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Towards modelling road surfacing seal performance: performance testing and mechanistic behavioural model

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KIM JENKINS graduated from the University of Natal in 1983 and worked for some 12 years in the consulting field. He was involved in geometric design, pavement materials and geotechnics during this period. While with A A Loudon & Partners he began to work in the field of road rehabilitation focusing on cold in place recycling. He completed a master's degree on this process. The technology captured his interest and he extended his research, completing a PhD at Stellenbosch University on bitumen emulsion and foamed bitumen treated materials. Kim is currently the incumbent of the Sanral Chair in Pavement Engineering at Stellenbosch University.

Pavement designers have a choice of two types of wearing course: either an asphalt wearing course or a surfacing seal. While asphalt surfacing design has received much attention, road seal design has remained dependent on empirical modelling and experience. With the modern trend of increased traffic loading and contact stresses, varying oil resources and related refining processes and by-products, it is postulated that current seal design assumptions and practice may not be directly applicable to the changing situation in practice, and require re-examination (Milne 2004).

In 1998 performance testing of road surfacing seals was initiated under the Chair in Pavement Engineering, University of Stellenbosch. The model mobile load simulator (MMLS3) was identified and a test method developed. From 1998 to 2002 a test regime using five different seal binders and three temperature regimes was implemented. A method of evaluating seal performance was developed to enable evaluation of the seals' behaviour. This paper presents a summary of the test results and provides an insight to the performance of the different seal binders under similar imposed loads and environment. Insight is provided for the identification of critical seal performance influences and criteria. A comparative performance test protocol was developed, with an initial seal performance visual assessment method.

The need for a mechanistic based numerical model enabling comparative numerical prediction of seal performance was identified as an additional design tool (Milne 2004). A finite element methods (FEM) prototype model of a single seal was developed and is demonstrated. The potential value to practice of both methods of comparative performance assessment were postulated after synthesis of the results.

INTRODUCTION

In South Africa, road surfacing seals are widely used to provide a durable, all weather pavement surfacing (CSRA 1998). However, with the changes in global oil resources, weather patterns and traffic loading and contact stresses, a need has been identified to re-examine the methods with which road surfacing seals are designed. Current South African road surfacing seal design practice utilises empirical methods, based on historical experience, and volumetric based assessment of bitumen binder application (Milne 2004).

The investigation into the potential of a performance based seal design method commenced at the University of Stellenbosch in 1998. The project entailed both performance testing and numerical modelling. This paper reports the process of performance testing on various seal types using scaled down accelerated pavement testing (APT) and the proposition of a comparative seal performance test protocol. Five bitumen binder types, through three different temperature regimes, were tested. The results are tabled, with discussion facilitating assessment of the relative performance of the different seal binder types, and the proposed contribution of performance testing to the further development of a performance based seal design method.

Seal performance criteria are examined and the need for a seal design method based on mechanistic principles is proposed. A prototype seal behavioural model examining the development of a mechanistic design tool for seals' performance prediction was initiated using finite element methods (FEM) (with the demonstration of the first multiple element seal FEM model). The potential benefits to practice of the mechanistic design tool could be enhanced as and if the design model is developed further. Initial contributions to practice, such as enhancing the understanding of the behaviour of seal components, are discussed.

SOUTH AFRICAN SEAL DESIGN PRACTICE

Current South African seal design methodology is presented in the Technical Recommendations for Highways 3, usually referred to as TRH3 (CSRA 1997 & 1998). Seal types are illustrated in figure 1. This methodology is based on Hanson's concept,

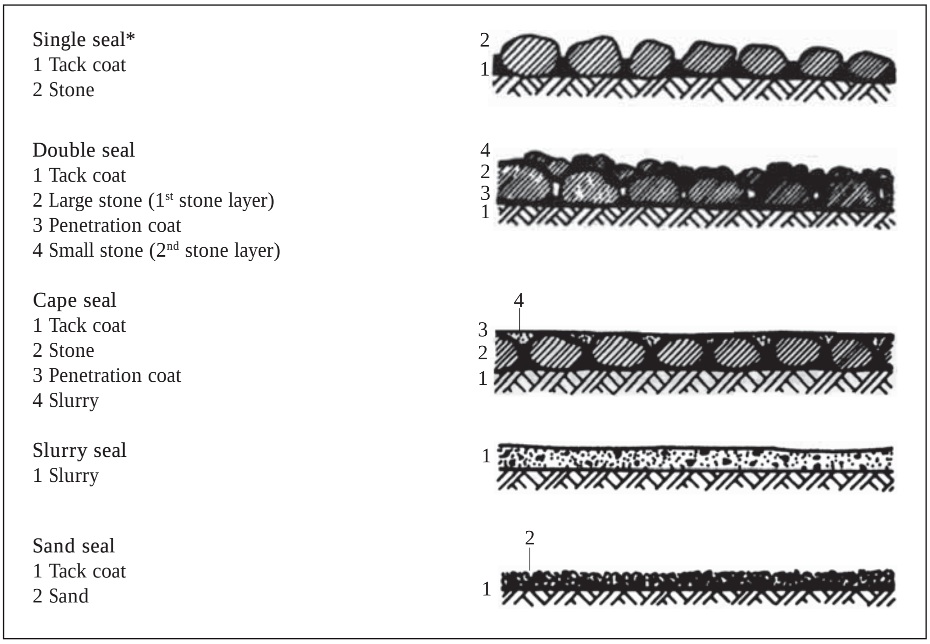

Figure 1 Seal types (CSRA 1998)
**Focus of the seal performance modelling and testing*

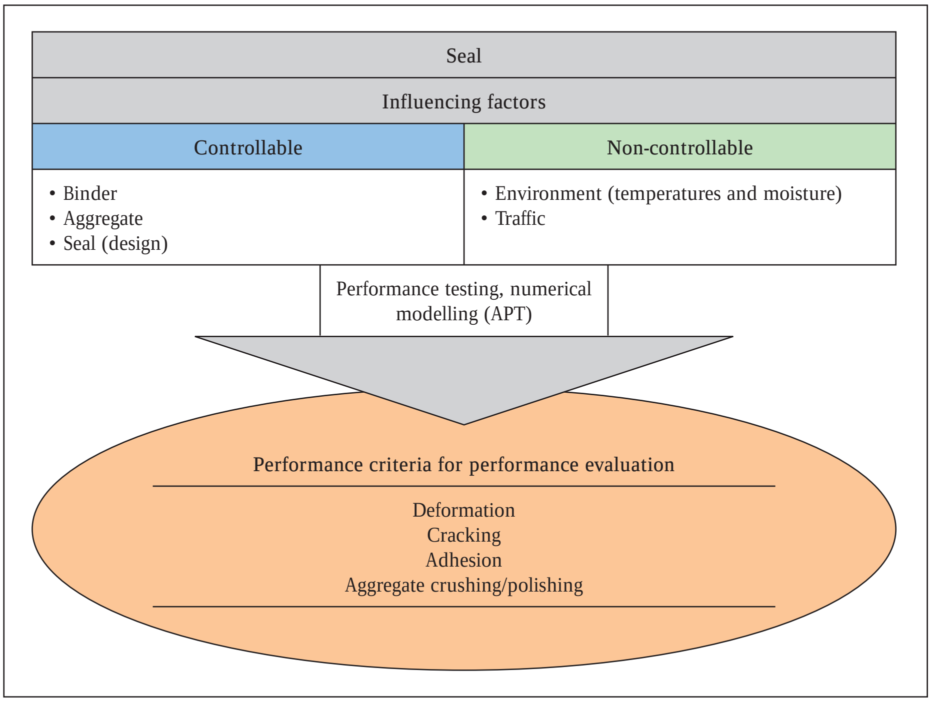

Figure 2 Interaction of influencing factors and identification of performance criteria (Milne 2004)

first tabled in the 1930s, of partially filling the voids in seal aggregate with binder, and that the volume of voids in the aggregate layer is controlled by the average least dimension (ALD) of the aggregate. Climate, binder type, traffic and existing surface all have an influence on the desired application rates for the seal bitumen binder. The current revised TRH3 (1998 draft) includes the following enhancements on the Hanson model (CSRA 1998):

- Minimum void space to be filled to retain the aggregate is 42 % for single seal, 55 % for double seals (if no embedment is to be accommodated).
- Void loss under traffic, due to wear of the aggregate, is dependent on aggregate hardness.
- Required minimum texture depth for adequate skid resistance is 0,64–0,7 mm.
- Embedment under construction is assumed to be 50 % of total lifetime embedment.

