Application of bitumen adhesion and cohesion laboratory tests in a finite element modelling approach of chip seals

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ABSTRACT

Chip seals are constructed throughout South Africa as the final layer on top of new or existing pavements. The seal layer provides a waterproof cover for the underlying pavement and a safe, all-weather, dust free riding surface for traffic with adequate skid resistance. The seal layer protects the underlying layer from the abrasive and destructive forces of traffic and the environment. The level of service provided by the seal is governed by its relations to various surface distress types. Distress affects the seal's ability to fulfil its functional and structural requirements. Surface ravelling and fatigue cracking are two major distress types which annul chip seal functionality. Bitumen adhesion and cohesion laboratory tests were therefore conducted and subsequent transfer functions were developed which were utilized in the response quantification of a chip seal finite element model. The response outputs of the finite element models were quantified in terms of wheel load repetitions to the initiation of failure for each distress type. A typical South African seal design assumption suggests a 40:1 equivalent damage ratio for light vehicles versus heavy vehicles. Quantification of the model responses indicated a 3:1 wheel load damage ratio for ravelling and a 2:1 ratio for fatigue cracking. The response model can therefore be utilized as a tool in facilitating the seal design process.

Keywords: Adhesion, Chip seals, Cohesion, Fatigue Cracking, Ravelling

1. INTRODUCTION

Finite element (FE) modelling of complex structures such as chip seals has become a viable practice to obtain insight into the structure's response behaviour. These responses are difficult if not impossible to measure in the field and are used to explain distress phenomena. Outputs from the FE simulation need to be quantified in terms of time to failure for the chip seal models to be of practical value. Transfer functions were subsequently developed by conducting bitumen-aggregate adhesion tests and bitumen fatigue tests [1]. Implementing the FE outputs into transfer functions, allow the quantification of adhesive and cohesive damage for a given geometrical setup, material condition and load case scenario. Subsequent model validation indicated that the FE outputs are in accordance with field and laboratory measured parameters, while the transfer functions need some additional development to translate the FE outputs to field obtained results.

2. BACKGROUND INFORMATION

2.1 Early chip seal model developments

FE modelling of chip seals was pioneered by Milne in collaboration with Delft University of Technology [2]. Milne realized that obtaining new insight into response dynamics of a chip seal would require a model consisting of individual components. With the support of Huurman et al. [3], algorithms were developed capable of generating a single layer of spherical idealized aggregates packed in a hexagonal structure, surrounded by bitumen (Figure 1). This is an idealized representation of a single seal, which consists of a single layer of aggregates and a single application of a bitumen tack coat.

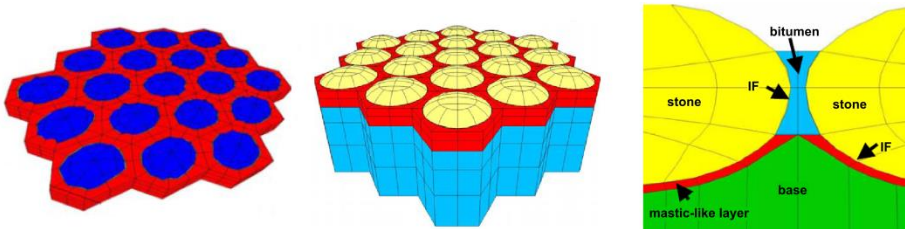

Figure 1: Milne's chip seal model (left) [2]; Base improvement by Huurman (centre) [4]; Detailed cross section of improved chip seal model (right) [4].

Although innovative at the time, Milne's model lacked a base layer and was improved by Huurman [4] at a later stage to incorporate aggregate embedment. Material properties of the chip seal model comprised of a Burger's model for the bitumen, linear elasticity for the aggregates and the aggregate-bitumen interface (IF) and a K-Θ like resilient model to represent the improved base. Milne's model was used to rank each simulation according to the responses obtained in the bitumen and at the bitumen-aggregate interface. It is therefore a response model, however, the research did not progress such that the response parameters were quantified to a failure time, where time is typically defined as the number of load repetitions to failure.

2.2 Recent chip seal model developments

Emanating from the chip seal project with Milne, Huurman [5] developed 2D idealized and photo-deduced FE models of porous asphalt concrete (PAC). Contrary to chip seals which consist of aggregates and bitumen, PAC consists of aggregates and mortar (Figure 2). Innovative material testing was conducted on the mortar to compliment the PAC FE model simulations. Mortar response testing was conducted with the dynamic shear rheometer (DSR) and translated to a Prony series that served as the mortar's constitutive material model. Adhesion fatigue testing was conducted by a newly developed stone column test [5]. This test consists of two cylindrical aggregate cores, drilled from the PAC parent rock and bound by a bitumen film (Figure 4). Modifying the DSR setup to include the stone column specimen allowed the development of adhesion fatigue transfer functions. An adhesion response parameter is thereby obtained by simulating a rolling wheel load. Implementing the response parameter into the transfer function results in the equivalent number of wheel load repetitions to failure. A similar approach was followed in developing cohesion fatigue transfer functions, by testing mortar column specimens (Figure 5) with the modified DSR setup [5].

