TOWARDS A PERFORMANCE RELATED SEAL DESIGN METHOD: New Test Method and Theoretical Model

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1. INTRODUCTION

This paper reflects the progress made on the research project ' Towards a Performance Related Seal Design Method', initiated in 1998 at the University of Stellenbosch.

The evolution of the new empirical test method of seal performance is discussed, with the summary of the first set of empirical performance tests of a full range of single seals at ambient temperature.

The initiation theoretical model of seal behaviour using finite element methods is also presented.

From investigation (both literature search and original research), a comparison of empirical and theoretical model parameters relating to all applicable performance aspects of the road surfacing seal performance is able to be made. These parameters will be used in identifying aspects for empirical research, and for inclusion in the development of the theoretical model of seal behaviour.

2. EMPIRICAL MODEL

2.1 Development of a New Test Method for Seals

A method for the accelerated testing of road surfacing seals was developed to enable the empirical modelling of the serviceability of seals, their performance evaluation and comparison with their expected behaviour. This enabled the examination of relationships between the controllable and uncontrollable influencing factors (factors as highlighted by Marais [1979] and expanded to reflect the TRH3 [CSRA Draft, 1997] influences on seal behaviour). The empirical test method has three components:

- the method of constructing seals in the laboratory,
- the test beds with pavement,
- the accelerated pavement tester.

2.2 Seal Construction Method

Due to the envisaged difficulties of applying hot seal binder in a conventional manner (by spraying) on a small scale an alternative method of constructing the seals was developed using prefabrication methods. After three alternative methods were examined, the following method was found to be the most acceptable:

Placing silicon paper into the tray mould, preheating the tray to 180^{o}C, and decanting the hot binder (at specified application temperature) onto the paper was the method that provided the best result enabling acceptable imitation of the seal binder application. After adding aggregate, and allowing to cool, the seal was kept in cold storage until required. At stored temperature (sub 10ºC), the seal was able to be pealed off the paper without distortion and applied directly to the test pavement.

2.3 <u>Accelerated Pavement Tester</u>

The Model Mobile Load Simulator Mk3 (originally used as a $^{1}/_{4}$ to $^{1}/_{3}$ scaled down accelerated pavement tester) is being used in this project. The MMLS has a pneumatic tyre footprint of up to 34cm^{2}, and is able to place up to 7,200 wheel loads per hour. Both load and tyre pressure can be varied to enable the examination of the traffic related influencing factors. The MMLS can be used in the laboratory and the field, is currently being refurbished to enable easier field maintenance and wet weather operation. In the research described in this paper the seal was not scaled down. It was determined that the MMLS adequately represented traffic load and footprint when considering the influences of the traffic on the seal structure type, in terms of load applied to the individual seal stones, and edge effects of the binder film around the stones under load.

Annexure A includes photographs of the MMLS and seal construction method.

2.4 <u>External Test Bed</u>

The performance testing discussed in this paper utilised an external test bed. Pavement thickness of 200mm, G5 quality base was constructed on a concrete slab floor, of area large enough to accommodate the full range of test seals. The test bed was protected from rain, but not insulated during the first set of tests at ambient temperature. The G5 base was specifically selected to enable measurement of the behaviour of the seals at induced failure of the pavement under economic traffic model levels.

2.5 <u>Test Method</u>

The three components described in 2.2, 2.3, 2.4: seal construction, test bed, accelerated pavement tester, are combined to enable the testing of different seals. The MMLS is utilised to apply a traffic load on the pavement structure consisting of the prefabricated seal on the G5 base layer, resting on a concrete floor.

2.6 <u>Summary of First Test Series on a G5 Base with MMLS-MK3 (Ambient Temperature)</u>

The empirical test series reported here reflects the results of different binder types and applications, with constant aggregate type at ambient temperature.

2.6.1 <u>Seals Tested</u>

Six binders were tested: 80/100 penetration grade bitumen, modified binders (3% addition by mass: SBR, SBS and EVA), and bitumen rubber (COLAS and TOSAS processes).

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

Binder applications are summarised in Table 2.1.