Further assumptions regarding the use of modified binders include:

- All embedment occurs under construction and that further embedment under traffic is reduced owing to the elastic 'mat behaviour' of the modified binder.
- Owing to the higher binder viscosity, the seal stones do not lie on average least dimension (ALD), but lie as they land in the bitumen, with increased voids being available, allowing higher binder application.
- The higher viscous behaviour of the modified binders is accommodated in the design through the use of 'binder adjustment factors' based on 'ring and ball' softening point (CSRA 1986) to make provision for stone orientation.

The traffic loading is measured in equivalent light vehicles (elv's) per lane, where heavy vehicles are converted to equivalent light vehicles using assumed 'equivalency factors' (currently one heavy vehicle to 40 elv's) (CSRA 1998).

The design process provides binder and aggregate applications based on the empirical design curves, with input in terms of ALD, stone hardness, and existing surface texture depth and hardness, and equivalent traffic.

It is evident that the current seal design method is not able to take cognisance of:

- Varying axle loads, tyre contact stresses and design speed
- Varying characteristics of the different binders (ie temperature–viscosity relationships, adhesion and visco-elastic behaviour)
- Varying service environments or micro-climates

The major areas identified for suggested improvement in current seal design methods are (Milne 2004):

- Inclusion of variable service environment characteristics, including traffic load and temperature and moisture influences
- Inclusion of material behavioural characteristics into the design methodology, especially regarding bitumen behaviour and characteristics, and existing base/asphalt wearing course behaviour

SEAL PERFORMANCE CRITERIA

Seal performance criteria have been defined as avoidance of certain failure parameters (Robertson *et al* c 1990), these being:

- Permanent deformation (punching, rotation of seal stone reducing voids)
- Early rutting of the supporting base
- Fatigue cracking
- Low temperature cracking
- Moisture damage
- Adhesion failure

Empirical research (Milne 2004) has demonstrated that the life of a seal is dependent on the performance of the base regarding:

- Permanent base deformation: punching (associated with bleeding) and rutting
- Moisture damage to the base and dependent on the seal material behavioural components for:
- Permanent deformation or loss of texture: rotation of seal stone, reducing voids (associated with bleeding), failure of 'mat' behaviour allowing punching
- Fatigue cracking (postulated due to brittleness of ageing seal)
- Low temperature cracking
- Adhesion failure (stripping)
- Aggregate crushing or polishing

Table 1 Seal types for performance testing (Milne 2004)

Binder type	Net binder application	Net binder application	Base bitumen	Aggregate size (Hornfels)	Penetration (dmm) (needle at 25 °C)	R&B softening point (°C)
	Lower application	Higher application				
80/100 pen[1]	0,9 l/m^2	1,1 l/m^2	80/100 pen	13,2 mm	90	44
80/100 pen grade base binder with modification						
• 3 % SBS[2]	1,2 l/m^2	1,5 l/m^2	80/100 pen	13,2 mm	80	64
• 3 % SBR[3]	1,2 l/m^2	1,5 l/m^2	80/100 pen	13,2 mm	85	54
• 3 % EVA[4]	1,2 l/m^2	1,5 l/m^2	80/100 pen	13,2 mm	63	53
• 20 % bitumen rubber (COLAS)	2,0 l/m^2	2,4 l/m^2	80/100 pen	13,2 mm	–	53
• 20 % bitumen rubber (TOSAS)	2,0 l/m^2	2,4 l/m^2	80/100 pen	13,2 mm	44	61

[1] Penetration grade (bitumen) (mm/10)
[2] Styrene butadiene rubber copolymer (bitumen modifier)
[3] Styrene butadiene styrene copolymer (bitumen modifier)
[4] Ethylene vinyl acetate (bitumen modifier)

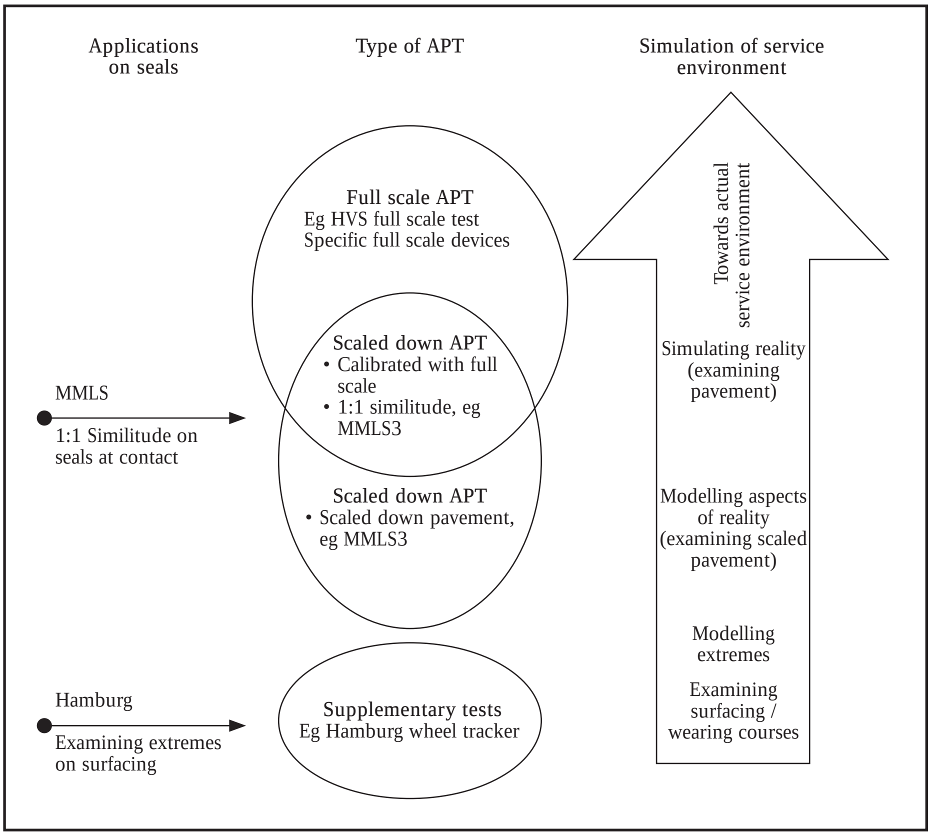

Figure 3 Types of pavement and surfacing accelerated performance test regimes (Milne 2004)

The failure parameters thus applicable to the modelling of a road surfacing seal (as opposed to the parameters applicable to the modelling of the structural layers) will be:

- Deformation and texture loss: rotation and punching of seal stone
- Cracking: fatigue (ageing of binder and loss of elasticity)
- Low temperature brittleness
- Loss of adhesion (of stone to bitumen, and bitumen to base)
- Aggregate (crushing or polishing)

In terms of performance evaluation it is usual to describe performance measured against failure criteria. However, when considering the role of the surfacing seal – the protection of the pavement layers from abrasion and the elements, and the provision of a safe riding surface – the question of sufficient time to failure must also be considered. The time to failure could be defined as the time to pavement failure, OR the time to reseal. This follows from the consideration that a pavement's serviceable life is determined by construction quality, traffic load, environment, substrate, pavement type, and many other factors (with seals there is also the possibility of single event catastrophic failure, such as cold weather stipping or hot weather binder flow).

The factors that influence seal behaviour (Marais 1979) as extrapolated (Milne 2004) are reflected in figure 2 with their influence on seal behaviour and with the criteria determined for the seal performance-evaluation.

EMPIRICAL PERFORMANCE TESTING

The empirical performance test method is summarised below, and is defined in detail in the literature (Milne *et al* 2002).

The model mobile load simulator (MMLS3), a one third scaled down accelerated pavement tester, was utilised for the execution of the empirical testing. Seal tiles were prepared and placed on a pre-constructed external base. The tiles were laboratory prepared single seals, with a range of different binders under different temperature conditions (figure 3).

Seals tested and traffic load

Single seals with five binder types (with variation of the rubber bitumen manufacture process, making a series of six binders) were tested, as summarised in table 1.

For comparison purposes, two different application rates were used, based on TRH3 (CSRA 1998) design parameters.

Three prefabricated seal tiles of each were manufactured to enable averaging of performan)ce under load and identification of dynamic effects where applicable.

Traffic load of single wheels at 600 kPa and 2,1 kN per axle was applied, with 200 000 applications applied (with no 'lateral wander'). This equates to an estimated equivalent five-year traffic load, using an equivalency factor of 40 elv's (equivalent light vehicle) per E80 (80 KN axle load) and a conservative factor of 3 increase owing to the effect of lateral wander in practice.