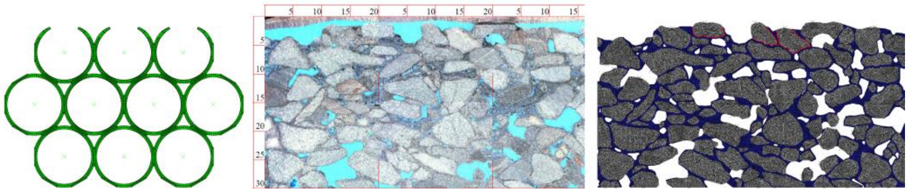

Figure 2: 2D idealized (left) and photo-deduced (right) PAC FE models [5].

Recent shifts in developments incline more towards computer tomography as an origin for the seal model geometries. Computer tomography is radiography (x-rays) in which a 3D image of a structure is constructed with a computer from a series of plane cross-sectional images. Kathirgamanathan [6] developed such a model from a chip seal core (Figure 3) and found that aggregate to aggregate interaction reduced the stress obtained within the bitumen tack coat. Aggregates were modelled as rigid bodies, while the bitumen was ascribed non-linear viscoelastic properties. Since this was a preliminary study the response was not quantified to give any indication of failure, but Kathirgamanathan [6] discussed the complexity of simulating tyre loading on a chip seal surface.

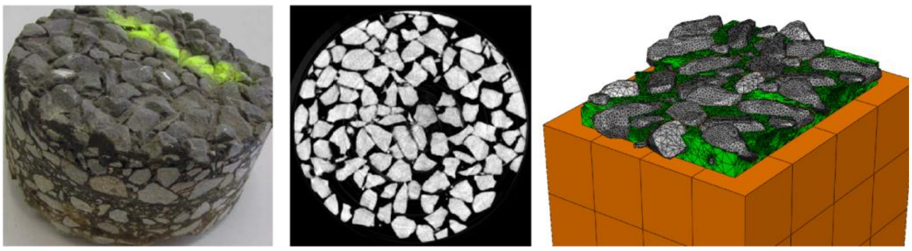

Figure 3: Chip seal core (left); X-ray image (centre); Chip seal model (right) [6].

The literature indicates that a chip seal model requires a detail material investigation, structurally representative geometry and an adequate strategy for traffic loads. Material characterization should complement the objectives of the model, while geometric simplifications are required to construct a robust and suitable FE chip seal model.

3. PAPER OUTLINE

The remainder of this paper is organized as follows. In Section 4 the bitumen material characterization is discussed, with the aim on developing response and transfer functions. Section 5 addresses the FE chip seal model development with reference to surface distress phenomena such as chip loss and fatigue cracking. The simulation results are discussed in Section 6, while the research conclusions are presented in Section 7.

4. MATERIAL CHARACTERIZATION

4.1 Bitumen response testing

Virgin 70-100 penetration grade bitumen was selected for characterization and parallel plate tests were conducted with the DSR at 0°C to 50°C. A master curve was subsequently determined with a reference temperature at 25°C. The master curve data was converted to a Prony series. This enabled the implementation of the response data into Abaqus, a FE software package.

4.2 Adhesion fatigue testing

Fatigue behaviour of the bond between virgin 70-100 penetration grade bitumen and dolerite aggregate cores was observed by conducting stone column tests (Figure 4) at 10 Hz and 25°C [1]. The contact surface of the aggregate was left untreated after cutting the 30 mm core in half and binding it with a 100 µm film of bitumen. Tests were conducted at different DSR torque settings, ranging from 50 Nmm to 200 Nmm.

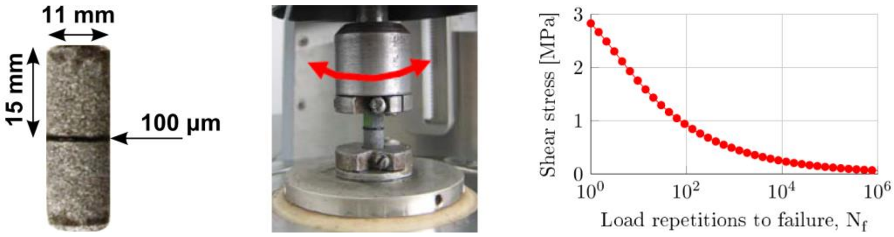

Figure 4: Stone column test specimen (left) [5]; Stone column DSR test setup (centre) [5]; Adhesion shear stress response transfer function at 25°C (right) [1].

