This process left solid asphalt with approximately 52 % bitumen, 39 % mineral matter, and 9 % insoluble organic matter. This material was softened using different fluxes (themselves usually residual products from the distillation of crude

petroleum). Other sources of note are the deposits of Kentucky, Alberta, Albania and Dutch East Indies.

The largest source of bitumen, for worldwide use, is the residue of the refining process of crude oils. Crude oil is a fossil fuel that originated from early time when marine organisms died and their organic remains accumulated on ocean and lake floors and were covered with inorganic sediments. Over time and under pressure, they were condensed to form a complex combination of organic components, resulting in the product today referred to as crude oil. These crude oils are sourced from the many oil fields around the world, including those found in the Americas, Atlantic Ocean, North Sea, Middle East and Asia.

The source of South African crude oils are governed by economics, and depend on availability of ships and the respective shipping routes, distance from the crude source and the going price of the crude oils (i.e. supply and demand). South African refineries source the crude oils from the Middle East, due primarily to the major shipping routes being clockwise through the Mediterranean and Suez Canal, making the Middle East a cheaper source than the Americas, and typically use the following crudes:

- Saudi Arabia: Arabian Light

  Arabian Medium

  Arabian Heavy

- Dubai

- Iranian Heavy

- Kuwait

Bitumen is a by-product of the petroleum industry, 85 % of which is used as a road paving or surfacing material. Few refineries produce bitumen as a principal product. Different crudes produce bitumen with different characteristics, further improved or altered by the refining or blending process. Dedicated bitumen runs at the refineries with a constant source of crude oil are the optimum. But it should also be considered that crude's are exploited from a natural source, and quality and characteristics may vary even for the same oil field. The chemical nature of a crude oil depends on the organic matter it originates from, as well as the environment (e.g. saline or sweet water). The more mature the oil the lighter it becomes, due to the separation of the heavy part (the extreme is the natural gas above coal layers). The lighter crude's are also found in the deeper structures, and the heavier crude's closer to the surface. Generally, the heavier the crude, the more refining it requires. In summary, bitumen is derived from the residue of the crude oil

refining process, and the characteristics and composition of the bitumen depend not only on the crude oil, but also on the refining process.

A2.2.2 Crude Oils for Bitumen

Bitumen is a natural constituent of a large number of crude oils (Hoiberg, 1965). Different crudes contain varying proportions of bitumen. Crude oils are classified in three broad groups: heavy, medium, and light (referring in part to the molecular type of the components and to the volume of "white product" (gas, diesel, petrol, etc.) yield). A further method of classification is the suitability of crudes for bitumen manufacture, by type of residue from vacuum distillation. Waxy, paraffinic or naphthenic are the classifications. Waxy crudes are temperature susceptible, while naphthenic crudes are suitable for emulsion production. Heavy metal content (which can affect certain catalytic processes), the amount and type of asphaltenes (influences stiffness of bitumen) and waxes (affect adhesion and temperature susceptibility) also determine crude suitability. Generally, the heavy asphaltic (aromatic) crude oils are high in residue, asphaltene and sulphur content. These oils are most suited to bitumen production. Of the 1500 crude oils known, only some 250 fulfil the requirements of adequate residue yield, and the primary residue properties which are of bitumen potential. The available current processing and specification requirements to be satisfied reduce the suitable sources of crude to between 15 and 20. Crude's may themselves be blended or blown to improve the properties, prior to refining.

A2.2.3 Crude Oil Refineries in South Africa

Four refineries are situated in the Republic:

- Caltex Refinery (CALREF) – Cape Town
- Engen Refinery (ENREF) – Durban.
- National Petroleum Refinery of South Africa (NATREF) – Sasolburg (Sasol & Total)
- South African Petroleum Refinery (SAPREF) – Durban (Shell & BP)

These refineries provide the fuel needs of the Republic, and also produce the bitumen for the Industry.

A2.2.4   Manufacture of Bitumen
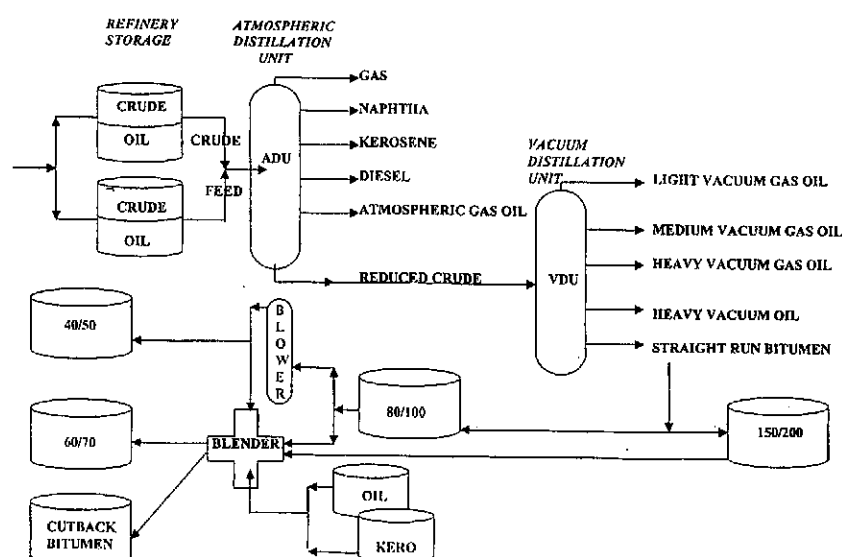
Figure A2.1: Distillation Process (SABITA, 1998)

The process of manufacture of bitumen from the petroleum oils (Hoiberg, 1965) is illustrated in Figure A2.1. The proportion of bitumen to other fuel products varies per crude oil. Bitumen is essentially one of the products of the refining process of crude oil. Crude oils were originally refined by distillation using batch stills, where large amounts of steam aided the vaporization or distillation of the more volatile components (Hoiberg, 1965). The distillation process is the primary means of separating crude petroleum, with bitumen being the highest boiling fraction. When bitumen base crudes were produced in this manner, they became known as "steam reduced" bitumen. As more efficient means of distillation were introduced, "straight run" and "straight reduced" bitumen became more commonly produced. These bitumens were separated in the refining process in a manner preserving its inherent properties, not being affected by cracking or oxidation, as occurs in the other processes. Figure A2.1 illustrates the process. The manufacturing process can be varied, depending on the grade or type of bitumen required. These are:

- Atmospheric distillation (lighter "white" products: gas, diesel, petrol, etc)

- Vacuum distillation (softer "straight run" bitumen: e.g. 150/200 and 80/100 penetration grades)

- Bitumen blowing (harder bitumen: e.g. 40/50 penetration grades)

- Blending of the different bitumen produced from the processes is also used to produce the desired characteristics: e.g. 60/70 penetration grades and cutbacks)

The bitumen produced in the refinery (Whiteoak, 1991) can be divided into three basic types:

- Penetration bitumen

    This is road bitumen, with penetration ranging from 15 to 500.

- Hard bitumen

    This bitumen is specified by softening point (identified by the letter K), and is virtually only manufactured by blowing. Due to its high viscosity and low temperature susceptibility, is applied in industrial applications.

- Performance and viscosity grade bitumens

    From the blending process, the following binders are produced:

- Cut binders

    Blending of penetration grade bitumen with a volatile oil (e.g. kerosene).

- Bitumen emulsions

    Two phase system of bitumen and water.

- Modified binders

    The distillation process is initiated at temperatures between 300 °C to 350 °C. This is the limit beyond which thermal cracking takes place, if sustained at temperatures in excess of these limits. By varying the distillation conditions such as vacuum and temperature, bitumen with different properties are produced.

    The air-blowing is a process through which a bitumen stock is converted at temperature ranging from 400°C to 550°C to a product of modified properties through contact with air. In this process dehydrogenation and polymerization occur. Oxygen is not added to the bitumen product but is a catalyst. The blowing of bitumen decreases penetration and increases softening point due to the hardening of the bitumen.

    Cracked bitumen occurs under high temperatures and pressures, and is characterised by high specific gravity, low viscosity, and poor temperature

susceptibility. In the cracking process decomposition takes place forming both lighter and heavier products, and an amount of carbon. This process is seldom used in the refining process.

Blending of bitumen stocks is common practice, where bitumen of intermediate properties displayed by the stocks is required.

Robertson *et al* (c.1990) examined the chemical properties of bitumen and their relationship to performance, to assist in enabling the selection of appropriate crudes and blends in order to obtain the desired properties in the product bitumens. They further maintain that since composition is the variable most readily altered, the formulation of composition – physical property relationships would be expected to serve as indications of modifications that will benefit the crude oil and bitumens that achieve sufficient characteristics. This would then allow the use of a wide variety of crude oils for manufacture of performance – specified bitumens.

A2.2.5 Classification of Crudes used for Bitumen Production

Crude oils are classified by:

- Heaviness — Light crude's have a distillate/residue ratio > 1

    Heavy crude's have a distillate/residue ratio < 1

    (Distillate boils below 350 °C, residue boils above 350 °C)

- Sulphur content — sweet crude's have sulphur content <1 % by mass

    Sour crude's have sulphur content >1 % wt

- Broad Chemical Type — paraffinic (waxy) from lighter crudes

    — Naphthenic (asphaltic) from heavier crudes (asphaltenes have a naphthenic structure: unsaturated and saturated ring structures)

    — Mixed base bitumen (including aromatic crudes)

Naphthenic and aromatic crude's contain large amounts of bitumen, and are low in wax (these are preferred) (see Table A2.1 for further description of bitumen fractions).

Older crudes (i.e. deeper in the earth's layers) are lighter, due to separation of the heavier part (e.g. ultimately as described above, as gas above a coal field). Lighter crudes

(paraffinic) are not suitable for bitumen production as a residue is required from the refining process.

A2.3 CHEMISTRY AND COMPOSITION OF BITUMEN

Bitumen is a complex compound, and as it is manufactured from different oil sources, the chemistry and composition varies between sources and processes. Understanding the chemistry and composition, and the behaviour of the different chemical fractions or constituents, will enable assessment of the potential behaviour of the bitumen, and of its performance, predicted and measured.

Robertson *et al* (c.1990) emphasize that the chemistry of bitumen can be considered at two levels: at *molecular level* and *inter molecular level*. At molecular level petroleum bitumen is a complex mixture of organic molecules that range in size from molecular weights of a few hundred to several thousand. These molecules also range from no polarity to highly polar or polarisable. At intermolecular level the different molecular types exhibit behavioural characteristics ranging from the **polar** molecules that organize through association interactions into networks or **matrices** forming the **dispersed phase** of the bitumen (imparting the **elastic**/spring like behaviour to the bitumen) to the less polar and **non-polar** portions that provide the **dispersing phase** of the bitumen (contributing to the **viscous** behaviour to the bitumen). The associations or matrices of the dispersed phase interact with each other by weak intermolecular bonds (polarization bonds – strength 3 to 10 Kcal/mole) while the discrete molecules are held together by covalent bonds of up to 80 Kcal/mole strength. The integrity of the matrix thus determines the bitumen behaviour. This also indicates that any change in bitumen behaviour as a result of the disturbance on the bonds between and within the matrices is not as a result of the change of molecular composition of the bitumen. The understanding of the behaviour of the dispersed phase (the matrices with the intermolecular bonds between the matrices), and with the establishment of the ratio between the quantity of dispersed phase to dispersing phase (the gel) will enable correlation between the chemistry of bitumen and its physical properties. Robertson *et al* report that the integrity of the matrices to a large measure rules the physical behaviour of the bitumen.

A2.3.1   Elementary Composition

A2.3.1.1 Basic Constituents

Bitumen is primarily a hydrocarbon compound. The chemical elements always present in highest amounts in bitumen are carbon and hydrogen, usually amounting to over 90 % of bitumen (Green, 1999). Bitumen is typically comprised mainly of:

Carbon   82 – 88 % by mass

Hydrogen   8 – 11 % by mass

Sulphur   0 –6 % by mass

Oxygen   0 – 1,5 %

Nitrogen   0 – 1 %

Metals   - Traces of Vanadium, Nickel, Iron, Magnesium, etc.

The hydrocarbons, with ratios carbon to hydrogen, are the major influence on the chemical make up and behaviour of the bitumen. The basic paraffinic structure of C_nH_{2n+2} being the benchmark ratio. Nitrogen and sulphur also have influence on the behaviour of the bitumen, while the small amounts of metals have minor influence on the properties of bitumen. Bitumen consists of compounds that have reached chemical equilibrium, and is a relatively inert product under atmospheric conditions.

A2.3.1.2 Composition and Behaviour of Organic Compounds

Due to bitumen being comprised primarily of hydro-carbons, and thus falling into the organic compound family, the composition of, and the primary reaction mechanisms (or basic processes) that dictate the behaviour of organic molecules, are discussed below to enable better understanding of the behaviour of bitumen.

Within the Periodic Table, Carbon is a member of period 2 (two shells of electrons), Group IV (four electrons in the outer shell, of the eight required to fill the shell: electrons in atoms are located in energy levels called orbitals, designated in order of increasing energy as s, p, d, and f). A characteristic of the Group IV atoms is their readiness in forming covalent bonding between each atom – to share the four electrons in their outer shells with other atoms in the striving for the lowest energy state. In such a manner chains, coiled structures, rings and plates are formed with the atoms, as the covalent bonding occurs between the atom and the neighbouring atoms. Due to the Group IV atoms requiring four atoms to fill the outer shell, covalent bonds may be formed with up to four carbon atoms in

a regular tetrahedron (the diamond structure). These bonds acquire directional properties, and three dimensional structures as indicated above are formed.

Carbon has the ability to exist in two different crystalline forms (graphite and diamond). This is termed polymorphism (or allotropy). This characteristic is demonstrated not only by molecules, but also by polymers. Polymers can also be found in glassy or more crystalline states, depending on the appropriate physical or chemical treatments.

Polymers have as a repeat unit an aggregate of atoms (monomers), whose replication in the form of long chain molecules is achieved predominantly through directed covalent bonding (Rosenthal, 1971). The properties of bitumen, as with other polymers, are dependant on: the bond between the atoms in the repeat unit, between the repeat units in the chain molecules, and between the chains within the bulk aggregate material. The *monomer* is the molecule that makes up the *polymer repeat unit that* in turn makes up the *chain* of the polymer. An example is: monomer ethylene (C_2H_4) becomes polymer polyethylene (-C-C-), with the –C-C- chains forming the basis of PE (with the replacement of one of the four H atoms in the monomer with Cl, polymer PVC is formed).

Temperature rise causes agitation of the elementary particles, ultimately destroying the stability of the molecular arrangement, converting the solid into liquid. Should the agitation be sufficient, cohesion will be destroyed, resulting in the formation of a gas.

Oxidation in polymer materials alters the properties of the material. The oxidation rate is limited by the rate at which the chemical reaction can take place. At high temperatures oxidation proceeds at a faster rate.

Five types of reaction with relevance to the chemistry of organic materials are described:

- *Substitution:* where an atom or group of molecules is substituted on the hydro-carbon molecule with a different atom or group.

- *Addition:* an atom, ion or group is added to the molecule.

- *Elimination:* an ion or group is removed from the molecule.

- *Oxidation:* any chemical change where there is an increase in the oxidation number. This results from a shift of electrons, due to their being pulled to another atom. The atom from which electrons are attracted is oxidised (the atom to which the electrons are attracted is said to be reduced). Oxidation and *reduction* always occur together, and compensate each other. The oxidizing agent does the oxidising (and is

reduced in the process). The loss of electrons by an atom in *any* chemical reaction is called oxidation, and the gain of electrons by an atom in any chemical reaction is called reduction. The oxidation number (or oxidation state) is the charge an atom has, or appears to have when combined with other atoms (e.g. the oxidation number of Na^+ is +1).

- *Rearrangement:* rearrangement of the hydrocarbon chain (to ring, etc.)

Where the valences (the number of shared electron pair bonds formed by a given atom is referred to as the valence) of the carbon atoms (Carbon is tetravalent) are not saturated, the compound/atom is said to be *unsaturated* (saturated valences are engaged in single bonds between other atoms, as opposed to the double bonds between neighbouring atoms). The unsaturated valences are in part responsible for the reactivity of the unsaturated hydrocarbons.

Aromaticity is properties of rings composed of Π (pi) bonds (the weak bonds between shared p orbital electron and stronger σ s-orbital electrons), empty orbitals or unshared pairs of electrons.

Hydrocarbon component atoms bond together through covalent (sharing of electrons) bonds. Due to the differing bond angles between atoms, the geometrical arrangement of the molecules can lead to polar molecules. Hydrocarbons thus exhibit polar and non-polar characteristics, depending on the molecule's geometry. Of note is that atoms forming chains, and being able to propagate themselves, must be able to form a covalent bond with an atom of its own kind, and at least three other covalent bonds, with other elements of its own kind. It is this characteristic that Carbon displays, and also leads to the variation in chemical composition and behaviour between the various fractions of bitumen.

Classification: Organic compounds are classified by their carbon skeleton as follows:

- Aliphatic: carbon atoms linked together in open chain structure. The chains may have branches, but no loops.

- Alicyclic: the carbon atoms are arranged in a ring structure.

- Aromatic: these atoms all have a ring structure of six carbon atoms, with alternating single and double bonds (and are all related to that of benzene: C_6H_6).

- Heterocyclic: these cyclic molecules include atoms such as oxygen, nitrogen, sulphur and others as part of the ring structure.

Classification also takes place on the basis of the functional groups. Examples of the terminology of these are:

- Alkanes: two carbon atoms, single bond between them

- Alkenes: two carbon atoms, double bond between them

- Alkynes: two carbon atoms, triple bond between them

- Alcohols: -OH

Figure A2.2 has been compiled from study of the various literature sources, and summarises the effect of molecular structure on behaviour of bitumen.
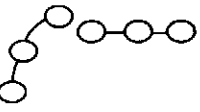
Phase	Property Imparted	Bonds	Compounds	Molecular Structure	Desired Proportion (by mass) (Robertson, ref 61)
Dispersed phase	Elasticity E	Covalent (∩) intra-molecular (share electrons) Polar (• • •) inter-molecular	Organics 88 % max carbon (period 2 – 2 shells of electrons) Group IV – 4 é in outer shell)	Basic: C_nH_{2n+2} (paraffinic) Aliphatic or paraffinic, (atoms in open chain), saturated structure	85 %
Dispersing phase (GEL)	Viscosity ν	Covalent intra-molecular Weak polar inter-molecular Van der Waals forces between molecules	1,5 % max oxygen % max hydrogen 1 % max nitrogen % max sulphur traces of metals	Alicyclic, asphaltenes, also referred to as naphtenic, saturated and unsaturated ring structure Aromatic – ring of 6 atoms always ring of alternating double and single bonds between C atoms	15 %

Figure A2.2: Influence of Bitumen Molecular Structure on Behaviour

General terms associated with hydrocarbons, and at times used to describe bitumen composition or behaviour is:

- Acids: any substance containing hydrogen in combination with a non-metal or non-metallic radical and capable of providing hydrogen ions in solution.

- Base: a material which neutralizes acids.

A2.3.2   Bitumen Composition by Fractionation

Fractionation of bitumen has been used for a variety of purposes, from research to manufacture, to enable the definition, description, and evaluation of bitumen and the prediction of performance. A major objective is to identify the different compounds making up the bitumen to determine chemical reactivity, which will in turn indicate the steps required or modify the bitumen for utilization. There are two types of fractionation:

- Physical separation – using techniques such as boiling range, filtration, settling, distillation and crystallisation.

- Chemical separation – using chemical properties, precipitation of components by chemical reagents, conversion to derivatives and subsequent splitting off of compounds formed.

Macroscopically, bitumens are physically homogeneous materials, with a number of common characteristics and properties, independent of their origin. Chemically, however they are heterogeneous mixtures of chemical compounds. Due to the complexity and range of different molecules in bitumen, chemists have preferred to characterise bitumen based on reactivity and/or polarity of the various molecular types, and not by the separate molecules. Also, the determination of relationships between rheological properties and molecules would be impossible. There is a generally accepted method of determining fractional composition of bitumen, with separation into asphaltenes and maltenes (maltenes being further divided into resins and oils).

Van de Ven *et al* (1999) summarise the various methods of separating bitumen into the generic functionally related groups of compounds. These methods are based on chemical precipitation, adsorption chromatography and size exclusion.

Acid precipitation is a destructive method of chemically separating the maltene fraction after initial precipitation of the n-pentane insoluble asphaltenes.

Liquid chromatography (High Pressure Liquid Chromatography – HPLC) is a non-destructive method where adsorbtion-desorbtion techniques are used to allow the recovery of the various fractions for discrete testing. Chromatography is the method of separating substances in a mixture (in this case bitumen) using different absorbents to take up different constituents of the mixture, that these certain solvents do not mix, and will be separated in layers one over the other. The results present the separated fractions in bands in a vertical tube.

Size exclusion chromatography – SEC- indicates similarities between molecular size and functionality. This method has already leaded to suggestion that molecular size and polarity are related.
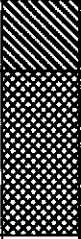
A2.3.2.1 Fraction Descriptions

The following descriptions are provided for use in discussing the different fractions of bitumen (Hoiberg, 1965):

- *Asphaltenes* – the fraction of bitumen insoluble in low-boiling hydro-carbons, e.g. pentane.

- *Maltenes* – fraction soluble in low-boiling saturated hydro-carbons (have relatively high boiling point).

- *Petrolene* - fraction soluble in low-boiling saturated hydro-carbons (have relatively low boiling point).

- *Bituminous resins* – soluble in low-boiling saturated hydro-carbons e.g. pentane, with high temperature susceptibility (glass-like behaviour at low temperatures, low viscosity at high temperature).

- *Bituminous oils* - soluble in low-boiling saturated hydro-carbons e.g. pentane, with low temperature susceptibility (little change in viscosity with temperature).

Table A2.1 provides a summary of the separation methods of the bitumen fractions.

Table 2.1: Definitions of Bitumen Fractions using n-Pentane

Fraction			Sub-fraction	Sub-fraction behaviour	
Petrolenes		Pentane soluble			Low boiling point
Maltenes			Oils	Low temperature Susceptibility	High boiling point
			Resins	High temperature Susceptibility	
Asphaltenes		Pentane insoluble			

A2.3.2.2 Broad Groups of Bitumen

Hoiberg (1965) proposed a general diagram of fractionation, further extrapolated by using O'Donnell and Corbet's methods:
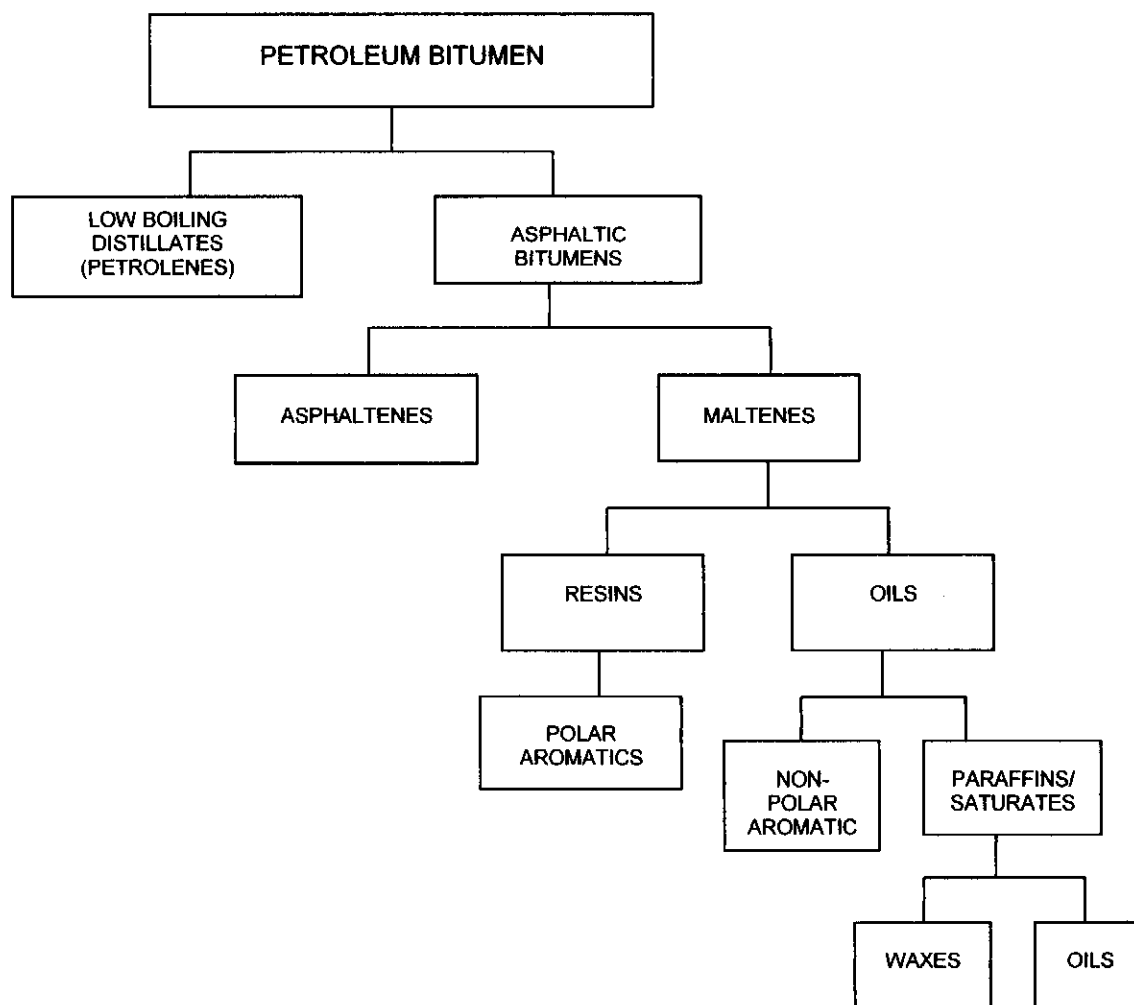
Figure A2.3: Fractions and Broad Groups of Bitumen

The alternative method of fractionation, that of O'Donnell, fractions the Maltenes further into:

Maltenes:

Saturates* ⟶ waxes ⟶ pariffins ⟶
            ⟶ oils   wax

*(single bonds (4 of) between C atoms)

Hoiberg: "Oils" including non-polar aromatics and waxes

Aromatics** ⟶ monocyclic aromatics

**(ring structure) ⟶ dicyclic aromatics

Hoiberg: "Resins"/polar aromatics
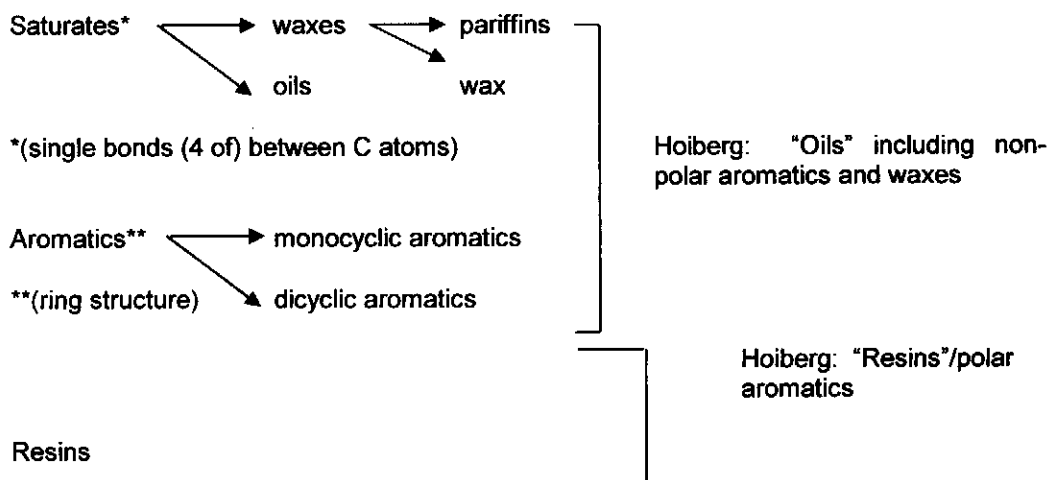
Resins

The Corbet fractionation scheme fractions the Maltenes as follows:

- Saturates (Aliphatics) – chains, single bonds, no loops, **no double bonds**

- Aromatics – 6 C-atom ring structure (Naphthene Aromatics)

- Resins (Polar Aromatics)

Thus according to the Hoiberg method, "oils" thus include the saturates (paraffins/ saturates) and non-polar aromatics ("aromatic oils").