Temperature regimes

Three temperature regimes were utilised:

Ambient temperature

On average, the road temperature varied between 20 °C and 36 °C throughout the days of testing, although it dropped to 16 °C minimum during the winter months. Testing was done throughout the day and no undue low temperatures were experienced on the test days.

Elevated temperature

Blowers were used to elevate road surface temperature to 50 °C for the full test duration.

Cold temperature

Cold air was blown onto the seal surface to reduce the seal temperature to 10 °C for the full test duration.

Table 2 Summary of seal performance (Milne 2004)

Summary: seal performance		Scale 100 maximum: worst / 0 minimum: best		
Binder	Overall performance	Test regime		
		10 ºC (cold)	Ambient	50 ºC (elevated)
Binder modified 80/100 pen grade with:				
3 % SBR	0–22	19	17-22	0-6
3 % SBS	0–28	28	0-16	6–15
3 % EVA	11–28	17	11-28	11
20% bitumen rubber BR • TOSAS • COLAS	 14–39 11–56	 17	 14–35 11-33	 25–39 17–56
80/100 penetration grade	22–56	22	31	56

Table 3 Binder performance ranking (Milne 2004)

Binder ranking* Ranking (1 best, 5 worst), (BR consolidated)					
Regime	1	2	3	4	5
Cold	20 % BR	3 % EVA	3 % SBR	80/100	3 % SBS
Ambient	3 % SBS	3 % SBR	3 % EVA	20 % BR	80/100
Elevated	3 % SBR	3 % EVA	3 % SBS	20 % BR	80/100
Overall	3 % SBR	3 % SBS	3 % EVA	20 % BR	80/100

**80/100 pen grade bitumen modified as shown*

Table 4 Summary of consolidated MMLS3 (dry) and Hamburg (wet) seal performance results (Milne 2004)

Performance seal: binder ranking under design application* (based on the MMLS3 tests and prototype performance index, Hamburg tests and rating system)					
Regime	Best ←				Worst
Cold	20 % BR	3 % EVA	3 % SBR	80/100	3 % SBS
Ambient	3 % SBS	3 % SBR	3 % EVA	20 % BR	80/100
Elevated	3 % SBR	3 % EVA	3 % SBS	20 % BR	80/100
Wet	20 % BR	•	3 % SBR	•	80/100
Aged	20 % BR	•	•	•	80/100

**80/100 pen grade bitumen modified as shown*

Development of performance evaluation model

The seals were evaluated in terms of the performance criteria determined through assessment of literature and the research process (Milne 2004).

The seal performance was measured in terms of the visual assessment method being developed by Milne (2004) in terms of assessment parameters. These parameters are shown in table 2, with the rating system developed to enable evaluation of the seal performance (see annexure 1).

The performance ratings of the seals were determined (calculated to percentage of worst possible performance rating, or performance index (lowest value is best performance)).

Seal performance summary

The results of the seal performance evaluation are summarised in table 2 and expanded upon in annexure 2.

From observations, performance of a fresh and mature (older than two months) seals is directly related to performance of the base.

Seal lifetime is thus influenced by ageing of the bitumen (loss of flexibility-cohesion and loss of adhesive ability) and performance of the base.

Aggregate was applied shoulder to shoulder – thus the viscous binders have higher application of aggregate than those less viscous at application temperature – owing to the stones not rotating to ALD under gravity during construction. Crushing was thus observed when the less viscous binders were not able to prevent the vertical stones' rotation under load.

Higher stone loss was experienced with the lower binder applications (as expected), namely the penetration grade bitumen.

In general, the colder regime favoured the bitumen rubber, with the relative higher binder contents, as flushing was reduced, with minimal stone loss. The elevated test regime, that is high temperatures, allowed the modified binders to settle under traffic and the modified binders' higher viscosities prevented excessive rotation or flow.

Each binder type has a specific regime where, for the tested base type, performance is enhanced. This is summarised in table 3.

The MMLS3 has since been modified to enable wet testing. For the purposes of this project the modified Hamburg test method was developed. The test protocol is however now applicable also to the MMLS3 APT performance test modelling. To provide an indication of the effect of moisture, table 4 reflects the ranking of wet and dry test regimes combined.

Performance summary

It is evident that the empirical test method using the MMLS3 APT apparatus enables comparative evaluation of the performance of each different binder type. The following points are extrapolated from the performance test results:

- Penetration grade bitumen binder performs satisfactorily in average environments, where extreme environmental effects are not evident (ie under ambient temperatures in the bitumen visco-elastic behaviour range).
- Each seal should be designed after examining the specific, unique pavement and environmental effects, specifically temperature and base condition.
- In context of the assumptions made in the seal design guide (CSRA 1998) the desired 'mat behaviour' of modified binders should be carefully assessed when considering the changing behaviour and characteristics of binder types with changing temperatures (especially where road temperature reaches softening point of the binder). Careful consideration of the assumed elastic 'mat' behaviour of seal stone with modified binder is required, especially the assumption that further seal aggregate embedment does not occur in service, after the initial construction compaction. With high temperature (above $T_{R\&B}$) this assumption could be questionable.
- Orientation of stone, and shoulder to shoulder application to prevent rotation of seal stone to ALD, specifically where the assumption that seal stones would not fall to ALD is made, with allowance for increased assumed voids and increased binder application. The assessed increase in bitumen rubber binder application based on increased viscosity at construction will only be evident if the seal stones are prevented from rotation under traffic (through interlock or viscosity).

The design of seals should be undertaken with additional consideration of the modified binder assumptions.

- Carefully consider the desired aggregate application rate, especially aim at preventing seal stone in modified seals rotating once service temperatures has exceeded $T_{R\&B}$.
- Be aware that when considering moisture, the increased performance of modified binders could in part be due to the increased binder content, in addition to the increased adhesive properties.

Table 5 Burgers model material parameters for prototype FEM model (Milne 2004)

Bitumen material parameters E_1 Series spring stiffness; E_2 Parallel spring stiffness; λ_1 Series dashpot viscosity; λ_2 Parallel dashpot viscosity												
Binder	Temperature											
	10 °C				25 °C				50 °C			
	(Pa) E_1	(Pa) E_2	(Pa.s) λ_1	(Pa.s) λ_2	(Pa) E_1	(Pa) E_2	(Pa.s) λ_1	(Pa.s) λ_2	(Pa) E_1	(Pa) E_2	(Pa.s) λ_1	(Pa.s) λ_2
70/100 pen	$2x10^8$	$1,5x10^6$	$5,34x10^6$	$5,34x10^5$	$2x10^8$	$1,5x10^6$	$8,67x10^4$	$8,67x10^3$	$2x10^8$	$1,5x10^6$	$6,98x10^2$	$6,98x10^1$
3 % SBS (L) modified	$2x10^8$	$2x10^5$	$8,4x10^7$	$1,5x10^6$	$2x10^8$	$2x10^5$	$1,46x10^6$	$2,61x10^4$	$2x10^8$	$2x10^5$	$1,47x10^4$	$2,63x10^2$

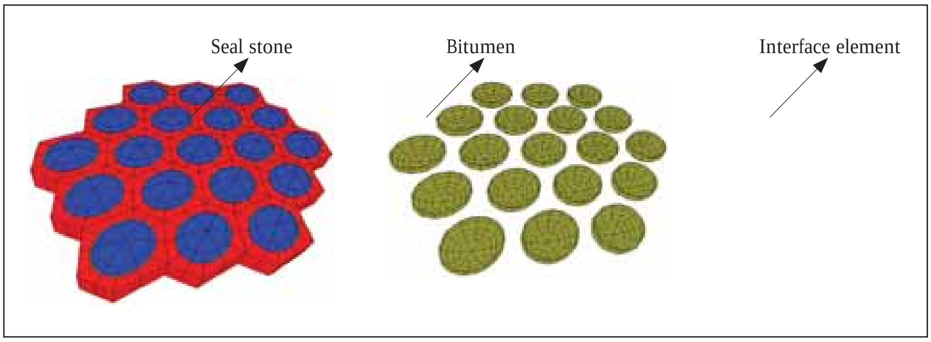

Figure 4 Basic layout of the FEM for seal surfacing with interface elements ('round stone') (Huurman et al 2003)

- The MMLS3 based performance test protocol will enable comparative seal performance tests under each additional expected service environment, as part of a performance based seal design method.

Further work is required in refining the visual assessment method of seal performance.

This model will be able to assist in the added determination of the fundamental binder properties on seal performance, and the seals ability to contribute to the overall performance of the pavement.

In conclusion, the performance testing has also assisted in identifying the critical parameters seal designer should consider during the design process.