Binder	Net Binder Application	Net Binder Application	Base Bitumen	Aggregate (Hornfels)	Pene-tration	R & B Softening Point
	Lower application	Higher application				
3% SBS	1,2 l/m^2	1,5 l/m^2	80/100 pen	13,2mm	80	46
3% SBR	1,2 l/m^2	1,5 l/m^2	80/100 pen	13,2mm	85	54
3% EVA	1,2 l/m^2	1,5 l/m^2	80/100 pen	13,2mm	63	53
80/100 pen	0,9 l/m^2	1,1 l/m^2	80/100 pen	13,2mm	90	78
20 % Bitumen Rubber (COLAS)	2,0 l/m^2	2,4 l/m^2	80/100 pen	13,2mm	-	53
20 % Bitumen Rubber (TOSAS)	2,0 l/m^2	2,4 l/m^2	80/100 pen	13,2mm	44	61

Table 2.1: Seal applications

Three prefabricated seal tiles of each were manufactured to enable averaging of performance and identification of dynamic effects where applicable.

2.6.2 Traffic Load

200,000 repetitions of load of single wheels 600 kPa and 2,1 kN per wheel were applied (with no "lateral wander"). This equates to an equivalent five year traffic load, using an equivalency factor of 40 elv's (equivalent light vehicle) per E80 80t axle load and a

conservative factor of 3 increase due to the effect of lateral wander in practice and the reduced serviceable lifetime of the G5 base.

2.6.3 Climate

On average, the road temperature varied between 20ºC – 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. The three seal tiles per binder type were tested at different times to accommodate the effect of temperature change on binder behaviour.

2.6.4 Summary of Results

The seal performance was measured in terms of parameters evolved from conventional visual assessment indicators. These parameters are:

1) stone loss
2) embedment
3) rotation to average least dimension (ALD)
4) flushing/bleeding

5) base distress
6) crushing
7) general performance (visual)

For initial development of a repeatable comparison method of performance, the following rating system was used:

Distress parameter	Rating	Range
Stone loss	0: none	3: stripping
Embedment	0: none	3: flushing (embedded to zero texture depth)
Rotation	0: as laid	3: ALD 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 maintenance of maximum void content was rated best for purpose.
Flushing	0: none	3: bleeding
Crushing	0: none	3: severe
Base distress	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.	
General performance	0: excellent	3: poorest This parameter was used to credit the negative numerical affect of rotation to ALD for seals that perform visually well.

Table 2.2: Seal Distress Ratings

The performance ratings of the seals were averaged (3 sets of tests per seal type and application), (lowest rating: calculated to percentage of highest possible "poor rating", or **performance index**).

From observations, seal performance is directly related to performance of the base. Seal serviceable lifetime can thus be expected to be determined by ageing of the Bitumen (loss of flexibility, hardening) and performance of the base.

Aggregate was applied shoulder to shoulder – thus the high viscous binders (modified) have higher application of aggregate than the less viscous at application temperature due to the stones not rotating to ALD under gravity during construction.

Crushing occurred possibly when the less viscous binders were not able to accommodate the vertical stone orientation and rotation under load. Further investigation at higher temperature is required.

Higher stone loss was experienced with the lower binder applications (as expected). Unexpectedly, the EVA modified binder rated best with the current performance index calculation, with the higher binder contents of the rubber bitumen seals being "numerically penalised" by flushing being evident.

At the next phase of field tests, at higher temperatures (±50, ^{o}C), different behavioural characteristics are expected.

Performance Index (lowest numerically is better performance)	Binder and Application	Remarks
11	EVA @ 1.5 ℓ/m^2	Good performance at ambient
11	SBS @ 1.5 ℓ/m^2	Good performance at ambient
13	BR Tosas @ 2.0 ℓ/m^2	Slight flushing
14	SBR @ 1.5 ℓ/m^2	Slight stone loss
17	BR (colas) @ 2.0 ℓ/m^2	Slight stone loss
17	BR Tosas @ 2.4 ℓ/m^2	Slight flushing
17	EVA @ 1.2 ℓ/m^2	Good performance at ambient, slight crushing
17	SBS @ 1.2 ℓ/m^2	Some stone loss
19	BR (colas) @ 2.4 ℓ/m^2	Some stone embedment
28	80/100@1.1 ℓ/m^2	Slight stone loss
39	80/100@0.9 ℓ/m^2	Stone loss

Table 2.3: Seal Performance (Ambient Temperature) on a G5 Base (Mean of Three Test Results)

3. INITIATION OF THE DEVELOPMENT OF A THEORETICAL PREDICTION METHOD: MATHEMATICAL MODEL

3.1 Method of Modelling

From assessment of literature, and understanding of the components of the seal and pavement, and influencing factors, an initial theoretical model of seal performance was developed.

