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

by

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DECLARATION

I, the undersigned, hereby declare that the work contained in this dissertation is my own original work and that I have not previously in its entirety or in part submitted it to any university for a degree.

Signature : 

Date : 26 August 2004
ABSTRACT

Bitumen based road surfacing seals and asphalt wearing courses have been used by society's Engineers "to counter the damage to the existing unsurfaced roadways by the newly developed automobile with its rubber driving wheels" since the early 1900's. Early experiments were conducted with both tar and bitumen to find a suitable material to alleviate the situation, and ongoing research has been carried out through the past century and into the new millennium, throughout the world, examining improvements, from materials used, to design and construction methods. However, there is still much to be understood, improved and refined, when considering road surfacing seal design.

Pavement designers have the choice of utilizing either an asphalt (graded aggregate pre-manufactured with a bitumen binder and applied as a complete product) or a surfacing seal (including variations of bitumen binder sprayed onto the road surface, with the addition of single size stones, either in one or two layers of binder and aggregate, i.e. single or double seals) as a pavement wearing course.

Current road surfacing seal design practice depends on empirical analysis and experience, being primarily a volumetric based assessment of bitumen application. This research project assesses South African seal design philosophy, investigates design areas where review or updating is required to accommodate changing bitumen sources and types, and traffic loading. Seal performance criteria are examined, with the development of a matrix of influences on seal performance. Using this, the need for a seal design method based on mechanistic material properties is proposed, and the prototype example of such a numerical model using finite element method is presented.

To contribute further towards a performance related seal design method, the feasibility of modelling of road surfacing seals using mechanistic principles was examined. The potential of developing failure and fatigue criteria or relationships to enable assessment of the expected seal performance, with inclusion of different component material characteristics and variations, varying traffic and environmental conditions, was also examined.

From assessment of literature, and understanding of the components of the seal, 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. The model was developed to enable examination of the interaction of individual seal components (i.e. stone and bitumen), at micro-mechanic scale.

The prototype 3-dimensional numerical seal model was undertaken in 2002 and 2003 at Technical University Delft, using the CAPA research program. On the basis of the linear calculations the
developed numerical prototype model is able to provide insight into seal behaviour and distinction between mechanical (seal geometry) and chemical (components) seal aspects, and insight into stress and strain development in the different seal types. Simulations of different seal, environmental and traffic scenarios are provided to demonstrate the potential of the model (excluding seal aggregate interlock and embedment effects at prototype stage).

In order to provide data for the verification of the prototype numerical model, and to further contribute to the development of a performance related seal design method, performance tests were developed, with a new tool for assessment of comparative seal performance using the Model Mobile Load Simulator Accelerated Pavement Testing apparatus. The performance of each different seal binder type - Penetration grade bitumen, SBS, SBR, EVA and Bitumen Rubber – was undertaken. A methodology for the assessment of in-service seal performance was developed, and the performance of the respective seals reported. The results of this examination showed that each binder type has its unique contribution to seal performance.

These new performance tests will be able to assist designers 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.

An additional comparative performance test method was developed to enable assessment of the effect of ageing and moisture, to complement the MMLS results.

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

From this research, it is evident that the current seal design method requires further development to enable designers to predict the effect of:

- Varying axle loads, tyre pressures and design speed;
- Varying characteristics of the different binders, (i.e. temperature – viscosity relationships, adhesion and visco-elastic behaviour);

on the performance of seals.

The major areas for suggested improvement in current seal design methods towards a performance based design method are:

- inclusion of variable traffic load and environmental characteristics, including temperature and moisture influences, and
- inclusion of mechanistic material characteristics into the design methodology.
SAMEVATTING

Bitumenengebaseerde padoppervlakseëlfers en asfaltsteëlfers is sedert die 1900's deur ingenieurs gebruik as teenwig teen die skade wat die pas ontwikkelde voertuig met sy rubberwiele aan bestaande ryvlakke sonder oppervlakbehandeling aangerig het. In vroeere eksperimente wat daarop gemoed was om 'n geskikte materiaal te vind om die probleem teen te werk, is 'n kombinasie van teer en bitumen gebruik. Sedertdien word voortgesette navorsing steeds wereldwyd gedaan om verbeterings te ondersoek, nie net ten opsigte van materiale nie maar ook ontwerp- en konstruksiemetodes. Wat die ontwerp van padoppervlakseëling betref is daar egter heelwat wat nog begryp, verbeter en verfyn moet word.

Plaveiselontwerpers het die keuse om of 'n asfalt te gebruik (gegradeerde aggregaat voorafvervaardig met 'n bitumen bindmiddel en aangewend as 'n klaarprouduct), of 'n oppervlakseël (een laag of twee lae [m.a.w. enkel- of dubbelseël] bitumen bindmiddel met aggregaat [enkelgrootte klippies] bygevoeg, gespuit op die padoppervlak).

In die praktiek berus die ontwerp van padoppervlakseëling tans op empiriese analyse en ervaring (wat hoofsaaklik 'n volumetriesgebaseerde assesering van die aanwending van bitumen is). Hierdie navorsingsprojek doen 'n waardebepaling van die Suid-Afrikaanse filosofie van seëlonterworp, en ondersoek ontwerpterreine wat hersiening of bywerking benodig om vir veranderende bitumenbronne en -tipes, asook verkeerslading, voorsiening te maak. Met die ontwikkeling van 'n matriks van die invloede op seëlprestatie is die kriteria vir seëlprestatie ondersoek. Op grond daarvan word aangevoer dat daar 'n behoefte is aan 'n seëlonterwerpmetode gebaseer op die meganistiese eienskappe van materiaal, en word 'n voorbeeld van 'n numeriese modelprototipe wat die eindige-element-metode gebruik, voorgelê.

Ten einde 'n verdere bydrae te lever tot die ontwikkeling van 'n prestasiegerigde seëlontwerpmetode, is die uitvoerbaarheid van die modellering van padoppervlakseëlfers gebaseer op meganistiese beginsels, ondersoek. Daar is ook onderzoek ingestel na die potensiaal vir die ontwikkeling van kriteria vir die vasstel van mislukking en vermoeidheid of verhoudinge wat die assesering van die verwagte seëlprestatie (ingesluit die verskillende kenmerke en variasies van seëlkomponentmateriaal en wisselende verkeers- en omgewingsomstandighede) moontlik kan maak.

Met oorweging van die bestudeerde literatuur en 'n begrip van die komponente van seël, plaveisel en inwerkende faktore, is 'n keuse van 'n numeriese model vir seëlprestatie gemaak. Die eindige-element-metode (Finite Element Method [FEM]) is gekies as die analitiese metode vir die modellering van seëlprestatie. Die model is ontwikkel om die ondersoek van die interaksie tussen individuele seëlkomponente (klip en bitumen) op mikromeganiiese skaal moontlik te maak.
Die ontwikkeling van die driedimensionele, numeriese, model-seëlprotoipe is tussen 2002 en 2003 by die Delft Tegniese Universiteit gedoen, met gebruikmaking van die CAPA-navorsingsprogram. Wat lineêre berekenings betref, kan die ontwikkelde numeriese modelprotoipe ‘n insig gee in seëlgedrag en in die onderskeid tussen aspekte van seëlgeometrie (meganies) en seêlkompomente (chemies), asook in die spanning- en vervormingsontwikkeling van die verskillende tipes seël. Simulasies van verskillende seël-, omgewings- en verkeerscenario’s word voorgestel om die potensiaal van die modelprotoipe te demonstreer.