NUMERICAL (MECHANISTIC) MODELLING OF SEAL PERFORMANCE

Identified need for mechanistic (FEM) modelling of seal behaviour

Design methods for prediction of structural pavement elements' lifetimes, and assessment of requirements for design traffic loads, are increasingly based on mechanistic design methods (methods based on principles of mechanics such as elasticity, plasticity, visco-elasticity), rather than empirical methods (based on experience or index properties – such as CBR, limiting deflections, etc) (Desai 2002). There is currently no available tool to assess the above performance parameters in service for different seals (Huurman *et al* 2003), nor is there an analytical tool available to differentiate between the performance of different seals under different environments and loading. There is thus a need for the further examination and evaluation of seal performance in terms of the performance criteria through an analytical tool (numerical behavioural model) to complement the current available design methods and the performance based evaluation method as discussed above.

The modelling of road surfacing seals using mechanistic principles with determined failure and fatigue criteria or relationships would enable assessment of the seal's expected lifetime, inclusion of different component material characteristics and variations, varying traffic and environmental conditions. It was with the above in consideration that the feasibility of the development of a mechanistic performance behavioural model for seal design and assessment was examined, using specific finite element analysis tools.

From assessment of literature (Milne 2004), and understanding of the components of the seal and pavement, and influencing factors, a choice of numerical model of seal performance was made.

The finite element method (FEM) analysis was selected for the purpose of modelling seal performance, for the following main reasons:

- The seal components and geometry are too complex to use simple isotropic models.
- The ability of FEM to model complex stress analysis problems.
- Enabling the approximation of material characteristics by the collective behaviour of all the elements (stress and strains are able to be determined in each of the elements using the applicable elastic and visco-elastic methods).
- The availability of proven existing modelling software.

In the above context, a prototype seal behavioural model was developed, using the influencing factors to design the input for the model and the performance criteria for comparison of the seal behaviour under determined service environments (temperature and traffic load).

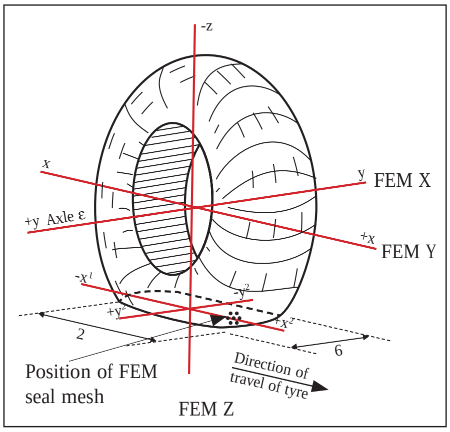

Figure 5 Relative position of FEM seal under tyre contact patch (not to scale) (from Woodside et al 1992 and Milne 2004)

Development of a mechanistic seal behavioural model

The development of the model from scratch is a process, with substantial new work required for not only the fundamental basis of the model, but for refining the specific material parameters required for ultimate calibration to enable accurate prediction of each specific seal's performance (Huurman *et al* 2003).

The components of a seal model must include (Milne 2004):

- Seal stone
- Bitumen
- Base
- Applied traffic load and contact stresses

The complexity of any seal model becomes evident when considering the fundamental material parameters to describe the components and their interaction.

To this end, the prototype model focused on the modelling of the basic seal components: stone and binder, with traffic load and temperature considerations. The prototype model was designed in such a manner that it can be placed onto a base, to allow further development towards a more complete performance behavioural model.

The setting up of the FEM model occurred in two phases:

Phase 1: Generation of the mesh

To enable accommodation for changing stone size and binder application, distance between stones, and other geometric parameters, the mesh generation should follow the method of being 'parametised' (Huurman *et al* 2003). This is implemented using a mesh generating spreadsheet based system, where element node coordinates are entered using

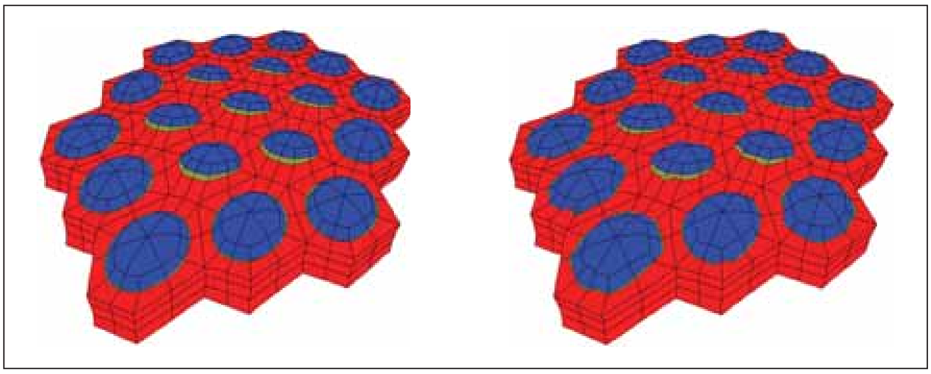

Figure 6 Deformation (50 x) of the meshes as per typical FEM run (Huurman et al 2003)

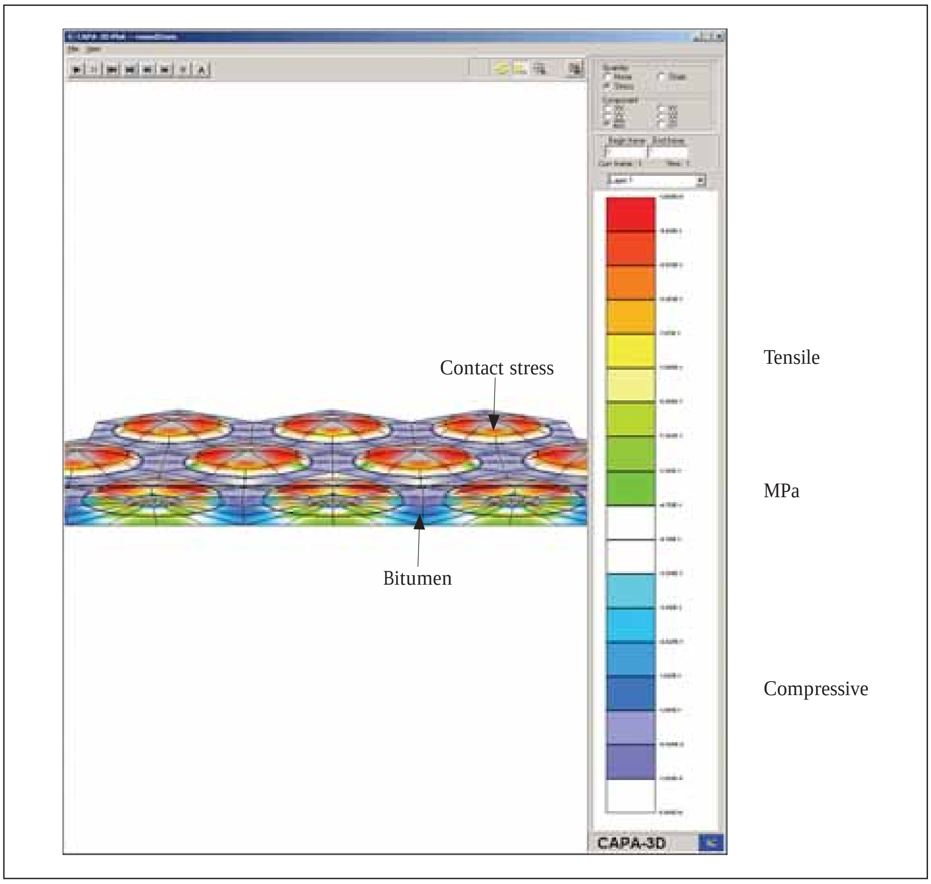

Figure 7 Example of vertical stress in a seal mesh with round stone (cut through centre stone) (Milne 2004)