The Finite Element Method (FEM) Analysis was selected for the purpose of modelling seal performance for the following main reasons:

- 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 from the determined collective displacements using the applicable elastic and visco-elastic methods).
- The availability of proven existing modelling software.

3.2 Dimensions of the Model

The dimensions of the seal elements for a 13,2mm single seal were determined using analysis of literature:

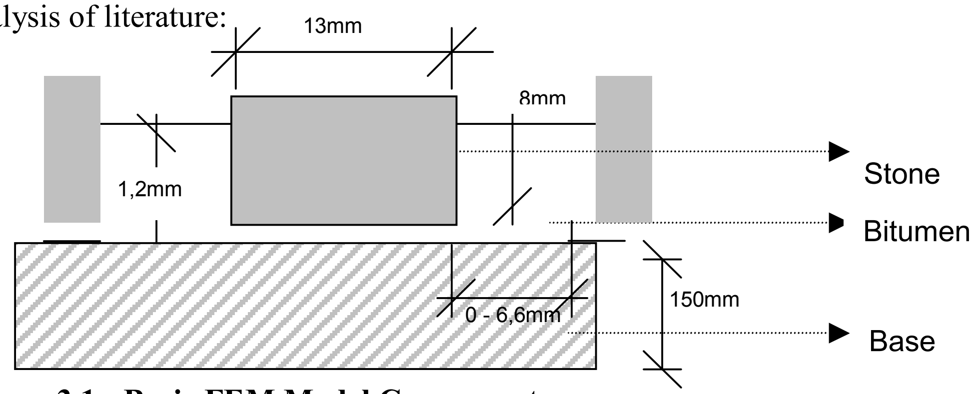

Figure 3.1: Basic FEM Model Components

3.3 Material Parameters

For the initialisation of the model the following parameters were determined through literature analysis:

- Stone

  Assume inert (i.e.: stiff), for the model. Marais (1979) indicates that voids in the seal are only reduced due to wear of the aggregate if no penetration occurs (i.e.: **no** stone deformation under load).

- Base

  TRH4: Materials deform through shear and densification under repeated stress.
  Semmerlink's K – mould E values for granular material, E ranges from E = 60Mpa minimum to 330 maximum Mpa. Mechanical Analysis of the structure assumed an E of 400Mpa, based on historical results (*Milne (2001) draft Thesis section*). Future models will include a range of stiffness values from literature.

- Bitumen

  G* (complex modulus) describing both elastic and viscous elements was used for the initial run: G* = 15Pa for straight bitumen and 205Pa for modified bitumen (*Milne (2001) draft Thesis*). Further models will include phase angles for viscous components and differentiation between the stiffness of the modified binders.
  Later, a method of reflecting changing visco-elastic parameters with temperature will be assessed per binder type.

3.4 Loads

- Wheel Load

  Two load configurations were used:

  690kPa, 2,7kN wheel (maximum applied loads by the MMLS), 600kPa and wheel load of 2,1kN (as used in the empirical tests).

  i.e.: For this example $\sigma_v = 690kPa$

  Note is also made of De Beer's (1995) finding that:

  - Transverse stress = up to 72% of σ_v inflation pressure (magnitude less than 3% of F_V).

  - Logitundinal stress = 30% maximum of inflation pressure (magnitude less than 3% of F_V).

  There are a number of formulae to determine transverse and longitudinal forces and stress – possibly for later inclusion as the model develops.

3.5 Summary of Theoretical Parameters

As indicated under a separate section of this paper, a first comparison of theoretical and empirical parameters is made.