Met die oog daarop om data vir die verifikasie van die numeriese modelprotoipe te voorsien, en om verder tot die ontwikkeling van ‘n prestasiegerigte seëlontwerpmetode by te dra, is prestasietoets, met ‘n nuwe instrument vir die assessering van vergelykende seëlprestatie met behulp van die Model Mobile Load Simulator Accelerated Pavement Testing apparaat, ontwikkel. Die prestasie van elke verskillende tipe seêlbindmiddel – penetrasiegraad bitumen, SBS, SBR, EVA en bitumenrubber – is getoet. ‘n Metodologie vir die assessering van die ingebruiksprestatie van seëlgae is ontwikkel, en daar is verslag gedoen oor die prestasie van die verskillende seëlgae. Die resultate van die ondersoek het getoon dat elke tipe bindmiddel ‘n eie unieke bydrae tot die prestasie van die seël lewer.

Die nuwe prestasietoets sal ontwerpers help met die bepaling van die grondliggende bindmiddel-eienskappe wat by seëlprestatie ter sprake is, asook van die seël se vermoë om tot die algehele prestasie van die plaveisel by te dra.

‘n Bykomende prestasievergelykingstoetsmetode vir die assessering van die effek van veroudering en vogtigheid is ontwikkel om die MMLS-resultate aan te vul.

Ter opsomming, die prestasietoetsing het bygedra tot die identifisering van die kritiese parameters wat die seëlontwerper tydens die ontwerpproses in gedagte behoort te hou.

Die navorsing wat gedoen is, dui daarop dat die huidige seëlontwerpmetode verder ontwikkel moet word om ontwerpers in staat te stel om die effek van die volgende te kan voorspel:

- Wisselende asias, banddruk en ontwerspoed
- Verskillende kenmerke van die verskillende bindmiddels (bv. temperatuur – viskositesverhoudinge, vashegting en viskoëlastiese gedrag)

Wat huidige seëlontwerpmetodes betref, is die hoofterreine waarop ‘n verbetering voorgestel word, die

- insluiting van veranderlike verkeerslas- en omgewingskenmerke, ingesluit die invloed van temperatuur en vogtigheid, en
- insluiting van meganistiese kenmerke van materiaal in die ontwerpmetodologie
DEDICATION

This dissertation is dedicated to my mother,

AVIS CLAIRE MILNE

23 August 1932 – 19 June 2003

who will not be able to see its conclusion, but who believed in its success.
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DEFINITION OF KEY TERMS

Road Surfacing Seal (Seal): Top layer (wearing course) of surfaced road, constructed by application of a binder and addition of aggregate

(Bituminous) Seal binders (binders): Bituminous material that is applied to the road base, to provide adhesion to retain seal aggregate of the wearing course under the force of wheel loads

Modified (bituminous) binders: Binders modified by addition (ranging usually from 3 % to 20 % depending on modifier) by latex, rubber or other compounds to improve functional characteristics

Asphalt: Asphaltic, or bituminous concrete, wearing or base course

Performance Testing: Testing, in this case, of seals under simulated wheel load in order to assist in the prediction of behaviour of the seal in a service environment

Empirical: Observation and experiment, not theoretically based

Numerical Modelling: Simulation of physical systems by use of computational tools where numerical methods are used to analyse complex mathematics

Mechanistic Methods: Design methods based on principles of mechanics (elasticity, plasticity, visco-elasticity)

Micro Mechanics: Analysis of behaviour of individual components or elements (in this case individual seal stones and binder) in the bulk or total system

Equivalent Light Vehicles: Number of light vehicles and 40 x the number of heavy vehicles (CSRA, 1998, "TRH3, Surfacing Seals for Road and Urban Roads", CSRA, South Africa

Heavy Vehicle: A vehicle with a carrying capacity of move then 4 000 kg (CSRA, 1989, "Technical Recommendations for Highway 4, Structural Design of Inter Urban and Rural Road Pavements", Committee of State Road Authorities, South Africa.)
**SYMBOLS AND ABBREVIATIONS**

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<tr>
<td>$\eta$</td>
<td>Dynamic Viscosity (poise, Pa.s)</td>
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<td>$\lambda$</td>
<td>Elongational Viscosity (Pa.s)</td>
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<td>$\rho$</td>
<td>Kinematic Viscosity (Stokes, mm$^2$.s$^{-1}$)</td>
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<td>$\delta$</td>
<td>Phase Angle (degrees °)</td>
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<tr>
<td>$\omega$</td>
<td>Shear Frequency (rad.s$^{-1}$)</td>
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<td>$\gamma$</td>
<td>Shear Strain Rate (viscosity)</td>
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<tr>
<td>$\tau$</td>
<td>Shear Stress</td>
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<td>$\Sigma$</td>
<td>Deviation Stress</td>
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<td>$\varepsilon$</td>
<td>Elastic Strain</td>
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<td>$\alpha$</td>
<td>Shear Angle</td>
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<td>$A$</td>
<td>Area (mm$^2$)</td>
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<td>ACV</td>
<td>Aggregate Crushing Value</td>
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<td>ALD</td>
<td>Average Least Dimension (mm)</td>
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<td>APT</td>
<td>Accelerated Pavement Testing</td>
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<td>CBR</td>
<td>Californian Bearing Ratio</td>
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<td>CSRA</td>
<td>Committee of State Road Authorities, South African</td>
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<td>$d$</td>
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<td>Ethylene Vinyl Acetate (Bitumen modifier)</td>
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<td>$F$</td>
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<td>Complex Modulus (G) (Pa)</td>
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<td>Kilo (K)</td>
<td>kilogram (kg)</td>
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<td>Kinematic Viscosity (mm².s⁻¹) (Kv)</td>
<td>Mega (M)</td>
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<td>Millimetre (mm)</td>
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s  second (s)
SABITA  Southern African Bitumen Association
SABS  South African Bureau of Standards
SBR  Styrene Butadene Rubber Copolymer (Bitumen modifier)
SBS  Styrene Butadine Styrene Copolymer (Bitumen modifier)
SG  Bulk Density/Specific Gravity in kg/m³
SR  Spread Rate
T  Temperature (°C)
t  Time (s)
\(T_{RB}\)  Ring and Ball Softening Point (Temperature) (°C)
TRH  Technical Recommendations for Highways
TU Delft  Technical University, Delft, Netherlands
v  Velocity (m.s⁻¹)
V  Volume (m³)
X axis  Transverse to direction of travel in FEM
Y axis  Lateral axis, in direction of travel in FEM
Z axis  Vertical axis, perpendicular to travel in FEM
\(\sigma\)  Stress (N.mm⁻², Pa)
FOREWORD

Professor JE Gordon, when discussing the "new science of strong materials", or as he put it "how to ask awkward questions" (Gordon 1976), highlighted the obvious when reflecting that what we can achieve technically is limited by the weaknesses of the materials of construction. Also, he continued, instead of accepting our materials as something provided, arbitrarily, by Providence – as people used to – the "new science of strong materials" would assist us in understanding more clearly how the materials may be modified and improved. As a consequence we are beginning to see our way to making radically better materials unlike anything which has existed before, and these may open new possibilities to engineers. These comments were made over twenty five years ago, but are, in my opinion, still relevant. The remarks assisted me in explaining my motivation to undertake this research project. My professional interest in the research subject developed from the time I became involved as a practicing Engineer in various projects with road surfacing seals using a range of seal binders (both bitumen and modified), where the predicted performance was not always demonstrated in practice. My objective was thus to improve the confidence we as engineers have between seal design prediction and performance, for bitumen and the modified (i.e. "improved") binders, and to contribute to the greater understanding of the behaviour of bitumen binders and seals, and the influence of environment and imposed loading.