Using the above fractioning methods, a four-component system is identified: **asphaltenes** and the **maltenes**: fractioned further into **resins, aromatics** (non-polar) and **saturates**. When combining the polar (resins) and non-polar aromatics, and referring to the saturates (as opposed to non-saturates with double bonds) as paraffins (chain of single bond between carbon atoms), three fractions are identified: **asphaltenes, paraffins** (saturates) and **aromatics** (non-polar and the polar resins).

The distinction between oils and resins is their temperature susceptibility (with oils having low susceptibility and resins high susceptibility, ref table A2.2).

Expanding on the above:

- Asphaltenes (the precipitate when bitumen is dissolved in pentane) are **cyclic** 3-dimensional "napthenic" (saturated and unsaturated ring structures), and comprise 5 – 25 % of the bitumen. These materials are very **polar**, dark black in colour, are

hard, with large molecules, and make bitumen harder and more viscous due to high density (rather than their polarity).

- Maltenes (soluble in pentane) are comprised of:

    - Saturates (paraffins): These are "white" oils, molecular mass of 300 to 1500. The Aliphatics are 3-dimensional chain-like **straight** or **branched** hydrocarbon chains and paraffinic (i.e. saturated) cyclic structures, and comprise 5 – 20 % of bitumen.

    - Aromatics: These aromatic oils have molecular mass 300 to 2000, and are **flat stacks** of **non-polar rings**, are dark brown viscous liquids, and comprise 40 – 60 % of bitumen.

    - Resins: These polar aromatics have molecular mass 500 to 50,000, are **very polar** solid or semi-solid, strongly adhesive due to their polarity. They are of stacked ring structure.

Apart from the many methods of fractionation based on the basic groups (Asphaltenes, paraffins, aromatics, resins) there is a further method that is noted here: that of Rostler-Sternberg. This method resolves bitumen into five broad bands of distinct chemical reactivity measurable by response to cold sulphuric acid of increasing strength (SO_3 concentration) (Hoiberg, 1965). These fractions are: asphaltenes (n-pentane), nitrogen bases, 1st acidaffins, 2nd acidaffins, and paraffins.

A2.3.2.3 Types of Molecular Structure within the Bitumen Fractions

Hoiberg (1965) noted that bitumen has been, and still is, seen as a low cost engineering material, and not as a chemical source, prompting that this is the reason little research has been undertaken to determine the chemistry of bitumen. Research has been aimed at the identification of the fractions of bitumen, rather than the determination of chemical structures of the material; added to this is the variability and complexity of bitumen.

As indicated previously, bitumen consists of, in terms of organic chemistry, mixtures of hydrocarbons and hydrocarbon derivatives. Investigation has revealed that in the elementary hydrocarbon structures, some of the carbon atoms have been replaced by

nitrogen, sulphur and oxygen, and some of the hydrogen atoms by nitrogen, oxygen and sulphur containing groups of linkages. Possible configurations are thus infinite.

Intermolecular forces between the hydrocarbon molecules are:

- Van der Waal's forces, between neutral non-polar molecules

- polarization forces

- electron forces

Bitumen can be described as a highly concentrated solution of a large number of solid solutes (asphaltenes, amorphous resins) in an oily medium (aromatic oils (non-polar resins), paraffins/saturates). This is termed a metastable state, with the molecules being randomly distributed at high temperatures, and **on cooling no crystallization** of the solute occurs. Robertson *et al* (c.1990) reiterate that bitumen consists of the dispersed phase (the *solid* polar matrices of asphaltenes and polar aromatic resins) and the *gel* of the less polar dispersing phase (aromatic oils/non-polar aromatics). The ratio of dispersing phase (maximum desired to reduce susceptibility to deformation) to dispersed phase is 85 % by mass provide an indication of durability expected by the bitumens, and its exhibited visco-elastic behaviour.

Waterman's ring analysis (Hoiberg, 1965), defines the fractions into three values:

- C_A: carbon atoms in aromatic rings (*resins and non-polar aromatics*)

- C_N: naphthenic rings (referred to also as cyclic) (*asphaltenes*)

- C_P: paraffins (referred to also as aliphatic) (*saturates*)

Types of molecular structure are:

- Aliphatics

   Linear or chain like molecules, with carbon atoms linked end to end. Also called *paraffinic,* or oily.

- Cyclics

   Simple, or complex, saturated or unsaturated ring structures. Also called *naphthenic.*

- **Aromatics**

Stable, unsaturated six atom rings, flat in shape. They can closely stack.

- **Phases**

  - GEL phase

    By using nuclear resonance, spectography and x-ray diffraction, it was concluded (Hoiberg, 1965) that aromatic rings (non-polar rings) are linked by short aliphatic chains (paraffins).

  - Dispersed phase

    Closely stacked polar rings (aromatic rings) and asphaltene napthenic rings.

Figures A2.4 (a) and (b) illustrate the respective molecular structures.

Aliphatic
(Saturates, paraffinic)

Aromatic
(Aromatic and resins)

Cyclic
(Napthenic asphaltenes)
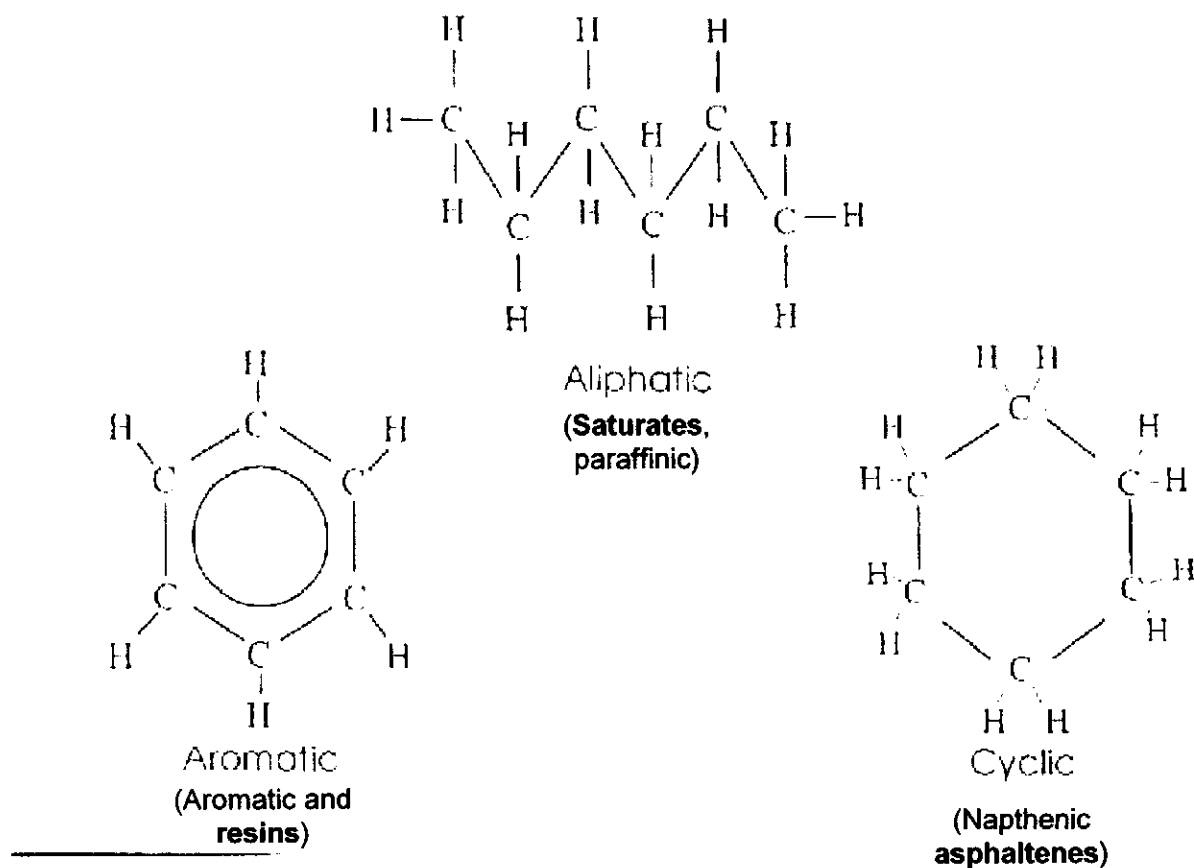
Figure A2.4 (a): Molecular Structures (Whiteoak, 1991, Shell)

Asphaltene structure

Aromatic structure

Saturate structures
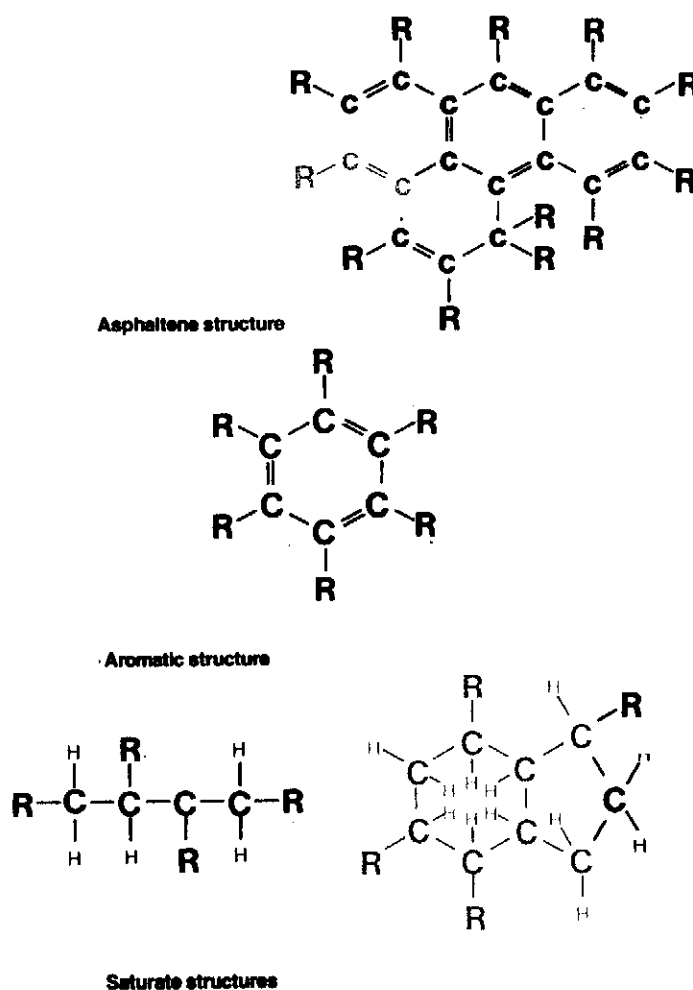
Figure A2.4 (b): Molecular Structures (Whiteoak, 1991, Shell)

A.2.3.2.4 Functional Groups of Molecules

Two functional groups are identified:

- Polar

    Polar molecules give bitumen its adhesive and elastic characteristics (these make up the dispersed phase).

- Non-polar

    Non-polar molecules give bitumen its body and viscous characteristics (these make up the dispersing phase or gel).

The various fractioning methods have been summarised in Table A2.2 below:

Table A2.2: Schematic Diagramme of Bitumen Composition by Fractionation

Bitumen	Holberg	O'Donnel	Corbet	Based on molecular structure	Water-man	Molecular characteristics	Phase	Molecular type
Asphaltenes	Asphaltenes	Asphaltenes	Asphaltenes	Asphaltenes	C_N	• Saturated, cyclic, napthenic structure • Very polar • Give hardness • High molecular weight • Viscosity due to density not bonds • Molecular weight 1000 to 100 000	Dispersed (solids) 5-25 % of the bitumen	Polar asphaltenes
Maltenes	Oils	Saturates / Waxes / Oils	Saturates (Aliphatics)	Paraffins	C_P	• Straight or branched molecules • Paraffinic structure (i.e. single bonds) • Average molecular weight molecular mass 300 – 1500 • "White" oils (white in colour)	Dispersing GEL or dispersed (temperature dependant waxes), fatty and oil (liquid) 5-20 % of the bitumen	Non-polar saturates
		Aromatics (non-polar aromatics)	Aromatics (non-polar aromatics)	Aromatics	C_A	• Stacks of non-polar rings • Brown in colour, viscous liquids (i.e. form the gel) (give bitumen viscosity) • Aromatic structure • Low molecular weight • Molecular weight 300 – 2000	Dispersing gel, viscous fluid 40-60 % of bitumen	Non-polar aromatics
	Resins	Resins aromatics (polar aromatics)	Resins: (polar aromatics)			• Very polar • Give bitumen adhesion and elasticity • Relatively high molecular weight • High temperature susceptibility • Increases bitumen hardness • Aromatic structure (stacked ring structure) • Brown in colour • Molecular weight 500 – 50 000	Dispersing agent for asphaltenes, dispersed with asphaltenes (solid/ semi-solid) (amorphous resins) (Asphaltenes micelles are dispersed in the maltene oily medium. However micelles are comprised of asphaltenes together with a sheath of the high polarity resins)	Polar resins (polar aromatics)

A2.3.3 Behaviour of the Bitumen Fractions

The behaviour of the different bitumen fractions and phases is summarised below.

A2.3.3.1 Asphaltenes

Asphaltenes, with the resins, comprise the **dispersed phase**. Highly condensed ring systems, resulting in large molecule sizes, difficult to disperse in the system. This fraction is solid at room temperature, with some crystallinity, with highest density and molecular mass. Increasing asphaltene content increases hardness (i.e. penetration).

A2.3.3.2 Resins (polar aromatics)

Resins, as above, comprise the **dispersed phase** with the asphaltenes while acting as the solvent for the asphaltenes. An increase in resin content, with constant saturates/aromatics ratio (of 25 %), the general rule is that increasing resin increases hardness (i.e. penetration), and increases softening point, increases viscosity and increases temperature susceptibility. These are amorphous solids. Next to the oils, these have the lowest molecular mass and density. The polar aromatics are more viscous and darker in colour.

A2.3.3.3 Saturates

The saturates, with the non-polar aromatics, comprise the **gel phase**. The saturate fraction is very temperature susceptible (the waxes component), being solid at room temperatures, and flowing at temperatures above 30 °C. This group is not chemically reactive due to the lack in functional groups. This fraction is also not affected by aging. For constant resins/aromatics ratio, increasing saturates decreases hardness, and lowers softening point, decreases viscosity (Hoiberg, 1965).

A2.3.3.4 Aromatics (non-polar aromatics)

The aromatics (non-polar) with the saturates, comprise the **gel phase**. This group has non-polar functional groups. The non-polar aromatics are yellow to orange, and are an oily fluid at room temperature. The oily constituents contain solid aromatic hydrocarbons, and have high viscosity.

Figure A2.5 reflects the influence of bitumen fractions on the behaviour (in this case Penetration Index) of bitumen (see also Section A2.4.1).
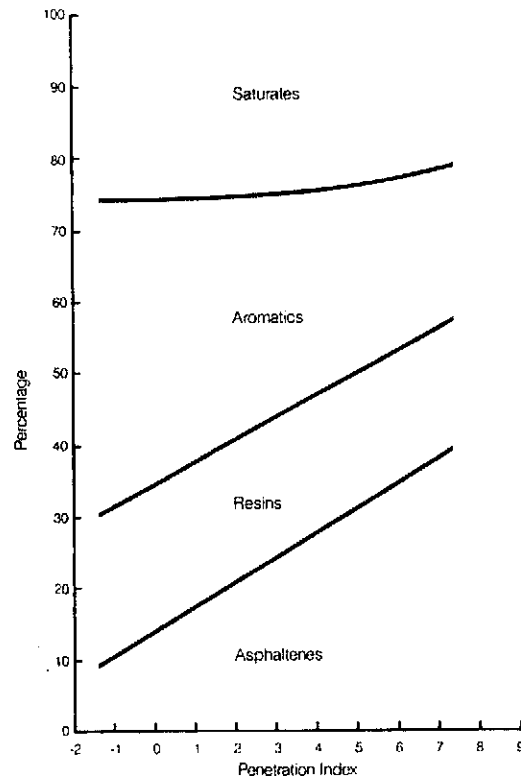
Figure A2.5: Bitumen Chemical Composition (Green, 1999, and Whiteoak, 1991, Shell)

A2.3.3.5 General Trends

The asphaltenes (polar) are soluble in the polar aromatic compounds (resins) which together make up the dispersed phase), while the non-polar saturates are soluble in the non-polar aromatics (together making up the dispersing phase). A stable, balanced system is formed through molecular interaction. Asphaltenes impart thickness to the solution.

Fluidity is imparted by the saturates and aromatic factions. Ductility is imparted by the resins/polar aromatics.

Waxes in the saturates can crystallise and cause phase separation from the oils.

Resins keep the asphaltenes dispersed in the saturates' oily phase. The non-polar aromatics, with the saturates, produce the flow characteristics of the bitumen.

On *aging*, through *heat, oxygen, or UV,* polarity tends to increase: this facilitates the formation of larger molecules, resulting in viscosity increase and changes in temperature susceptibility. The net effect is an increase in asphaltene fraction, and a decrease in the polar and non-polar aromatic compounds. If aging is not severe, there may be an increase in polar aromatics (resins).

Durability is not affected by composition in terms of the maltene fractions, but is affected by components of high volatility (minimum molecular weight of 400 is desired).

Robertson *et al* (c.1990) when the gel (dispersing phase) is in excess of 85 % by mass of the bitumen, the bitumen more easily deforms, while when too low in proportion, the bitumen will tend to be brittle (resulting in cracking). Also, many of the bitumen molecules are susceptible to oxidation, especially at higher temperatures. This leads to the formation of more *polar* molecules, which will be attracted to the matrices, resulting in harder bitumen (higher dispersed phase content).

The resins from a sheath around the asphaltenes, to enable the combination (the Micelles) to be soluble in the saturates (due to the saturates and asphaltenes differing too much in properties). The ratio of fractions with each other determines the compatibility of the bitumen, and provides the visco-elastic properties. Bitumen is a collided system, with the Micelles (asphaltenes and resins sheath) dispersed or discharged in the oily medium (remainder of the Maltenes). The SOL type bitumen has sufficient mixture of resins and aromatics to enable fully "peptised" asphaltenes.

The GEL type bitumen has insufficient resin fractions, and insufficient solvent power. This can lead to separation of oil and undesirable characteristics being imparted to the bitumen.

The more favourable SOL type of bitumen has sufficient resin to "sheath" the asphaltenes, and sufficient aromatics (dispersing gel) to fully mobilize/saturate the asphaltenes.

The GEL type bitumen has insufficient resins or aromatics to ensure saturation of the asphaltenes. This leads to a bitumen that can be unstable in practice.

A2.3.4 Chemical Properties and Performance

This section focuses on the chemical properties and performance of bitumen. Their physical properties are of direct relevance to the performance assessment and modelling of the seals, and are discussed in detail in the main text of the dissertation. The summary of the chemical properties will however provide insight in to the physical properties.

Robertson *et al* (c.1990) used size exclusion and ion exchange chromatography procedures, and appropriate test methods and procedures under the Strategic Highway Research Programme (SHRP) to enable the determination of chemical properties of various bitumens and compare these with their performance. They found that in cases bitumens classified under the same specification as being of similar grade showed variation in terms of both chemical composition and performance. They indicate that oxidation (which occurs at molecular level) influences intermolecular chemistry, thereby also affecting the physical properties. Oxidation results in the production of increased amounts of polar molecules, which have increased levels of polarity. Research using SEC by the above authors has enabled comparison of bitumens with different molecular composition, with their expected performance. The results reflect three types of bitumen: *bitumen with a large fraction in the smaller molecular range, with a small amount in the large range (sample G), a sample (K) with the reverse - large fraction in the large range and relatively small fraction in the small range*, and a *third (M) with a continuous distribution* (i.e. not bimodal). Further investigation (vapour phase osmometry) showed that the sample with a large fraction in the large range (K) had the large molecules comprised primarily of agglomerates of smaller molecules whereas the sample (M) with continuous grading had primarily large molecules in the large molecule fraction. The large agglomerates will however dissociate with increase in temperature, while the large molecules in the continuous sample (M) will not dissociate. The sample (G) with a large fraction of small molecules implies that the less – polar small molecular mass fraction will dominate behaviour, and this bitumen will be able to accommodate the inclusion of an increased number of large polar molecules without major change in behaviour. This type of bitumen would thus be able to tolerate a degree of oxidation before any viscous changes would result (this was in fact an observed characteristic). The sample (K) with a large fraction of large agglomerated molecules would be affected by oxidation with the resulting increase in polar, large, molecules. The authors indicate that although SEC indicated that the three bitumens were different, conventional testing would show that they are similar.

It has also been found that some asphalts have as an inherent property of limited association between the molecules. This property occurs not only with the smaller molecules, but also with the larger non-polar molecules. The less associated (neutral and low polarity) molecules behave as dispersant for the polar molecules. The difference in type of molecule and behaviour explains the differences in variation in behaviour between bitumen, and their different performance. It was shown that when the ratio of dispersing phase to dispersed phase is high (bigger than 85 % by mass) there is a large increase in the ratio viscous modulus G"/elastic modulus G' – this implies lowered performance in terms of rutting resistance and resistance to deformation. Also when there is too little dispersing phase (limits not yet determined) brittleness results. The authors summarise: *bitumen is a collection of non-volatile, polar and non-polar molecules. The polar and polarizeable molecules tend to associate strongly to form organized structures (a matrix) throughout the continuous phase of the low polarity and non-polar materials.* The non-polar dispersing phase is sometimes referred to as the solvent phase. As temperature is increased, the associations of polar molecules decrease and the bitumen becomes more dissociated and therefore less viscous and less elastic. As temperature is reduced, the reverse occurs even to the extent that the non-polar phase becomes organized (from temperatures below 0°C) – this behaviour explains the temperature dependant behaviour of bitumen.