Future development may allow the following to be included in the model:

Bitumen	Pavement	Seal	Aggregate
G* (complex modulus) η (viscosity) S (stiffness modulus) (variation of the above with temperature)	E and CBR Ball penetration	Binder and aggregate application	ACV, PSV, R & W (adhesion), FI, ALD

Table 3.1: Theoretical Model Parameters

3.6 Results of Initiation Model

The FEM programme PLAXIS is being used to develop the model. The initiation model was implemented in partnership with Africon: Structural Services and the Civil Services Divisions using the material parameters mentioned in 3.3 above:

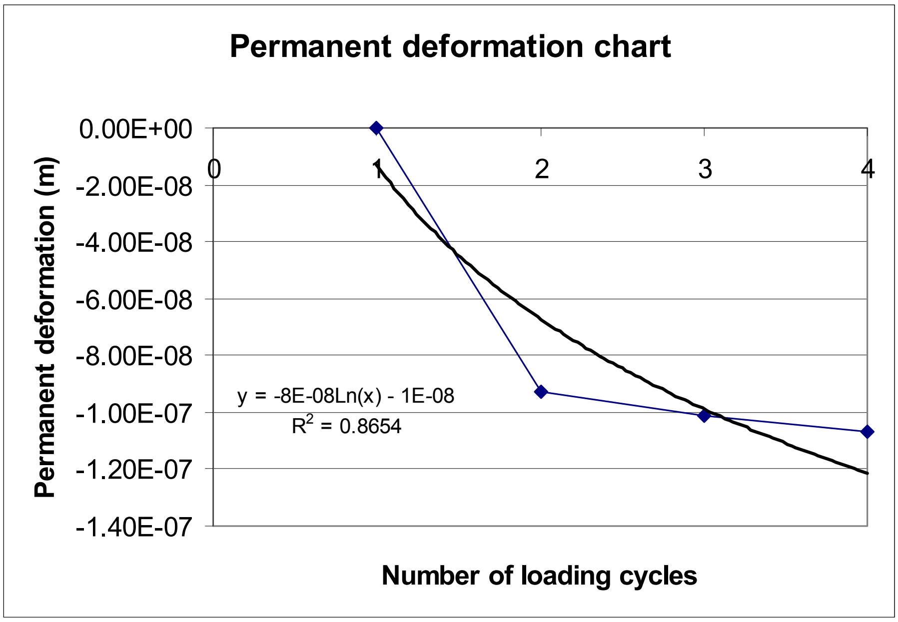

Figure 3.2: Deformation at Point A (bottom of seal stone, figure 3.3)

Examples of the initial output were promising, and are presented as a good indication that further development of the model should provide a sound initiation into the progress of development of the mathematical model. Objectives of the model are to predict number of repetitions to failure: Failure can only be defined as:

- Stripping off of stone
- Punching of stone
- Bleeding or flushing of seal

It is evident that in a pure elastic system, failure would occur when the applied load exceeded the yield stress of one of the components (failure would then be stripping of or punching of the aggregate). An additional failure mechanism is when plastic deformation occurs under sufficient repetition (i.e.: under sufficient repeated loads, to induce punching or bleeding of the seal as the voids are reduced). Failure would then be evaluated by the TRH3 texture parameters.