Through the research process, in examining the behaviour of single seals under performance tests, and in developing a prototype numerical single seal model, it became evident that much is still to be learned and understood regarding the behaviour of the seals. This dissertation presents a contribution towards a performance related seal design method, and proposes avenues where further research could focus.
REFERENCES

1. INTRODUCTION

1.1 BACKGROUND

The use of bitumen and asphalt has been chronicled since biblical times (Hoiberg, 1964, 1965), the Incas in Peru, and more recently between 1900 and 1910 — "to counter the damage to the existing unsurfaced roadways by the newly developed automobile with its rubber driving wheels". The public naturally looked to its Engineers in the early 1900's to save the road network under the "fast motor traffic". It apparently took the Engineers some time to realise the cause of damage — that of the "tyres eroding the fine binding material from the stone base". Early experiments were conducted with both tar and bitumen to find a suitable material to alleviate the situation. Since then, almost every developed or developing country has adopted the use of a range of bitumen surfacings to protect their road networks. Ongoing research is carried out to continually improve all aspects of the construction and maintenance of the road networks, throughout the world, from improvements to the materials used, to refining the design and construction methods. This project forms a small part of this continuous movement, and concentrates on the road surfacing seal, specifically in examining performance prediction and design methodology.

1.2 PROJECT PROBLEM DEFINITION, AIM AND OBJECTIVES

Modified bitumen binders for road surfacing seals (generally referred to as "seals") were developed as a more cost effective alternative to, or in parallel with, bitumen rubber binders, with the objective of producing seals capable of providing the additional performance over and above "straight" bitumen. These bitumen rubber and modified bitumen seal binders were developed primarily for use on existing pavements requiring remedial action to extend their serviceable life, and for roads that require a seal to withstand heavy traffic loading.

Practice has shown that seal binders did not always provide the expected additional benefits, and in fact at times exhibited characteristics that could promote rapid deterioration of the seals' serviceability and create surface conditions that might seriously affect the long term serviceability of the pavement structure. This is in contrast with historical characteristics experienced on many other projects using modified seals. Wardlaw and Shuler (1992) editors of ‘Polymer Modified Asphalt Binders, in their overview to the proceedings of the symposium of the same name, also highlighted this, with the remarks that "the current (bitumen) binder being supplied has not, in many cases,
performed as expected, bitumen which has had a good performance history in the past does not have the engineering properties to meet the demands placed on it by the traffic stress of today."

The performance of surfacing seals remains under review, illustrated by the New Zealand initial investigation into chip seal performance (Ball and Owen, 1998 and Oliver, 1999 who examined reasons for differences in seal lifetimes and performance).

My own experience has also given indication that under conditions of high ambient temperatures, and heavy traffic, seals placed on existing surfaces, with both straight and modified binders, could perform other than predicted. These seals would then under certain circumstances be especially susceptible to bleeding, adhesion to vehicles' wheels, with the resulting failure of the seal with deterioration of riding quality and reduction of the pavement's serviceable life. There is also the possibility that current laboratory test methods and resulting analysis of the modified and straight seal binder may not always reflect the characteristics of the binder on the road. This, it is proposed, holds especially true for some of the historical extraction methods used to recover the bitumen from the emulsions. There is continued effort by certain authorities regarding the development of design guidelines and laboratory test methods aimed at providing the engineer with results at design stage that provide fair indication of what the expected seal material performance will be.

Current seal design practice depends on empirical methods and experience. With the trend in increased traffic loading, changing oil sources, and refining processes, it is proposed that some of the historical assumptions and postulates are not directly applicable to our current design process.

However, an indication of the potential that modified bitumen has is reflected in the excellent performance of rapid hardening slurry manufactured with modified bitumen, and other successful seals. The binder characteristics discussed above, the proposed need to investigate applicable test methods to assess relative performance of different binders and the application of modified bitumen binders, and an examination into the influence of bitumen binder and modified binder rheological properties on seal performance form the basis of this project.

In addition, insight into the critical seal performance parameters and their effect on performance will be investigated, and to initiate a prototype numerical model of seal behaviour.
The aim of the project is to contribute to the development of a performance related seal design method for bitumen and modified seal binders, through both experimental and prototype numerical methods.

In the context of this project, "performance" refers to "the manner of functioning" (Oxford English Dictionary) of the seal, specifically in terms of seal design. "Performance" of the seal will be described and measured against functional requirements in relation to the factors that are found to influence the seal. It is postulated that to enable network performance prediction and life cycle costing required for the planning of optimal road network management (made on the basis of assessing benefit/cost ratios with costs including road user and road authority expenditure), the ability to predict seal functional performance must be refined to narrower limits than currently available. Current seal design guide estimating of seal lifetime expectancies vary by an excess of 50 % (CSRA, 1998 and SABITA, 1992). The project will contribute in this field by initiating tools that, with further evolution and refinement should enable more accurate seal performance prediction. This trend will assist in providing data for economic assessment, should further research be carried out, specifically regarding reseal cycles, and enhancing the current predicted reseal frequencies (see Table 5, SURF, of SABITA Manual 7, 1993).

The project objectives are to address the problem definition in terms of:

- the development of a seal performance test improving the confidence between design prediction and in service performance of bitumen and modified bitumen road seals, and to

- develop a prototype numerical model that could be used to further our available design aids.

1.3 STUDY LOCATION

The research process geographically spanned South Africa, and stretched over two continents. Figure 1.1 reflects the study and research locations. The performance testing on the seals was carried out in South Africa (primarily MMLS tests on the test bed at University of Stellenbosch, and Supplementary wheel tracking tests in Pretoria, while the development of the numerical model was done at and with the TU Delft resources. The literature assessment, writing up and analysis was carried out at the above Universities, and at my place of residence in South Africa (East London and later Pretoria). The seals were prepared at the Colas laboratory, Epping, South Africa.
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

Figure 1.1: Research Locations
1.4 METHODOLOGY

1.4.1 Investigation Methodology

The structure of the project investigation, carried out as phases (concurrently at times), is:

Phase 1: Literature Survey: Current Theory and Practice

The objective of this phase was to identify for bitumen and modified bitumen binders:

- Past performance of binders and modified binders
- The effect, in theory and practice of:
  - Traffic load and the environment
  - Temperature (and the environment)
  - Pavement condition and type
  - Curing
- Seal design theory
- Current specifications and test methods
- Binder characteristics (including rheological and adhesive characteristics)
- Behaviour and modes of failure (macro and micro)
- Manufacture process

Phase 2: Needs Analysis

This phase is the consolidation of the results of the literature survey with the aim of identifying performance criteria and performance parameters for analysis by research, both empirical and numerical.

Phase 3: Development of Numerical and Experimental Performance Methods and Desired Seal Characteristics for Verification by Research

The identified and desired characteristics must be verified in actual binders, giving the experimental backing for the proposed prototype performance related seal design methods. The desired characteristics will then be tested in the experimental phase to
determine whether they are suitable as a basis towards the development of a prototype performance related seal design method.

Phase 4: Experimental Phase

The seals' characteristics and modes of failure were verified by laboratory testing. This phase was carried out in the laboratory and the field, and included the analysis of results.

In addition to the experimental testing, the development of the prototype numerical model was initiated, examining firstly the feasibility of such a process, and then later the development of a prototype numerical model and examination of effect of critical performance parameters on the behaviour of the model.

Phase 5: Consolidation of Theory and Research

This phase entailed the consolidation of the experimental results, comparison with theory and the output of the numerical model, synthesis of findings, and postulation towards future performance related design methods.