The four fractions of bitumen identified through the various fractionation schemes discussed above can be broadly identified with the two-phase model as identified by the above authors:

- Dispersing phase: saturates/aliphatics, non-polar aromatics

- Dispersed phase: asphaltenes, high molecular mass polar aromatic resins

A2.4   MODIFICATION OF BITUMEN CHARACTERISTICS

The reasons for modification of bitumen characteristics and the properties of modified binders are discussed in Chapter 2 (2.1.3.1). Under this section the chemistry, processes and types of modification are discussed, as additional information and background understanding.

A2.4.1   Modification in the Refining Process

As is evident from Section A2.3.3, the different bitumen fractions need to be in proportion to each other for a stable, balanced system. Where the different fractions are not in the desired quantity in relation to each other, modification in the refining process is required.

A2.4.1.1 Air Rectification

Bitumen produced from some crude oils is deficient in the high molecular mass components (the asphaltenes). Marais (1979) reports that it was practice in the United Kingdom and many other countries to increase the asphaltene content of low-asphaltene bitumen by the oxidation of the hot straight-run bitumen by having a current of air blown through it. This process is called **air-rectification** (a different process than the "blown" grades of bitumen used for industrial applications, where the oxidation is more extensive, and produces bitumen of high softening point and rubbery qualities). These bitumens can be produced in a wide range of viscosity grades. In terms of this modification on the performance of the bitumen, Marais (1979) concluded an analysis of a case study (Umbilo & Hammarsdale Roads, Natal) by noting that the lowering of temperature susceptibility of bitumen through air-blowing has no practical effect on the performance of bitumen, in that the effects generated are too small to have any meaningful practical significance.

A2.4.1.2 Blending

The blending of vacuum column (straight run) bitumen with blown bitumen is carried out to produce blends to desired penetration grades. Roets *et al* (1994) describe the process, where blends were derived from different straight run and blown bitumen combinations. In this manner bitumens of different behaviour were produced, as each combination had a different chemical composition, with specific reference to asphaltene content. With increasing asphaltene content came decreased penetration (i.e. increased hardness). Decreased asphaltene content results in increased penetration, ductility, decreased viscosity and softening point. Also, for blends with the same penetration but made from different straight and blown bitumens, the durability of bitumens increased when comparing the blend with hardest blown bitumen and softest straight run bitumen, they found that the durability of straight run bitumen is greater than that of blended bitumen.

A2.4.2   Modifiers (Post Refining Modification)

Where the bitumen properties require enhancement (as discussed in Section 2), post refining addition of modifiers are utilised.   These modifiers are either elastomers, or plastomers, and take various forms. This section describes the modification processes.

A2.4.2.1 Elastomers

Elastomers are modifiers used to modify (thereby aimed at improving) the characteristics of the base bitumen. The improvements in the bitumen characteristics are expected in the following ways (Hoiberg, 1964):

- Increase in softening point

- Reduction in cold flow

- Reduced change in penetration with change in temperature

- Lowering of brittleness temperature

- Elastic recovery imparted

- Increased resistance to deformation under stress, improved toughness and tenacity

- Increased ductility, especially under low temperature

Elastomers are rubber-like polymer modifiers. The different types of elastomer modifiers are:

- Natural rubber

- Reclaimed rubber

- Butadene-styrene copolymers (SBR, SBS)

- Polychloroprene (neoprene)

- Butadene-nitrite copolymers (PB, polybutadene)

- Isobutylene-isoprene copolymers

- Polyethelene (PE)

When classified according to functions and behaviours, these polymers can also be divided into three types: **dispersed thermoplastics** such as polyethylene, **network thermoplastics** (behave like resins and form a network inside the bitumen) such as SBS,

SEBS (styrene-ethylene-butadene-styrene) and SBR, and **reacting polymers** such as Elvaloy AM (Khattak *et al*, c. 1996).

A2.4.2.2 Plastomers

Plastomers, such as ethylene vinyl-acetate (EVA), are thermoplastic polymer modifiers, and are also used to modify the characteristics and behaviour of bitumen, in a similar manner as the elastomers, although they are characterized by the modified binders exhibiting a component of plastic deformation in the elastic range of the base bitumen.

A2.4.2.3 Form of Modifier

Concentrations of modifiers range from 1 % to 10 %. These are added to the bitumen in various forms:

- Massive forms

  Crude and reclaimed rubbers are sold in sheet, slab, bale or chunk form. A relatively heavy duty blade type mixer is required to blend rubber in this format. Usually the massive rubber forms are subjected to mastication prior to the mixing process. The benefit of this method is that it has been found that by the time the rubber is blended, the rubber is so thoroughly swollen and dispersed that the mix can be considered homogeneous, though it cannot be considered fully dissolved. Blends of this type have high elasticity.

- Crumbs or Granules

  Crumbs or granules of rubber may be blended with bitumen in an easier fashion, with less energy consumption, than massive forms. The end mixture is then non-homogeneous, with the particles, although swollen with bitumen, remaining discrete.

- Fluxes

  By blending low viscosity, low melting bitumen, and applying high temperatures and long mixing times, fluxes can be prepared by mixing these bitumens with rubber. The resulting bitumen-rubber flux can then be used as rubber modifiers for other products. The rubber-bitumen flux may be added to the bitumen by simple stirring.

- Solutions

  Certain raw rubbers dissolve in organic solvents – naphtha, kerosene, and toluene – to form cements that can be stirred into molten bitumens. This method can only be used where the solvent can be tolerated in the final product. The amount of solvent may be considerable as the solvents cannot tolerate more than 20% rubber without the solution gelling. Bitumen cutbacks with rubber latex have been prepared in this manner.

- Powders

  Elastomer powders, when fine enough to ensure the correct amount of swelling in the bitumen, are effective modifiers, and easy to use. Rubber (natural and latex – SBR, Neoprene) powders disperse easily in the liquid bitumen.

- Masterbatches

  Similar to the flux method, rubber and blown bitumen are blended at the mill, granulated, and added as a masterbatch to the bitumen. Heat and agitation are then applied.

- Latices

  One of the most common methods is the addition of an elastomer to the bitumen in its latex form. Latex is added at high temperature to the molten bitumen. Foam occurs as the water in the latex evaporates, greatly assisting in the dispersion of the elastomer in the bitumen.

  Non-aqueous latex has also been used, with an organic fluid replacing the water in the latex.

A2.4.2.4 Other Types of Modifiers

Many other modification processes are available for specific needs:

- Hydrocarbon Pitch Modifier

  Hydrocarbon Pitch is a naturally occurring resinous pitch found in the Americas. When powdered it can be blended with the bitumen to lower penetration value, increase softening point and viscosity.

- Fatty Amines

   Used as anti-stripping or adhesion agents, enhance coating and allows binder adhesion on damp aggregates (dosage 0,5 to 1 % of total binder).

- Aromatic Oils

   High boiling point aromatic oils are used as rubber extenders in the manufacture of bitumen rubbers, assisting in the swelling and softening of the rubber crumbs, enhancing the digestion process. They are also effective in the rejuvenating of oxidised bituminous surfaces.

- Hydrocarbon Solvents

   The addition of hydrocarbon solvents to bitumen lowers the binder viscosity to facilitate the proper wetting and adhesion of the aggregate to binder. This softer binder reduces the risk of whip-off due to brittle fracture in early seal life. After evaporation the binder reverts to the residual properties. These solvents include power paraffin, white spirits, jet fuel and aromatic solvents.

- Sulphur

   The addition of sulphur improves the visco-elastic properties of bitumen.

- Fibres

   Cellulose, polypropylene and polyester fibres are used to modify the bitumen, not for seals, but more suited to asphalt and slurry mixes.

A2.4.2.5 Common Modifiers: Homogenous Binders

The most commonly used homogenous modifiers are summarised below.

Homogeneous binders contain **no solid or semi-solid particulate matter**, and include:

- SBS

   Styrene-butadiene-styrene (SBS) is a network forming polymer, combining the compatibility of low molecular weight SBR (at high mixing temperatures) with the strength of vulcanised rubber (at service temperatures). The core of the SBS molecule comprises the rubbery poly-butadiene with glassy polystyrene molecules.

The networking is based on Vanderwaals forces between the molecule ends, forming a three-dimensional structure of polybutadiene. At concentrations higher than 5% the polymer network occupies a major phase of the blend, and increases softening point (up to 100 °C), cohesive strength, elasticity, low temperature flexibility, zero shear viscosity at moderate temperatures (rutting resistance). SBS is an electrometric modifier.

	Polybutadine
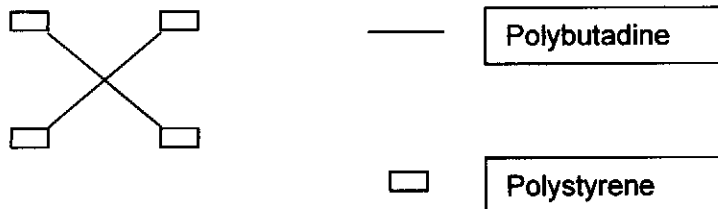
	Polystyrene

- SBR

SBR is based on the same monomers as SBS – styrene and butadene, but the polymers are distributed randomly. Networking does not occur, and SBR thus does not provide modification to the extent SBS does. The increase in softening point, cohesive strength and shear viscosity is thus not as great as SBS, but ductility is greater. SBR is an electrometric modifier.

- SB Diblock

This product is similar in performance to SBR, but does not achieve the levels of modification as SBS.

- PB (Polybutadiene)

Similar to SBR and SB diblock in performance, this is used mainly in hot mixes in Germany, and spray seals in Australia.

- EVA

Ethylene vinyl-acetate forms three dimensional structures as SBS, but the polyethylene combines into crystalline structures. Also, in SBS the glassy portion (polystyrene) of the molecule comprises 30% of the molecule, but in EVA 70%. EVA is stiffer through the temperature range, but provides a lower increase in softening point, poorer ductility, but a strong increase in viscosity. EVA is a plastomeric modifier (plastomer), and is thermoplastic in character. Easy dissolving and fairly compatible.

- PE (polyethylene)

  PE has poor compatibility with bitumen, and is always present as dispersion in a bituminous matrix. Other than viscosity increase (increased resistance to rutting), no real increase in performance is provided.

- Latex

  The above are usually applied as anhydrous polymers, latex is used occasionally in modified binders, generally for spray seal applications. Modified binders are also manufactured into emulsions, with the latex blended with the hot bitumen prior to emulsification.

A2.4.2.6 Common Modifiers: Non-homogeneous Binders

Non-homogeneous binders contain, by contrast to homogeneous binders, **particulate or semi-solid particulate** matter.

Although the benefits of adding rubber to bitumen were realized as early as 1843 in Britain, and in 1902 was used in Cannes in France as a road seal, bitumen rubber was only introduced to the South African road industry in approximately 1983. The modification to the binder's properties enhanced performance, especially in the prevention of reflective cracking. It was initially used in stress-absorbing membrane single seals, and subsequently in asphalts and surfacing seals. Due to the manufacturing process, of rubber crumbs being added to the bitumen, there was initially large variation in the binder properties (Nachenius, 1988), caused primarily by variation in the composition, blending times and temperatures during production, and by having to keep the bitumen rubber at temperatures above 200 °C for long periods, as required if source or batch plant are a distance from site, or from each other.

In the first published results on experience in the USA, it was reported that the rubber content exceeded 5 %, the bitumen became too viscous to distribute or apply (Nachenius, 1988). Rubber content from 1 to 3 % appeared to reduce the seal's tendency to crack or bleed, and reduced the tendency of aggregate to strip. However, natural rubber tends to break down on heating, and as such extra care is required in the manufacture and application. This type of binder is one of the more costly, when compared to the other types of bitumen and homogeneous binders. Charles McDonald initiated the use of pulverised rubber from vehicle tyres. In 1983 South African Bitumen and Tar Association considered the implementation of a standard specification.

A2.4.3   Chemistry of Modification

Further to the section on chemical properties of bitumen (A2.3.4), the chemistry of modification is briefly discussed as additional background. Hoiberg (1965) reports that it is generally agreed that the effect of an elastomer on a bituminous material is **physical rather than chemical**. To be effective, the rubbers must be dispersed in the bitumen, and swollen by the bitumen. If the elastomer is highly resistant to swelling, it is essentially inert. Depolymerising or dissolving of the elastomers into the bitumen reduces any improvement in basic characteristics of the bitumen to nil. The desired characteristics are that the elastomer particles (natural and latex) become dispersed and swollen within the bitumen. The maximum concentration of natural rubber, neoprene and SBR is 5 % to 10 %, after which gelatine of the blend, or separation of jelly-like bitumen swollen rubber occurs. Similar problems are experienced should the blend be exposed for long period to high temperature.

Jordaan (1995) summarises that the basic reaction of bitumen and modifier, whether latex or rubber crumbs, is that when the polymer is added to the bitumen, the aromatic oils in the bitumen react with the polymer, causing it to become digested into the bitumen to form a complicated polymer - bitumen chain link system. The different polymer types form links of different sizes and strengths, giving the resulting product different properties.

The most notable aspects of the polymer modification process are:

- Polymer must be compatible with the bitumen

  A difference in colloidal stability or other chemical disparities will result in incompatibility of bitumen and polymer. Asphaltene flocculation or oil bleeding may occur.

- Digestion temperature must be lower than that at which the polymer is destroyed or vulcanized.

- Digestion time must be shorter than after which the polymer becomes vulcanised.

  However, if digestion is not completed, particles of undigested polymer will float in the bitumen without improving characteristics. Over digestion results in destruction of the polymer, with no benefits of the modification process.

- Additional aromatic oil (snake oil) may have to be added to complete the digestion process – which should have the same properties as the aromatic oils present in the bitumen.

  Insufficient aromatic oils may result in the digestion process not being completed, and insufficient links being formed. The addition of these oils is to replace the oils that have been taken up in the swelling of the rubber. Colloidal instability may result, where asphaltene flocculation occurs, and adhesion is reduced (resulting in stripping problems). Flocculation of asphalt will occur if the aromatics in the dispersing phase (gel) cannot adequately disperse the asphaltenes within the modified blend.

- Sufficient modifier must be added to ensure that a network of links can be formed within the bitumen.

  Without sufficient polymer concentration, the link network cannot be formed, and although viscosity may increase, the associated properties of reduced flow, increased temperature sensitivity may not show associated improvement from that of the base bitumen.

- Srivastave *et al* (1992) report that when adding modifiers to bitumen, the morphological structure and dispersion of the binder must be controlled, as the coarser the bitumen structure, the more brittle the binder at low temperatures. Their study showed that the SBS group of polymers is technically and economically a most effective method of modifying the characteristics of bitumen.

Shin *et al* (1992) emphasize that modifiers are added to the base bitumen to alter or enhance the desirable properties of the binder, which results in a more complex and complicated structure within the binder. Micro-structural and morphological information of the binder mixtures are important in predicting the seal and pavement performance, based on the physical and chemical data of the binders and aggregates.

A2.5   BITUMEN RHEOLOGY

Bitumen is a visco-elastic material. This section provides insight in to the concept of deformation and flow of bitumen, under load, to enable understanding of the criteria to be considered in the modelling of seal performance and behaviour. An investigation into rheology is also required to add understanding of some of the bitumen grading, classification and specification methods (described in Section 2.6).

Rheology is the science of deformation and flow of matter. The term *Rheology* was apparently first used by Bingham in 1929 to define the deformation and flow of matter. Flow occurs when a material's degree of deformation changes continually with time. Rheology has as its aim the prediction of the force system necessary to cause a given flow or deformation in a material (or body), and to predict the deformation or flow resulting from an applied force (Fredrickson, 1961). A practical definition of *rheology* is *the study and evaluation of the time – temperature dependent response of materials which are stressed or subjected to an applied force* (SABITA, 1996, CR – 96/034). Reiner (Marais, 1979) adds that as such, rheology can be expressed in terms of *movement* of matter, in particular with the relative movement of parts of bodies (as opposed to mechanics, which is concerned with the relative movement of whole bodies).

When fluids are placed under an applied load, **flow** will result. When an elastic solid is placed under load, deformation will result under load, returning to the original state upon release of the load. When a plastic solid is placed under load, the material will flow like a fluid. These ideals of elasticity, plasticity and flow are all exhibited by bitumen, under certain environmental or load characteristics. The knowledge of bitumen rheology is important to the engineer for production, construction and quality control.

Marais (1979) indicated through his studies of the behaviour of bitumen, that the chemical composition of bitumen dictates its rheological properties. As such, in order to be able to predict the behaviour of bitumen, knowledge of the chemistry of bitumen is required, coupled to knowledge of the behaviour of bitumen and the influence of the various fractions. The previous sections have summarized the chemistry aspects, and this section will summarise rheology as required for later initiation of a seal performance prediction model.

A2.5.1 Basics of Viscosity for Bitumen

Viscosity of a fluid is the resistance of a fluid to shear forces and hence to flow (SABITA, 1996) (in basic terms the resistance of a fluid to flow). *Viscosity is measured by the tangential force on a unit area of either of two parallel planes (separated by a unit thickness of the substance) required to move one plane with unit velocity in reference to the other plane. The dimensions are [mass x length^{-1} x time^{-1}]. A further definition is: a proportionality constant that relates the force per unit area, F, to the rate of shear, S – thus: viscosity (dynamic) η = F/S poise, and is the constant ratio of shearing stress to rate of shear of a homogeneous fluid (Hoiberg, 1965).*

Dimensional analysis is used to provide a clearer insight to the definition of viscosity:

F in the above definition is Force/unit area (which is in effect shear STRESS):

$$F \quad = \quad [m.a/l^2] = [m.l.t^{-2}/l^2] = \quad [m.l^{-1}t^{-2}]$$

S in the above definition is RATE of SHEAR: [t^{-1}]

$$S \quad = \quad [t^{-1}]$$

thus:

$$F, \text{ or } \tau \quad = \quad \eta.S$$

$$\eta \quad = \quad F/S$$

$$\eta \quad = \quad [m.l. \, t^{-2}/l^2 \, .t^{-1}] \text{ or } [m.l^{-1}t^{-2}/t^{-1}]$$

$$\eta \quad = \quad [m.l^{-1}. \, t^{-1}] \text{ (the dimensions of unit of measure: } poise) \text{ (NB a stoke is poise/density)}$$

η is thus the stress required to produce a rate of strain, or more correctly put, the force per unit area required to move a plane at unit velocity.

Viscosity of bitumen is affected by temperature, both before or during application, and after application to the road as the binder of the road seal. *The viscosity at any given temperature and shear rate is basically the ratio of shear stress to shear strain rate. For a Newtonian fluid, the ratio of shear stress/shear strain rate is constant – true for bitumen at high temperature.* At lower temperatures (90 °C and below), this is no longer constant.

Bitumen thus behaves as a non-Newtonian fluid. The SI (System International) system of measurement unit for viscosity is the Pascal second (Pa.s). **Dynamic viscosity**, η, is usually measured using the centigrade-gram-second (c.g.s) system, unit *poise*, where **10 poise = 1 Pa.s**. In the higher temperature ranges, as indicated above, to which bitumen is heated to enable enough reduction in viscosity to enable it to be sprayed on the road, and where gravity forces thus also play a role in the flow of the liquid, *kinematic viscosity*, Kv, is usually reflected, which is defined as the dynamic viscosity divided by the density of the fluid, i.e. η/ρ. This ratio has the SI unit of m^2s^{-1}. The dimensions of this ratio are determined as thus:

1 [Kv] = 1 Pa.s/ρ with ρ in kg/m^3, i.e.: $[m.l^{-3}]$

1 Kv = 1 Pa.s.m^3/(kg)   where 1 kg = 1 $Ns^2.m^{-1}$ from 1 N = 1 $kg.m.s^{-2}$ and

and 1 Pa = 1N.m^{-2} thus 1 kg = $\dfrac{1N}{m.s^{-2}}$

$$= 1 \ N.m^{-1}.s^2$$

$$= 1 \ N.s^2.m^{-2}$$

1 Kv = 1 $N.m^{-2}.s.m^3$/($Ns^2.m^{-1}$)

1 Kv = $m^2.s^{-1}$.

Thus Kv = $[l^2.t^{-1}]$

Comparing with the above dimensional analysis, confirming:

Kv   = η/ρ from η = [m. $\ell^{-1}.t^{-1}$] and ρ = [m. ℓ^{-3}]

Kv   = $[m.l^{-1}.t^{-1}]$ / $[m.l^{-3}]$

     = $[l^2.t^{-1}]$ (units = poise/density = stoke)

In the c.g.s system, the unit of **kinematic viscosity** is a *stokes*, where **10⁴ stokes =1m².s¹**.

The range in viscosity of bitumen from spray temperature to that of applied bitumen on a road surface in a cold environment varies considerably. Marais (Marais, 1979) notes the variations thus:

On roads of temperatures below 0 °C: η=10^9 Pa.s

Typical bitumen at spraying (above 145 °C): $\eta = 0,1$ Pa.s

Due to the large range of viscosity depending on temperature, different methods are used through the temperature range for the measurement or **indication** of viscosity:

- Penetration (25 °C) (empirical indication)

- Ring and ball softening point (varies, approximately ranges from 40 °C to 55 °C), equiviscous temperature for all bitumens

- Kinematic viscosity (u-tube viscometer, 135 °C). (At 135 °C, kinematic viscosity is measured in Stokes, units mm^2s^{-1}).

- Dynamic viscosity is measured at 60°C (units Poise, $g\,mm^{-1}sec^{-1}$).

The values from the Ring and Ball (R&B) representative test can be converted to approximate viscosities using Pfeiffer and van Doormal's findings (Marais, 1979) as follows:

η (dynamic viscosity) $= 5,13.10^8/pen^{1,93}$ Pa.s, pen = penetration at 25 °C, standard test

for bitumen behaving as a pure viscous liquid, and penetration (pen) at 25 °C, and the density at a specific temperature is known. Thus, at softening point, when bitumen behaves as a pure viscous fluid, $\eta = +/- 1,2.10^3$ Pa.s. For all bitumen, it is clear that the softening point is an *equiviscous value*. Further to this, they determined that at softening point, pen = 827,15 (at R&B softening point).

It has been further reported in literature (Marais, 1979) that the temperature susceptibility of the different binders is characterized by the slope of their viscosity – temperature plot. This relationship was used to determine the optimum mixing or spraying temperatures for all bitumens available from the South African refineries, and viscosity – (application) temperature curves were compiled, from which plant mixing and spray temperature curves were compiled (ref Figures A2.6 (a) and (b)).
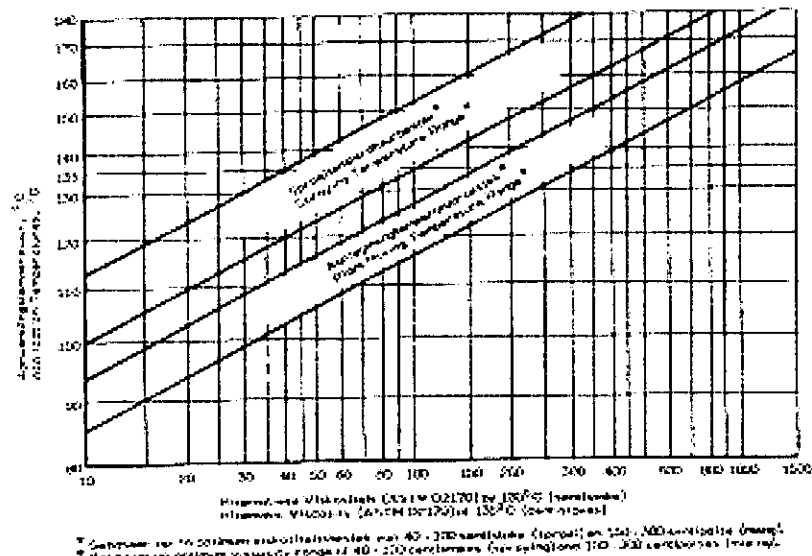
Figure A2.6 (a): Bitumen Application Temperature Plot: Kv @ 60 °C (Marais, 1979)
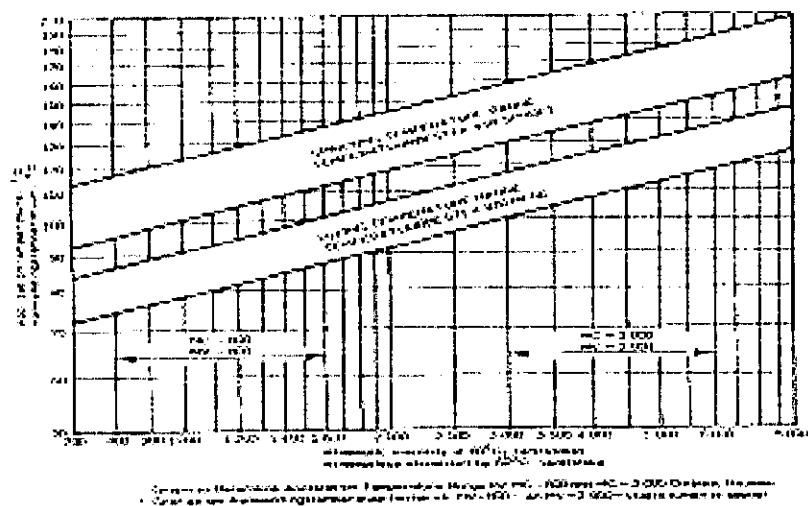
Figure A2.6 (b): Bitumen Application Temperature Plot: Kv @ 130 °C (Marais, 1979)

Van der Poel (1954) describes the *penetration index (PI)* as introduced by Pfeiffer and Van Doormaal as:

If the logarithm of the penetration is plotted against the Temperature, an almost straight line is obtained. The slope of this line could thus be used as a susceptibility index. To determine this, penetration is required at two (at least) temperatures for each bitumen.