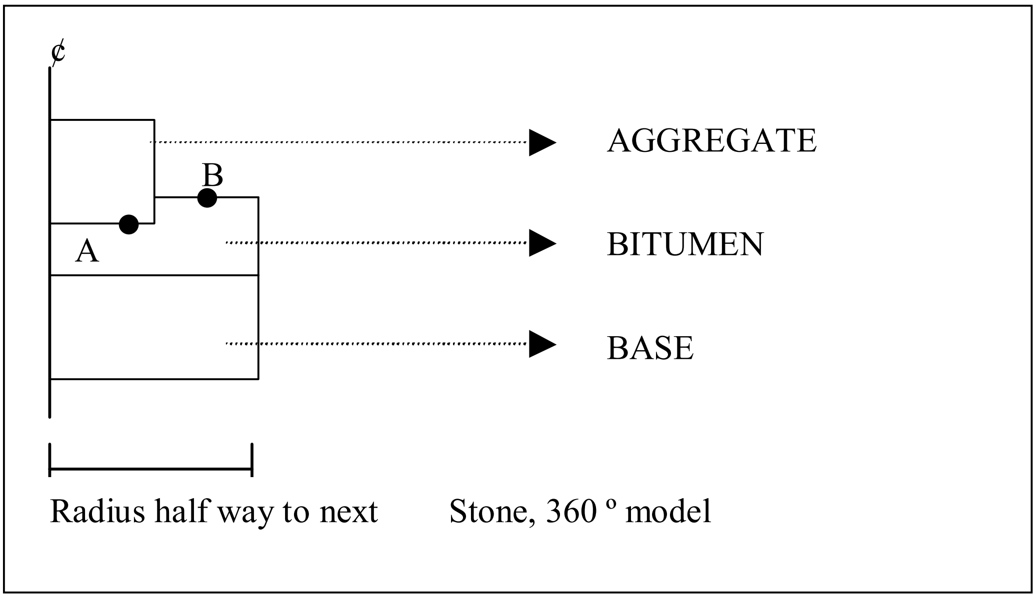

Figure 3.3: Positions of Reference Points

Figure 3.3 is an output of the first FEM run, clearly indicating that for the chosen material characteristics, there is initial large plastic deformation or embedment (confirmation by experience – 50% of total penetration occurs under construction) with gradually reduced plastic deformation, as the base consolidates.

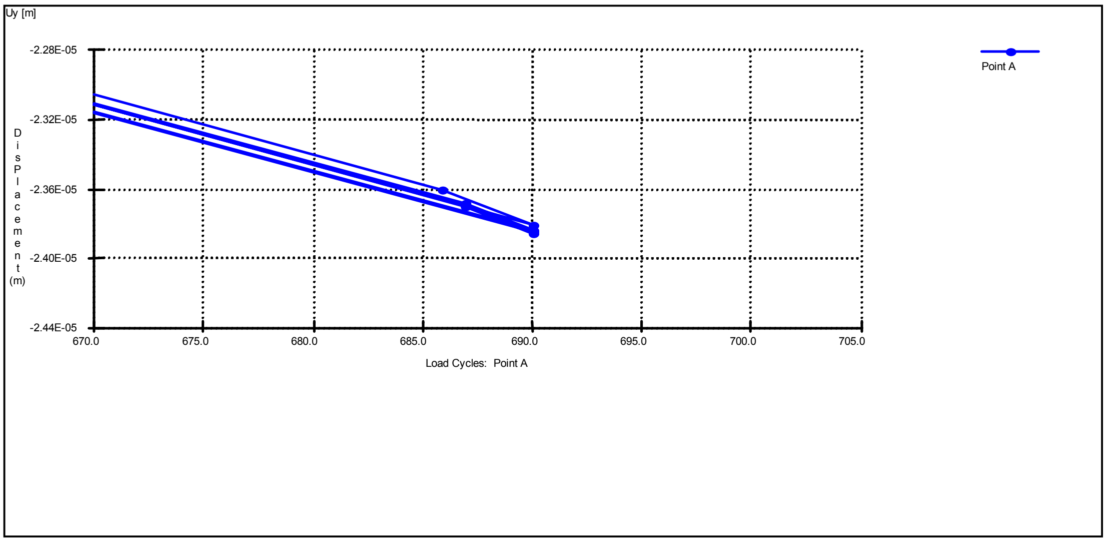

Figure 3.4: Displacement of Points A (bottom of seal stone) and B (top of bitumen), refer to figure 3.3