1.4.2 Structure of the Document: Fields of investigation within the Project and their Interaction

The interaction of the various aspects and phases of the project is illustrated in Figure 1.2 below, as an overview of the research process. This document has also been structured in this order to ensure reporting in a logical and cohesive manner. Figure 1.2 reflects the flow of the investigation, from literature review, needs analysis (developed from the assessment of influencing factors and current seal design), prioritisation of factors for examination, through to the experimental and theoretical (numerical behaviour modelling) phases of the project. The research process is concluded by the recommendations towards a performance related seal design method.
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

ROAD SEALS
LITERATURE SEARCH, ANALYSIS OF CURRENT THEORY AND PRACTICE (Phase 1: Chapter 2)

- FORCES OF TRAFFIC
- EFFECTS OF ENVIRONMENT

BITUMEN
AGGREGATE

SEAL

PAVEMENT

CHARACTERISTICS AND BEHAVIOUR
MODES OF FAILURE

NEEDS: Seal Performance Parameters: Influencing Factors for Examination
(Phase 2: Chapter 3)

TOWARDS A PERFORMANCE RELATED SEAL DESIGN: DEVELOPMENT AND NEW RESEARCH (Phases 3 and 4)

- NUMERICAL MODEL (Chapter 4)
- EXPERIMENTAL COMPONENT: PERFORMANCE TESTS (Chapter 5)

DEVELOPMENT OF NUMERICAL BEHAVIOUR MODEL (based on modelled material parameters)

ASSESSMENT AND DETERMINATION OF NUMERICAL MATERIAL AND LOADING PARAMETERS (use of existing knowledge of numerical material behaviour models and application of load)

LABORATORY PERFORMANCE TESTS

FIELD TESTS

SUPPLEMENTARY COMPARATIVE TESTS

SYNTHESIS AND CONCLUSION (Phase 5)

CONCLUSION AND RECOMMENDATIONS TOWARDS PERFORMANCE RELATED SEAL DESIGN METHODOLOGY (Chapter 7)

Figure 1.2: Fields of investigation and interaction
1.4.3 Research Components

Marais, in his dissertation (Marais, 1979) provides guidance to the civil engineer who wishes to make a meaningful contribution to the technology of asphalt pavements. This advice can be applied equally to all aspects of pavement and bituminous research, quoted as follows:

"The study of bituminous materials necessitates a clear understanding of the behaviour of the materials constituting the road pavement, the in-service environment and states of stress."

This project's study components embody the above philosophy fully, encompassing study of each of the components of the project topic – bituminous seals – and the pavement, loading and applicable environmental effects. As part of this project, research tools are used, to collate and expand on the current knowledge base within the bituminous road surfacing industry.

The study commences with literature assessment of:

- bitumen, straight and modified,
- aggregate

and also the components that will have an effect on the seal behaviour:

- pavement,
- traffic loading and
- environment.

As bitumen has the most influence on the performance of seal, and is most complex in terms of characterization, a detailed study of this material was undertaken. The results of the literature survey in the body of the dissertation includes the study of aspects that focus on the research components, while literature analysis of supporting topics, that will facilitate a clearer understanding for the reader that requires additional background, is included in Appendix A.
The research process was undertaken in two distinct components:

- Accelerated performance and supplementary testing of the seals, to enable empirical comparative performance assessment of the different seal and binder types.

This dissertation expands on the development of these test methods.

- Numerical model

The feasibility of the initiation of a prototype numerical model of seal performance, in the words of Professor André Molenaar, "never before attempted in history", is reported on, and the process to develop a feasible prototype numerical model using micromechanics and numerical materials parameters.

The presentation of the project research process, from literature review, through the research components and processes to synthesis of results, validation, reporting and concluding statements are indicated in Figure 1.3 below:

<table>
<thead>
<tr>
<th>Prologue</th>
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<tbody>
<tr>
<td>• Subject introduction</td>
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<tr>
<td>• Problem statement</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Literature Review and Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common to Numerical Model and Performance Testing components</td>
</tr>
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<table>
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<tr>
<th>Research</th>
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<tbody>
<tr>
<td>Performance Test Component</td>
</tr>
<tr>
<td>• Interpretation and extrapolation of literature, specific to Performance Test component</td>
</tr>
<tr>
<td>• Development, research process</td>
</tr>
<tr>
<td>• Findings</td>
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<table>
<thead>
<tr>
<th>Synthesis and Conclusions</th>
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<tbody>
<tr>
<td>• Synthesis of Performance and Numerical Modelling Components</td>
</tr>
<tr>
<td>• Validation</td>
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<tr>
<td>• Conclusions of Research</td>
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<tr>
<td>• Recommendations on future research and way ahead</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Appendices</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Supplementary information</td>
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</table>

**Figure 1.3: Presentation of Project Components**
After assessment of the research components, the synthesis and collation of the performance and numerical modelling tools are discussed, with the contribution to the Science of Engineering summarised, in terms of the development towards empirical assessment tools for comparative seal performance, and the development of a prototype numerical seal performance prediction model validated within the constraints of the available tools and knowledge.
REFERENCES


Oliver JWH, 1999, The Performance of Sprayed Seals, ARR 326, ARRB Transport Research (Ltd), Victoria, Australia.


2. SUBJECT LITERATURE REVIEW: ROAD SURFACING SEAL

This chapter focuses on the relevant literature to establish the basis of current knowledge of the components, behaviour, design and performance of road seals. The review includes the assessment of the seal components (binder and aggregate) and seal design, with focus on the influence on seal performance. These and other aspects will be considered in the research phase with the performance testing (presented in Chapter 4), and in the development of a prototype numerical model (presented in Chapter 5). While this chapter explores the performance related aspects of the seal, supplementary information on bitumen, specifically regarding composition, chemistry, manufacture, and information on seal components, including design, that may be required to enhance the reader or practitioner's understanding of the broader aspects, are provided for completeness in Appendix A.

Included also under this chapter are the results of the review of numerical modelling aspects of the seal components, which will be used in the development phase of the prototype model of the road.

In order to enable a logical progression of the assessment of the aspects of the seal, the literature review focuses firstly on the components of the seal, and then on the seal itself. The numerical modelling aspects are included in this chapter after the discussion of the physical aspects of seal performance to enable reflection what the prototype should initiate reflection of in reality, and to allow reflection of the complexities facing the modelling component. This chapter is structured as such.

2.1 ROAD SEAL BINDERS

Bitumen and modified bitumen binders are utilised in the construction of road surfacing seals due to their qualities of strength, adhesion, waterproofing and durability. Bitumen is a critical component in seal design, having temperature and load dependant properties, and being the binder of the seal aggregate to pavement. The principal properties of bitumen, when used as a road binder, that affect performance of the surfacing, are the rheological and adhesive properties, and its durability (Marais, 1979). This section provides the assessment of the seal binder, and provides the basis of information required in the research process regarding the binder aspects.
2.1.1 Definition of Bitumen

Many definitions of bitumen were found in literature, of which the most common expression was "mixture of hydrocarbons". Other key words were "variable hardness and volatility" (Hoiberg, 1964). The definition describing bitumen satisfactorily for the purposes of this study was compiled from various sources (Sabita (2002) Manual 2), BS 3690: Part 1: 1989 (British Standards Institution, 1998) and Sabita (1992) Manual 9:

"Bitumen is a dark brown to black, viscous liquid or solid cementitious material, possessing waterproofing and adhesive properties. The major components are hydrocarbons and their derivatives. It is essentially non-volatile and softens gradually when heated. Bitumen occurs naturally or is more usually derived as a by-product of the crude oil distillation process. It is a visco-elastic material, with properties varying under different temperatures and time or type of loading."