When the straight line so obtained is extrapolated to the ring & ball softening point, the corresponding penetration is found to be 800. Thus the PI can be determined from the penetration at 25 °C and the ring & ball softening point (with penetration assumed as 800 at this point). The slope of this line is thus:

For PI the slope of log penetration vs. temperature curve for a bitumen:

$$PI = (Log\ 800 - log\ penetration\ at\ temperature\ T\ ) / (T_{R\&B} - T) \qquad \text{(Eq. A2.1)}$$

Pfeiffer and van Doormaal further found, basing their deductions on the assumption that at moderate temperatures ($\pm$ 60 °C) the logarithm of the penetration is usually a linear function of temperature T, so:

$$\log pen = K_1 + \alpha T, \qquad \text{(Eq. A2.2)}$$

where α is characteristic of the temperature susceptibility of penetration. K_1 represents the logarithm of penetration at 0 °C, is defined by the hardness, and thus by the degree of distillation of the bitumen. They also found that after plotting the different penetrations on a log penetration (ordinate/vertical) – temperature (abscissa) curves for various bitumens, the extrapolated straight lines of penetration would intersect the pen = 800 ordinate at the R&B softening point of the respective bitumens. From the above equation, for the same bitumen (or bitumen with the same hardness at 0 °C):

$$\log 800 - \log pen\ (25\ °C) = \alpha(T_{R\&B} - 25\ °C),\ or \qquad \text{(Eq. A2.3)}$$

$$\alpha = (\log 800 - \log pen\ (25\ °C)) / (T_{R\&B} - 25\ °C) \qquad \text{(Eq. A2.4)}$$

Using an arbitrary Penetration Index (PI) = 0, for the Mexican steam-refined bitumens, α = 1/25, i.e. to satisfy PI = 0 at α = 1/25, PI is further defined as:

$$PI = (20 - 500\ \alpha)/(1 + 50\ \alpha) \qquad \text{(Eq. A2.5)}$$

Using this formula, PI varies from -3 for highly temperature susceptible bitumen to +7 for bitumens of low temperature susceptibility (with the Mexican refined bitumen PI at PI = 0 benchmark).

From work reported by Marais (1979), for South African Bitumens, $T_{800\ pen}$ should replace $T_{R\&B}$ (also noting that the penetration at $T_{R\&B}$ is approximately a penetration of 800).

Viscosity is measured in two ways in many of the current specifications:

- Saybolt – Furol, where the time of efflux of 60 ml material from the S-F instrument is measured. Viscosity is calculated:

η/ρ= 0,0216 x (F, the Saybolt-Furol seconds), units stokes (m^2 s^{-1} c.g.s system) (kinematic viscosity Kv).

- Brookfield rotating spindle, where the spindle rotates at a constant speed in the liquid. Drag on the spindle is indicated on the instrument units poise, or Pa.s (dynamic viscosity η).

A2.5.2 Viscosity Defined For Newtonian Liquids

The material property studied in rheology is the relation between stress & strain or strain rate. If the shear stress is linearly related to the shear strain rate, the liquid is purely viscous, and is defined as being a Newtonian liquid. *Newtonian behaviour: As indicated above, is the characteristic where the ratio of shear stress/shear strain rate is constant (above 90 °C bitumen behaves as a Newtonian fluid).*

When studying most elastic properties, normal stresses and strains are examined, with unaxial deformation. However, when determining the properties of bitumen, which is a visco-elastic fluid, viscosity must also be examined. To describe viscosity, shear and deformation in shear must also be analysed.

When a material between two parallel planes has the one plane displaced in its own direction at a certain speed or rate, and there is no slip (and mass forces are neglected) then. Deformation (at a certain speed) is determined by:

Deformation or shear rate γ = t.g. α .dx_1/dx_2 = x/h, where α is the shear angle (illustrated in Figure A2.7).
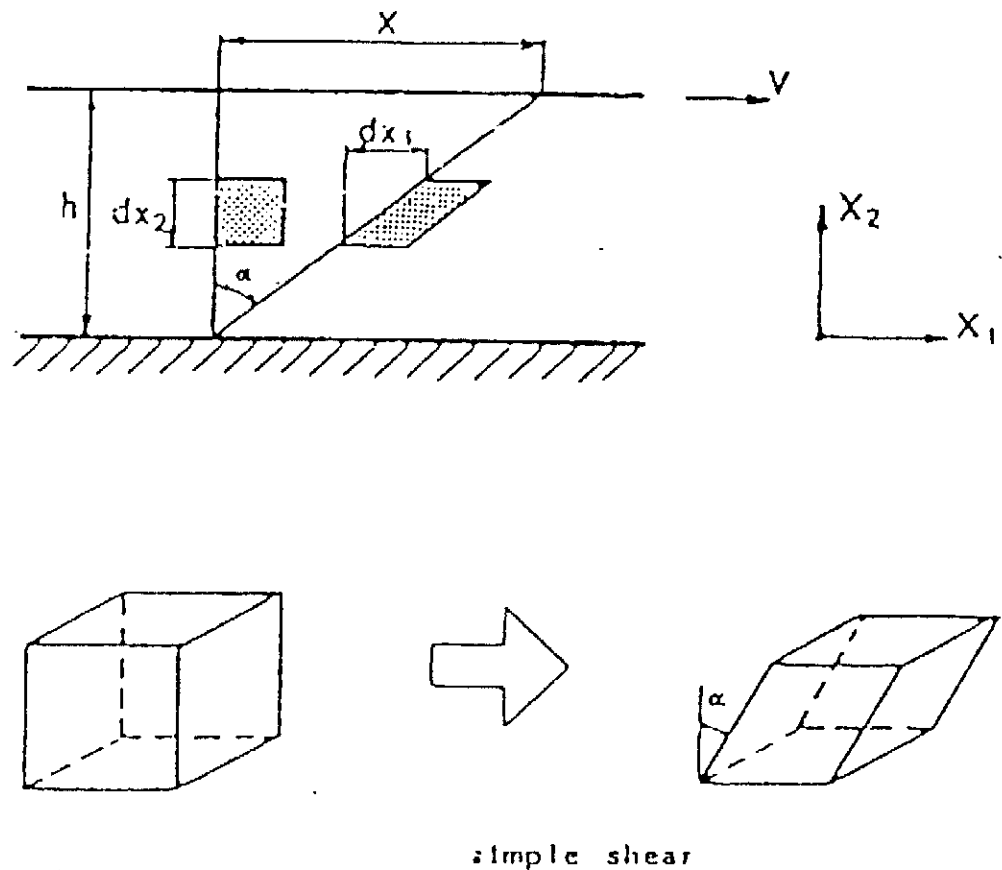
simple shear

Figure A2.7: Determination of Simple Shear (SABITA, 1998)

At CONSTANT SHEAR SPEED (v), at which bitumen is usually tested, local shear strain rate will be:

$$\gamma = dy/dt = v/h$$

(Eq. A2.6)

which is steady simple shear.

In Newtonian liquid, shear stress is linearly related to shear strain rate, the liquid is purely viscous. The material function is a constant, dynamic viscosity η, relating shear stress to shear strain rate:

$$\text{Shear stress} = \tau = \eta \, dy/dt$$

(Eq. A2.7)

Or, as indicated by the definition of viscosity,

η = shear stress/rate of shear, $\eta = \tau / (d\gamma/dt)$,for constant shear

speed $\eta = \tau/\gamma$ (Eq. A2.8)

For Newtonian liquids, a single constant, Viscosity η is able to predict the stress situation of the liquid under deformation.

Elongational viscosity λ $(\sigma = \lambda\epsilon)$, for Newtonian liquids, $\lambda = 3\eta$ (Eq. A2.9)

Most soft bitumens behave essentially as Newtonian fluids (Hoiberg, 1965). The chemical composition of the crude oils and refining process greatly influence the flow characteristics of the bitumen. The softer the bitumen (i.e. higher penetration) from a particular source, the more closely it approaches Newtonian behaviour. At higher temperatures most bitumens show Newtonian characteristics (90 °C and above, i.e. including spraying temperatures).

A2.5.3 Non-Newtonian Behaviour

For materials where viscosity varies with shear strain rate, viscosity is a curve, not a point at a certain temperature.

$\eta = \eta(\gamma)$, where γ is shear strain rate (Eq. A2.10)

and the relationship between elongational viscosity and shear viscosity varies. Non-Newtonian materials structure changes as a shear strain rate varies, i.e. viscosity depends on shear rate and time. *Ratio shear stress/shear strain rate not constant (Bitumen at temperatures below 90 °C):*

$\eta = \eta(\gamma.t)$ (Eq. A2.11)

Elongational viscosity λ can differ from the shear viscosity. The ratio between elongational and shear viscosity is the Trouton number. This varies from 3 for Newtonian liquids as indicated above to 10^3 or 10^4 for some polymer solutions.

The cause of non-Newtonian behaviour is attributed to the complexity of the structure of the material as discussed in the previous sections. Structure can also change as a function of the shear strain rate. As viscosity varies with shear strain rate for non-Newtonian fluids, viscosity will also change with time, as indicated in the formula above:

$\eta = \eta(\gamma.t)$ (Eq. A2.12)

Different forms of **shear dependant** behaviour are:

- Shear thinning

  The viscosity of the liquid is decreasing with increasing shear strain rate (also referred to as pseudo plastic). This occurs with dispersions (solids suspended in liquids) or emulsions (liquids suspended in liquids), where seemingly homogeneous liquids are actually composed from different components.

  The power law describes thinning (empirical):

  $$\tau = K.\gamma^n \text{, where K and n are constants for a certain material,}$$
  $$\text{and } n < 1 \text{ for shear thinning} \qquad \text{(Eq. A2.13)}$$

- Shear thickening

  This is where the viscosity of a liquid increases with increasing shear strain rate (dilatency). This is true for a suspension, where the collisions between particles increase as the shear strain rate increases, thus creating volume expansion.

  $$\tau = K.\gamma^n \text{ where } n > 1 \qquad \text{(Eq. A2.14)}$$

- Bingham Materials

  These materials behave as elastic materials below a certain stress level, above which the material will demonstrate plastic behaviour and flow. Material with linear behaviour (after plasticity - or flow - has occurred) above yield stress are called Bingham materials.

  $$\tau = \tau_0 + K.\gamma \text{, where } \tau_0 \text{ is the yield value} \qquad \text{(Eq. A2.15)}$$

  Non-linear behaviour beyond yield can be expressed using the power law:

  $$\tau = \tau_0 + K.\gamma^n \qquad \text{(Eq. A2.16)}$$

Most bitumens display non-Newtonian characteristics to a degree, especially at lower temperatures. Where these characteristics are pronounced, the bitumen may be considered a "gel" type material. In this case it is thought (Hoiberg, 1964) that the non-Newtonian flow arises from poor dispersion of the high molecular weight asphaltenes in the oily phase (petrolenes) of the bitumen.

Different forms of **time dependent** behaviour are:

- Thixotropy

  This is the situation where viscosity is dependent on both shear strain rate and time duration, and viscosity decreases with time (shear thinning):

  $$\eta(t) = \tau(t)/\gamma(t) \qquad \text{(Eq. A2.17)}$$

  a hysteresis loop develops between increasing and decreasing shear strain rates. Figure A2.8 (a) illustrates this behaviour.

Hagos (2002) summarises Gordon's work undertaken in 1997, and presents the shear stress vs. rate of shear plot with shear strain rate dependant material behaviour as illustrated in Figure A2.8 (b).
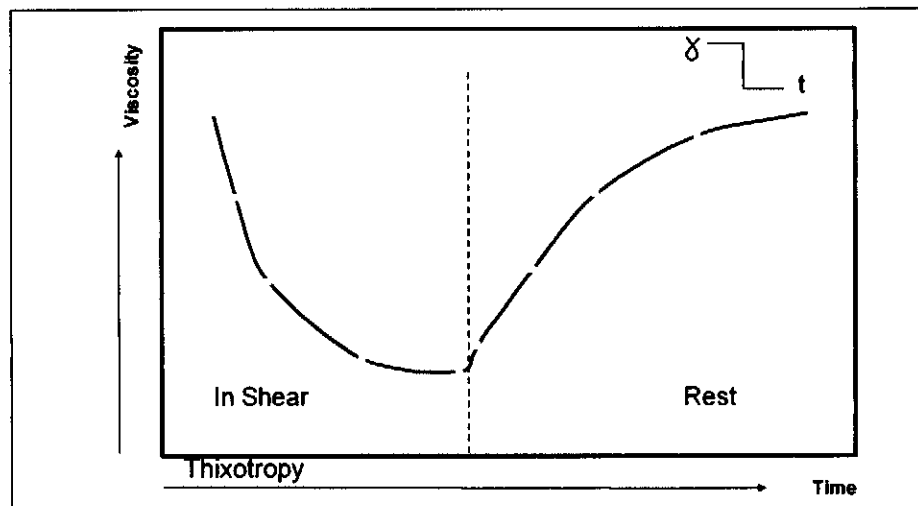
Figure A2.8 (a): Thixotrophic Behaviour (after SABITA, 1998)
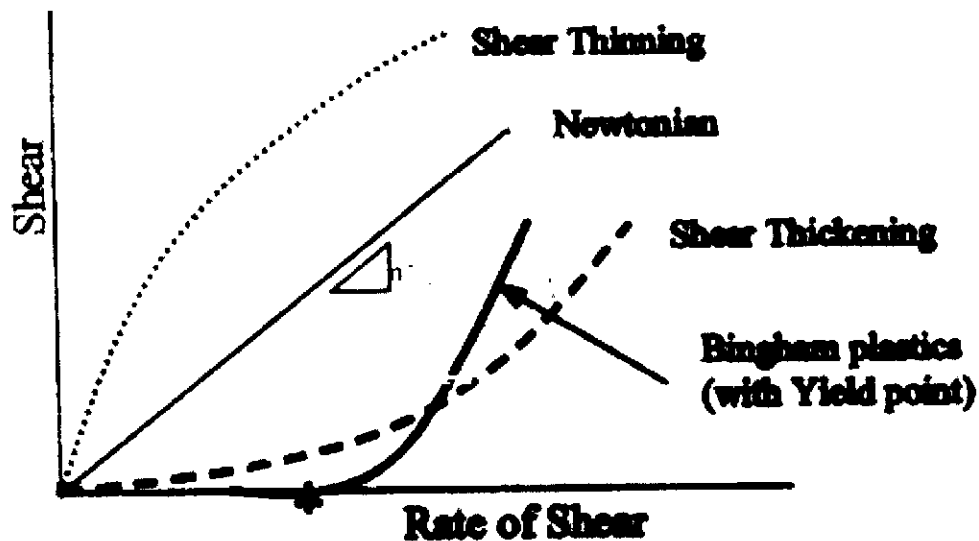
Figure A2.8 (b): Shear Rate Development Viscous Characteristics (Hagos, 2002)

- Rheopecty

Where with constant shear strain rate, viscosity increases with time, the material is termed rheopectic, or reverse thixotropic (shear thickening).

A2.5.4 Visco-Elasticity

Bitumen is a visco-elastic material, exhibiting behaviour between the two extremes. The mechanical behaviour is dependent on both the *temperature* and *duration* of loading. These concepts are summarised as:

- Elastic: completely recoverable, energy stored in the material during loading, is used during unloading to return to initial position

- Viscous: completely non-recoverable, energy dissipated (lost) in permanent **flow &
heat**. Upon unloading, material stays at deformed condition.

- Plastic: non-recoverable, energy dissipated in permanent deformation and heat under load (flow occurs with viscous fluid materials, plastic flow for solids).

- For bitumen, viscosity & elasticity vary with temperature and rate of loading. It should be noted that bitumen can behave in a brittle manner (i.e. fracture failure) under very low temperatures.

At low temperature and short loading duration, i.e.: fast traffic, the behaviour is as an elastic solid. At high temperature and/or long loading time (slow or stationary vehicles) the behaviour is as a viscous fluid. At intermediate temperatures the behaviour is more complex, and is in effect visco-elastic. Van der Poel (Marais, 1979) described the behaviour of thermorheologically simple liquids in terms of a stiffness modulus:

S = σ/ε= tensile stress/ total strain.

The Stiffness Modulus, S, will in general depend on:

• loading procedure

• duration of loading or frequency

• temperature

Various researchers/applied mathematicians have provided mathematical models to represent, and enable understanding of, visco-elastic behaviour. Some of these models are provided below to enable an understanding of visco-elastic behaviour. Under the sections expanding the numerical modelling of the bitumen and seal, the specific models and their representative values were developed further (Chapter 5). The Figures A2.9 illustrate visco-elastic behaviour.
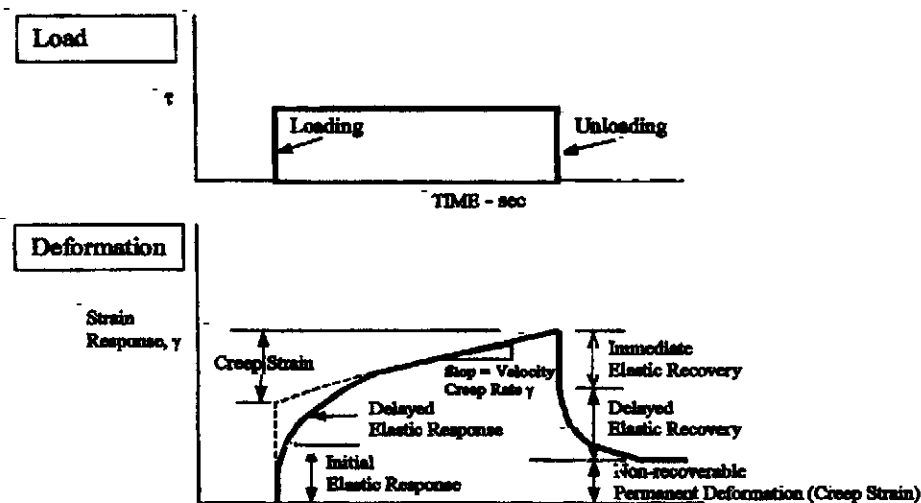

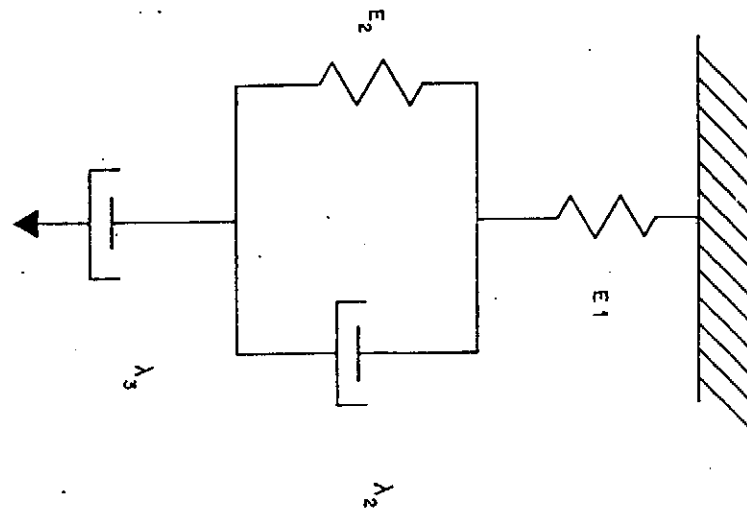Figure A2.9 (a): Visco-Elastic Behaviour Representation (SABITA 1998)
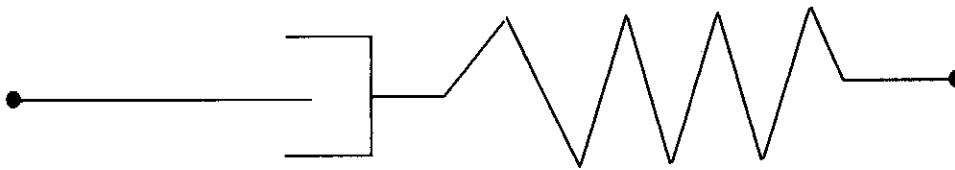
Figure A2.9 (b): Berger Element (Nachenius, 1988)

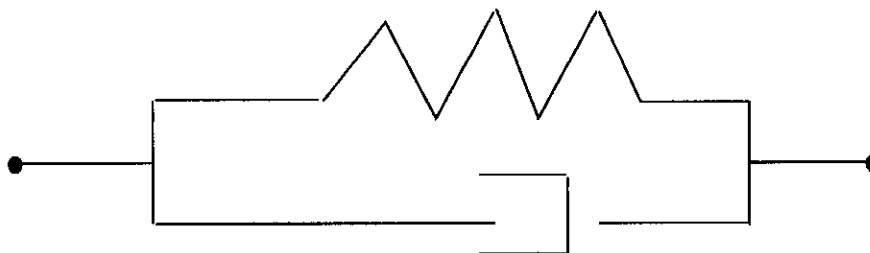**Figure A2.9 (c): Maxwell Element (Sluys *et al* 2002)**

Figure A2.9 (d): Kelvin element

Figure A2.9: Bitumen Visco-Elastic Behaviour Representation

λ = elongational viscosity $(\lambda = {}^{\Delta}\!/_\varepsilon)$, and $\lambda = 3\eta$ for Newtonian fluids (Eq. A2.18)

A model proposed by Burger (Figure A2.9 (b)), and discussed by Nachenius (1988) combines the viscous behaviour (represented by dashpots) and the elastic properties (represented by springs). When plotting strain against time, the slope of the line

represents the rate of strain that would occur only if viscous elements were present in the model. By dividing the applied stress by the rate of strain, apparent viscosity is obtained. Nachenius reports that shear strain is not always proportional to shear stress, and this is a property of bituminous binders – and is a property of non – Newtonian fluids.

Viscosity can be defined in two ways:

- slope viscosity $\eta(\gamma) = d\tau/d\gamma$ (Eq. A2.19)

- apparent viscosity $\eta_a(\gamma) = \tau(\gamma)/\gamma$, γ is shear strain rate   (Eq. A2.20)

When determining the Stiffness Modulus, S, for a static load, applied at time t=0, and kept constant, then the deformation of the binder, ε, is then measured as a function of time, and $S_{s\ (static)} = \sigma/\varepsilon$ is plotted as a function of time.