Debonding resulted in test termination. The number of cycles to adhesion failure N_f corresponds thus to a single DSR torque setting. Higher torque settings result in fewer cycles to failure. Translating the torque magnitude to a shear stress parameter τ and analysing the τ, N_f pairs formed the basis of the transfer function (Figure 4) as defined in Equation 1. The transfer function parameters are summarized in Table 1. It should be noted that shear stress responses exceeding 3 MPa result in catastrophic failure i.e. single load rip-off.

$$\tau = a\left(1 + N_f\right)^b \tag{1}$$

Table 1: Adhesion transfer function parameters.

Temperature [°C]	a [MPa]	b [-]
25	3.448	-0.2871

4.3 Cohesion fatigue testing

Fatigue behaviour was investigated by creating bitumen column specimens (Figure 5) and conducting fatigue testing with a modified DSR setup, similar to that of the stone column test regime [1]. The torque settings ranged from 5 Nmm to 40 Nmm, with a test temperature and frequency of 25°C and 10 Hz respectively.

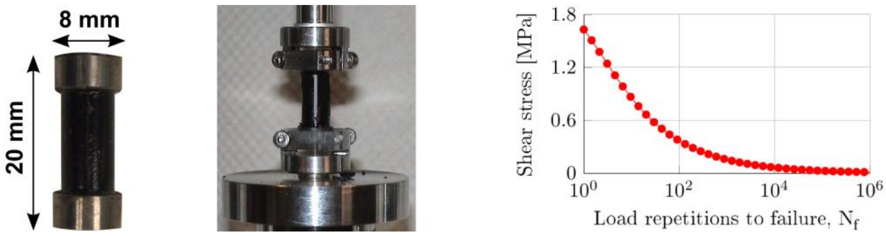

Figure 5: Bitumen column test specimen (left) [5]; Bitumen column DSR test setup (centre) [5]; Cohesion shear stress response transfer function at 25°C (right) [1].

A 50% reduction in the bitumen column's complex modulus signalled test termination. The number of cycles to cohesion failure N_f corresponds to a single DSR torque setting. The transfer function is very conservative and a cause of concern since self-healing effects of virgin bitumen was not included in the test regime. According to Molenaar [7], introducing a self-healing period will increase the number of cycles to failure. The same procedure as discussed in Section 4.2 was followed to develop the cohesion transfer function. The cohesion transfer function is also defined with Equation 1, while the transfer function parameters are summarized in Table 2. Shear stress responses exceeding 1.6 MPa will result in instantaneous bitumen disintegration.

Table 2: Cohesion transfer function parameters.

Temperature [°C]	a [MPa]	b [-]
25	2.119	-0.3797

5. FINITE ELEMENT CHIP SEAL MODEL DEVELOPMENT

5.1 Model geometry

The FE chip seal model development was confined within the 2D domain, mainly to simplify the geometric complexity and increase over-all model control over component variations. Individual chip seal components (Figure 6) were identified and attributed with unique material properties. These components include: aggregate, adhesive zone, bitumen, air voids and supporting substructure. Inclusion of three different types of chip seals i.e. single, double and cape seals (Figure 7) was a prerequisite for model development, while adjustable seal design parameters also formed part of the development criteria to investigate chip loss and fatigue cracking.
Algorithms were developed at the backend of a graphical user interface (GUI), capable of generating the architecture for an Abaqus FE model simulation. The GUI allows the user to select the: seal type, number of aggregates, size and spread of the aggregates, bitumen type and application rate, surface temperature, structural support and strength, traffic load, tyre inflation pressure, traffic speed and wheel motion conditions [8].

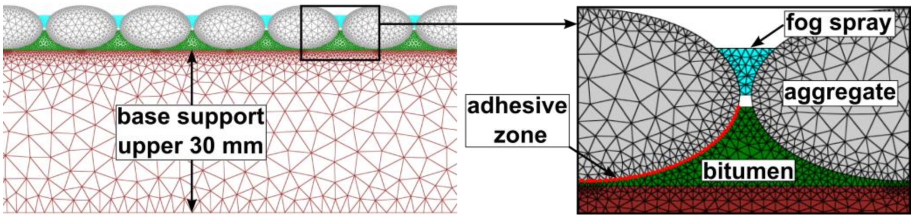

Figure 6: Individual chip seal components.

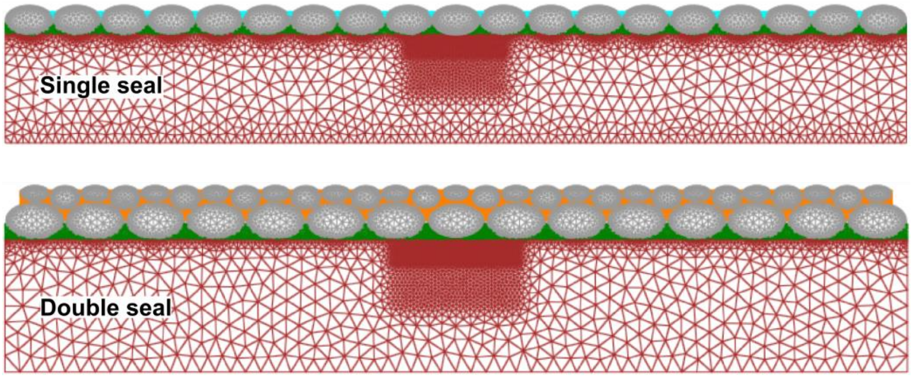

Figure 7: FE single and double chip seal models.