For the record, the SABS 307-1977 (SABS, 2002) standard defines bitumen as: "A non-crystalline solid or viscous mixture of complex hydrocarbons that possess characteristic agglomerating properties, softens gradually when heated, is substantially soluble in trichloroethylene, and is obtained from crude petroleum by refining processes."

The origin, production, chemistry and composition of bitumen are discussed in Appendix A as supporting information.

2.1.2 Function of the Bituminous Binder

The functions of the bituminous seal binder are defined in the design guide (CSRA, 1997 (TRH3)):

- to provide adhesion, between binder, aggregate and road surface, and retain the aggregate under the force of wheel loads
- provide flexibility and durability of the seal
- waterproofing to the pavement

The performance of the seal binder should be assessed in terms of its capacity to satisfy the functional requirements.

2.1.3 Properties of Bitumen and Modified Bitumen Influencing Performance

This section examines the physical properties of seal binders, both straight and modified bitumen. Of specific relevance to this project is the reported in-service behaviour of the
seal binder, as this will be required as reference for both the assessment of performance and the numerical modelling of the bitumen. A discussion on the chemical properties of bitumen is included in Appendix A, including the processes, types and chemistry of modification.

2.1.3.1 Improvement of Bitumen Properties by Modification

Bitumen characteristics are modified, primarily to improve the performance of the pavement system (pavement and surfacing), to enable accommodation of increased demands and loads due to:

- Increased traffic volume
- Increased tyre pressures
- Changes in wheel geometry (causing increased loading)

Modification of the bitumen seal binder is aimed at providing economic remedial actions for deteriorating road condition, to increase performance of the current binder materials through increasing the binders' resistance to external influences such as traffic loading and the environment (with emphasis on temperature).

The bitumen characteristics primarily considered for improvement are:

- Reduced temperature susceptibility (improving the range over which the binder is not too brittle or too soft). Hanekom et al (1999) describe this as extension of the plasticity interval - the difference in temperature between the softening point and Fraas breaking point - and also note the desire of practitioners to increase low temperature flexibility, reduce temperature sensitivity, and to increase high temperature viscosity.

- Cohesive strength (the ability of the binder to perform in a visco-elastic manner without losing integrity).

- Adhesive properties (the ability of the binder to retain aggregate and adhesion to the pavement).

- Resistance to ageing.

- Flexibility and resilience (ability to recover after deformation loading).
Modification can occur either during the refining process, where bitumen is produced as part of the distillation processes, or by modification of the bitumen itself, after refining. This post-manufacture modification is carried out through the addition of modifiers.

2.1.3.2 Influence of Molecular Behaviour

The bituminous binders respond in a combination of viscous, plastic and elastic manners when placed under stress. The polymers modifiers are however visco-elastic and this is the behaviour imparted to the modified binder. The elastic behaviour is due to the molecules' crystallinity of the (polar) asphaltenes and chain entanglements of the amorphous (polar) resins. Chain slippage in the gel dispersing component (non-polar aromatics and saturates) introduces the viscous behaviour and plastic flow.

The two major elements of visco-elastic behaviour are creep and stress relaxation, where reorganization of the microstructure occurs.

2.1.3.3 Temperature Susceptibility

The effect of temperature on the performance of bitumen as reported substantially in literature predominantly reflects on the behaviour of the binder in asphalt. However, in terms of behaviour, much is relevant to seal binders, and as such is discussed in this document. When considering the effect of temperature on bitumen, even the definition of bitumen (above) indicates that bitumen is temperature susceptible. Figure 2.1 summarises the effect of temperature on bitumen behaviour, showing that stiffness (the ability of bitumen to resist deformation under load) reduces as temperature increases to the upper extremes of service environment. At low temperatures, brittleness is demonstrated. Modification of the behaviour extremes is thus desired with the objective of improving bitumen performance through the temperature range. Examples of the effect of modifiers on temperature susceptibility are discussed.

When considering the influence of the various modifiers, Anderson et al (1992) reported that the addition of 3% by mass polymer modifier (SBS, SBR and Neoprene) had a significant effect on the softening point increasing over that of the residue binder. Of the modifiers, SBR showed the highest increase.

Anderson et al (1992) in their investigation showed that the modifiers had little effect on the temperature susceptibility of the binders when considering penetration against temperature behaviour. However, viscosity of the modified binders was higher than the “straight” control bitumen above 25°C. At low temperatures there was little evidence of
improvement of properties after modification when considering viscosity. This contradicts the expected behaviour, as reported by Serfass et al (1992).

Serfass et al (1992) reported that the major effect of incorporating SBS copolymer into bitumen is a significant decrease in the binder's temperature susceptibility. They reported an increase in the Penetration Index (PI), with increasing SBS content.

Emery et al (1999) confirm that there is a slight decrease in penetration value for modified binders over that of the base bitumen, due probably to the extender or diluents oils the modification process requires.

With reference to the bitumen temperature behaviour regimes, the following specific behaviour is exhibited:

- **High Temperature Behaviour**
  Using the ring and ball softening point ($T_{R&B}$) as an indicator of high temperature behaviour, it was found (Serfass, 1992) that the $T_{R&B}$ increased with SBS content, from approximately 2% addition of SBS, increasing rapidly to 4%, thereafter increasing at a slower rate. This "S" class bitumen effect (refer to A2.6.2.5) when plotting the increase in $T_{R&B}$ against SBS content, is due to there being no polymer network at below the lower content (the SBS only acting as filler), and at above upper level the polymer has already formed a network, and thereafter acts as an extender. The SBS structure (linear or branched), the butadine/styrene ratio and molecular weight of the polymer all contribute to the influence the SBS has on the bitumen properties.

  Emery et al (1999) confirm that softening point $T_{R&B}$ increases drastically with increasing SBS content, especially in the 2.5 to 4% levels. The branched (also referred to as "radial") SBS type of molecule shows a larger increase than the linear type.

- **Low Temperature Behaviour**
  Using the Fraas Breaking Point (FBP) as an indicator, the modified binders showed steady decrease in FBP with increasing SBS content (Serfass, 1992).

  Jordaan (1995) indicates that modified binders display improved temperature sensitivity at low temperature (i.e. less sensitive to temperature change), with binder stiffness consistently below that of the straight bitumen control, confirmed by Emery et al (1999).
Figure 2.1: Bitumen Properties vs. Temperature (Whiteoak, 1991, Shell)

The effect of temperature on behaviour of bitumen and the temperature – behavioural zones is summarised from various sources and is interpreted in Table 2.1 below:

Table 2.1: Temperature Zones of Bitumen Behaviour

<table>
<thead>
<tr>
<th>Approximate Temperature Zone*</th>
<th>Behaviour Zone</th>
<th>Flow Behaviour</th>
<th>Temperature Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10°C</td>
<td>Brittle</td>
<td>Brittle glass (linear)</td>
<td>Cold</td>
</tr>
<tr>
<td>10°C – 25°C</td>
<td>Elastic</td>
<td>Transition, elastic solid</td>
<td>Operational</td>
</tr>
<tr>
<td>25°C – 50 to 60°C</td>
<td>Visco-elastic</td>
<td>Visco-elastic solid (dispersal phase dissolves)</td>
<td>Operational</td>
</tr>
<tr>
<td>50°C to 60°C – 90°C</td>
<td>Viscous</td>
<td>Viscous non-Newtonian fluid behaviour (structure changes under load with time) viscosity varies with shear rate</td>
<td>Hot</td>
</tr>
<tr>
<td>90°C – 135°C</td>
<td>Viscous</td>
<td>Newtonian liquid (linear) (constant viscosity $\eta$)</td>
<td>Mixing, application</td>
</tr>
<tr>
<td>&gt;135°C</td>
<td>Viscous</td>
<td>Newtonian fluid (linear)</td>
<td>Mixing, application</td>
</tr>
</tbody>
</table>

*Approximate temperatures: Exact range depends on bitumen modifiers and chemical composition, and load type.
From literature it is evident that bitumen is temperature susceptible even in the operational range, and that the performance of the binder can be influenced by the addition of modifiers.