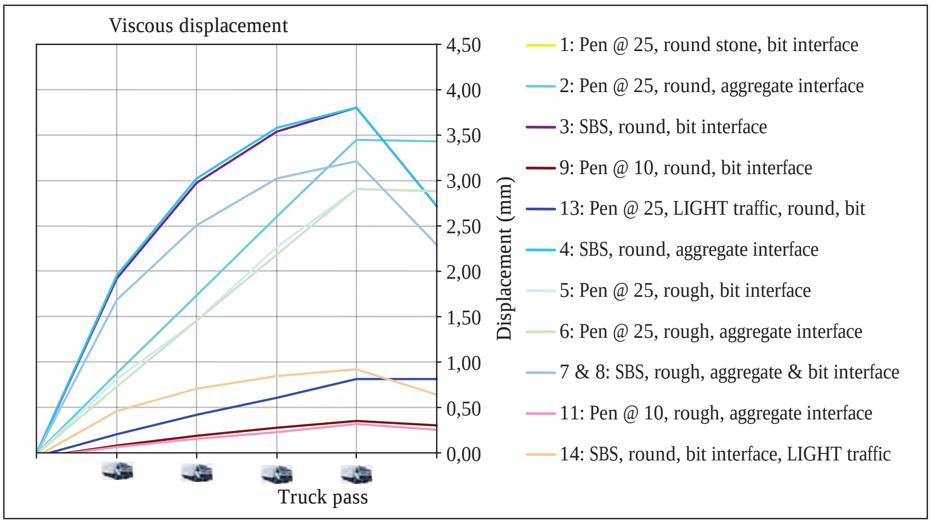

Figure 8 Maximum viscous displacement of top of centre stone (values comparative, not absolute) (Milne 2004)

formulae linked to the geometric parameters. In this manner a model has been initiated that can include variations of:

- Average least dimension (ALD) of the seal stone
- Aggregate (seal stone) nominal sizes
- Bitumen (binder) application rate
- Lateral and longitudinal distance between the seal stones
- Initial texture depth
- Stone shape and stone orientation are able to be randomised through the parameterised model

Phase 2: The finite element analysis

- This includes the input of material parameters.
- In the finite element analysis itself, the actual material parameters are entered, allowing assessment of differing materials and environmental effects (on the temperature dependent items) without influencing the mesh generation.

Prototype mechanistic seal behaviour model

In figure 4 the basic layout of the prototype model is presented. Various shades refer to different materials. The model is made up of modules that consist of individual stones encompassed by bitumen. By adding modules together, the model is compiled to a size that allows assessment of central seal stone free of edge effects.

Material parameters

Bitumen binder

From the literature review (Milne 2004 and Hagos 2002) the material parameters for the bitumen were determined for the prototype numerical model. Of importance was the necessity to include parameters for:

- 'Straight' penetration grade bitumen
- Modified bitumen through the temperature ranges from brittle to viscous fluid, that is, 10 °C to 50 °C

Using Hagos' (2002) parameters, plus the time temperature supposition principle (TTSP), a full range of data was obtained for use in the prototype model and future numerical modelling of the seal binders.

For the simulation of the straight binder, the results for the 70/100 pen grade bitumen was selected from Hagos (2002). For the modelling of a modified binder, the 3 % SBS (linear) modified binder was selected. The linear (L) rather than radial (R) SBS was selected with the Burgers model (Milne 2004) (elastic spring and viscous dash pot) material simulation in the FEM program) consideration. The temperature ranges considered were in line with the performance tests at 10 ºC, 25 ºC and 50 ºC and the behavioural ranges of bitumen: brittle/stiff (± 10 ºC), elastic (± 25 ºC) and viscous fluid (± 50 ºC).

The Hagos (2002) Burgers model featured one Kelvin element and one Maxwell element in parallel. Table 5 reflects the elastic (E) and viscous (λ) parameters as used by the FEM model.

With reference to the selected parameters, the spring stiffness (E) of the binder

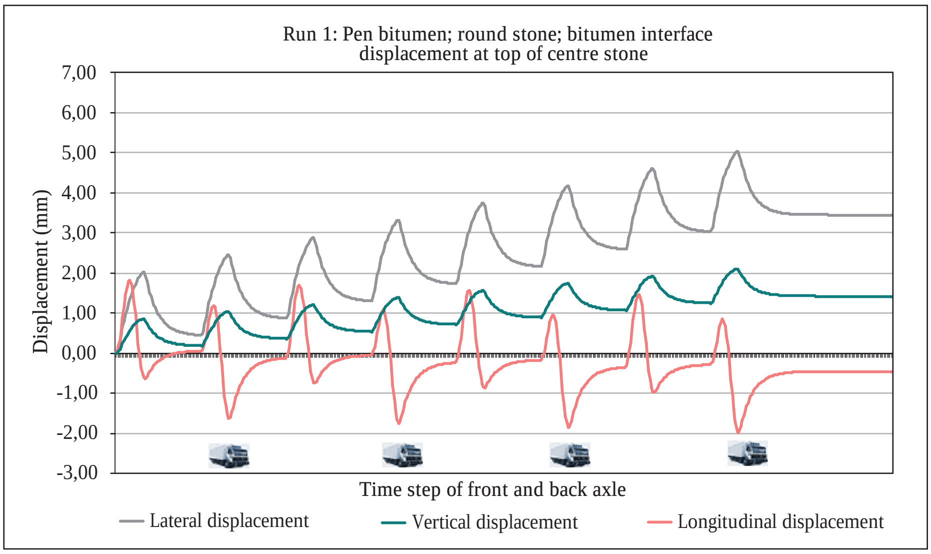

Figure 9(a) Penetration grade bitumen: displacement under sequential loading: 25 °C (Milne 2004)

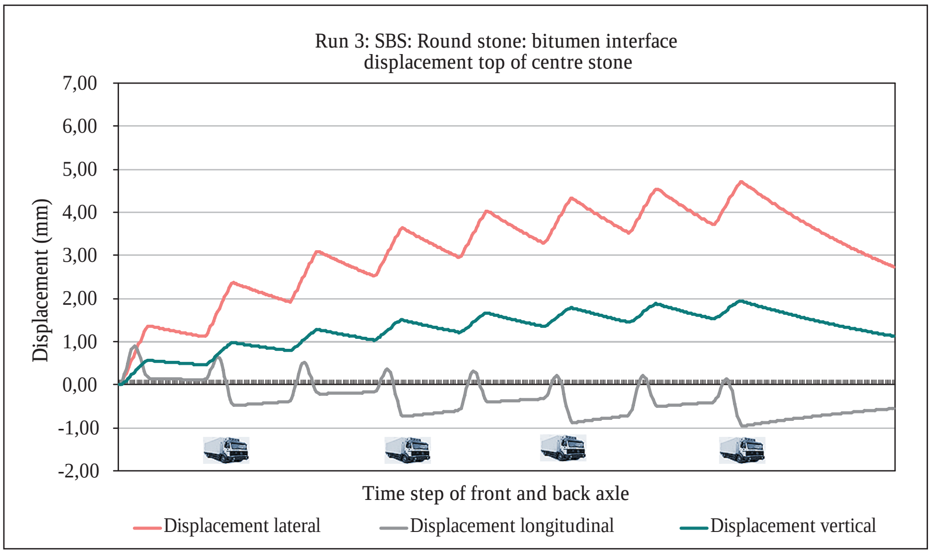

Figure 9(b) SBS modified bitumen: displacement under sequential loading: 25 °C (Milne 2004)

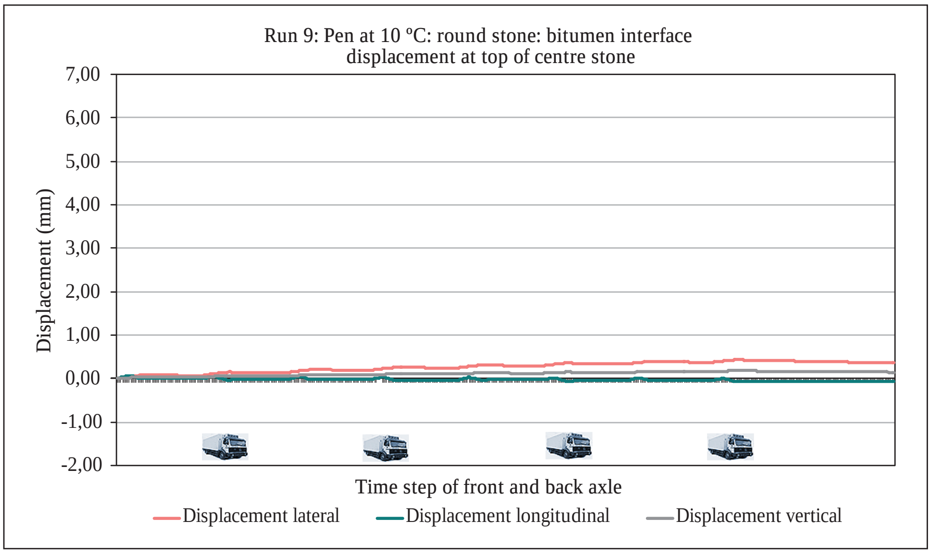

Figure 10(a) Penetration grade bitumen at 10 °C: round stone: displacement (Milne 2004)

remained constant (reflecting the time of loading function, that is, bitumen binder's elasticity under rapid loading), while the dashpot viscosity (λ) showed order size reduction with increase in temperature. This reflects the physical nature of bitumen.