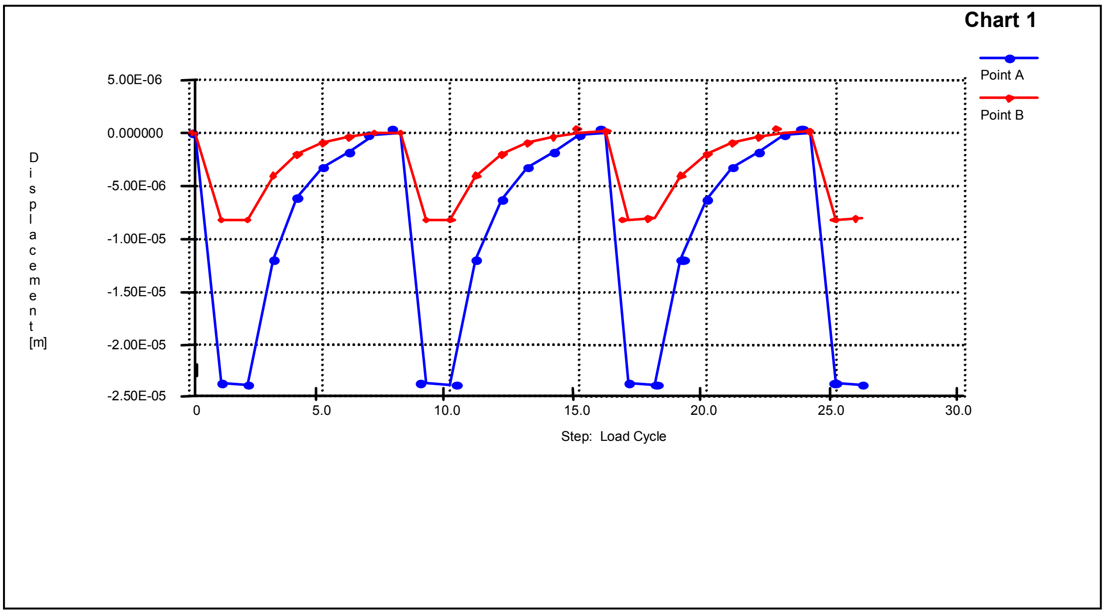

Figure 3.5: Displacement at Peak Load

Figure 3.4 depicts the elastic nature of the displacement of the stone and bitumen under load. The fact that the bitumen is also displaced downwards at the recovers indicates that failure of the bitumen in terms of plastic flow has not yet occurred. In this scale it appears that all deformation is elastic, although Figure 3.2, a scale a magnitude smaller indicates slightly plastic deformation of the end of the repeated load cycle.

Figure 3.5 indicates the displacement of the seal stone and binder during the load cycles, under peak load (690kPa) while Figure 3.6 indicates permanent or plastic deformation (small magnitudes) at zero load under the cycles of loading, confirming the Figure 3.2 deformation.

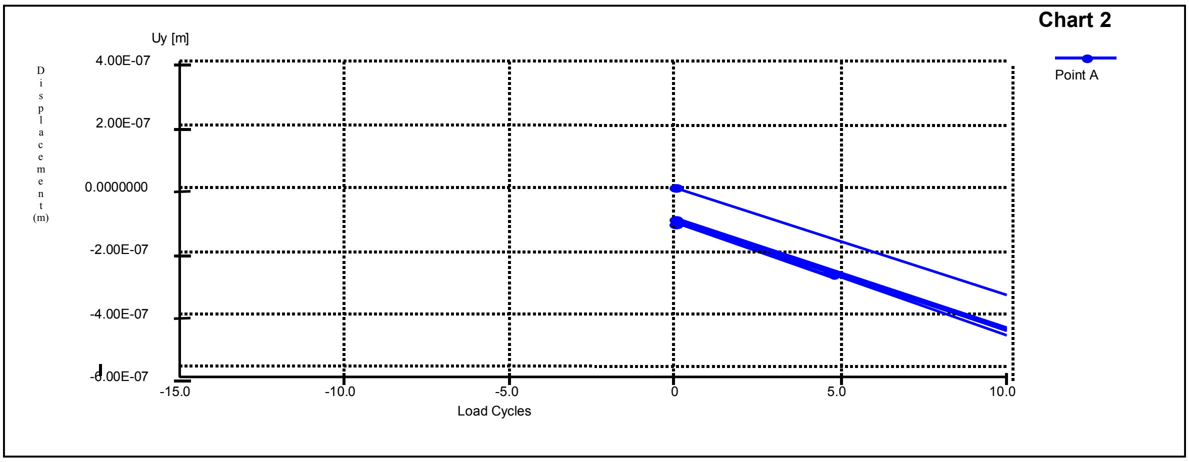

Figure 3.6: Displacement at Release of Load – Point A

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

4. INFLUENCING AREAS

From assessment of literature and the development of the theoretical and empirical models through the research process, parameters for the assessment of performance and the describing of the elements of the seal have been identified. The identification has been made for both types of model, to enable comparison of the inputs (either seal components, influencing factors) and outputs (seal performance). Annexure B includes the tabulation of the influencing parameters that are being used on this research project's models. These influencing areas, with their descriptive parameters, will be used in the further development of the theoretical model.