2.1.3.4 Viscosity

Viscosity is the resistance of a fluid to flow (refer to A2.5.1). It is a desirable performance of characteristic that bitumen's viscous flow and permanent deformation is limited under load.

Viscosity is determined by bitumen chemistry, specifically the non-polar molecules (the aromatics and saturates of the dispersing phase or gel as described further under section A2.3). To enhance the desired viscosity characteristics and to create a bitumen more resistant to flow (yet not at the expense of brittleness), modifiers are added.

Serfass et al (1992) reported that the addition of SBS results in an increase in viscosity. Dynamic viscosity showed an increase above that of the straight penetration grade bitumen through the temperature range examined (125 °C to 200 °C) for SBS contents from 2 to 5 %. A limiting factor regarding SBS content in surfacing seal binders is thus viscosity at application (spraying) temperature, where currently available distributors have a limit of spraying viscosity of 20 mPa.s (200 centipoise) – the approximate viscosity of 3 % SBS modified bitumen at 180 °C. Cutters, fluxing agents or emulsification are also alternative methods should higher SBS contents be required to enhance service viscosity and excessive heating at application avoided. These authors also report lower viscosity at lower temperature (below 0 °C) and higher viscosity at higher temperatures (40 °C - 60 °C).

Anderson et al (1992) reported that the addition of 3 % by mass polymer modifier (SBS, SBR and Neoprene) had a significant effect on the kinematic (at 135°C) and absolute (at 60 °C) viscosity of the residue binder. Of the modifiers, SBR affected the highest increase.

The addition of rubber was also found to increase the viscosity of the base bitumen. This was explained by the two phase rheological model, with the bitumen being a continuous phase, and the rubber forming a dispersed phase. Added to this was the belief that the rubber particles were absorbing the maltene fraction from the bitumen. (Nachenius, 1988).

Emery et al (1999) confirm that SBS modified binders show large increases in viscosity in the temperature region 40 to 70 °C (providing improved resistance to flow at service temperatures), but relatively small increases at handling temperatures.
It is thus expected from these observations that under performance testing the modified binders should show greater resistance to flow under load, especially at higher temperature. The higher viscosities of modified binders are also the reason that in the design of modified seals (ref A5.1.3 and A2.7) seal stones are expected not to rotate to ALD under construction or load, allowing higher void content in the stone mat.

2.1.3.5 Adhesion and Cohesion

The adhesive strength is the strength of the bond between aggregate of the seal and the binder, while cohesion is the ability of the bituminous binder to remain intact. The increase in polymer modifier content leads to increase in adhesion (Serfass et al, 1992). Both adhesion and cohesion are increased over that exhibited by unmodified binders. Networking forming polymers, such as SBS and EVA are the most effective of the modifier types in this case. The binder is required firstly to ‘wet’ the aggregate, and then to fix it – the adhesion should be strong enough between binder and aggregate to resist stripping in cold or rainy weather. Serfass et al (1992) found when comparing SBS modified hot modified bitumen to straight penetration grade bitumen, that active adhesion of the modified binder (the ability of binder to adhere to damp aggregate) is poor. However, when using modified SBS emulsions, these emulsions show ability to properly wet aggregate, where damp aggregate can be used, i.e. SBS modified hot applied bitumen has medium to poor wetting ability to damp aggregate, with the higher SBS contents having the poorest result, while SBS modified emulsions or cutback binders improve wetting (and thus adhesion) to damp aggregate.

These authors also found that the addition of SBS significantly increased cohesion of the bitumen (measured as the energy per surface unit absorbed by the rupture of a 1 mm thick film of binder) with increasing SBS content. The same investigation showed that there is maximum adhesion at a specific temperature for each binder type, with brittle behaviour below and viscous behaviour above this point. This was extrapolated to the prediction that the retention of road seal stone under traffic will improve with increased SBS content in the seal binder. The effect of the addition of SBS was found to be more pronounced on ‘stabilised’ binders (i.e. binders aged in the laboratory to simulate year old binder, where the evaporation of the volatiles is accelerated). The observed gain in cohesion at lower temperatures with increasing SBS content was considerable.

The differing behaviour of modified and unmodified binders could lead to different failure mechanisms. Should the adhesive characteristics of modified binders exceed the cohesive capabilities, the seal could fail in cohesion. Practical “pull out test” of seal stones from seals thus showed that the seal failed in adhesion.
Shin *et al* (1998) investigated crack propagation in fresh and aged samples, and in straight and modified binders. They found that the crack propagated mainly by inter-facial adhesion failure between binder and aggregates, primarily on the larger aggregate planes where stress concentration is the largest. As strain continued, micro voids and fibrils developed in the yielded zone. General failure in aged samples was characterised by yielding, cracking, then fracture, mostly in interfacial mode. Fresh samples failed mainly by the formation of micro voids and fibrillation. The mode of failure were common to both straight fresh and modified binders, but with the number and length of fibrils being greater for the modified (SBS) binders prior to failure through the breaking of the fibrils. However, the amount of adhesive failure was found to be reduced through the addition of SBS (up to 5% by mass examined), and the fibrils in the modified binders were much thinner and longer at failure. Healing characteristics were observed in the modified binders where the fibrils tended to rejoin on release of the tensile stress. At low temperatures brittle failure was observed, along the aggregate-binder interface. The addition of polymer modifiers was found to greatly affect the mode of failure in bituminous asphalt.

From literature, it is found that researchers experienced increase in both adhesion (greater resistance to stripping) and cohesion (greater resistance to binder cracking or failure). Performance of the binder is thus enhanced in this regard.

2.1.3.6 Ductility

Ductility is the ability of the seal to deform without breaking. Ductility is also postulated to be able to provide an indication of resistance of ageing of the binder.

Srivastava *et al* (1992) report that the ductility of bitumen is increased by an order of magnitude if SBS modification is applied (refer also to 2.1.4.1).

2.1.3.7 Ageing

Ageing of the binder is reflected in the changing of characteristics over time, in service. The binder matures after being applied to the road (SABITA, 1996). The ageing process was observed to affect performance operative in the following manner:

- **First day**: viscosity should be high enough to prevent chippings being pulled by traffic, but low enough to allow the aggregate to settle into the mosaic.

- During the **first two months** the bitumen slowly becomes stable as the viscosity increases (as the lighter fractions evaporate or oxidise).
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

- During service life viscosity increases and decreases, depending on the season (cracking and bleeding are the extremes that should be avoided).

When considering available literature, it is postulated that experience from asphalt research, is also applicable to seal binders regarding binder characteristics. Srivastava et al (1992) report that the aging of SBS modified bitumen is less pronounced, as the molecules in the bitumen that are chemically active and which would have been likely to oxidise have already been engaged by the modifier (the styrene component in the case of SBS). The other aging mechanisms such as evaporation of the lighter fractions will not be affected.

Jordaan (1995) indicates that due to the thicker binder film being able to be accommodated by the polymer modified binder, age hardening is thus reduced.