Aggregates consist of elliptical shapes where the vertical and horizontal dimensions are dictated by the aggregate nominal size and average least dimension (ALD). The nominal sizes include: 6.7 mm and 13.2 mm for single seals, and 13.2 mm and 19.0 mm for cape seals. The combinations of nominal sizes for double seals include: 13.2 mm + 6.7 mm, 19.0 mm + 9.5 mm and 19.0 mm + 6.7 mm + 6.7 mm. Since the models are developed in 2D an adjustable aggregate edge to edge spacing is incorporated to account for the aggregate spread rate. The number of aggregates determines the size of the FE model and selection range from 5 to 99 per model.
An adhesive zone is included at the bitumen-aggregate interface and consists of a node set which represents the bond strength. The model can therefore simulate the bond strength of any bitumen-aggregate interaction combination type if the bond response properties are known. These properties differ from pure bitumen properties.

Bitumen is represented by a homogeneous, continuous layer of which the geometry is formed and shaped by the surrounding aggregates and supporting substructure. The application rate of the bitumen for each tack coat, penetration coat or fog spray is adjustable within general design limits. The FE model assumes that all tack coats are fully bound to the supporting substructure. In the case of a single seal with a fog spray or in the case of a double seal with a penetration coat, it is possible to obtain air voids between the first and the second application and this effect is included in the models.
The base is modelled as a homogeneous layer. Since aggregate embedment occurs at the surface of the base, only the upper 30 mm of the base is included. Near the region of embedment interest the model algorithms generate a refined mesh to observe this phenomenon. Additional information on aggregate embedment is addressed by Gerber [8] and will therefore not be discussed in this paper.

5.2 Constitutive material models

Each component in Figure 6 was accredited with a unique set of material parameters. Aggregates were attributed with linear elastic properties which included an elastic modulus and Poisson's ratio. These properties were deduced from literature [9] and due to the assumption of linear elasticity, aggregates could not exhibit wear, be crushed or display permanent deformation. Since these phenomena were not of interest, elasticity was considered an effective assumption.
Response characteristics of the adhesive zone were determined from the bitumen complex moduli as defined in Equation 2 and Equation 3 and discussed by others [2, 5]. These characteristics where implemented into an Abaqus traction separation model (Equation 4), where K_{nn} is the normal stiffness response parameter and $K_{ss,tt}$ the shear stiffness response parameters.

$$K_{nn} = \frac{E^*}{film\ thickness} \tag{2}$$

$$K_{ss,tt} = \frac{G^*}{film\ thickness} \tag{3}$$

$$t = \begin{Bmatrix} t_n \\ t_s \\ t_t \end{Bmatrix} = \begin{bmatrix} K_{nn} & & \\ & K_{ss} & \\ & & K_{tt} \end{bmatrix} \begin{Bmatrix} \varepsilon_n \\ \varepsilon_s \\ \varepsilon_t \end{Bmatrix} = K\varepsilon \tag{4}$$

A Prony series was selected to represent the bitumen response characteristics. The Prony series consists of a number of Maxwell elements and a single spring element (Figure 8). Implementation into Abaqus requires the translation of the elements into α_i, τ_i pairs which describes the normalized stiffness reduction and relaxation rate of the i^{th} Maxwell element respectively as defined in Equation 5. Additional parameters such as the instantaneous modulus E_0 and Poisson's ratio ν are required. No material properties were attributed to air voids, while linear elastic properties were ascribed to the base.

$$E(t) = E_0 \left[1 - \sum_{i=1}^{N} \alpha_i \left(1 - e^{\frac{-t}{\tau_i}} \right) \right] \tag{5}$$

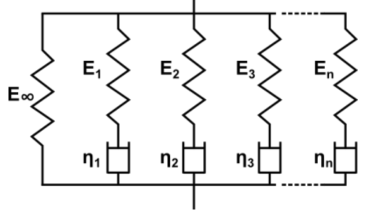

Figure 8: Schematic representation of the Prony series.

5.3 Traffic loads

Traffic load data was obtained from Tyre Stress Seal, a software package developed by the Counsel for Scientific and Industrial Research (CSIR) of South Africa. Tyre Stress Seal was compiled from research conducted on different wheel loads with the stress in motion (SIM) system [10]. SIM data was converted into time-force functions and implemented into the 2D FE seal model architecture.