For a dynamic sinusoidal load, where the stress applied is $\sigma = \sigma\text{-sin }\omega t$. The deformation displayed by the binder is $\varepsilon = \varepsilon \text{ sin } (\omega t - \phi)$, where at various frequencies $\omega = 2\Pi x$ frequency. ϕ is the phase lag, and $S_{d\ (dynamic)} = \sigma/\varepsilon$ is plotted as a function of 1/ω (Marais, 1979). It has been reported that both Moduli coincide for time = t and 1/ω are for practical purposes are taken as interchangeable for a given temperature or frequency. This is referred, in literature, as the frequency/temperature superposition principle.
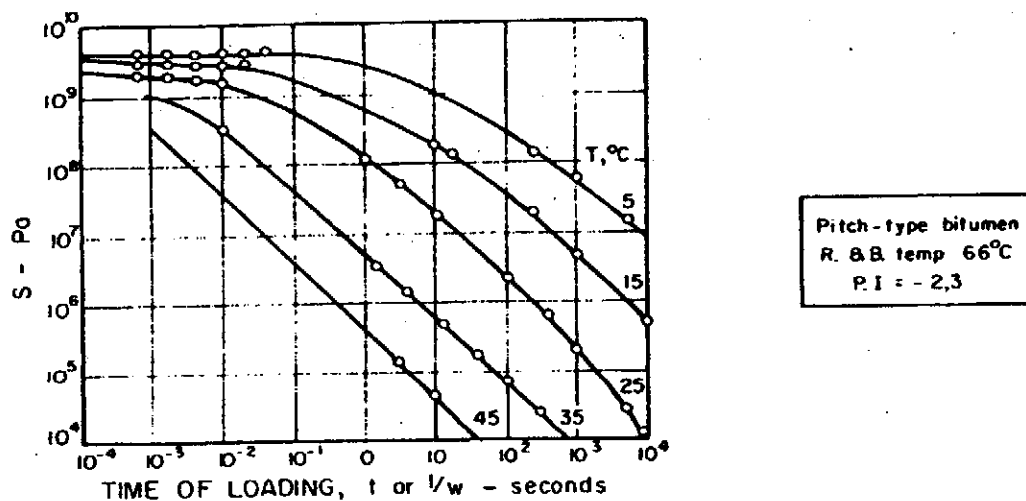
Figure A2.10: Bitumen Frequency/Temperature Superposition Principle (Marais, 1979)

From this relationship (illustrated in Figure A2.10), it is evident that at a very short loading, bitumen acts as a solid (constant elastic stiffness), and in intermediate time of loading, is neither elastic nor viscous. Stiffness decreases with time, but less than for a purely viscous material. As indicated above (4.5.3), if the viscosity is dependant on shear rate and the time duration of shear load, the material is termed thixotropic or rheopectic:

$$\eta(t) = \tau(t)/\gamma(t) \hspace{4cm} \text{(Eq. A2.21)}$$

In addition to the Berger, Maxwell and Kelvin models illustrated above, the mechanical behaviour of bitumen binders can been described by various models or combinations thereof, where simple springs represent the elastic component with a stiffness E, and dashpots to represent the viscous response of viscosity η, thereby producing different time dependent behaviour as illustrated in Figure A2.11. Marais (1979) shows that for all models, when stress is applied for a period of time, there is either instantaneous deformation followed by a gradual deformation, or only a gradual deformation. The response of the material thus consists of an elastic as well as a viscous response, where under an instantaneous shear stress τ or σ in this example, an instantaneous elastic deformation occurs $= \sigma/E_1$. If the shear stress is maintained for time $t_1 - t_0$, then the element will flow at constant velocity. If η_1 is the viscosity of the element, then the displacement will be σ/η_1, which is time dependent. Thus the rate of change of displacements is:

$$d\varepsilon_{elastic}/dt = 1/E_1 \cdot d\sigma/dt \hspace{4cm} \text{(Eq. A2.22)}$$

$$d\varepsilon_{flow}/dt = 1/\eta_1 \cdot \sigma \hspace{4cm} \text{(Eq. A2.23)}$$

$$\varepsilon_{total} = \varepsilon_{elastic} + \varepsilon_{flow} \text{ and } d\varepsilon_{total}/dt = 1/E_1 \cdot d\sigma/dt + 1/\eta_1 \cdot \sigma \hspace{2cm} \text{(Eq. A2.24)}$$
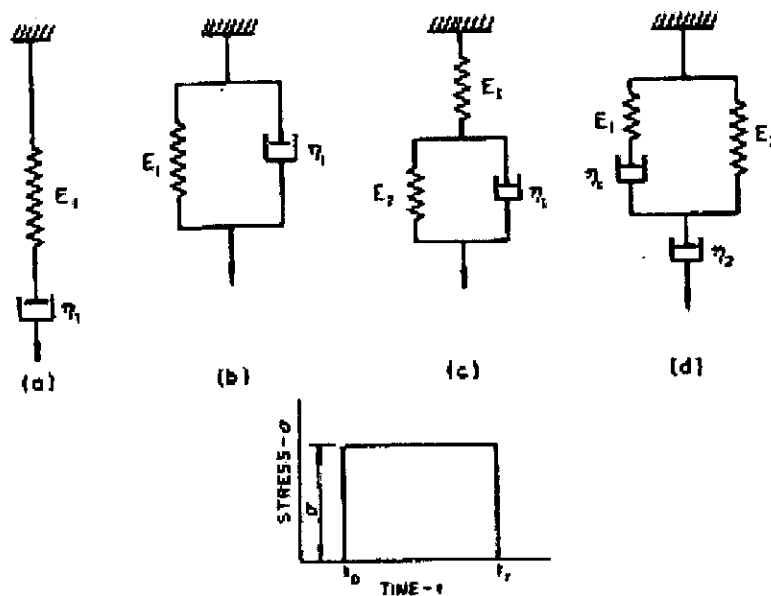
Figure A2.11: Visco-Elasticity (Marais, 1979)

In practice the above equation implies that if a visco—elastic material is forced to assume a certain deformation, the material will experience internal flow which relaxes the imposed stress, that smaller and smaller forces are required to keep the sample deformed, with time (Stress relaxes exponentially with time, with the ratio η_1/ E_1 being the *relaxation time* (Marais, 1979)).

It has been reported (Marais, 1979) that road bitumens behave linearly with respect to applied stress and deformation response at low temperatures and short loading times up to the point when brittle – fracture occurs. At high temperature and long loading times, bitumen behaves almost entirely as a Newtonian fluid, that linearity is again fulfilled. In the range of moderate temperature and loading times, non-linear effects occur, being marked with an increase in deformation. In practice, however, where the performance criteria are to limit deformation on the road, a fair indication of the rheological behaviour of bitumen is obtained if the stiffness as a function of temperature and time of loading or frequency is known. Van der Poel conducted experiments in this regard (Marais, 1979), to determine the stiffness of bitumens over a wide range of temperature and time of loading, and combined his results into a Nomograph relating time of loading, temperature, Penetration Index and stiffness (Figure A2.12 below).
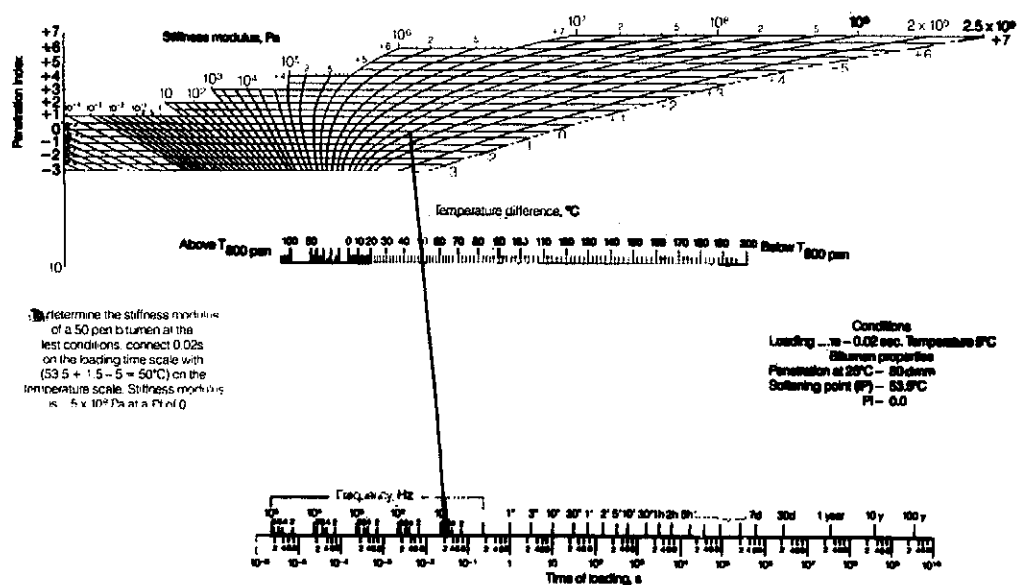
Figure A2.12: Van der Poel Nomograph (Whiteoak, 1991, Shell)

Marais reports (Marais, 1979) that using the Van der Poel Nomograph and comparing it to South African bitumens, stiffness of a binder is a good indicator of the likely performance in surface treatments, where the film thickness is relatively large (± 1 mm) and where the binder is the principal constituent in maintaining the integrity of the surfacing i.e. before significant embedment has taken place.

Van der Poel examined the mechanical behaviour of bitumens in an attempt to incorporate the essential properties of the bitumens in a single system, where the deformations can be determined as functions of stress, time and temperature (Van der Poel, 1954). Van der Poel has provided a system where the mechanical properties of the bitumen are provided through a temperature range and different times of loading. Young's Modulus is used to indicate the relationship between stress and strain of a pure elastic material, while this concept is extended to visco-elastic materials in terms of a *Stiffness Modulus S:*

$S = \sigma/\varepsilon$ = tensile stress/total strain

Van der Poel examined two types of loading experiments:

- constant stress – static creep test

    Load σ is applied at time $t = 0$, and kept constant; the resulting deformation ε is measured as a function of the time of loading.

$S_s = \sigma/\varepsilon$ is plotted as a function of time   (Eq. A2.25)

- dynamic test with alternating stress of constant amplitude and frequency

A stress $\sigma = \sigma'$ sin ωt is applied, and the material displays alternating

deformation   (Eq. A2.26)

$\varepsilon = \varepsilon'$ sin $(\omega t - \varphi)$, and angular frequency $\omega = 2\pi x$ frequency   (Eq. A2.27)

$S_d = \sigma'/\varepsilon'$ plotted as a function of $1/\omega$ (Eq. A2.28)

S_s and S_d are plotted on a single logarithmic chart, with the same scales of time of loading and $1/\omega$ (also has a time dimension). For practical purposes, it was found that there was no difference between the two loading procedures. Linear behaviour was postulated: at short load duration, and low temperatures, linearity occurs (until brittle failure), and at high temperatures bitumen behaves as a Newtonian fluid, and linearity again occurs. In the range of moderate loads and duration of loading, and temperatures, non-linear effects occur. For the range of temperatures and acceptable deformations experienced in practice, a fair indication of the rheological behaviour of bitumen can be obtained if the stiffness can be determined as a function of temperature, time of loading or frequency. Stiffness is inversely proportional to time of loading for a purely viscous material.

Stiffness S is the ratio tensile stress/tensile strain, shear modulus G is the ratio shear stress/shear strain. In general, for an incompressible material,

S = 3.G (as indicated previously, $\lambda = 3\eta$)   (Eq. A2.29)

Van der Poel related the respective variables influencing stiffness to an interpretable form, using:

- hardness of bitumen

- rheological type of bitumen

- temperature

- loading time or frequency

Using the relationship described by the Penetration Index, where the extrapolated plot of log penetration is plotted against the test temperature, and most bitumens penetration at ring and ball softening point coincides with a penetration of 800, it was found that if the log

of penetration is plotted against the difference in the ring–and–ball softening point temperature and test temperature, the plots for bitumens for the same PI will coincide. When plotting Stiffnesses for $T_{R\&B} - T$ for different load frequencies and load durations, the Van der Poel Nomograph was developed to enable determination of the *average* rheological properties of the specific *grade* of bitumen, such as stiffness, stiffness modulus and viscosity for the desired temperature point.

Van der Poel has also found that when plotting stiffness against time of loading for bitumens of same penetration (at 25 °C but different PI's), the plots of each bitumen for same penetrations coincide at a value of 0, 4 sec load duration, which indicates that the bitumens of same penetrations at 25 °C have the same stiffness at load duration 0,4 sec. Also, practically speaking, all unmodified bitumens have penetration of 800 at ring & ball temperature, and the stiffness at this point has been found to be 10^4 N/m^2.

Van der Poel summarises that hardness of bitumen is completely characterised by the ring and ball temperature, and rheological type by the Penetration Index. The Shell Bitumen Handbook (Green, 1991) also summarises that the PI gives an indication of the temperature susceptibility of bitumen, with the higher the PI the more heat that is needed to reduce the viscosity to a given level, and a low PI indicating that the bitumen will become soft more readily as the temperature rises.

Robertson *et al* (c.1990) determined complex dynamic visco-elastic data when examining the chemical properties of bitumen and relating them to performance. These are:

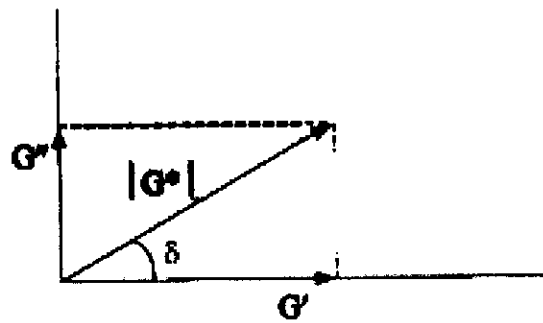$$\eta^* = \frac{\sqrt{(G')^2 + (G'')^2}}{\omega}$$

(Eq. A2.30)

where:

G' – Storage modulus (elastic modulus)

G'' – Loss Modulus (viscous modulus)

$\tan(\delta) = \dfrac{G''}{G'}$

η^* - complex dynamic shear viscosity

ω - shear frequency (radians/second)

Figure A2.13: Representation of Complex Modulus

Superpave accommodates two types of measurement of stiffness modulus as a parameter of visco-elastic behaviour. These are the bending beam (static loading) and dynamic shear rheometer (dynamic sinusoidal loading). For fully elastic materials there is no lag between applied stress and shear strain response (i.e. phase angle of 0 °C) while fullv viscous materials applied stress and strain response are out of phase (phase angle of ⸺ ⸺, ⸺⸺ ⸺astic materials thus have a phase angle of between 0° and 90°. Using the above terminology as illustrated in Figure A2.13:

$$G' = G^*.\cos(\delta) \hspace{3cm} \text{(Eq. A2.31)}$$

$$G'' = G^*.\sin(\delta) \hspace{3cm} \text{(Eq. A2.32)}$$

$G^* = $ maximum applied shear stress τ_{max} / resulting maximum

shear strain γ_{max} \hspace{4cm} (Eq. A2.33)

and;

G^* - complex modulus

δ -delta: phase angle/ shift between applied shear stress and resulting shear strain (i.e. the delay between applied load and shear strain) measured by the sliding plate rheometer, as:

- δ (shear displacement)

- d (vertical displacement)

Bitumen displays different phase angles at different temperatures or types of load

A2.6 BITUMEN GRADING AND SPECIFICATION

Van de Ven and van Assen (1999) summarise that previous bitumen specifications in South Africa were focused on similar types of highly aromatic crude oils (from the Middle East). Since the post 1994 political situation has enabled South Africa to become part of the international market place, many other sources of crude oil have become available. This greater variability in crude oil sources is reported to have resulted in it becoming more difficult to produce constant quality bitumen. The authors acknowledge that the SHRP programme has initiated the examination of the relationship between chemical composition and performance, with the resulting development of the performance graded (PG) system based on fundamental rheological tests. The authors summarise that bitumens are currently being characterised in South Africa by physical tests, that these may be variable with respect to chemical composition, and in spite of the link between the chemistry of bitumen and its behaviour, chemical tests are currently not generally included in bitumen specifications. The results of investigating both chemical composition and bitumen behaviour will enable changes in bitumen composition to be examined relative to the performance properties of the bitumen.

This section examines the manner in which bitumen is graded and specified and represented to practice, and has relevance when describing performance criteria of the respective types of bitumen.

A2.6.1 Standard Bitumen Testing Methods

Within the Republic, since 1991, the specification of modified binders has evolved, and with this, so have the standard testing methods. The rheological behaviour was recommended to be measured and specified through the use of the Brookfield viscometer. Low temperature ductility and elastic recovery were also recommended as inclusion into the specification.

Due to the temperature dependency of bitumen characteristics, bitumen is tested at different temperatures to ensure compliance through the full temperature range. It is thus a requirement that the bitumen satisfies all the specification requirements at all temperature ranges. Three temperature ranges are used, representing the temperature ranges of the various bitumen behaviour regimes: elastic, visco-elastic and viscous fluid ($25\,^\circ$C, $60\,^\circ$C & $135\,^\circ$C as representative temperatures). Some tests are carried out at temperatures below $0\,^\circ$C for primarily European or US expected operational temperatures, representing the brittle behaviour range.

The most common tests are:

- Penetration @ 25 °C   *indicating consistency and material behaviour*

- Softening Point (ring & ball)   *reflecting temperature susceptibility*

- Kinematic viscosity @ 135 °C   *indicating consistency*

- Dynamic viscosity @ 60 °C   *indicating consistency*

- Ductility @ 25 °C   *reflecting cohesion*

- Rolling thin film oven test @ 163 °C   *reflecting aging susceptibility*

- Flash point   *for safety reasons*

- Solubility in trichloroethylene   *indicating purity*

A2.6.2   Specification and Representation Methods

There are various specification methods available for consideration.

A2.6.2.1 Penetration Graded Bitumen

Penetration (road) grade bitumen is classified by penetration @ 25 °C and viscosity. The temperature-viscosity relationship gives the temperature range for spraying. Penetration @ 25 °C is the primary measure of material behaviour. But this gives control at only one temperature. Bitumen with low, medium or high temperature susceptibility could have the temperature – stiffness (penetration) curve passing through the same point at 25 °C where pen is measured. Thus the other tests, such as viscosity at 60 °C and 135 °C are required, to give behaviour trends at all temperature ranges. The penetration value gives no indication of low temperature behaviour or aging. The rolling thin film oven test (RTFO) is included to enable assessment of the bitumen characteristics after ageing.

The penetration ("pen") grade specified bitumen must conform to limits set for the following indicators:

- Penetration @ 25 °C

- Softening point

- Viscosities

- Ductility @ 25 °C

- Solubility (xylene spot test)

- RTFO test requirements

The South African bitumen specification is provided in Appendix B for completeness. Bitumen can be applied **hot** or used as a **cutback** or **emulsion**. The specification for these types is included in the Appendices.

A2.6.2.2 Viscosity Graded Bitumen

Viscosity graded bitumen conform to limits set for the following tests:

- Viscosity @ 60 °C

- Viscosity @ 135 °C

- Penetration @ 25 °C

- Flash point

- Solubility

- RTFO Test Ductility & Viscosity

For interest, 40/50 pen grade equates to AC-40 & AC 20 viscosity grade, 85/100 pen to AC –20, AC-10 & AC-5.

The above methods characterize bitumen behaviour through empirical methods and measurements (illustrated in Figure A2.14). The properties give relative values, with no measurement of fundamental engineering properties. There is no indication of the effect of time of loading and the actual deformations expected in practice. The viscosity measures describe only Newtonian fluids.
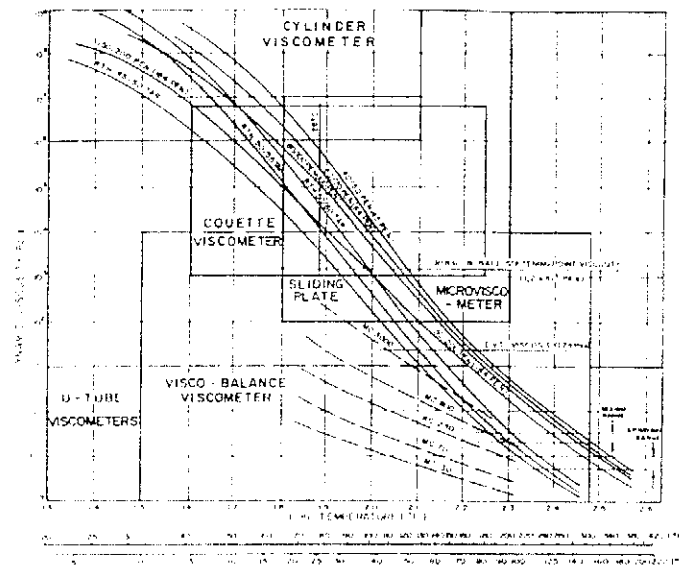
Figure A2.14: Relationship between Temperature and Dynamic Viscosity (Marais, 1979)

A2.6.2.3 Performance Graded Bitumen

The complexity of bitumen visco-elastic behaviour gives a material with the following behaviour trends:

• Extreme variation of properties within application conditions

• Stiffness can vary between 6 – 7 orders of magnitude with changing temperature

• Relative elasticity varies between 0 °C and 90 °C

• Aging changes behaviour

Superpave Binder Physical Property Tests have been developed to test physical properties, with a related Performance Graded Bitumen Binder Specification. Approximately 36 grades of bitumen are specified. The grading uses average 7 – day maximum pavement design temperature and minimum pavement design temperature as the performance grading requirement, with performance indicators (giving one sided limits,

i.e. not an envelope) providing the specification, e.g. PG 46 -34 is for a road that will experience 46 °C MAX and −34 °C MIN air temperatures.

Characteristics measured include:

- Viscosity

- Dynamic shear

- Creep stiffness

- Direct tension (failure strain)

- Physical hardening

A2.6.2.4 Equation for Computing Temperature Susceptibility

Temperature susceptibility can be described by the Penetration Index (PI), as discussed in A2.5.1.

Bitumen for roads should satisfy:

-1<PI<1   where PI is the Penetration Index

$$PI = \frac{30}{1 + 90PTS} - 10$$ where PTS = Penetration Temperature

Susceptibility   (Eq. A2.34)

or from (Eq. A2.4) above:

$$PI + \frac{20 - 500\alpha}{1 + 50\alpha}$$

$$PTS + \frac{\log 800 - \log pen @ 25^\circ C}{(R \& B Soft.Pt, ^\circ C) - 25^\circ C} = \Delta \log pen / \Delta T$$

(Eq. A2.35)

Assuming penetration at softening point = 800 for all bitumen (this is the assumption for Type S bitumen).

Large negative values indicate greater temperature susceptibility. Typical bitumens are between +2 & -2.

There are also: Penetration Ratio, Pen/Viscosity Number & viscosity-temperature susceptibility (VTS) equations to describe temperature susceptibility of bitumen.

Lowest limit is PI = -10, with infinite temperature susceptibility, and upper limit of +20, with behaviour independent of temperature. Normally experienced range of PI's is -2,6 to +8, illustrated in Figure A2.15 below:
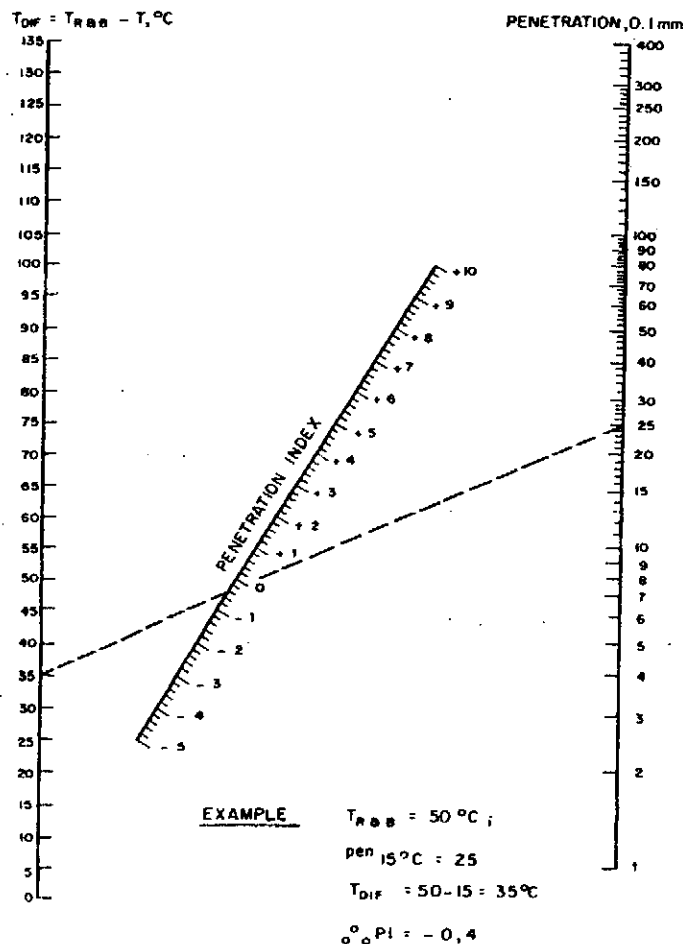

Figure A2.15: Temperature Susceptibility Determination (Marais, 1979)

A2.6.2.5 Bitumen Test Data Chart

To enable representation of the change in bitumen characteristics with temperature, Heukelom (Green, 1999) developed the Bitumen Test Data Chart (BTDC) (see Figure

A2.16). The BTDC reflects the change in the _empirical_ characteristics of penetration, and _fundamental_ characteristic of viscosity, for the three classification types of bitumen distinguished by the BTDC:

Class S: "Straight" (normal wax and asphaltene content)

Class B: "Blown" (high asphaltene content, higher pen)

Class W: "Waxy" (high wax content, viscosity lower at high temperature)

Stability requirements are defined by stiffness modulus. For S – class bitumen this property can be translated into pen @ 25 °C, softening point & PI via nomogrammes (Van der Poel). The Bitumen Test Data Chart defines S-type bitumen which have a **straight line** for temperature/pen and viscosity – temperature curve. The slope depends on the PI. S-type bitumen has normal wax content. Waxy bitumen (wax lowers higher temperature viscosity) "W – type", and blown "B – type" bitumen (higher asphaltene contents affect behaviour at lower temperature) are the other two types of bitumen defined on the BTDC limits for acceptable bitumen.

The Shell Bitumen Handbook (Green, 1991) shows that the Bitumen Test Data Chart (BTDC) describes both penetration and viscosity as a function of temperature. The BTDC uses one horizontal scale for temperature, and two vertical scales: one for penetration, and the second for viscosity. At Fraas breaking point pen is taken as 1¼, at softening point pen is approximated to 800. The Class S bitumens are thus represented on the BTDC as a straight line plot. Most penetration grade bitumens have a wax content, thereby showing a discontinuity between the viscosity and penetration portions of the curve, but with the two portions being essentially parallel. The shape and position of the curve within the discontinuity will depend on the type of wax and thermal history of the bitumen being tested. The Class B (Blown) bitumens have curves on the BTDC made up of two straight lines, with the slope of the low temperature region flatter than the high temperature curve. The slope of the low temperature portion of all curves gives an indication of the PI.
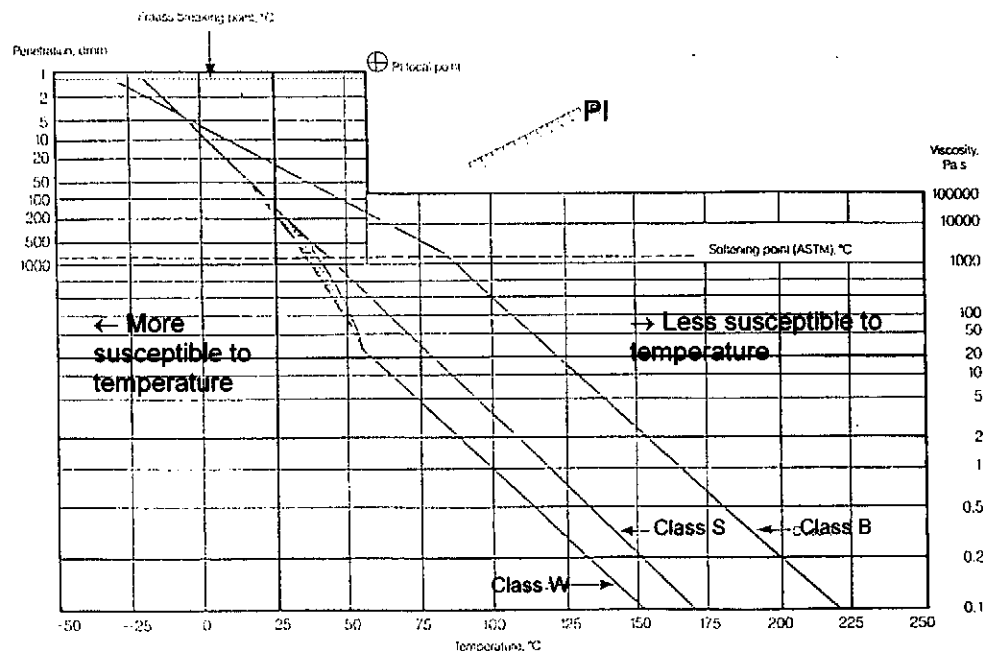
Figure A2.16: Typical Examples of Class S, B and W Bitumens on the Bitumen Test Data Chart (Green, 199)

The current bitumen specification used within South Africa, the penetration grading system of SABS 307 (SABS, 2002), uses tests and properties not determined by engineering behaviour, but rather tests that relate laboratory test values with empirically determined boundary values. The USA through the SHARP programme are striving towards a specification where material characteristics related to actual engineering properties, i.e. rheological and mechanical tests are implemented over the whole temperature range. To this end, when testing bitumen for surfacing application, it is imperative to ensure that ALL required tests are implemented and complied with, as these tests measure behaviour at different temperatures.