Robertson et al (c.1990) indicate that aging of bitumen through oxidation imparts permanent hardening in bitumen, while the hardening from lowered temperature and molecular association are reversible. Hardening from lowered temperature is reversed when the temperature is again raised, and hardening due to association of molecules may be reversed by recycling (these two methods will not reduce the effects or products of the oxidative hardening). Reversible ageing is caused by dipole orientations – a slow process, as the forces involved are small. The resulting "best" orientation of the molecules under the dipole derived forces is termed the thermodynamic stable state or equilibrium, where a better packed and bound together system is derived. Aggregates contribute in terms of assisting in the evolution of a stiffer (more rigid) material as equilibrium is approached. In service, the equilibrium state is constantly changing as the changes in composition caused by oxidation result in polarity changes, with resulting change in "best packaging". Temperature also changes constantly in the pavement, and thermodynamic equilibrium varies with temperature. Traffic tends to "work" the pavement and reorient molecules, especially under heavy traffic loads. This further affects the achievement of equilibrium. The authors report that it is currently unknown whether the orientation of the molecules is accelerated by the provision of additional energy, or if orientation is slowed by the agitation of the bitumen. Some bitumens oxidise and accommodate the oxidation products without major changes in viscosity, while other bitumens oxidise and show substantial increase in viscosity, particularly at higher aging temperatures. Virtually all bitumens eventually quench their oxidation, which leads to a limit of the increase in viscosity due to oxidation. Again, composition of the bitumen influences the amount of viscosity increase at different temperatures. Bitumens with poorer solvent power (i.e. dispersed (associated) phases having greater tendency to agglomerate and immobilise the most chemically reactive
molecules) will have the greatest tendency to quench oxidation. The ability of the bitumen to quench oxidation is a measurable chemical property and is related to the visco-elastic properties, and thus relates to the performance properties of the bitumen.

A general impression of ageing when using asphalt related research – the ageing index (the ratio of the viscosity of the aged bitumen to that of virgin bitumen) - indicates (SABITA, 1996) that the order of 65% ageing of the bitumen occurs during manufacture, 15% during storage, transportation and application, and the remainder of ageing during service. As seal binders can be applied at high temperature (to achieve the required viscosity reduction) and can be stored at these high temperatures prior to distribution, ageing of the binder can occur during the construction process. Thus long term performance of bitumen is dependent of care taken during manufacture (of the binder), storage and application.

The mechanisms of bitumen hardening (thus causing “ageing”) are:

- Loss of volatiles
- Atmospheric oxidation
- Physical hardening
- Exudative hardening (porous aggregate)

2.1.3.8 Tensile Strength

Addition of a polymer leads to an increase in tensile strength, due primarily to the interwoven polymer links. This enhances performance under heavy traffic.

Structural strength of the binder is required to prevent cracking and retain the aggregate. Modified binders have improved adhesive strength and can thus withstand higher traffic stress without loss of stone. This higher strength is more rapidly achieved, and the greater elasticity allows recovery from higher deformations. Hesp and Woodhams (1992) reported that with regard to crack resistance of the binder, it is more desirable to have a fine dispersion of (modifier) particles (finer particles closer together, as opposed to larger particles further apart). It would be more difficult to propagate stress cracking, and also limits brittle type failure at low temperatures.

Khattak et al (c.1996) summarise findings reported by various studies that tensile strength increased significantly with the addition of 6 % SBS polymer to bitumen over the straight bitumen through the range of temperatures from -21 °C to 41 °C.
Serfass *et al* (1992) found an increased strength in tension with increasing SBS content in the bitumen binder (large elongation with elastic recovery), especially in uncured binder. Stabilised binders showed that the SBS modified binders do not exhibit the same brittleness as unmodified bitumen after the fluxing agents (diluents) have evaporated.

2.1.3.9 Plastic Flow

Due to the reduced temperature sensitivity of modified binders, and higher viscosity of the binder (especially at high temperatures), a thicker binder film is accommodated without causing bleeding of the binder. Plastic flow is thus reduced with addition of polymer. The addition of modifiers thus can be expected to improve the performance of bitumen.

2.1.3.10 Durability

Due to the thicker film being accommodated by modified binders, (due to increased temperature sensitivity, and higher viscosity allowing seal stone to remain oriented at higher dimension than ALD, with resulting higher voids) durability may be increased. However Jordaan (1995) indicates that durability of some modified binders may be decreased due to oxidation of the polymer.

2.1.3.11 Voids

Shin *et al* (1998) examined voids in bitumen and asphalt. They found that there were three locations of voids, which also have relevance to seals:

- **Voids in binder phase**

  These voids are predominantly circular or rounded, governed by the flow characteristics of the binder.

- **Voids in binder-aggregate interface**

  These voids are elongated due to surface energy of the bitumen.

- **Trapped interfaces between interlocking aggregate**

  These are relatively large and irregular in shape, determined by the configuration of the aggregate.

It was found that polymer modification did not affect void morphology. Voids in the constructed seal would be expected to be beneficial to performance of the seal if there
was sufficient binder to retain the aggregate, as these voids would be expected to accommodate the binder and prevent bleeding if seal stones punched into the base under load. The concept of "voids" in seal design (in contrast to voids in asphalt design), and desired "texture", or "texture depth", requires further examination and discussion.

2.1.3.12 Binder Morphology

Shin et al (1998) investigated binder morphology, and the effects of polymer modification. By utilising electron beam etching on a thin film of bitumen for straight and modified binders, it was found that a structure was present in all types of binder. It was postulated that the binder structure was the network of the high molecular weight asphaltenes and resins, which form the dispersed phase in the suggested two phase bitumen model. It was also observed that this structure disappeared above 50 °C, and reappeared after cooling. The structure of the binders was also examined under tensile load, where the entangled chains were seen to elongate considerably, retaining the network structure. In aged samples the networks were observed to be thicker, eventually causing higher stiffness of the system.

2.1.3.13 Fatigue

Khattak et al (c.1996) report on studies that the addition of SBS to bitumen significantly improves fatigue resistance properties at 0 °C and 20 °C.

2.1.3.14 Flexibility

Muthen and Bergh (1997) reported that flexibility of binders change according to composition, operating temperature and aging characteristics. Comparison between bitumen binders indicated:

- Penetration Grade bitumens remain flexible for between 2 to 3 years. These binders become brittle at temperatures below 5 °C.
- Modified binders retain flexibility for between 5 to 7 years, depending on the type of elastomer.
- Bitumen rubber remains flexible for up to 15 years, and at temperatures down to -5 °C.

This study showed that performance of bitumen was increased due to the addition of modifiers to the binder.
2.1.3.15 Stiffness and Hardness

Using their performance related approach to determination of the properties of binders, Anderson et al (1992) reported that the results of their “bending beam test” showed that the effects of polymer modifiers on low temperature stiffness are small, when compared to the ‘straight’ bitumen control.

They also reported that the addition of 3% by mass polymer modifier (SBS, SBR and Neoprene) had little effect on the penetration (hardness) of the residue binder at 25 °C. Of the modifiers, SBR reflected the lowest penetration, i.e. hardest bitumen after modification.

2.1.3.16 Bleeding and Fatting Up

Bleeding and fatting up of a seal is related to hardness of road surface and the viscosity of the binder. Modified binders reduce the risk of bleeding or fatting up due to the increase in viscosity (CSRA, 1998, TRH3).

2.1.3.17 Elasticity

The properties of the bitumen rubber are dependent on the type of rubber used. Rubber tyres have both natural and synthetic rubber content. Nachenius (1998) reports that Oliver found that rubbers with a high natural rubber content showed higher elasticity than synthetic rubbers. However, the natural rubber became unstable at high reaction temperatures.

Emery et al (1999) confirm that the nature and concentration of modifier, nature of bitumen, ageing, thermal and mechanical behaviour of the blend, and the temperature at which the properties are tested will influence the indicated properties of the modified binders.