Aggregate

The seal stone aggregate, when compared with the numerical model parameters, is very stiff.

The Young's (E) modulus for the stone was taken as 200 GPa (Milne 2004)

The E-modulus for aggregate is thus 10^3 order size greater than bitumen.

Loading

The FEM seal stones are situated adjacent to the centre line, as reflected in figure 5.

The determination of applied loads representing as real a reflection as possible of actual traffic loading and contact stresses on seals was required. A detailed assessment and interpretation of current available data, focused on the geometry of the textured FEM model, was undertaken with the objective of defining a prototype model traffic load. The loading has been discussed in the literature (Milne *et al* 2004) and is summarised in annexure 3.

SOME RESULTS

Stress and strain distribution

Examples of the induces stresses and strains are provided by the model, both as 3-D images and in terms of values.

The figures illustrate the stone displacement, stress and strains for particular runs (Huurman *et al* 2003 and Milne *et al* 2004). Figure 6 reflects the deformation of the seal mesh under load.

Figure 8 is a graphic represention of comparative permanent (viscous) displacement.

Binder type

The ability of the prototype FEM seal model to differentiate between binder types was assessed (Milne 2004) by comparing two binders: 'straight' penetration grade and a modified binder. A temperature of 25 °C was decided upon for material parameter determination, as this is in the accepted zone of visco-elastic behaviour; 70/100 penetration grade binder, and styrene butadiene styrene copolymer (SBS) modified (3 %) bituminous binder.

The series of graphs (figures 9 and 10) (Milne 2004) demonstrating the behaviour of the different binder types are provided below, in terms of cumulative elastic and viscous displacements under four truck passes (of two axles each). The displacements of the top, central node of the central stone is provided for the comparison.

From figures 9(a) and (b), 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 SBS 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 viscous recovery.

Figures 9(a) and 9(b) reflect the differing comparative magnitudes and behaviour between the modified and straight pen grade binders, with the permanent or viscous displacement after the immediate

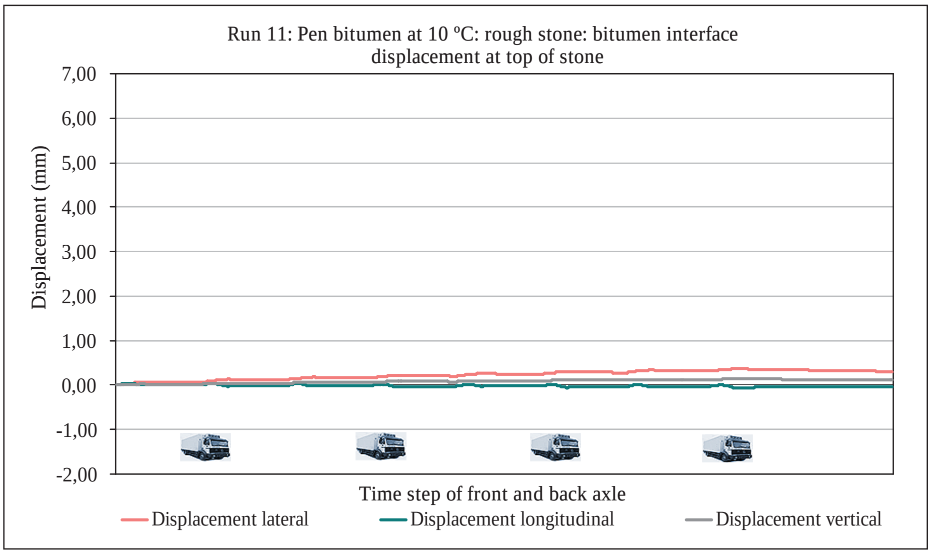

Figure 10(b) Penetration grade bitumen at 10 °C: rough stone (Milne 2004)

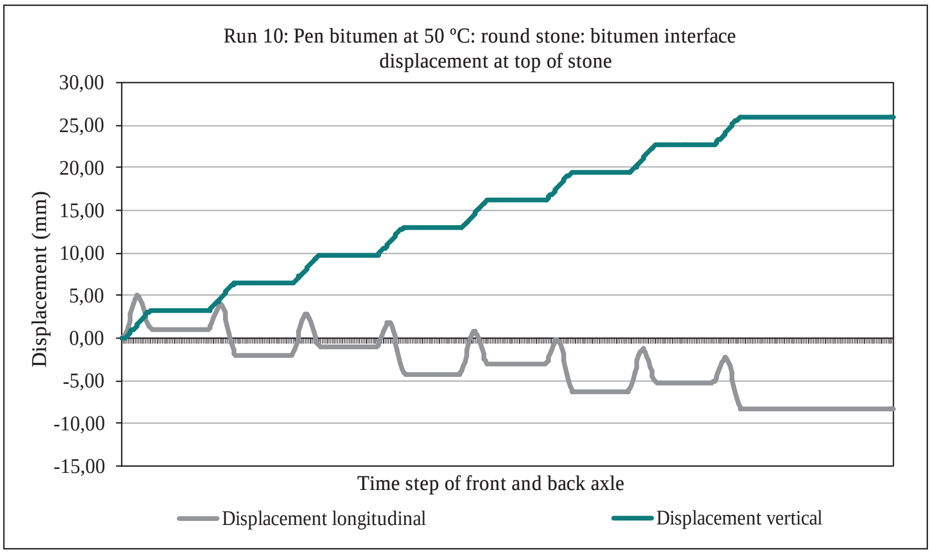

Figure 10(c) Penetration grade bitumen at 50 °C: round stone (Milne 2004)

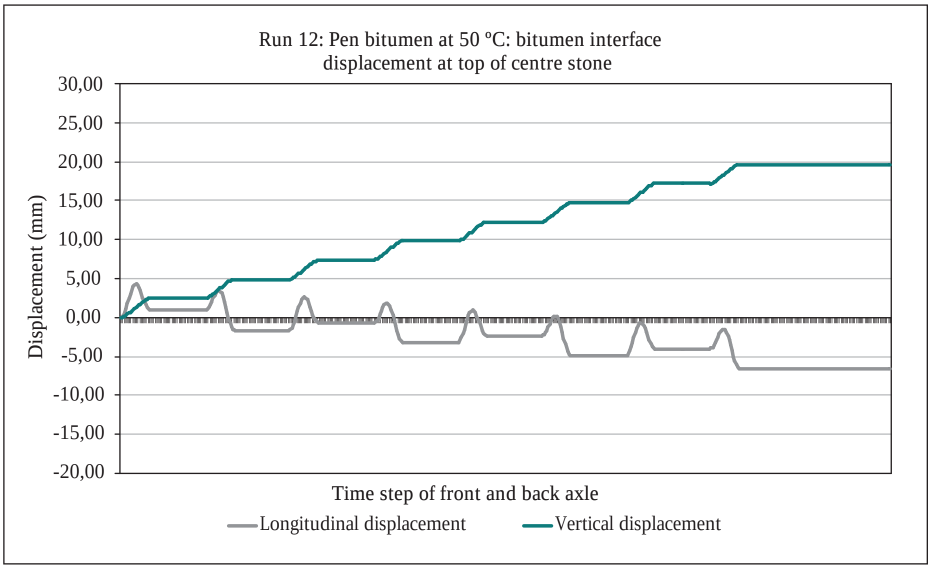

Figure 10(d) Pen bitumen at 50 °C: rough stone bitumen interface: displacement at top of centre stone (Milne 2004)

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 the modelled truck passes is greater for the SBS modified bitumen, but also the elastic recovery is greater.

Temperature

Figures 10(a) to 10(d) and figures 9(a) and 9(b) 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 displacements, where at 10 ° there is still recovery of visco-elastic displacement at the end of the computed rest period. It should be noted that the indicated high displacements at high binder temperatures were due to geometric instability of the mesh, as the bitumen is approaching fluid with only viscosity reflected under load. The development of the model to include a base with embedment will limit this effect, where the stone will receive constraint and support from the base.

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 is the elastic component 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 effectively softening point) 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.

Traffic load and stresses

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.