Vertical and longitudinal time-force functions (Figure 9) were applied at the vertex node of each aggregate with constant time offsets. This resulted in artificially simulating a rolling wheel across the surface of the FE seal models, without including an actual tyre on top of the seal structures. Traffic loads were confined to the aggregate except in the case of cape seals, where a fraction of the load was also applied to the slurry surface [8].

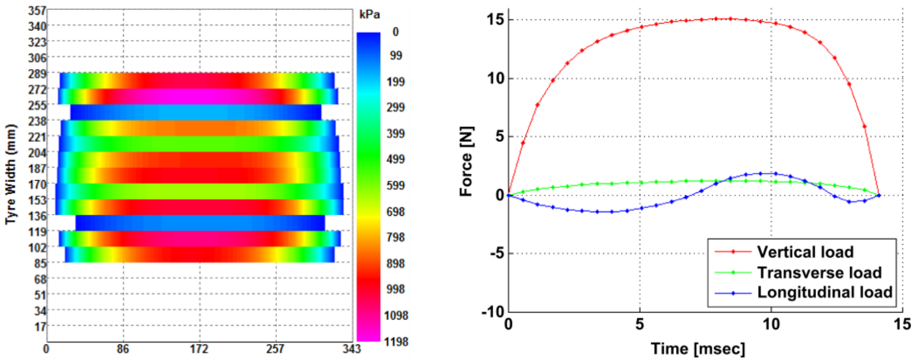

Figure 9: SIM contact patch output (left); Traffic load time-force function (right).

The traffic load formulations included a list of variations such as the: wheel size, vertical load, rolling motion conditions i.e. free rolling, driven or braking and travelling speed. The magnitudes of these variables are selected from GUI within the relevant limits prior to each FE simulation.

6. CHIP SEAL MODEL SIMULATION RESULTS

6.1 Chip loss

All chip seal response results presented in this paper, were obtained from 13.2 mm single seal simulations at 25°C, unless specified otherwise. The model variables included: an aggregate spacing of 0.5 mm, ALD of 8 mm and a bitumen application rate of 1.2 l/m² which corresponds to an aggregate wetted height of approximately 40%. Since equivalent damage ratios were calculated, traffic loading comprised of 6 kN light vehicle (LV) wheel loads and 20 kN heavy vehicle (HV) wheel loads. A 20 kN wheel load is one quarter of an 80 kN dual wheel axle load (E80).

The adhesive zone shear stress response zone is illustrated in Figure 10. The response parameters indicate a general increase with an increase in the tyre contact stress. These

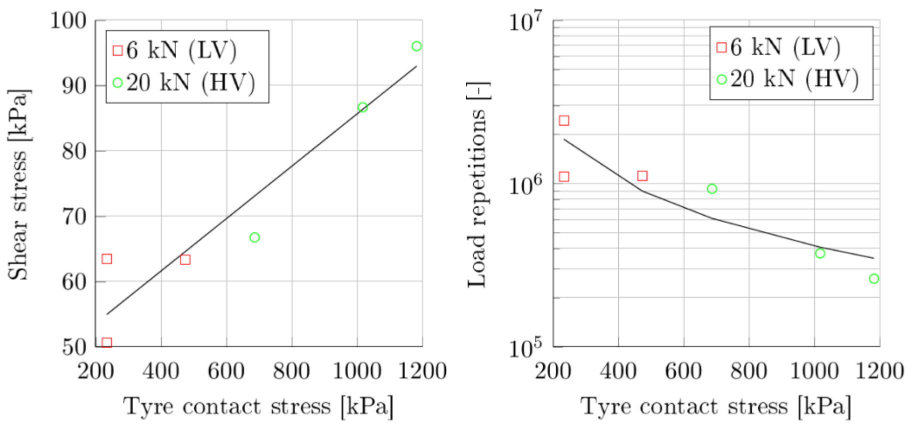

Figure 10: Adhesion response and associated load repetitions to failure.

responses were implemented into the adhesion transfer function and resulted in the corresponding wheel load repetitions to failure initiation. No catastrophic failure i.e. single load rip-off is observed, indicating that adhesive bond fatigue will ultimately be responsible for chip loss in this case. LV wheel loads will result in failure at an average of 1.55 million repetitions, while HV wheel loads will result in failure at an average of 0.52 million load repetitions. The equivalent LV:HV wheel load damage ratio is therefore 3:1.

6.2 Chip loss validation

Over the years South African practitioners have developed empirical chip seal design guidelines. These guidelines are compiled in the TRH3 manual [11] and present amongst other things, data on the critical minimum bitumen application rates for a given traffic volume and chip seal size. The TRH3 suggests that chip seal designs should incorporate greater bitumen application rates than presented in Table 3, since immediate chip loss occurs at application rates below the critical value. FE modelling of the 6 mm and 8 mm ALD cases served as the chip loss validation process. Comparison between the modelled load repetitions to failure and the empirically TRH3 critical minimum bitumen application rate records are presented in Figure 11. Lateral wander adjustments was included according to [12].