A2.6.2.6 Modified Binders

The Asphalt Academy (2001) have compiled an updated specification for Modified Binders (including polymer and bitumen rubber) for South Africa. The specifications are included in Appendix C. New Test Methods ("report only tests") have been included, that will enable collation of performance data, for possible inclusion in future specifications.

New classification classes have been included. The relevant classes for seal binders are given in Table A2.3:

Table A2.3: Classification of Modified Binders

Modified Binder Class (S – "seal")	Application
S – E1	Surface seal – hot applied
S – E2	Surface seal – hot applied
S – R1	Surface seal – bitumen rubber
SC – E1	Surface seal – cold applied (emulsion)
SC – E2	Surface seal - cold applied (emulsion)

The following test methods give an indication of the expected bitumen behaviour:

(a)   Hot applied modified binders

- **Ring and Ball Softening Point (ASTM D36):** good correlation is obtained between increase in softening point and polymer content. This test provides a consistency test, and indication of heat susceptibility.

- **Dynamic Viscosity (ASTM D4402):** provides an indication of the sprayability of the binder. Test temperature is 60 °C (modified binders display non-Newtonian behaviour at 60 °C). Kinetic Viscosity test temperature is 135 °C.

- **Ductility at 15 °C (DIN 52013):** provides indication of compatibility between constituent chemical components, and of the cohesive strength of the binder at low temperature.

- **Elastic Recovery at 15 °C (Ductilometer):** the test performed at low temperature ensures that sufficient modifier is used, and is of sound composition and incorporated within the bitumen to impart good elastic recovery properties to the binder. Percentage recovery is determined. Torsional recovery has also been added as a test.

- **Storage Stability:** gives an indication of the compatibility of binder and modifier when stored at extended period at high temperature compares the softening point of three sections of a cooled tube of bitumen. This reflects the stability in terms of resistance to segregation between modifier and bitumen when the binder is stored hot.

- **Modified Adhesion Test:** the adhesive and cohesive properties of the modified binder to road stone at 5 °C and 50 °C are determined (using a steel ball dropped onto the back of a steel plate, covered on the underside with a specified amount of binder and aggregate). This is not always specified.

- **RTFO** test also specified.

(b)   Cold applied binders (emulsions)

The properties of cold applied modified binders are provided:

- **Modified Binder Content:** percentage of binder, polymer and fluxing agents within the emulsion.

- **Saybolt Furol Viscosity at 50 °C:** lower viscosity limits are set to control runoff on gradients.

- **Residue on Sieving:** primarily to prevent blocked sprayer nozzles, also indicates the degree of dispersion of binder droplets within the emulsion.

- **Particle Charge:** determines cationic or anionic nature of the emulsion.

- **Sedimentation:** indicates the storage life of the product.

- **Recovered Binder Properties:** vacuum recovery or evaporative methods are used to recover the residual binder (distillation with high temperatures is not acceptable due to the associated degradation of the binder).

(c)   Bitumen rubber

Specific specifications for bitumen rubber include:

- **Softening Point:**

  The ring and ball softening point ($T_{R\&B}$) is the indication of temperature susceptibility.

- **Haake Viscosity:**

  This test gives the instantaneous indication of the consistency of a bitumen rubber binder, through the use of the Haake viscometer.

- **Compression Recovery:**

  This test measures the elastic contribution made by the rubber crumbs.

- **Resilience:**

  This test measures the relative consistency of the bitumen rubber, and its relative hardness (using the ball penetration value).

A2.7 TYPES AND SELECTION OF BINDER

Bitumen can be provided for construction in various forms, and modified to enable post-construction performance requirements to be met.

For adaptation to specific construction methods, bitumens are diluted or cutback to liquid bituminous materials to either solid or semi-solid bitumen. Bitumen as liquid is defined as having a penetration at 25°C (50 g/5 sec) of more than 350 (Hoiberg, 1965), and this is achieved by emulsifying or cutting back.

A2.7.1 Cutbacks

Cutback bitumen is made by diluting the bitumen with a petroleum distillate fraction (solvent) to obtain easily workable viscosities for construction purposes. The distillation range of the solvent produces the desired curing behaviour (rapid, medium or slow). There are three types, designated by the curing behaviour, which differ in the type of dilutent used:

- SC (slow curing): gas oil (or heavy diesel fuel) as dilutent. Crude residue, possibly blended with 50 – 60 pen bitumen may be used as a base. This product was referred to as road oil, as the SC oil may be made directly off the refining unit.

- MC (medium curing): Kerosene as dilutent. Base bitumen can vary from 70 pen to 250 pen.

- RC (rapid curing): Naptha is used as dilutent. The base bitumen varies from 70 pen to 110 pen in order to leave a residue bitumen of 80 to 110 pen.

- The process of manufacture is to blend the dilutent with the hot base bitumen. The volatile petroleum distillate cuts back the bitumen to a relatively fluid state by lowering the viscosities, improving the workability. Upon curing by evaporation of the solvent, the cured-out bitumen will be in approximately the same condition as before being taken into solution. The lesser volatility of the MC or SC solvents leaves the bitumen somewhat softened for a longer period of time than the RC type, due to the slower rate of evaporation of the higher boiling fractions of the diluents.

Specification is in terms of viscosity: RC 3000 has a viscosity of 3000 centistokes at 140 °C.

Applications vary as follows:

- RC grades are used as a tack coat or prime or penetrating coat for very open surfaces (± 40% naphtha). Lower dilutent content RC grades (10 to 20% naphtha) are used for mixed in place asphalt or surface treatments.

- MC grades are used for priming (MC-30), also in cooler weather, cold mixes, and dust palliative treatments.

- SC grades are used for priming, dust palliatives, patching mixes, and sometimes hot mixing.

A2.7.2   Emulsions

A means of liquefying bitumen is by emulsification, a process first used in 1906 in the USA. An emulsion is defined as a mixture of two immiscible liquids, one of which is dispersed in the other in the form of droplets (of size approximately 5 microns in diameter average). In this case bitumen is the dispersed liquid, or internal phase, and water is the dispersing liquid or external phase. In essence, an emulsion is a penetration grade bitumen in an easier – to – use form. A stable product is desired, and one of the critical factors to consider is the third component, the emulsifier (which determines many of the properties of the emulsion and keeps the emulsion stable). Anionic emulsions have the emulsifier imparting a negative charge to the dispersed droplet, with cationic emulsions imparting a positive charge to the droplets. Anionic agents are usually fatty acids, from vegetable, wood or animal source, while cationic agents are amine salts made by reacting hydrochloric or acetic acid with an organic amine or dimene.

The emulsification process requires the agent, bitumen and water to be mixed, with high shear action through simple mixing, centrifugal pumps, etc., to allow the bitumen particles to disperse in the water phase. 1 to 3 % naphtha (stabiliser) can be added to improve stability. Rapid setting types use cationic type emulsions (usually), and are designed as spray type.

Emulsifiers are usually long chain hydrocarbons, with the molecule terminating in either a cationic or anionic functional group.

A2.7.2.1 Anionic Emulsion

The three grades of emulsion are: RS – rapid setting, MS – medium setting, SS – slow setting. Base bitumen is usually 180 – 200 pen (Hoiberg, 1965). Potable water is the medium for carrying dispersed droplets. RS emulsions are primarily produced with fatty acids (± 0,04 %) as emulsifier, and MS (0,4 %) and SS (1,4 %) with fatty acid/resin combination. These emulsions are difficult to use with siliceous aggregates due to the delayed setting times of their stones electro-negative charge, but are suitable for use with limestone and similar aggregates.

Anionic emulsifiers are usually based on fatty acids – a long hydrocarbon chain terminating in a carboxyl group. Saponification – the addition of sodium hydroxide – is required in the preparation of the emulsifier. A soap is then obtained.

- R-COOH   fatty acid

- $R\text{-}COO^- + Na^+$ anionic soap

A2.7.2.2 Cationic Emulsion

These emulsions are suitable for use with nearly all types of aggregate, and are less easily damaged by sudden showers due to their natural adhesion to the aggregate. Cationic emulsions have the most satisfactory adhesive properties of the emulsion types. The emulsifier has both polar and non-polar portions, such as sodium palmitite, where the large non-polar alkyl portion on the one side imparts oil solubility, while the polar sodium carboxylate group on the other end imparts water solubility. These emulsions are used over a broader range of aggregates, as amongst other reasons, the cationic emulsifier approaches the aggregate surface closer than the anionic type, and the Van der Waal forces of attraction come into effect. Consequently the emulsion breaks more rapidly on contact than anionic emulsions. The charge on cationic emulsion particles is also approximately twice that of the anionic particles, this greater force contributing to the attraction, breaking and plating (on the aggregate) actions. The limit of bitumen content in the emulsion is 70 % to 80 % - thereafter there is insufficient place in the water without deforming the dispersed bitumen droplets, and the bitumen droplets will eventually adhere to each other. The stability of the emulsion depends on the strength of the electric charge imposed on the bitumen droplets by the ionised emulsifier particles.

Cationic Emulsions are usually long hydrocarbon nitrogen compounds, such as alkylamines – powerful surface active compounds with great influence on the surface

tension. In most cases the treatment of the emulsifier with an acid (usually hydrochloric acid) is required, where the acid reacts with the nitrogen in the amine and forms ammonium ions.

- monoAmine – $R-NH_2$: rapid setting

- diamine : rapid setting

- quaternary ammonium compounds : medium & slow setting

- alkoxlated amines : slow setting

- amidoamines : rapid to medium setting

- $R-NH_3^+$: ammonium ion

As with anionic emulsions, there are RS, MS and SS emulsions. RS are used for seals, and SS for slurry seals. Rapid set emulsion breaks rapidly on aggregate surfaces, leaving a film of bitumen. Slow setting bitumen breaks very slowly, allowing time for mixing and other work procedures.

A2.7.2.3 Behaviour of Emulsion Types

Viscosity increases rapidly with increasing bitumen content from 60 % bitumen. In the range from 30 to 60 % bitumen, viscosity is between 30 to 40 cSt, increasing to the order of 180 cSt. An example of the temperature – viscosity relationship is: viscosity decreases from the order of 240 cSt at 35 °C to 50 cSt at 90 °C. If the emulsion is stable, **settlement** that occurs under storage will not lead to coalescence of the bitumen particles, but agitation will re-disperse the particles. The addition of solvent decreases the density of the bitumen, reducing the difference in density between water and bitumen, and thus reducing or preventing settlement (however too much solvent causes the bitumen to rise to the surface – creaming).

Flocculation is the process where droplets of bitumen adhere to each other – these can be segregated by agitation.

Coalescence is where droplets merge to form bigger droplets (usually follows flocculation).

Breaking is the transfer of the emulsion to fluid state. Emulsion should be stable during transport and storage, but break at a predetermined rate when in contact with aggregate or pavement surface. Rate of breaking is controlled by type and dosage of emulsifier

(influenced also by type of aggregate, temperature and climatic conditions). When the emulsion comes into contact with aggregate, the electrical charges on the stone absorbs electrical charges in the emulsion, reducing the number of emulsifier ions in the emulsion to such an extent that coalescence starts, and resulting breaking of the bitumen. Clay content contaminating the aggregate increases the breaking rate. The absorption of emulsifier ions on the aggregate surface changes the nature of its surface from hydrophilic to lipophilic, so that the bitumen released from the breaking process easily adheres to the aggregate surface. Most seal aggregate types used in South Africa have negative charges on their surface – thus the positive charges on the bitumen droplets of cationic emulsions make cationic emulsion generally more suitable for use than anionic emulsion. Anionic emulsions used with such aggregate eventually break due to water evaporation and absorption into a porous aggregate. As the volume of water becomes less, available room for the bitumen droplets is reduced – causing pressure on the droplets. When this pressure is greater than the repulsive forces, coalescence starts. During this phase inversion occurs as water gets trapped inside the bitumen phase. Traffic and rolling can accelerate breaking. Aggregate with a higher proportion of filler will break faster, due to the greater surface area of fines and the corresponding large number of electrical charges.

Adhesion is the result of breaking. Anionic emulsions have the inorganic ion K^+ or Na^+, which are absorbed onto the aggregate surface – this provides no oleophilic property (i.e. does not assist affinity to oil), has no surface active effect and resultant adhesion is poor. Cationic emulsions have the organic action $R\text{-}NH_3^+$ absorbed on to the aggregate surface - this provides an oleophilic property to the aggregate, with a water displacing effect. Stronger adhesion results and the aggregate takes on a water displacing effect

A2.7.3   Inverted Emulsions

Water-in-oil (bitumen) emulsions are used primarily for cold mixes, and mix-in situ, and are rapid or medium cure. Up to 10 % water is added.

A2.7.4   Elastometer and Plastomer Modified Binders

Modified binders (SABITA, 1994, Manual 15) are suited for seals on roads that have cracks up to 3 mm in width and crack activity up to 200 μm movement (medium active cracks) without pre-treatment of the cracks. The cracking in most cases will not be permanently prevented, but will delay the onset of cracking after resealing. Modified binders also may be used on new construction where the base is flexible, and low

maintenance is required. These binders are also used as stress-absorbing membranes and interlayers.

Other uses include:

- Road is to be opened within 1-2 hrs after application

- Enhanced performance of seal under traffic or harsh environmental conditions

- Repair fatigue cracking

RMB, Rubber Modified Bitumen, is manufactured with 150/200 pen or 80/100 pen (the more general binder used), and has between 2 % and 5 % SBR added, depending on the requirements from the seal.

Emery et al (1999) summarise the concentration levels of modifier used in practice:

3 % SBS by mass provides benefits similar to SBR of similar concentration levels, i.e. RMB, where bitumen still dominates the binder properties, and there is limited modification benefit. 3 to 8 % SBS allow distinct network formation, and both the bitumen and SBS influence the properties (this is the usual range for modification for seals and asphalts). Above 8 % SBS dominates the properties, and typical use would be crack sealant.

Common types of SBS used in South Africa include both branched and linear structure types of SBS, with 30 to 31 % styrene content in the SBSpolymer. Both linear and branched types of SBS are recommended for use in seals (and asphalts), but the branched types provide the greatest increase in softening point.

A2.7.5   Bitumen Rubber

Bitumen rubber is utilized to reduce the seals tendency to bleed, wash or strip, especially in the prevention of reflective cracking.

A2.7.6   Penetration, Viscosity and Performance Graded Bitumen

These bitumens are supplied to the required specification, and applied through heating to spray (applications) temperature. Penetration grade hot applied bitumen is the base bitumen for road seals, usually of 80/100 or 150/200 penetration grade depending on climate and season applied.

A2.7.7   Selection of Binder

A2.7.7.1 Factors Influencing Binder Selection

TRH3 (CSRA, 1998) summarises the factors influencing choice of binder:

(a)   Type and Purpose of Seal

Hot modified binders allow for a thicker film of binder, which enhances the ability to retard crack reflection, and ensures rapid adhesion to aggregate when traffic has to be accommodated immediately after resealing. These binders are less sensitive to bleeding under high traffic volumes and have better elastic properties than straight bitumen binders, allowing accommodation of higher pavement deflection, and low temperatures.

Fog sprays will be better applied by emulsions due to the low viscosity and resulting better penetration and lower binder application rates required, ensuring that the binder lies between the aggregate with only a thin film of binder on top of the aggregate, thus reducing the risk of pickup under traffic.

Sand seals will require the use of penetration grade or cut-back bitumen, depending on ambient temperature. An emulsion might form a wave in front of the sand curtain if sand spreader velocities are high.

Penetration coats are suited to emulsions due to their lower viscosities, while **tack coats** are best suited to penetration grade or cut-back bitumens due to high adhesive effects and higher viscosities, preventing run-off.

Anionic emulsion is usually suited to slurry production due to its slower breaking rate, and less sensitivity to the fine aggregate, although **cationic emulsion** may be preferred when the slurry is prone to stripping (when there is a high proportion of natural sand).

(b)   Climatic Conditions

Selection of binder depends also on climate: penetration grade bitumens can be cut-back in the field to suit colder weather conditions, or emulsions can be used.

Cationic emulsions are better suited to humid or colder climates (or moist aggregates from stockpile) due to their quicker breaking action than the anionic emulsions.

(c)   Price of Bitumen at Application

Life cycle costing will determine what type of binder to use, although available budget will often influence the choice of binder type.

(d)   Ease of Application

Available resources will determine which type of binder is most practically suited to an application, for example the more viscous hot applied modified binders have specific requirements from the distributors.

(e)   Durability and Long Term Performance of Binders

Penetration grade, cut back and emulsion bitumens are durable, and thus suitable for single and double seals. Experience (TRH3, CSRA, 1998) has shown that modified binders are superior to conventional "straight" binders. There is also distinction between homogeneous and non-homogeneous binders with their superior qualities.

(f)   Compatibility with Aggregates

The properties of aggregates in South Africa vary a great deal. The binder must be selected to ensure good adhesion with the specific aggregate to be used. Dusty aggregates must be avoided.

(g)   Traffic

The type and volume of traffic are the main criteria to be considered during the selection of binder. Where the traffic volume is high, and additional binder is required to develop enough strength to hold the aggregate in the critical period after spraying (24 to 48 hrs), a binder that is resistant to bleeding (bitumen rubber or modified binder) could be used.

Recommended choice of binder is summarised as follows in Table A2.4 (TRH3, CSRA 1998):

Table A2.4: Recommended Bitumen Binder for Service Conditions (CSRA, 1998)

Traffic (elv/l/d)	Winter: Dry	Summer: Dry	Winter and Rain	Summer and Rain
<10 000	(i) 80/100 pen bit + cutter (ii) MC 3000 (iii) Emulsion (80/100 pen base bitumen) (iv) Lowveld – 80/100 pen bitumen (v) Modified hot binder or emulsion	(i) 80/100 pen bitumen (ii) 65% emulsion (80/100 pen base bitumen) (iii) Highveld – 80/100 pen bitumen (iv) Modified hot binder or emulsion	(i) Cationic emulsion (quick setting) (ii) MC 3000 (iii) Modified hot binder	(i) 80/100 pen bitumen + 2 % cutter (ii) Cationic emulsion (iii) Modified hot binder
10 000 – 20 000	(i) 80/100 pen bitumen + cutter Modified hot binder or emulsion	(i) 80/100 pen bitumen (ii) Modified hot binder or emulsion	(i) Modified hot binder or emulsion	(i) 80/100 pen bitumen + 2% cutter (ii) Cationic emulsion (iii) Modified hot binder
20 000 +	(i) Modified hot binder	(ii) Modified hot binder	(i) Modified hot binder	(i) Modified hot binder

(h)　　Road Geometry

Steep gradients or intersections require the use of modified binders to increase viscosity and elasticity, to counter the additional traffic forces.

A2.7.7.2 Factors Influencing Selection of Binder Grade

TRH3 (1998) provides guidance into the selection of binder grade:

- Purpose of binder (pre-coating, tack coat, penetration spray, etc.).

- Road surface temperatures (minimum temperatures affect brittleness, maximum temperatures affect softness, especially in the early life of the seal).

- Road geometry (softer grades run off during construction, intersections and curves add load to the seal).

- Traffic (higher traffic: harder binder).

- Pavement deflection (higher deflection, softer binder).

- Aggregate adhesion (greater adhesion allows use of a harder binder).

A3   AGGREGATE

A3.1   SCOPE

This section provides additional background regarding the influences aggregate, and "seal stone" have on seal performance. Aggregate is used in the seal as the wearing course.

A3.2   CLASSIFICATION OF ROCK TYPES USED IN ROAD SURFACING SEAL CONSTRUCTION

Classification of rock types, as defined in TRH 14 (CSRA, 1985) for road construction, are grouped on the basis of similar engineering properties. This grouping is based primarily on the presence or absence of quartz due to its influence on the durability of the aggregate processed from the parent rock.

The groups most suitable for use as road surfacing seal aggregate are summarised below:

- **Basic crystalline rocks**

  Granular to dense, usually dark coloured (except for diorite), with little or no quartz (become positively charged in water) (Hoiberg 1965). Decompose to expansive montmorillonite clay.

  Within South Africa frequently used members of this group include: dolerite, andesite, basalt, diabase, and diorite.

- **Acid crystalline rocks**

  Granular to dense, light in colour, with much quartz. Minerals other than quartz decompose to non-expansive kaolinite clay (become negatively charged in water).

  Within South Africa, frequently used members of this group include granite, felsite and gneiss.

- **High-silica rocks**

  Light and dark colours, dense, very hard, composed entirely of quartz or silica, and decompose to sand or gravel.

  Members of this group include chert, vein quartz and quartzite.

Acid and basic crystalline rock types are the most frequently used natural road construction materials in Southern Africa. Apart from the high-silica rocks, rocks of the remaining groups – **Aranaceous, argillaceous, carbsonate, diamictite, metalliferous and pedogenic** – are not usually used in surfacing seals due to their inherent characteristics (strength, durability) not being suitable for adequate seal construction or performance. The exception is the arenaceous rock types (e.g. sandstone, siltstone) with a siliceous matrix, which are known commercially as "quartzite", but have sufficient crushing strength.

An alternative method of classification arranges aggregates in terms of silica and alkaline, as shown in Figure A3.1 below:

BASIC

←

("electropositive")   Content of alkaline, %

```
        100   90    80    70    60    50    40    30    20    10    0
      ┌─────────────────────────────────────────────────────────┐
      │ Marble │                                                  │
      │   Limestone                                              │
      │                                                          │
      │                    │ Basalt │                           │
      │                       │ Diorite │                       │
      │                              Sandstone                  │
      │                          │ Granite │                    │
      │                                      │ Quartzite │       │
      └─────────────────────────────────────────────────────────┘
        0    10    20    30    40    50    60    70    80    90   100
```

Content of silica, %   ACIDIC

→

("electronegative")
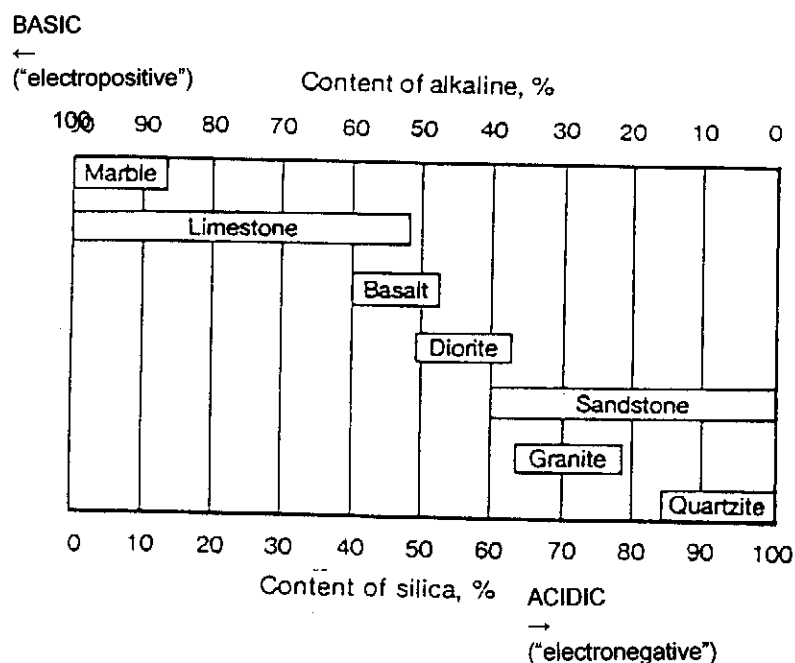
Figure A3.1: Classification of Aggregates (CSRA, 1985)

A3.3   SPECIFICATIONS AND PROPERTIES

Aggregates recommended for use in surfacing seals in South Africa, to ensure optimal performance, must comply with the SABS 1200 M (1996) specification (referring also to SABS 1083), for grading, crushing strength (Aggregate Crushing Value – ACV and 10 % FACT), Flakiness Index, polished stone value, fines and dust content, adhesion and sand equivalent values (TRH 3, CSRA, 1998).