The effect of heavy (80 kN axle) and light vehicle traffic (elv of 25 % tyre

Table 6 Effect of traffic loading and contact stresses on displacement (Milne 2004)

Binder	Stone	Traffic	X-lateral displacement (wheel on top of stone) (total displacement: elastic and viscous)	
			Under 1st wheel	Under truck's 4th rear wheel
			Displacement	Displacement
Run 1: Pen @ 25 %	Round	Heavy	1,94 mm	4,96 mm
Run 13: Pen @ 25 %	Round	Heavy	1,35 mm	4,69 mm
Run 3: SBS @ 25 %	Round	Light	0,485 mm (25 % of heavy)	1,23 mm (24,7 % of heavy)
Run 14: SBS @ 25 %	Round	Light	0,337 mm (24,96 % of heavy)	1,17 mm (24,95 % of heavy)

Table 7 Effect of traffic loading and contact stresses on imposed stress under stone (Milne 2004)

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

+: Tensile stress *-: Compressive stress*

Table 8 Common parameters: performance tests and prototype numerical model (Milne 2004)

Seal performance criteria	Effect of influence examined	
	Performance model	Prototype numerical model
Deformation • Rotation • Punching	 √ √	 √ (X, Y) √ (limited: Z)
Cracking • Fatigue/cohesive • Brittle	 •	 √ Mohr type – future project
Adhesion	√	Interface – future project

Table 9 Validation of prototype numerical model by examination of performance test results (Milne 2004)

Influence	Factor	Failure criteria: displacement	
		Performance testing	Prototype numerical model
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
Binder type @ 25 °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
	Pen grade bitumen	• More rotation towards ALD (X or Y) • Similar embedment as SBS modified binder	Displacement larger in X direction than SBS. Only immediate elastic recovery after last truck passes. No further recovery after rest period
	SBS modified bitumen	• Less rotation to ALD than pen grade bitumen • Similar embedment as pen grade bitumen	Displacements (X) slightly less than 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*

inflation pressure of heavy vehicle) on imposed stress is summarised in table 6.

Through table 6 it is clear that lateral displacement is directly proportional to the traffic loading and contact stresses 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 model output as summarised under the 4th truck wheel.

The results in table 7 show that the factor heavy vehicle to elv is dependent on tyre inflation 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) (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.

CONCLUSION

It is evident that there is a need for the development of a mechanistic model for seal performance prediction to complement current South African seal design codes and experience. The prototype model is a proposed micro-mechanical model for surfacing seal performance prediction.

On the basis of the prototype's performance discussed in this paper, it is concluded that the model will prove to give insight into seal behaviour, and with further development should offer the following:

- Distinction between physical/chemical adhesion (interface behaviour) and mechanical adhesion (stone shape)
- Enable better understanding of loss of adhesion and thus loss of stone
- To provide insight into stress and strain development in the binder
- To explain various types of cohesive seal cracking
- Prediction of deformation in the binder and supporting base resulting in stone rotation and punching

As a result of the above, insight into stresses in the stone/binder interface is obtained.

Within the philosophy for the model discussed, future work into the prototype FEM model should include the addition of an elastic plastic supporting base layer, enable interaction between base and seal to accommodate punching of stones into the base, and the refinement of the bituminous binders to further refine computational output the model provides. Also, the inclusion of geometric non-linearity in the FEM analysis will further refine the prototype model.

SYNTHESIS

This paper has described the development of two aids towards assessing the comparative performance of bitumen and modified bitumen seal binders: the performance testing, and the prototype mechanistic model. Both aids have indicated that the comparative performance of different seal types can be made for differing materials, traffic, pavement and environmental conditions.

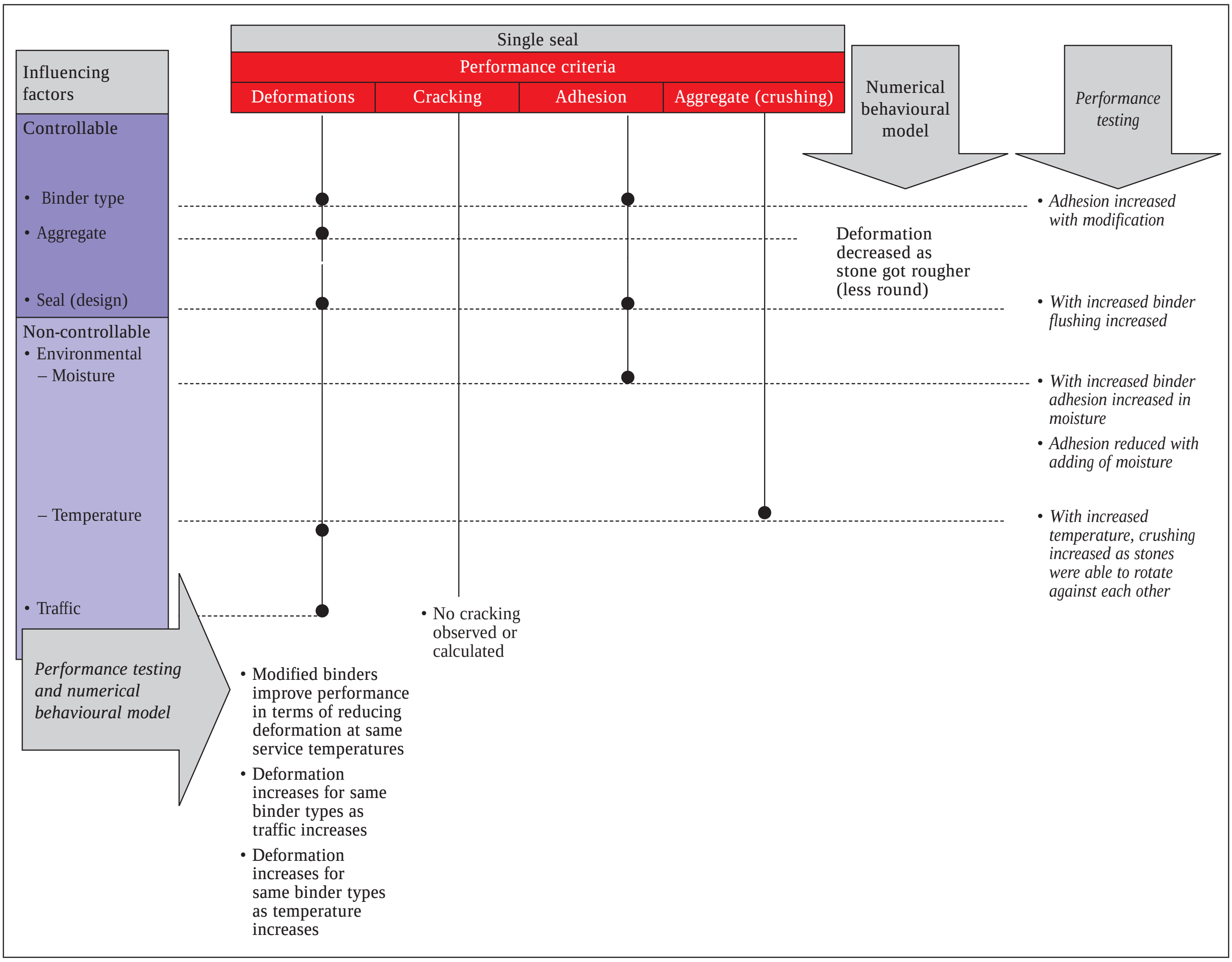

Figure 11 Synthesis of seal performance modelling (Milne 2004)

Table 8 reflects the common seal performance criteria examined. Table 9 reflects the prototype conformance validation of behaviour modelling.

The potential of the performance testing and mechanistic behaviour (FEM) model of seals as a design aid has been demonstrated. The critical performance areas and parameters have been identified. Industry will determine whether either method is developed further and exposed to practice. Figure 12 reflects the development of seal performance modelling.

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ANNEXURE 1: PERFORMANCE INDEX DETERMINATION

Seal performance parameters (Milne 2004)

Performance criterion	Performance parameter	Performance rating	
		Highest	Poorest
Adhesion	Stone loss	0: None	3: Stripping (5 % of trafficked area or more)
Deformation	Embedment	0: None	3: Flush (embedded to zero texture depth)
	Rotation	0: As laid	3: ALD *Note:* Rotation is desirable but for the purpose of this evaluation, maximum voids are desired (modified binders are used), and as such the viscous property of the binders with maximum void content was rated best for purpose
	Flushing	0: None	3: Bleeding – severe
Aggregate	Crushing	0: None	3: Severe
(Crushing, polishing)	Polishing	**	**
(Includes cracking)	General performance (visual assessment)	0: Good visual appearance *Note:* This parameter was used to credit the negative numerical affect of rotation to ALD for seals that perform well and to note cracking (in this project)	3: Poor
	Base distress* * Record only ** Note taken only, not visible on these tests	0: None	3: Failure *Note:* When distressed base occurred the overall rating was reduced to 'credit' the seal to counter the negative affect numerically of poor performance of the seal due to embedment, flushing. However, this is only REPORTED, as assessment of seals is made EXCLUDING base effects

The performance ratings of the seals were determined, (calculated to percentage of worst possible performance rating, or performance index (lowest value is best performance)). Performance index is defined as:

$$\text{Performance index} = \left[\frac{(R_{SL} + R_E + R_R + R_{F/B} + R_C + R_A)\,x\,100}{18}\right]$$

Where:

R = Performance rating (0–3)
SL = Stone loss
E = Embedment
R = Rotation to ALD
F/B = Flushing or bleeding
C = Crushing
A = Appearance

Of note is that under the initiation project, each of the above performance parameters have equal rating in the formula.