5. CONCLUSION

The Empirical model (with new seal performance test method) has been developed, and further research is planned to enable evaluation of performance of surfacing seals.
The theoretical model is to be developed with calibration and verification through the empirical parameters.

REFERENCES

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2. Committee of State Road Authorities, (Draft 1997), *Technical Recommendations for Highways 3, Draft, Surfacing Seals for Rural and Urban Roads,* RSA Department of Transport (Draft Document).
3. T I Milne, (2001). *Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders*. Draft PhD Thesis, University of Stellenbosch.
4. De Beer M, (December 1995). *Measurement of Tyre/Pavement Interface Stresses Under Moving Wheel Loads*, CSIR.

ANNEXURE A:
MMLS AND SEAL PREPARATION

ANNEXURE B:
TABULATION OF INFLUENCING PARAMETERS

INVESTIGATION FIELD	**THEORETICAL MODEL**	**EMPIRICAL MODEL**	**FUNCTION**
CONTROLABLE FACTORS			
Bitumen • Binder type (SBS, BR, EVA, SBR, 80/100 pen)	• E_1 • G* (complex modulus), G',G'' G' = G*cosγ (storage/elastic modulus) G'' = G*cosγ (loss / viscous modulus) γ = phase angle • η (temperature and frequency/time of load) (section 4.5.1,2,3; 4.7.4.19) : Temperature dependent *below 90°C – Non-Newtonian* *above 135°C – Fluid* *below 10°C – brittle* *at 25°C – elastic solid* Time dependant • Ring & Ball softening point • S = Stiffness Modulus = tensile stress/total strain • λ = 3.η (newtonian fluids)	• Temperature Susceptability (Van der Poel) • Viscosity* • Adhesion • Cohesion • Ductility • Ageing • Tensile strength • Plastic flow • Elasticity • Stiffness • Hardness • Modification	• Adhesion (retain aggregate under wheel load) • Flexibility • Durability • Waterproof
Aggregate	• FI • Resistance (*PSV)* • Adhesion (*R&W)* • Grading • ALD • Strength (*ACV)*	• Strength • Adhesive properties • Wear properties	• Transfer of Load • Durability

INVESTIGATION FIELD	THEORETICAL MODEL	EMPIRICAL MODEL	FUNCTION
CONTROLABLE FACTORS			
Pavement	• E_1 • Plastic deformation • CBR • Ball penetration	• Density • strength • embedment	• Load distribution to subgrade/bearing capacity
Seal	• Single seal • Seal design: • applications • aggregate, • binder • void volume	• Single seal • Seal design: • applications • aggregate, • binder	• skid resistance • Protect bitumen • Provides a structure to carry the waterproof elastic layer without flushing • Durable, all weather protection of pavement • Strength at surface to resist traffic force
Traffic	• Equivalency factor • Actual measured stress • Foot print • Pressure • Load • Time and frequency of loading	• Tyre pressure • Load varied • volume	
Environment	• E_1 η temperature variation • G* (complex modulus) per 4 temperature zones	• effect of temperature (4 temperature zones) • Effect of moisture	
Behaviour	• Degrees of freedom • Limits: adhesion • Composition • Fractions • Measure – Penetration Index • Temperature and behaviour	• Interlock, space to rotate (ALD or not, voids)	

INVESTIGATION FIELD	THEORETICAL MODEL	EMPIRICAL MODEL	FUNCTION
CONTROLABLE FACTORS			
Failure	Bitumen • Punching (flushing) • Adhesion failure (stone to bitumen, bitumen to base) • Rotation • Plastic flow • Cracking • Moisture Aggregate • Polishing • Crushing	• Punching (flushing) • Rotation • Binder flow (plastic deformation) • Bleeding • Fatigue cracking • Low Temperature cracking and brittleness • Loss of aggregate (adhesion failure)	
Measurables / Performance	• Texture depth • No. of repetitions to stone loss or binder failure • No. of repetitions to punching	• Texture depth (laser) • Stone rotation • (Skid resistance) • Stone loss, crushing	

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