Fresh or slightly weathered rock should be crushed for use in surfacings. TRH14 (CSRA, 1985) provides further insight into the desired specifications and properties of surfacing seal aggregate.

A3.3.1 Grading

The recommended grading envelopes for the various types of single and double seals are provided in TRH 14 (CSRA, 1985). Nominal sizes range from 19,0, 16,0, 13,2, 9,5, and 6,7 mm. Lately 4,75 mm nominal size is used in some seals, such as choke seals.

Fines and dust content should be kept as low as possible, and the above gradings reflect the single size aggregates as required in surfacing seals.

A3.3.2 Crushing Strength

Strength is one of the most important criteria for the assessment of durability and quality. Strength (crushing strength as applicable to road construction materials) is a natural property of rock, which varies with the type of rock and its stage of weathering. Strength provides a measure of the rock, and thus, aggregate durability.

Either the 10 % (ten percent) Fines Aggregate Crushing Test (10 % FACT: Force required to crush 10 % of the stone rock), 210 kN force required minimum, or Aggregate Crushing Value (ACV), 21 % maximum crushing under the prescribed test load, are specified.

As indicated above, in South Africa only the basic and acidic rock types have the required crushing strength to satisfy the SABS 1083 specification for aggregate for surfacing seals, with the possible exception of siliceous matrix sandstones.

A3.3.3 Flakiness Index

The tendency of a rock to break into cubical or flaky chips during crushing is partly a natural property, and partly a product of the technique of crushing. Coarse grained rock is especially difficult, however, to crush satisfactorily, with respect to cubical or flakiness properties required. Flakiness index required, maximum, is between 25 % and 35 % passing through the test gauges, depending on nominal size.

A3.3.4   Polished Stone Value

The Polished Stone Value (PSV) indicates the frictional resistance of the aggregate, and is also a natural property of the aggregate. A stone of PSV value in excess of 80 is considered not to polish. The minimum desired PSV value is 50 to 55.

A3.3.5   Stone-Bitumen Adhesion

Bitumen does not adhere well to "acid" rocks, such as rocks containing quartz. Cationic bitumen emulsions are used in these circumstances to limit the non-adhesion risk with the fresh bitumen, and to enhance as much as possible the adhesion to the bitumen. Texture, however, is also a guide to where adhesion problems will occur. Medium to fine grained rocks are not likely to cause stripping of binder, while the coarse grained rocks, which produce the flat and smooth faces of large minerals, are inclined to strip. Very dense to glassy rocks which develop smooth textured crushing faces are very prone to stripping from the bitumen. The Riedel and Weber test (CSRA, 1986, TMH1) is available as a stripping test, with value <1 unsatisfactory ranging to 5 as excellent.

A3.3.6   Fines, Dust Content, Sand Equivalent Value

The presence of fines and dust content must be limited as specified to ensure maximum opportunity for the seal aggregate to adhere to the bitumen. Fines content is limited to 0,5 % and zero dust is desired (grade N stone). Sand equivalent value is specified to limit the degree of contamination by clayey material (minimum value 35 %).

A3.4   PRETREATMENT

A3.4.1   Precoating

Precoating is carried out when the wetting and adhesion of the stone by the binder is required to be enhanced specifically when a binder with high viscosity is used, or dust content is to be neutralised. Precoating is not used for emulsions (due to their lower viscosity). The fluid used to precoat the stone is usually a low viscosity tar product.

A3.4.2   Wetting

The slight wetting of aggregate when emulsion binder is to be used, is recommended, to lower surface tension, and thus accelerate breaking of the emulsion.

A4   PAVEMENTS

A4.1   SCOPE

This section summarises the background aspects of the supporting structure for the seal in the pavement.

A4.2   SOUTH AFRICAN TRENDS

The pavement layers are the structure that transfers the imposed traffic loads to the underlying in-situ sub-grade. In South Africa both flexible and rigid pavements are utilised.

Flexible pavements are comprised of either natural or cemented, or modified gravel or crushed stone layer works (as opposed to rigid concrete pavements). The higher volume roads usually have the higher cost and quality cemented gravel sub-base/ crushed stone base combination, while the wetter climate coastal roads are often characterised by the use of asphalt base layers.

The road surfacing seal is used to provide protection from traffic load abrasion, and the environment, to the pavement base.

The seal is thus applied usually to a granular base, either of crushed or natural unbound gravel material. However, with the recent trend to in-situ pavement layer recycling, and on roads constructed with marginal materials, seals are often being applied to stabilized gravel layers, either cemented or bitumen stabilised material.

A4.3   MAJOR MATERIAL TYPES AND BEHAVIOUR

The classification of materials for road construction is made according to their behaviour. The most common types of material used for the construction of pavement layers are:

- Granular Materials

    These Materials show stress-dependent behaviour, which under repeated stresses, deforms through shear and/or densification (CSRA, 1996, TRH4). Deformation is usually visible in the form of rutting or longitudinal cracking. This type of material ranges in quality from dense-graded, unweathered, crushed stone, through to blends with natural fine aggregate (for use as base and sub-base), and high and low quality natural gravels (for use as selected layers).

- Bituminous Materials

Bituminous materials for pavement layer works include:

- Bitumen emulsion stabilised or modified

- Hot mix asphalt materials

Specifically the hot mix asphalts are visco-elastic, and may be temperature dependent. Under repeated stresses this type of material may crack and deform.

- Cemented Materials

Cemented materials are initially elastic, have tensile strength and usually crack under repeated flexure, shrinkage or drying. Cement or lime treated materials are used. Usually an unbound pavement layer is desired to cover this material to avoid reflective cracking from the cemented layers to the surface.

A4.4 MATERIAL DEPTH

Material depth is the concept (CSRA, 1996, TRH4) used to denote the depth below the riding surface of the pavement to which the soil characteristics have a significant effect on pavement behaviour. This depth of influence is affected by the moisture regime, due to moisture influencing the unbound (i.e. un-stabilised or unmodified) materials load bearing characteristics. Below material depth the strength and density are assumed to have negligible effect on the pavement behaviour (in terms of response to load). This material depth approximates the "cover" needed over an in-situ soil of one to two percent soaked CBR.

The material depth varies according to load, as a higher or concentrated load will require greater distribution than a light load. Material depth varies from 1,0 m to 1,2 m for a high class road with heavy traffic, to 700 mm for a low class road, with lightly trafficked pavement.

Of relevance to this project will be the need to ensure the scaled down performance tests have sufficient material depth below the seal to ensure seal performance is not unduly influenced.

A4.5   STRENGTH AND DENSITY

Of specific reference to the seal are the parameters affecting the surface to be sealed. As indicated above, the base is usually a granular material, although in some cases stabilised with cement or bitumen.

The strength of a granular material is specified in TRH 4 (CSRA, 1996) and TRH 14 (CSRA, 1985). The base varies usually from:

- G1 and G2

    Graded crushed stone, uncemented, maximum size 37,5 mm, compacted to 86 – 88 % apparent relative density. Plasticity index < 4 (G1) and < 6 (G2).

- G4 and in some cases G5 (lower trafficked roads)

    Crushed or natural gravel, minimum CBR 80 % (G4) and 45 % (G5), density 95 % (G5) to 98 % (G4) of Mod AASHTO density.

- C3 and C4

    Cemented natural gravel, UCS 0,75 – 15 MPa (C4) and 1 to 3,5 MPa (C3), compacted to 95 – 97 % Mod AASHTO.

- BEM and BES

    The modified and stabilised bitumen treated gravel (residual bitumen 0,6 to 5 %), CBR = 45 %, UCS = 500 kPa at 95 % Mod AAHSTO, compacted to 100 – 102 % Mod AASHTO density. ITS = 100 kPa specified for BES.

The base layer is thus a densely compacted layer, of strength adequate to accommodate the expected traffic load. For the seal design, the expected penetration under load of the seal stone is measured, to enable adjustments to the bitumen binder to be made.
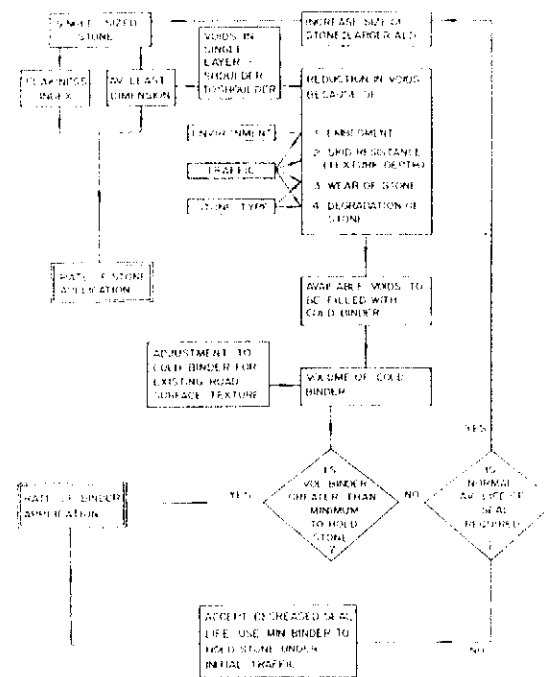
A5   SEALS

Additional information supporting that of the literature analysis is provided in this section of the Appendix.

A5.1   DESIGN METHODS

A5.1.1   Rational Design Method

The evolution of the aggregate void volume based seal design method introduced by Hansen in the 1930's is the Rational Method, described by Marais (1979) in Figure A5.1 below:

Figure A5.1: Design Process: Single Surface Treatment (Marais, 1979)

The rational approach calculates the actual void percentages based on the properties of the aggregate and adjusts these voids depending on quantitative assessment of:

• Degree of embedment of the aggregate in the underlying layer

• Surface wear of the aggregate due to traffic

• Minimum surface texture required to provide adequate skid resistance

The rational method also determines the quantity of binder needed to fill the remaining voids and other factors that influence the quantity of binder:

- Texture of the surface to be sealed

- Absorption of the binder by aggregate

- Effect of the environment and traffic on the condition of the binder

- Minimum quantity of binder required for stone retention

Minor adjustments to allow for other factors such as geometry and slick surfaces can be made.

From Marais, the plot of **void content** of single sized stone against flakiness index of stone (NAASA, 1988):

$$V_1 = 0.22 \, FI + 42.1$$ (Eq. A5.1)

V_1 = % void volume in loose stone

FI = Flakiness Index

Voids (%) $V_2 = 67(0,8 - e^{-0,16ALD})$ – as % of ALD (Eq. A5.2)

Thus, available voids are:

$$V_a = V_2 - V_e - V_w$$ (Eq. A5.3)

Where V_e is % voids embedded, and V_w is % voids lost through wear (NAASA, 1988).

From NAASA (1988), **binder application rate** (BR), is:

$$BR = V_a/100 \times ALD +/- \text{ texture allowance}$$ (Eq. A5.4)

% voids are related to ALD to give a unit area application rate of binder, and are calculated in terms of a % of ALD volume.

Aggregate Spread Rate is given as determined above:

$$SR_t = 1000/ALD \, (100-V_1 \, / \, 100-V_2)$$ (Eq. A5.5)

The above description of the Rational Method has been developed and used by South Africa (Marais and Semmelink), and is also used in Australia (NAASRA), as amended by Potter and Church, although some Australian States use a simplified rational approach, and the USA as described by Marek and Herrin (this has been summarised by NAASRA (1988)).

The Modified Tray Test as reported by Marais *et al* (1979) may be used for theoretical void calculation. NAASRA (1988) report that the theoretical assumption that aggregate re-orientates to ALD normal to the pavement is not always realised in practice, especially under light traffic, use of the negative embedment allowance has been propagated.

A5.1.2   Single and Double Seals

Semmelink (1987) proposed a rational seal design approach using actual measured void content, and the accurate determination of aggregate spread rate. The determination of correct binder and aggregate application was identified as critical to the performance of seals.

An amount of empty space - voids - is present in single and double seals. A portion of the voids is lost due to embedment of aggregate and wear of aggregate. A portion of voids is required for skid resistance and resistance to hydroplaning (0,64 mm Mean Texture Depth – sand patch test – is recommended). Most design methods recommended determination of void content as a function of Average Least Dimension of the aggregate. The NIRTR (Semmelink, 1987) found scatter in results examining this supposition.

Semmelink proposed the determination of binder quantity in a seal through the Modified Tray Test (Semmelink, 1987). This test measured the actual – true – void content and the Equivalent Layer Thickness (ELT). In this test a standard 0,05 m^2 circular tray is lined with a loose membrane cloth placed above aggregate packed at desired orientation shoulder to shoulder. The volume of space occupied by aggregate and voids is determined when sand volume is subtracted from sand volume required to fill the total tray volume. Void volume is determined by then subtracting aggregate volume (calculated from mass of aggregate divided by relative density of the aggregate). Equivalent Layer Thickness is determined by dividing the original calculated volume of aggregate and voids by the tray area.

Estimated embedment is determined by the Ball Penetration Test (using a 19 mm steel ball and given one blow with a Marshall Hammer, adjusted for temperature – Semmelink, 1987, TRR1106), and wear using the 10 % FACT, both as indicated by Marais (1979).

The total expected void loss is then calculated from the expected void loss due to wear, and embedment. The method assumes *that rolling embedment under construction is 50 % of total expected embedment.* The method then uses the assumption that at least 50 % of the voids then remaining must be filled with bitumen to prevent whip-off. The remaining fraction must be greater than the minimum void fraction to ensure adequate

skid resistance, using an expected seal life of 10 years. A pro rata determination of the remaining life can be calculated should the remaining void fraction be less than the desired minimum.

Aggregate spread rate is determined directly using the bulk volume of the aggregate used to fill the pan used in the modified tray test. A check of this can be made by calculating the theoretical spread rate using the ELT, void content of the single layer of stone, and the void content of the bulk volume. The NIRTR found a direct correlation between these two methods. Practically it was found that the actual spread rate should be increased by 5 % to allow for fluctuation in void content of the loose aggregate.

When considering double seals, Semmelink found that there was good relationship between the void contents of each of the separate seal layers and the void content of the double layer. There was also good relationship between the ELT's of the separate layers and that of the double layer, the only proviso that the bottom layer spread rate be reduced by 5 % to allow for keying in of the top layer. 65 % of the voids of the double seal were to be filled to ensure that at least 50 % of the top layer is covered with binder. The method then proceeds as with the single seal, including the determination of aggregate spread rate.

A5.1.3   Modified Binder Seals

Semmelink (1987) modified the "modified tray test" as part of the rational design method of bitumen rubber seals. The modification requires the use of adhesive on a paper lining of the tray, with aggregate being dropped onto the adhesive, as opposed to being placed on the tray bottom. This simulated the higher viscosity of the modified binder, and aggregate not rotating to average least dimension. The method then proceeds as above.

Hanekom *et al* (1999) report on the postulate that **due to the differing stone orientation of aggregate for modified binder seals, and reduced expectation of penetration,** binder can be increased between 1 and 1,6 times that of straight binder seals. The Draft TRH3 (CSRA, 1998) design curves reflect the increased binder design application for modified binder, and also relate the effect to the expected impact of traffic.

TRH3 (CSRA, 1998) provides an indication of the reduced expected embedment, and higher remaining voids due to binder application viscosity for the modified binders.

A5.1.4   Summary of TRH3 (CSRA, 1998) Seal Design Method

The design procedure for single seals is summarised as:

- Determine most probable traffic for each unique section.

  Use an equivalent light vehicle (elv) factor of 40 for **heavy** (E80) to **light** (elv) vehicle conversion. Calculate total *elv/lane/day*.

- Determine potential embedment from ball penetration tests (CSRA, 1984, TMH6-Method ST-4).

- Use ALD value of aggregate to determine, with required texture depth and ball-penetration value, to determine theoretical minimum and maximum binder application (net cold) from design curves.

- Adjust binder application rates for surface texture, or determine pre-treatment required.

- Adjust binder application for climate.

- Adjust binder application for steep gradients and slow speeds.

- Further adjustments to aggregate and binder spread rates are advised for: flakiness of aggregate, porous, fatty surfaces, low traffic, cold micro-areas, porous aggregates, construction traffic.

- For modified binders: revise aggregate volumes, orientation, and penetration, due to increased viscosity of the binder.

A5.1.5   Historical Design Methods (Roads Authorities)

Within South Africa, prior to 1994 (and prior to the evolution of the new TRH3 (CSRA, 1998)), five design methods were commonly used by the different Roads Authorities.

These methods were the CPA, OFS, TPA, NPA and NIRTR methods. These methods vary in the determination of the binder content required to hold a single layer of stone in place on the underlying surface, under traffic. The amount of binder is always based on the ALD of the stone, the relationship constant with some methods, but varying with traffic, surface hardness or traffic action.

The NIRTR method is a summary of the Rational method (including Semmelink's modified pan test), with predetermined tables provided to determine minimum and maximum binder

application against measured ball penetration and stone ALD, stone spread rate, embedment and wear under traffic, and allowance for additional binder for varying surface texture.

The CPA method uses the relationship between ALD and binder application, varying with surface texture and traffic (for the double seal).

The NPA method makes allowance for embedment and traffic, while the OFS method makes allowance for traffic only. The TPA method makes allowance for climatic zones.

Regarding *Empirical Methods*, on the International front, Australia uses a design procedure based on that developed by Hanson (based on the assumption that aggregate exposed to traffic rotates to ALD, and a predetermined portion of the voids within the layer must be filled). This method is similar to that of the NIRTR. Australian pavements are predominantly constructed from a base of crushed or natural material over a compacted sub-grade, with a light sprayed seal surface treatment. Traffic over much of the network is low volume however. Specific care is taken during construction to ensure satisfactory performance of the seal.

In Australia, the NAASRA (1988) reviewed the status of sprayed seal design, and in 1988 highlighted that the basis of Australian seal design was the Hanson method, where the original void assumptions were developed at the time with traffic and material assumptions not directly applicable to universal use, and required adjustments based on experience of the user. Research into a more rational approach (amongst others Marais and Semmelink) had contributed to revision of the design practice, in terms of allowance for voids in aggregate, embedment and surface texture. Aggregate spread rate and bitumen application rate were identified as the main factors in bitumen spray seal design. The voids available to be filled with bitumen are expressed as available volume: unembedded void volume less volume embedded and volume reduced by wear. Aggregate application rate is calculated in terms of Average least dimension, and binder application either empirically or in terms of available volume and ALD. Of interest is that when using the empirical method, the refined Hanson method, Australian practice (NAASRA, 1988), of the initial voids in loose aggregate, void volume is 50 %, reducing to 20 % when compacted. In the empirical method the 20 % voids are further adjusted to allow for traffic effects, with further refinement to accommodate surface texture. A revised seal design guide was provided in 1995, based on the same principles: ALD and Traffic (Giummarra, 1995).

NAASRA (1988) examined seal design procedures elsewhere, and reported that New Zealand authorities base aggregate spread rate on a recipe approach, and binder application of 0,15 x ALD adjusted for texture depth and traffic usage, with a spray rate chart for reseals and second applications, including the sand circle texture test which determines when a reseal should be preceded by a void filling treatment.

The ARRB (Oliver, 1999) report that the Australian design procedure was further validated in 1999. The new proposed method arising from this validation was still based on the ALD and traffic volume, with the revision on the allowance for surface texture inclusion in the method. Oliver reports that the basic bitumen application rate in the new method is higher than the existing method. Also, for reseals the binder allowance for texture in the existing seal must be adjusted for the degree of intrusion (interlock) of the new reseal, where a texture allowance is subtracted from the binder application rate. This texture allowance is dependent on traffic volume and existing surface texture. A revised seal design guide was published in 1995, based on the same principals: ALD and traffic (Giummarra, 1995).

The United Kingdom roads authorities utilise the TRRL Road Note 39 (Nicholls, 1996). Aggregate spread rate is selected from a table in terms of nominal size, adjusted for shape and specific gravity. Binder application is selected for each type of pavement, binder, traffic category and aggregate size, as tabulated. Overseas Road Note includes adjustments for traffic, existing surface condition, climatic conditions and type of aggregate.

The USA (NAASRA, 1988) Empirical seal design methodology is characterised by three general groupings:

- Asphalt Institute method, similar to the Australian NAASRA method

- Modified Kearby method

  The basis of this method is:

$$A = 5.16(1 - W/62.4G)T + V \qquad \text{(Eq. A5.6)}$$

  A = binder application (gal/sq. yd)

  E = embedment

  W = loose unit wt of aggregate

G = specific gravity of aggregate

T = traffic correction factor

V = correction for surface condition

T ranges from 1.0 to 1.2 (from heavy to light traffic)

- Kandhal method

    PS Kandhal developed a Nomograph to assist in the design of low volume, low cost roads for use by Maintenance Managers and Contractors. Nomographs are available for aggregate spread rate and binder application rate.

NAASRA (1988) report:

- More research is required to define more accurately the optimum design aggregate spread rate as reflected in their Empirical Method. Assumptions on whip-off, using V_1 as 50 % void volume of loose bulk stone, and 25 % as void volume of single layer of stone V_2. The use of the Modified Tray Test as a possibility has been identified.

- Effect of traffic on reduction of voids through wear and embedment requires additional refinement.

- Additional research into allowances for surface condition has been identified.

Texas DoT (TxDoT, 2004) have focussed on the modified Kearly Method (with adjustment for synthetic binder and season of construction) and the McLeod Design Method. The McLeod Method is based on the application of a single stone layer (i.e. single seal) and filling 70 % of voids with binder. Voids in the loose aggregate layer are calculated in a ratio of loose weight/volume to 62,4 times bulk specific gravity. Binder applications are still related to ALD, and the determined voids.

A5.1.6   Modified Binders (Additional Aspects)

In addition to the design aspects included under the rational method, Davidson (Davidson, c.1988) differentiates between the Stress Absorbing Membrane (SAM) (effectively a bitumen rubber single seal) and the Stress Absorbing Membrane Interlayer (SAMI) (a bitumen rubber single seal that is overlain by an asphalt wearing course). Larger aggregates are recommended in order for maximum use being made of a high bitumen

application, to enable the elimination of the reflection of surfacing cracks: SAM, 9,5 ,13,2 or 16 mm aggregate, and SAMI 9,5 or 13,2 mm aggregate. Davidson reports that a binder application of 1,8 to 2,5l/m² is required to prevent crack reflection into the new surfacing. Increased aggregate application of up to 10 % was recommended for the SAM due to the aggregate not rotating to ALD in the higher viscosity binder. Precoating of the aggregate is required.

Typical composition of the binder blend is:

Bitumen: 77,5 %

Rubber: 20 %

Cutter: 2,5 % by mass

Application temperature is 180 °C, applied within 150 minutes of completion of blending and digestion (60 to 75 minutes).

Davidson provides recommended application rates with factoring for traffic and condition of existing surface.

A5.2   PREDICTION OF SEAL COAT LIFE

Roque *et al* (1991) report that from their investigation it will be possible to develop a method that could be used to predict seal coat life (with the consideration that excessive aggregate loss does not occur). When using test seals constructed with bituminous emulsion, placed on an existing asphalt, they experienced consistent patterns of reduction in Mean Texture Depth (MTD) over time (and thus traffic) for all test sections. It was also found that the rate of reduction was greater in the warm months than in the cool months. They also deduced that the reduction in MTD in the cooler months was due to aggregate wear, as the asphalt underlying layer was felt to be sufficiently stiff to limit further embedment. It was also assumed that the rate of wear was the same in the warm and cool months.

Using the above findings, a simple model was developed to develop a prediction model, calculating the number of wheel passes to reach a terminal MTD. Terminal MTD can be deduced from that required for an acceptable level of skid resistance.

The basic elements required for the prediction of seal coat life are:

- Wear rate of the aggregate under traffic loading

- Stiffness characteristics of the underlying surface as related to the rate of embedment

- Estimated traffic volume and distribution

In the determination of their model, it was assumed that embedment reaches equilibrium after three years (as suggested by Marais). However, the above investigation did not indicate that embedment equilibrium was reached.

Rust and Hugo (c.1988) have initiated an investigation into the use of the crack movement simulator to determine the performance characteristics of binders with respect to the behaviour under fatigue testing, towards determining performance related criteria for the design and specification of binders (with special emphasis on modified binders).