Table 3: Critical minimum bitumen application rates for strong bases [11].

Traffic analysis per lane per day					Average least dimension, ALD (mm)				
AADT	**HV**	**LV**	**E80s**	**ELVs**	**4**	**6**	**8**	**10**	**12**
5848	20	5828	13	6628	0.57[i]	0.87	1.16	1.45	1.73
4501	50	4451	49	6451	-	0.72	1.01	1.3	1.58
3692	100	3592	121	7592	-	0.63	0.92	1.21	1.49
3028	200	2828	288	10828	-	0.56	0.85	1.13	1.41
2697	300	2397	472	14397	-	0.52	0.8	1.08	1.36
2330	500	1830	873	21830	-	-	0.74	1.02	1.29
2037	800	1237	1522	33237	-	-	-	0.94	1.22

[i] critical minimum bitumen application rate (l/m²)

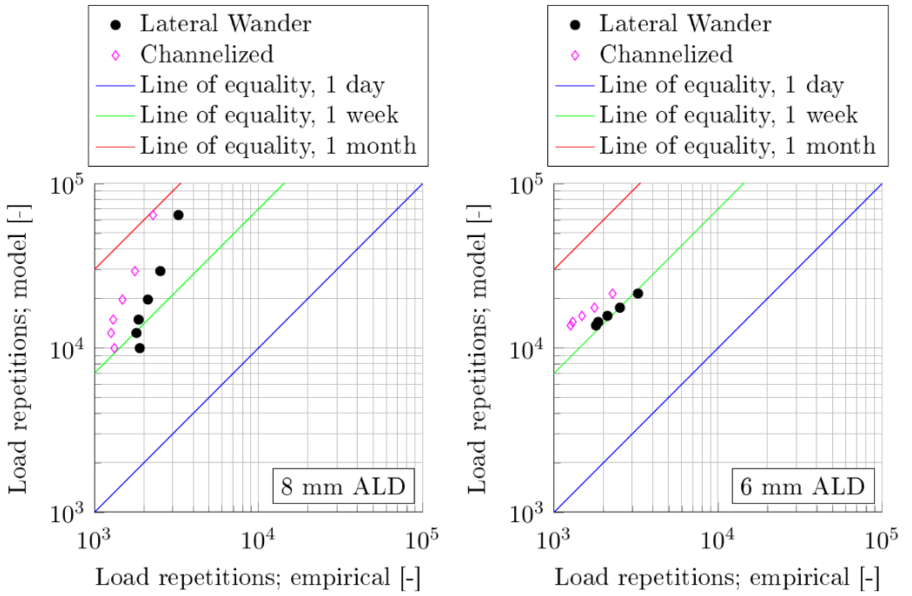

Figure 11: Empirical versus FE modelled 20 kN wheel load repetitions to failure for the critical minimum bitumen application rate values of Table 3.

Although the TRH3 suggests immediate chip loss the simulations indicate that chip loss occur only after one week to one month of traffic. A reason for this observation is ascribed to the aggregate orientation of the FE model that is already in ALD. There are no isolated aggregate asperities that may result in a single load rip-off effect due to the resultant peak bond stresses. The adhesive transfer function [1] is also questioned since it does not include tensile stress or strain components. In a classic Mohr-Coulomb like failure envelope, the shear stress is unable to indicate whether stress development is within or outside the failure envelope without a normal stress component

6.3 Fatigue cracking

Shear stress response obtained within the bitumen is illustrated in Figure 12. An over inflated LV wheel load responded with a greater shear stress in comparison to an underinflated HV wheel load, underlining the contact stress as indicative to the expected extent of damage. The latter statement also suggests that the longitudinal and transverse forces have a significant contribution to the damage evolution of chip seals.

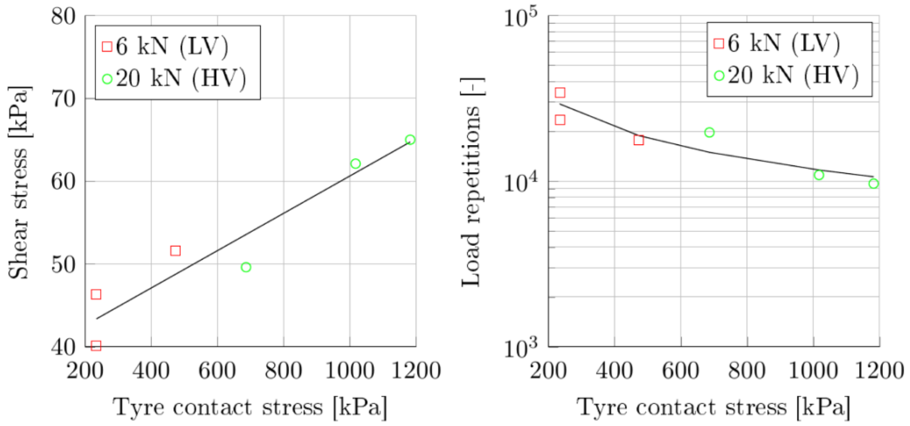

Figure 12: Cohesion response and associated load repetitions to failure.