The performance index is a start at enabling qualitative assessment of seal behaviour and was developed as a research tool. Notwithstanding the refinement still required through future research, the use of this tool will assist in the identification of critical parameters, and the unknowns in seal behaviour that require further investigation.

ANNEXURE 2: MMLS3 ADT TESTING ON VARIOUS SINGLE SEAL TYPES

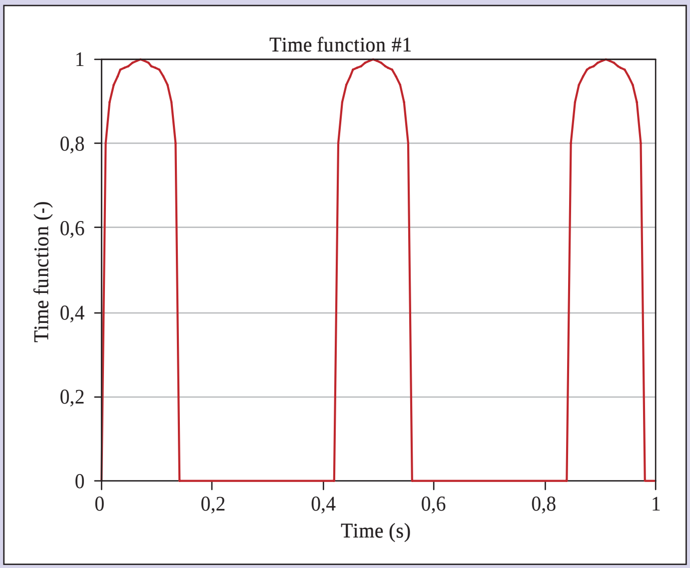
Description of performance results (Milne 2004)

Performance parameter	Binder and temperature	Binder and surface hardness	Binder and application rate
Seal binder			
80/100 penetration grade	This binder performed better overall at ambient temperature than elevated or cold. Marginally more stone loss, similar embedment and better visual rating at ambient than elevated. At lower temperature, the binder had less embedment, some stone loss, slight crushing, and less rotation. Excluding the rotation assessment, the binder performed better at ambient, however in the rating system, where original void content is valued, the cold tests provided the best performance	Slight effect on performance (embedment) but visible distress limited, probably due to low binder content	The higher application rate allowed better performance (limited stone loss)
3 % EVA modified bitumen	This binder performed better at higher temperature. This could be due to the higher softening point of the binder and possible higher adhesion At cold temperatures, more stone loss and visually unsettled, that is, not bedded under traffic, than ambient	Surface hardness had slight detrimental effect on performance under these tests, slight embedment evident	The binder application rate was not a major influence on performance
3 % SBR modified bitumen	The binder performed slightly better at higher temperature, although this was possibly due to unrelated parameters (embedment). The binder performed better at ambient than cold tests, visually unsettled, due to lack of embedment, or settling under the wheel load	Surface hardness slight effect Higher resistance to embedment	-
3 % SBS modified bitumen	Binder performed better at ambient temperature than elevated – less rotation and embedment of stone. Much stone loss at cold tests. Best performance at ambient. The binder performed better at ambient than cold tests, visually unsettled, due to lack of embedment, or settling under the wheel load	Binder performed better on harder surface	Better performance at higher application rate, based on appearance (ie stone settled, surface texture visually as desired)
20 % bitumen rubber (COLAS)	Binder performance better at ambient than elevated due to increased flushing, and sensitivity to higher binder applications. Better performance at cold weather due to less flushing	Surface hardness affected seal performance due to embedment	Better performance for lower application rates (less flushing displayed)
20 % bitumen rubber (TOSAS)	Better performance at ambient temperature (less flushing)	More embedment for softer surface, better performance on harder surface	Lower binder application rate performed slightly better (less flushing), better appearance
Summary	In general, the binders performed better at ambient temperature. The binders tended to flush or embed to a greater extent at elevated temperature, and the reverse is evident at cold temperature: the binder does not allow settling of the seal under traffic	Surface hardness a major effect on performance, especially at ambient and elevated temperatures	For modified binders, better performance at lower binder application at elevated temperatures

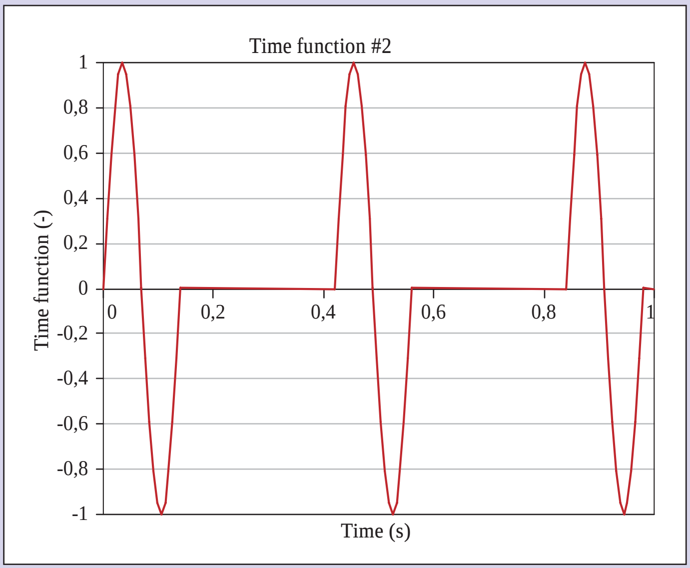
ANNEXURE 3: SUMMARY OF TIME BASED LOAD FUNCTIONS

Basic wheel load time functions were determined, and when applied to the magnitudes of maximum applied stresses, the micro/stone stresses were determined. The figure reflects the basic time functions with the load magnitudes (as described below) (from Woodside *et al* 1992 and Groenendijk 1998).

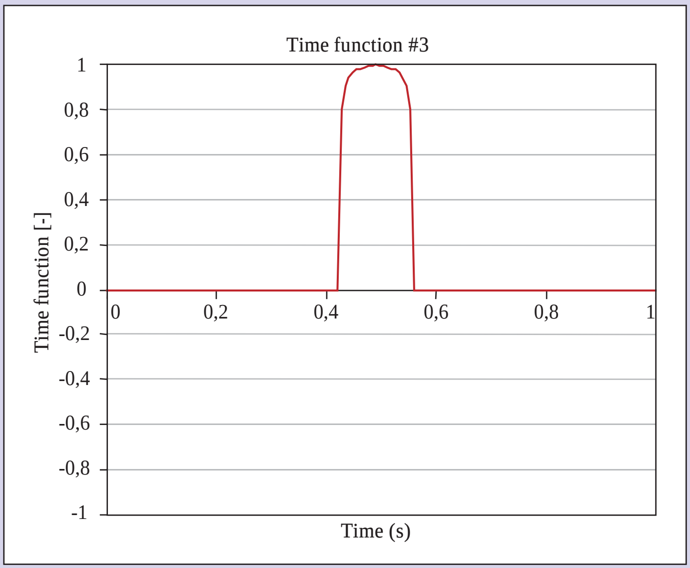
Function #1



Function #2



Function #3 (Function #1 for driven wheel): engine output



Maximum applied stresses			
Direction	Driven	Rolling	Weight and Tyre contact and friction
XX			0,24 MPa #1
YY	0,16 MPa #3	0,48 MPa #2	0,04 MPa #1
ZZ			1,6 MPa #1

With these time functions the following input is applicable

Time function	Stress direction	100 % of maximum stress
Time function #1	Weight and tensionin tyre surface: • Vertical stress zz • Lateral stress xx • Rolling friction stress yy	1,6 MPa 0,24 MPa 0,04 MPa
Time function #2	Free rolling longitudinal and tension in tyre surface: stress yy	0,48 MPa
Time function #3	Engine output: stress yy	-0,16 MPa