Zhu and Pidwerbesky (1998) utilised three of the available limited models for predicting seal performance, and enhanced these for application, although they indicate further implementation work in laboratory and field is required to validate the prediction models. Of the number of factors that influence the performance of the seal, three independent criteria were identified for application for laboratory seal performance and estimating its serviceable life. These are:

- Cracking : parameter measured is percentage sealed with visible cracking

- Stripping : parameter stone loss in wheel path

- Flushing : texture depth (mm) in wheel path

The indication and progression of the distress types are illustrated in Figure A5.2.
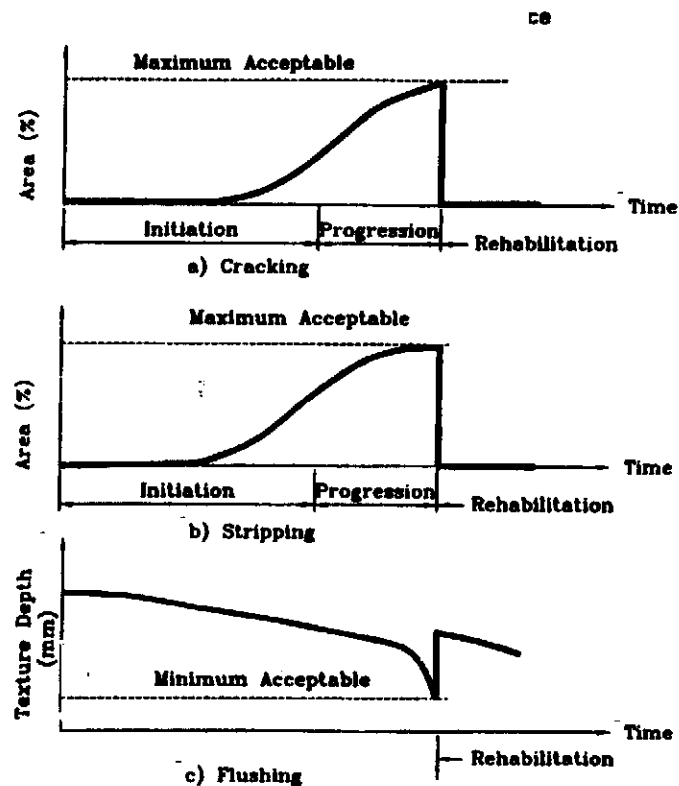
Figure A5.2: Type of Seal Distress and Performance (Zhu, Pidwerbesky (1998))

The summary of the form of the performance models are:

- Cracking Model

    Cracking occurs under the continued actions of traffic and environment (especially thermal movement). The model proposed is as function of the form:

    AGE at initiation of cracking = ƒ (critical viscosity at cracking,

    modified pavement structural number, construction quality indication, mean minimum and maximum daily air and bitumen temperature, seal durability test result, annual traffic) (Eq. A5.6)

- Stripping Model

    Stripping occurs under traffic loading, bitumen harding, and affected by quality of construction. The model proposed is a function of the form:

AGE at initiation of stripping = ƒ   (roller (construction), factor,

speed factor, annual traffic, mean annual minimum
temperature, seal durability test result)   (Eq. A5.7)

• Flushing Model

Flushing occurs as a result of chip embedment into the road surface, under traffic.
The model proposed is a function in the form:

AGE at initiation of flushing = ƒ   (vehicles per day, ALD of

stone, limit of texture depth required, bitumen application rate,
embedded voids ratio, i.e. embedment under construction)   (Eq. A5.8)

The performance parameters of stripping, cracking and flushing are included in the
analysis of literature and in the identification of critical parameters for examination through
research (refer to Chapter 3).

A5.3   CONSTRUCTION ISSUES

SABITA (1994) summarised the construction issues regarding seal application.

A5.3.1   Plant

All plant and equipment operated on the road during construction of road surfacing seals
must be of rated capacity and in good working order (SABITA, 1994, Manual 15). No fuel
or lubrication or hydraulic fluid leaks should be accepted.

The equipment required is:

• **Binder distributor**

Binder distributors are used for both hot and cold applied modified or "straight"
binders. High viscosity, hot applied modified binders may require a specialised
distributor (i.e. with high capacity pump and larger spray nozzles). The distributor
must comply with TMH2 "National Standards for the Spraying Performance of
Binder Distributors". The variation of spray application between 100 mm strips of
the spray bar length (excluding the outer 300 mm) must not be greater than 12 %,
especially with the viscous modified binders.

- **Chip spreaders**

  The chip spreader must be able to apply the aggregate uniformly over between 2,4 and 4 m width, and must be adjustable to allow the correct application of stone. At least one self-propelled chip spreader is required. The non-self propelled spreader must be capable of being quickly attached to the rear of a truck.

- **Rollers**

  The following rollers are required:

  Pneumatic Tyred Rollers

  These are to be self-propelled, smooth pneumatic wheels of uniform size and diameter. The minimum weight is 15 t. Suitable devices for keeping the wheels clean must be attached. The wheels must be spaced to provide complete coverage on one roller pass.

  Flat Steel Rollers

  These should be self propelled, three wheel or tandem rollers, of mass 6 to 8 t. Suitable devices for keeping the wheels clean must be attached.

- **Brooms**

  Drag and rotary brooms are required to enhance even distribution of stone chips over the surface without dislodging stone from the binder film.

- **Front end loader**

  A front end loader of adequate capacity to ensure a continuous supply of aggregate from the stockpiles to the trucks must be available.

- **Haul trucks**

  Sufficient trucks must be available to ensure continuous supply of aggregate to the chip spreader during the sealing operation.

A5.3.2 Preparation of Surface to be Sealed

Areas to be sealed are to be dry and free of all dust, dirt, animal dung, oil or any other deleterious material. Newly constructed surfaces must be checked for compliance with the specification (non-compliance must be corrected before sealing). Existing surfaces to be sealed should be pre-treated if required to correct any failures or distress. Major failures must be repaired as specified.

The area to be sealed (centerline where applicable) is to be marked by hemp or sisal twine, secured by nails every 15 m and every 5 m on curves.

A5.3.3 Construction

- **Weather**

  Minimum application temperatures are specified:

  Hot applied binders

    B8(80/100 pen): 25 °C and rising (modified)

    B4(150/200 pen): 20 °C and rising (modified)

  Cold – applied binders

    Cationic emulsion: 10 °C and rising (modified)

    Sunny and fine conditions are preferable.

- **Application of Binder and Aggregate**

  Rates of application of seal aggregate and binder will be determined through the seal design process.

  Plant and material must be available and ready for use.

  Should prevailing weather conditions be suitable, construction may proceed:

    - Binder to be sprayed, and immediately covered with aggregate by the chip spreaders in a manner as close behind the binder distributor as possible. All aggregate must be applied within 15 minutes of application of the binder. No

wheels of the plant may pass over the binder before aggregate has been applied. Binder volume sprayed must be within the capacity of the plant available to deliver and apply the aggregate.

-   Initial rolling by pneumatic roller is required immediately on hot-applied binders, and the roller must not be more than 10 m behind the spreader on the first pass. Emulsions: initial rolling should be with a 6t steel wheel roller, or with a pneumatic roller only after sufficient set is available to secure the aggregate firmly to prevent displacement under the pneumatic tyres.

-   Any areas with insufficient aggregate must be back-chipped.

-   Final rolling is required with a 15 to 20 t pneumatic tyred roller only, with a minimum of four coverages. The finished surface should have a well-knit appearance, uniform, and free from tyre marks. Loose aggregate must be broomed off with either a rotary broom or hand brooms, as directed.

•   **Joints between binder sprays**

Transverse junctions between separate binder applications (at beginning and end of run) must be constructed by using reinforced building paper (or equivalent) covering the previous work along the joint for a sufficient distance behind the joint. This ensures a straight joint, and that the distributor is travelling at required speed prior to application. Longitudinal joints must be constructed using the end nozzle flared to ensure $1/3^{rd}$ to $2/3^{rds}$ distribution of binder on the adjacent and actual distributor pulls.

•   **Protection of kerbs, channels, etc.**

Adjacent kerbs, channels, etc must be protected from being soiled by binder spray or run-off during application. Sheeting must be applied to these areas (sand is not recommended).

•   **Heating and circulation of binder**

Modified binders are more sensitive to the heating rate of gas burners compared to emulsions or straight bitumens. A slower heating rate (about half usual) combined with good circulation is recommended. In the case of SBR modified bitumen emulsions circulation is important to prevent rubber deposits on heating flues that

will result in blocked spray jets. Although SBR modified bitumen emulsions must not be excessively circulated as this could lead to premature breaking of the rubber latex, causing erratic spray application.

REFERENCES

Asphalt Academy, 2001, *"Technical Guideline: The use of Modified Bituminous Binders in Road Construction"*, TG1, CSIR, South Africa.

Committee of State Road Authorities (CSRA), 1998, *Technical Recommendations for Highways 3 Surfacing Seals for Rural and Urban Roads and Compendium of Design Methods for Surfacing Seals using in RSA,* Department of Transport, RSA for CSRA.

Committee of State Road Authorities, 1985, *Technical Recommendations for Highways 14 Guidelines for Road Construction Materials,* Department of Transport (RSA).

Committee of State Road Authorities, CSRA, 2996, *Technical recommendations for Highways 4 Structural Design of Interurban and Rural Road Pavements,* Department of Transport (RSA).

CSRA, 1984, *TMH6,* RSA, DoT, Pretoria.

CSRA, 1986, TMH1, Technical Methods for Highways, RSA DoT, Pretoria.

Davidson LK, c.1988, *A Surfacing Design Procedure to be used for Bitumen Rubber Single Seals.*

Emery S, O'Connell J, 1999, *Development of a High Performance SBS Modified Binder for Production,* 7th Conference on Asphalt Pavements for Southern Africa, Zimbabwe.

Fredrickson A G, 1961, *Principles and Applications of Rheology,* Prentice-Hall Inc.

Giummarra, GJ, 1995, *Sealed Local Roads Manual, Guidelines to Good Practice for the Construction, Maintenance and Rehabilitation of Pavements,* ARRB.

Green G, 1991, *South African Shell Bitumen Handbook,* Shell South Africa.

Hagos ET, 2002, *"Characterisation of Polymer Modified Bitumen (PMB)",* Dienstweg en Waterbouwkunde, Netherlands.

Hanekom AC, Fletcher E, Lewis T, 1999, *Rehabilitation of Roads with Double Seals Using Modified Binders,* 7th Conference on Asphalt Pavements for Southern Africa, Zimbabwe.

Hoiberg AJ (Editor), 1964: Vol 1, 1965: Vol 2 and 3, *Bituminous Materials: Asphalts, Tars, Pitches (Volumes 1,2 and 3),* Interscience Publishers.

Jordaan G, 1995, *Polymer and Rubber Modified Bitumen: Pro's and Cons,* SA Construction World.

Khattak MJ, Baladi GY, 1995, *Engineering Properties of Polymer-Modified Asphalt Mixtures.*

Marais CM, 1979, *Advances in the Design and Application of Bituminous Materials in Road Construction*, University of Natal.

NAASRA, 1988, Sprayed Seal Design Working Group (Editor Walker, N):, *Review of Sprayed Seal Design*, NAASRA Technical Report.

Nachenius R, 1988, *Some Properties of Bitumen Rubber Asphalt and Binders*, University of Stellenbosch, Thesis.

Nicholls JC, 1996, *Design Guide for Road Surface Dressing*, TRL Road Note 39 (Fourth Edition), Transportation Research Laboratory.

Oliver, J, 1999, *The Performance of Sprayed Seals*, AARB, Research Report ARR 326.

Robertson RE, c.1990, Branthaver JF, Plancher H, Duval JJ, Ensley EK, Harnsberger PM, Peterson JC, *Chemical Properties of Asphalts and their Relationships to Pavement Performance*, SHRP Asphalt Programme Symposium.

Roets PNJ, Renshaw RH, Edler T, 1994, *Effect of Changes to Manufacturing Process on Physical and Chemical Properties of Bitumen*, 6th Conference on Asphalt Pavements for Southern Africa.

Roque R, Anderson D, Thompson M, 1991, *Effect of Material, Design, and Construction Variables on Seal-Coat Performance*, Transportation Research Record 1300.

Rosenthal D, Asimov R M, 1971, *Introduction to Properties of Materials (Second Edition)*, Van Nostrand Reinhold Company.

Rust FC, Hugo F, c.1988, *Towards Performance – Related Design Criteria and Specifications for Modified Binders.*

SABITA, 1994, *Technical Guidelines for Seals Using Homogeneous Modified Binders, SABITA Manual 15.*

SABITA, 1996, *Review of South African bitumen specification to take cognisance of compositional balance relative to long term behaviour,* Contract Report CR-96/034, SA Department of Transport.

SABITA, 1996, *Review of South African bitumen specification to take cognisance of compositional balance relative to long term behaviour,* Contract Report CR-96/034, SA Department of Transport.

SABITA, 1998, *SABITA Advanced Bitumen Course*, Course Notes, Pretoria, RSA, February 1998.

Semmelink CJ, 1986, *Rational Design of Bitumen Rubber Seals According to the NIRTR Method using the Modified Tray Test*, National Institute for Road and Transport Research, CSIR, RSA.

South African Bureau of Standards, SABS, 2002, *Penetration Grade Bitumens*, SABS 307, Pretoria.

Srivastava A, Hofman PC, Molenaar AAA, 1992, *SBS Polymer Modified Asphalt Binder and its Implications in Overlay Design*, American Society for Testing and Materials.

TxDoT, 2004, *Seal Coat and Surface Treatment Manual*, Texas DoT.

Van de Ven MFC, van Assen EJ, 1999, *South African Bitumen Specifications and Compositional Balance*, 7th Conference on Asphalt Pavements for Southern Africa, Zimbabwe.

Van der Poel, 1954, *A General System Describing the Visco-Elastic Properties of Bitumens and its Relation to Routine Test Data.*

Whiteoak D, 1991, *"the Shell Bitumen Handbook"*, Shell Bitumen UK.

Zhu D, Pidwerbesky, 1998, *Chip Seal Performance Prediction Models*, Proceedings of the 9th Road Engineering Association of Asia and Australasia Conference, New Zealand, Volume 1, Transit New Zealand.

APPENDIX B

SPECIFICATIONS: BITUMEN FOR ROAD CONSTRUCTION

B1   HOT APPLIED BITUMEN

Source: SABS 307 (SABS, 2002): Extract

B1.1   SPECIFICATION: HOT APPLIED BITUMEN: GRADE REQUIREMENTS

The bitumen shall comply with the requirements specified below.

Property	Penetration Grade				Test method
	40/50	60/70	80/100	150/200	
	Requirements				
Penetration at 25 °C/100 g/5 s, 1/10 mm	40-50	60-70	80-100	150-200	ASTM D5-IP49
Softening point (ring and ball), °C	49-59	46-56	42-51	36-43	ASTM D36*
Viscosity at 60 °C, Pa.s	220-400	120-250	75-150	30-60	ASTM D4402[+]
Viscosity at 135 °C, Pa.s	0,27-0,65	0,22-0,45	0,15-0,40	0,12-0,30	ASTM D4402[+]
Performance when subjected to the rolling thin film oven test:					ASTM D2872
a) mass change, % (by mass fraction), max	0,5	0,5	0,5	0,5	ASTM D2872
b) viscosity at 60 °C, % of original, max	300	300	300	300	ASTM D4402[+]
c) softening point (ring and ball), °C, min	52	48	44	37	ASTM D36*
d) increase in softening point, °C, max	9	9	9	11	ASTM D36*
e) retained penetration, % of original, min	60	55	50	50	ASTM D5-ip49
Spot test[#], % xylene, max	30	30	30	30	AASHTO T102

[+] Recommended apparatus is the RV viscometer, using SC 4 spindles with thermosel system.

[#] Actual values to be reported in five-unit intervals.

* Using shouldered ring.

B2   CUTBACK BITUMEN

Source: (Emery, 1996)

B2.1   TYPICAL BINDER CONTENTS OF REFINERY CUTBACK BITUMENS

Grade	Typical Bitumen Content (% Volume)
MC-30	60
MC-70	67
MC-800	82
MC-3000	92
RC-250	78

General note: The bitumen content varies by batch, and so does the cutter: flux may be used.

B2.2   BINDER, CUTBACK, EMULSION AND MODIFIED BINDER SPECIFICATIONS

SABS 307 penetration grade bitumen specification applies to base bitumen:

Property	Penetration Grade				Test Method
	40/50	60/70 Road	80/100 Grade	150/200	
	B24	B12	B8	B4	
Penetration at 25°C/ 100 g/ 5s, 0,1 mm	40-50	60-70	80-100	150-200	ASTM D5 or IP49
Softening point, °C	49-59	46-56	42-51	36-43	ASTM D36*
Viscosity at 135°C, Pa.s., min	0,27	0,22	0,15	0,12	ASTM D4402[+]
Ductility at 10°C, cm, min	-	-	100	100	DIN 52013
Ductility at 15°C, cm, min	100	100	-	-	DIN 52013

Performance when subjected to the rolling thin film oven test:

Property	Penetration Grade				Test Method
	40/50	60/70	80/100	150/200	
Mass change, % (m/m), max	0,5	0,5	0,5	0,5	ASTM D2872
Viscosity at 60°C, % of original, max	300	300	300	300	ASTM D4402[+]
Retained penetration, % of original, min	60	55	50	50	ASTM DD5 or IP49
Spot test, xylene, max[+]	30	30	30	30	Aashto t102
Optional property Viscosity at 60°C, Pa.s	170-400	105-250	55-150	25-60	ASTM D4402[+]

Notes:

(i)   Penetration grade nomenclature is used when viscosity at 60°C is not specified.
      Road grade nomenclature is used when viscosity at 60 °C is also specified.

(ii) Brookfield RV series viscometer using SC4 spindles with Thermosel system.

(iii) Actual values to be in 5-unit intervals.

(iv) Using shouldered ring.

B2.3   CUTBACK BITUMENS

SABS 308	RC-250		MC-30		MC-70		MC-800		MC-3000		Test Method
	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	
Kinematic Viscosity 60°C, cSt	250	500	30	60	70	140	800	1600	3000	6000	ASTM D2170
Distillation, % by val of total distillate to 360°C											IP27 (ASTM D402)
to 190°C	-	-	0	15	-	-	-	-	-	-	
to 225°C	35	-	15	60	10	50	0	35	0	25	
to 260°C	60	-	50	85	40	80	10	60	0	40	
to 316°C	80	-	80	100	80	95	50	90	35	85	
Residue from distillation to 360°, % val of original sample	65	-	50	-	55	-	75	-	80	-	IP27 (ASTM D402)
Penetration at 25°C on residue from distillation	80	120	90	180	90	180	90	180	90	180	IP49 (ASTM D5)

General: The bitumen bases from which these cutback bitumens are manufactured comply with specifications for penetration grade bitumens. The cutback bitumen will be homogeneous, free from visible water and will not foam when heated to application temperature.

B3   BITUMEN EMULSIONS

Source: (Emery, 1996)

B3.1   ANIONIC BITUMEN EMULSIONS

	Spray		Premix		Stable		Test Method
	MIN	MAX	MIN	MAX	MIN	MAX	
Viscosity at 50°C, sec, Saybolt Furol	20	50	20	50	-		ASTM D244
Binder content, % (m/m)	60	62	60	62	60	62	ASTM D244
Residue on sieving, g/100 ml	-	0,25	-	0,25	-	0,25	SABS 309 6.4
Sedimentation after 60 complete rotations		nil		nil		nil	SABS 309 6.5
Coagulation value, % (m/m) Dolerite chippings	25	-	-	25			SABS 309 6.2
Portland Cement					-	2	SABS 309 6.3

General: The SABS specification relevant to these types of bitumen emulsion is SABS 309 – Anionic Bitumen Road Emulsions.

The bitumen bases from which these emulsions are manufactured comply with the requirements of SABS 307 – Penetration Grade Bitumens.

B3.2   CATIONIC BITUMEN EMULSIONS

	Spray 60		Spray 65		Premix 65		Stable Mix		Test Method
	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	
Viscosity at 50°C sec, Saybolt Fural	20	50	5T	200	51	200	-	50	ASTM D244
Binder content, % (m/m)	60	63	65	68	65	68	60	63	ASTM D244
Fluxing agent content % (m/m) of binder		5		5	5	10		nil	ASTM D244
Residue on sieving, g/100 ml		0,25		0,25		0,25		0,25	SABS 548 6.2
Particle charge - modified procedure - standard procedure	Pos		Pos		Pos		Pos		SABS 548 6.3 ASTM D244
Binder deposit on cathode after 30 min, g	1,0	-	1,0	-	-	-	-	-	SABS 548 6.3
Sedimentation after 60 complete rotations		nil		nil		nil		nil	SABS 548 6.1

General: The SABS specification relevant to these types of bitumen emulsions is SABS 548 – Cationic Bitumen Road Emulsion.

REFERENCES

South African Bureau of Standards, 2002, *Penetration Grade Bitumens*, SABS 307, Pretoria: SABS.

Emery S, 1996, *Colas Products and Services Handbook*, Colas Southern Africa (Pty) Ltd.

APPENDIX C

INTERIM SPECIFICATIONS FOR MODIFIED BINDERS

C1 SPECIFICATIONS FOR MODIFIED BINDERS

Source: Asphalt Academy (2001)

C1.1 SPECIFICATION FOR HOT-APPLIED POLYMER MODIFIED BINDERS FOR SEALS

Table 10: Properties Of Polymer Modified Binders For Hot Sealing Applications					
Property	Unit	Min/max	Test Method	Binder Class	
				S-E1	S-E2
Softening Point (R&B)	°C	Min	MB-17	50	57
Dynamic Viscosity @ 165°C	Pa.s	Max	MB-18	0,55	0,55
Ductility @ 15°C	cm	Min	MB-19	75	50
Force Ductility @ 15°C	N	(*4)	-	Report[*1]	Report
Complex Shear Modulus (G*/sin δ @ 10 rad/s) [*2]	°C	-	AASHTO: TP 5	Report	Report
Creep Stiffness: Bending Beam Rheometer	MPa	-	AASHTO: TP 1	Report	Report
Elastic Recovery @ 15°C	%	Min	MB-4	50	70
Flash Point	°C	Min	ASTM: D93-97	230	230
Stability (R&B diff. @ 160°C)	°C	Max	MB-6	5	5
Adhesion @ 5°C	%	Min	MB-7	90	90
Torsional Recovery at 15°C [*3]	%	-	MB-5	Report	Report
Torsional Recovery at 25°C	%	-	MB-5	Report	Report
Properties after ageing (RTFOT)			MB-3		
Difference in Softening Point	°C	-	MB-17	-2 to +8	-2 to +8
Elastic Recovery @ 15°C	%	Min	MB-4	40	50
Mass Change	%	Max	MB-3	1.0	1,0
Dynamic Viscosity @ 165°C	Pa.s	-	MB-18	Report	Report
Torsional Recovery @ 25°C	%	-	MB-5	Report	Report

C2 SPECIFICATION FOR MODIFIED EMULSIONS

Source: Asphalt Academy (2001)

C2.1 SPECIFICATION FOR MODIFIED EMULSIONS

Table 11 : Properties of polymer modified emulsions for surface seals							
Property	Unit	Min/ Max	Test Method	Modified Binder Class			
				SC-E1		SC-E2	
Modified Binder Content	(% m/m)	-	MB-22	65-68	70-73	65-68	70-73
Viscosity @ 50°C (Saybolt Furol)	Sec.	-	MB-21	51-200	51-400	51-200	51-400
Residue on sieving	g/100ml	Max	MB-23	0,5		0,5	
Particle charge	-	-	MB-24	Positive		Positive	
Sedimentation after 60 rotations	-	-	SABS 548	Nil		Nil	
Properties of recovered binder residue			MB-20 [*1]				
Softening Point	°C	Min	MB-17	48		55	
Ductility @ 15°C	Cm	Min	MB-19	75		50	
Elastic recovery @ 15°C	%	Min	MB-4	50		55	
Torsional Recovery @ 15°C [*3]	%	-	MB-5	Report [*2]		Report*	
Force Ductility	N	[*4]		Report*		Report*	

C3   SPECIFICATIONS FOR BITUMEN RUBBER

Source: Ref 86: Asphalt Academy (2001)

C3.1   SPECIFICATION FOR HOT-APPLIED POLYMER MODIFIED BINDERS FOR SEALS

Table 13: Properties of Bitumen-Rubber for use in Surface Seals and Asphalt						
Property	Unit	Test Method	Binder Class			
			S-R 1 (Seal)		A-R1 (Asphalt)	
			Min	Max	Min	Max
Compression Recovery: 5 minutes	%	MB-11	70	-	80	100
Compression recovery: 1 hour	%	MB-11	70	-	70	95
Compression recovery: 4 days	%	MB-11	25	45	25	55
Softening point (R&B)	°C	MB-17	55	62	55	65
Resilience	%	MB-10	13	35	13	35
Flow	mm	MB-12	15	70	10	50
Dynamic Visc. (Haake @ 190°C)	dPa.s	MB-13	20	40	20	50

REFERENCES

Asphalt Academy, 2001, "Technical Guideline: The use of Modified Bituminous Binders in Road Construction", TG1, CSIR.

APPENDIX D

FEM 3-D PLOTS

Notes to Appendix D

Run 6: Typical example of visual output

1. The plots in this Appendix depict:

    - Centre stone of the FEM seal mesh, in cross-section on longitudinal direction (i.e. in direction of traffic)

    - Plots for:

        - peak of each of the rear truck (driven) wheels (four passes), and

        - at end of relaxation period

2. Plots provided are:

    - Stress (X, Y and Z direction - definition of axes in text (Chapter 5)) and shear stress at the above time steps.

    - Strain in each of the above directions.

    - The colour distribution reflects stress or strain as indicated in the key.

3. To observe are:

    - The displacement of the stone under load.

    - The plastic strain after unloading especially after the rest period after the last truck wheel.