Implementing the responses into the cohesive transfer function, result in the number of load repetitions to fatigue failure initiation. The outcome is very conservative and raises concerns about the validity of the transfer function. It would be worth reviewing the DSR stress controlled bitumen column test regime [1] and include strain components in the form of the dissipated energy approach [5] in the development if the cohesive transfer functions. Nevertheless, an equivalent LV:HV wheel load damage ratio of 2:1 is obtained for the cohesive failure analysis.

6.4 Fatigue cracking validation

Similar to a four point bending beam fatigue analysis, van Zyl [13] postulated that repeated surface deflection results in fatigue cracking of chip seals. Van Zyl obtained Benkelman Beam deflection data subjected to a standard 80 kN axle load, annual traffic counts, traffic growth rates (Table 4) and the time in years when fatigue cracking was first observed on 34 sites throughout South Africa. An assumption was made that the chip seal accounts for the difference in the D_0 and D_{127} deflection measurements. The response results of the FE chip seal models (Figure 13) indicate that the models are within the linear viscoelastic range for penetration grade bitumen [8] and compare well with radius of curvature and deflection data assumptions of van Zyl.
The surface deflection was assumed to have remained constant throughout the service life of the seal. Interpretation of the deflection data is presented in Figure 14. Here the cumulative D_0 - D_{127} deflection resulting from the annual traffic count is illustrated with superimposed data points representing the time of initial fatigue cracking. The resulting trend, termed the trigger line, indicated that chip seals exposed to higher deflections exhibit earlier fatigue cracking compared to chip seals exposed to lower deflections.

Table 4: Traffic volumes and growth rates.

Regions	Traffic volume description	Number of E80s/day/lane	Annual growth rate *i* [%]
Region 1	High	600 – 300	1, 3, 5
Region 2	Moderate	300 – 150	1, 3, 5
Region 3	Low	150 – 38	1, 3, 5

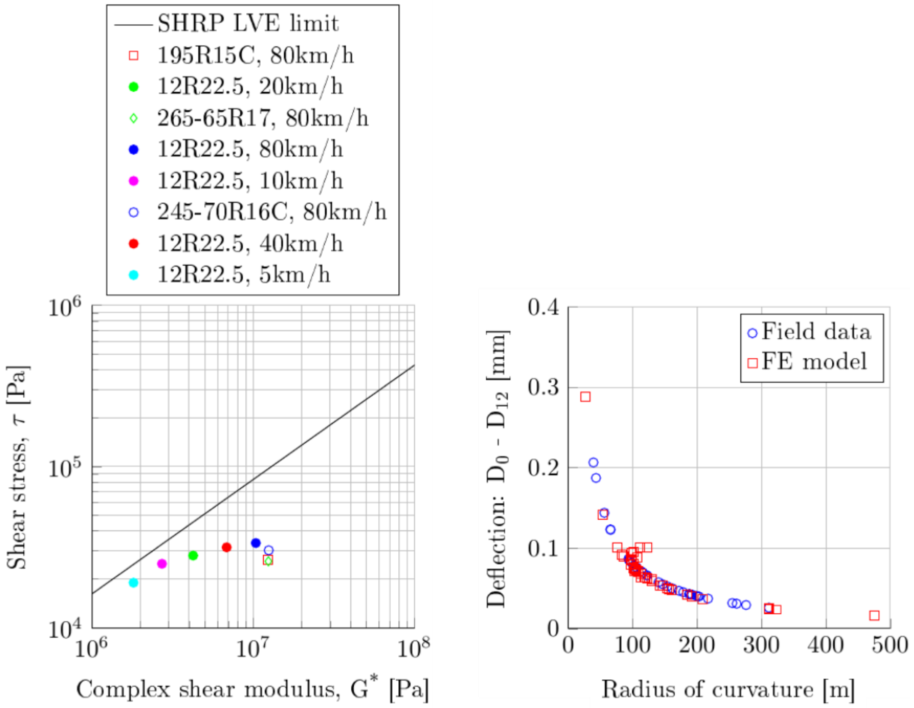

Figure 13: Linear viscoelastic (LVE) shear stress response range (left); Radius of curvature and vertical deflection validation with Benkelman Beam data [11].

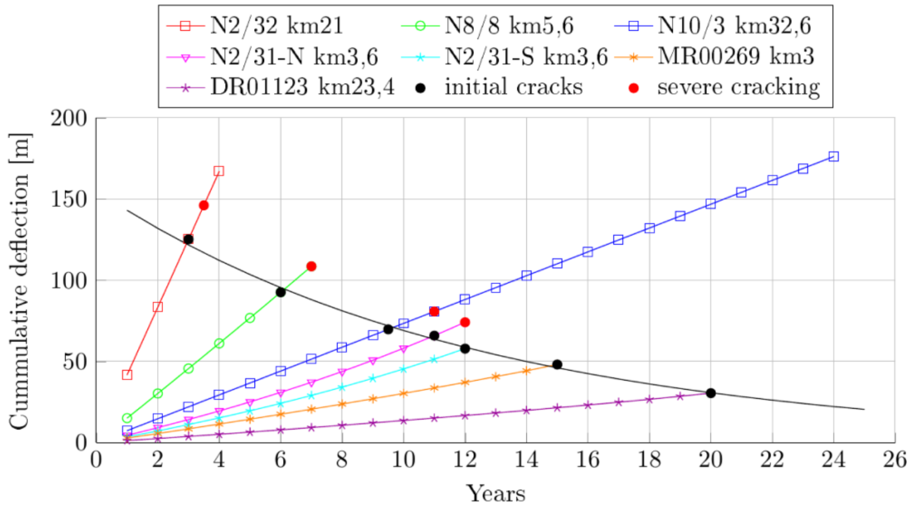

Figure 14: Trigger line for chip seals [13].

Comparing the chip seal simulation analysis to the trigger line indicates that failure will occur within the first year of the seal's service life (Figure 15). This is contrary to expectation. Van Zyl assumed constant surface deflection (strain controlled), since the majority of the deflection is dissipated within the base and sub-layers of the pavement. This assumption challenges the stress controlled DSR test setup of the bitumen columns and subsequent transfer function development [1], with resurge sentiments on self-healing effects.

Applying rest period adjustment factors [7, 8] indicates that a better comparison with the trigger line can be obtained. It should be noted that the adjustment factors were developed for asphalt beams and serve only as an indication to the contribution that rest periods make towards chip seal fatigue resistance.

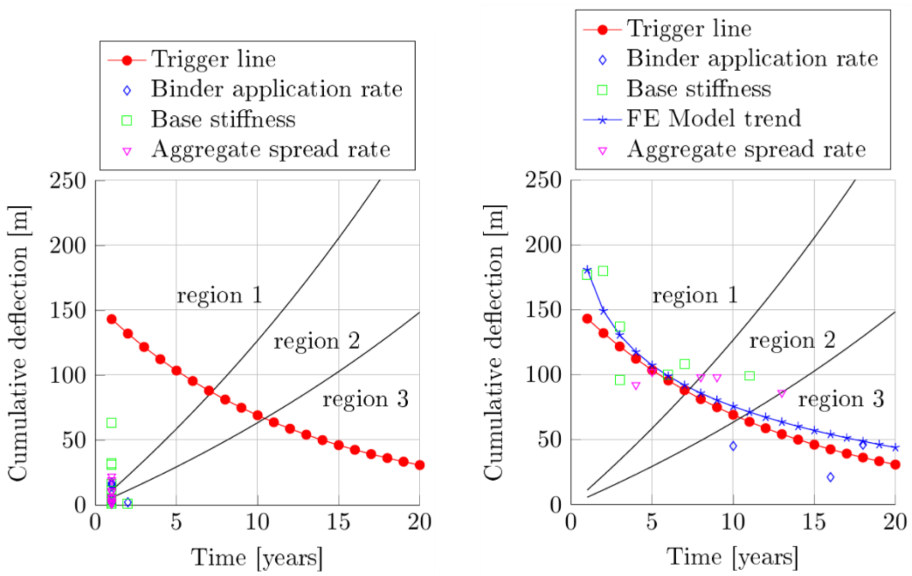

Figure 15: Modelled results compared to the trigger line (left); Adjusted results compared to the trigger line (right).

7. CONCLUSIONS

- Single seals exhibit unique equivalent damage ratios per surface distress type. Surface chip loss demonstrates a 3:1 LV:HV damage ratio, while the fatigue cracking analysis indicates a 2:1 LV:HV damage ratio. The finding challenges the 40:1 LV:HV design guide assumption.
- The aggregate ALD orientation of the model excludes the possibility of isolated asperities therefore not creating a simulation environment that results in single load rip-off effects. Random aggregate orientation may result in observing this effect.
- The cohesion transfer function is too conservative. Reviewing the DSR stress controlled test setup and including rest periods to allow self-healing should be incorporated for a more accurate representation of field conditions.
- A promising aspect of this paper is the fatigue cracking validation processes, but requires a verified transfer function.
- This research can be used to identify an appropriate chip seal given a list of prerequisites such as materials, climate and traffic volume and facilitate the process of deciding which type of seal would best suit the conditions.

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