2.1.3.18 Engineering Properties

The table below summarises (SABITA, 1996) the significant properties of bitumen, and type of behaviour that is expected for combinations of environmental and loading circumstances. At mixing and construction (requiring high service temperatures) the properties can be considered in terms of viscosity, while at service temperatures the bitumen behaves visco-elastically, and stiffness moduli are used to describe the engineering properties, as indicated in Table 2.2 below.
Table 2.2: Engineering Requirements of Bitumen (from SABITA, 1996)

<table>
<thead>
<tr>
<th>Behaviour during</th>
<th>Condition</th>
<th>Time of loading, s</th>
<th>Significant property of the bitumen in the surfacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixing (modification process)</td>
<td>High (&gt;100 °C)</td>
<td>-</td>
<td>Viscosity, approx 0.2 Pa.s</td>
</tr>
<tr>
<td>Spraying</td>
<td>High</td>
<td>-</td>
<td>Viscosity</td>
</tr>
<tr>
<td>Rolling in seal stone</td>
<td>High</td>
<td>-</td>
<td>Viscosity, min. 5 Pa.s max. 30 Pa.s</td>
</tr>
<tr>
<td>In service</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permanent deformation (rotation)</td>
<td>High road temperature (30 – 60 °C)</td>
<td>Long &gt;10^2</td>
<td>Minimum viscosity determined by penetration index and the softening point of the bitumen</td>
</tr>
<tr>
<td>Fatting up</td>
<td>High road temperature (30 – 60 °C)</td>
<td>Long &gt;10^2</td>
<td>Minimum viscosity determined by penetration index and the softening point of the bitumen</td>
</tr>
<tr>
<td>Cracking</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Traffic stresses</td>
<td>Low road temperature</td>
<td>Short (10^2)</td>
<td>Max. bitumen stiffness</td>
</tr>
<tr>
<td>- Thermal stresses</td>
<td>Low road temperature</td>
<td>Long</td>
<td>Max. bitumen stiffness</td>
</tr>
<tr>
<td>Stripping</td>
<td>Low road temperature</td>
<td>Short (10^3)</td>
<td>Max. bitumen stiffness</td>
</tr>
</tbody>
</table>

2.1.4 Experienced Behaviour of Binders

Knowledge of the experienced behaviour of the various binders is discussed and has relevance to both the performance and numerical study components.

2.1.4.1 Ductility

The Ductility test was introduced in 1903. To date it is believed by many who apply the test that it gives an indication of the "stickiness" of the material. Extensive work by the then US Bureau of Public Roads has shown that the ductility-penetration relationship of the residue from the ASTM thin-film oven test provides a useful means of predicting the expected behaviour or characteristics of bitumen in service, especially for those bitumen’s most likely to exhibit unsatisfactory behaviour in practice. Climatic aging and traffic will affect the ductility – penetration relationship of binders in service. Marais (1979) reported that still by 1979 this could not be predicted with a laboratory test.
2.1.4.2 Durability and Hardening

Durability of a binder is affected by the amount of hardening of the binder during construction and under traffic. Marais (1979) indicates that when both penetration falls below 20 and ductility is low, bad cracking of the surface results, affecting the functionality of the binder. The critical factor is the rate of hardening, in service, and not purely hardness. Hardening is due to both volatilisation and oxidation, both of which proceed slowly at low temperatures, and increase at high temperatures.

Conversion of the resin fraction was also observed by Spielman (Hoiberg, 1985) with associated increase of the asphaltene fraction (from 17 % to 42 %) at heat of 170 °C (with air). This would be expected to reduce adhesive properties and increase hardness and brittleness. Oxidation in service occurs by:

- Addition of oxygen: leaving unsaturated compounds, which polymerize
- Formation of carbonyl derivatives, followed by polymerization
- Elimination of volatile oxidation products

Oliver (1987) reports that the sun-catalyzed reaction of bitumen with oxygen from the air (photo-oxidation) occurs rapidly, although confined to the top 5 μm of exposed material due to bitumen's good light absorption. The effect of photo-oxidation appears slight, and the majority of thermal hardening is considered to be due to the slower thermal reaction mechanism (at a slower rate than photo-oxidation, although the rate of reaction doubles for every 10 °C rise in temperature). The rate of hardening depends on the temperature of the surfaceing, thickness of bitumen film and the bitumen type. Hardened bitumens, with reduced adhesive and elastic properties, will detrimentally affect the performance of the seal.

2.1.4.3 Flushing

Muthen and Bergh (1997) summarise the findings (including that of Semmelink, 1997) that modified binders can be applied at higher applications than penetration grade bitumens, due to their greater viscosities and orientation of seal stone in the binder. Application rate can be increased over that of unmodified bitumen to 120 % for polymer modified bitumen and 160 to 180 % for rubber modified bitumen. However polymer modified binders has been noted to be susceptible to flushing at high application rates, due to punching of aggregates into soft base. Bitumen rubber is least susceptible to flushing with respect to
high temperature and high traffic stress, due to its inherent superior engineering properties.

Towler and Ball (c.2000) confirm that flushing is due to relative effects of traffic levels, seal type, seal binder rheological properties (binder type) and pavement structure directly under the seal.

Towler and Ball (c.2000) confirm that flushing is due to relative effects of traffic levels, seal type, seal binder rheological properties (binder type) and pavement structure directly under the seal. They also indicate that flushing not only occurs due to aggregate being pushed into the base, but by binder rising to the seal surface under water vapour pressure from water that had penetrated into the base through permeable seals. This flushing is not primarily traffic induced, and also occurred in seals with effective texture depth (i.e. no previous loss in texture due to traffic).

2.1.4.4 Recommended Marginal Material Limits

Modified binders are able to perform better than unmodified binders when used as surfacing seals for highly flexible pavements or on marginal material bases. The following limits are recommended by Muthen and Bergh (1997):

- Penetration Grade Bitumen: G5 and above, minimum base CBR 50
- Polymer Modified Bitumen: as above, as punching into weaker aggregate will cause seal distress
- Rubber Modified Binder: G7 material and above

2.1.4.5 Road Performance of Specific Binder Types

SABITA (1996) indicates that performance related effect of heating of the binder treatment can be considered at different phases during the bitumen’s life (specific to seals): spraying, construction, and service life. Performance related aspects affected by the bitumen heating are suggested as: cracking, bleeding, ravelling, and stripping. An overview of experienced road performance of the various binder types is provided below.

- SBR Modified Bitumen

Marais et al (c.1990) reported that the performance of sample jobs located in various parts of the country was examined, and generally very good performance resulted. This was especially of note when the elastic and ductile properties were
evaluated, even after over 4 years in service. The binders were between 2 and 5% RMB latex modified, hot applied bitumen. The seals were predominantly 13.2 mm single seals. The binders all were very elastic, with no indication of cracks reflecting through, although some areas of seal in the wheel tracks on hill grades had deteriorated slightly. Seal construction was recommended to have an 18 t pneumatic tired roller compact the seal aggregate into the bitumen during the construction process. It was also found that the properties exhibited by the modified emulsion were also slightly better than the RMB due to the latex not being heated higher than 85 °C, with no rubber degradation, as occurs at the high (190 °C+) required for the application of the hot applied bitumen. Emulsion easily penetrated into any cracks, thus being better suited for this operation than the hot applied binder.

- **SBS Modified Bitumen**

Serfass et al (1992) reported that SBS modified binders require sufficient period of fine and hot weather after application to allow the solvents to evaporate and the aggregate to find a firm position. Rainy or cool weather immediately after application will result in whip-off. Unexpected heat would also result in damage to the seal when fresh, while the highly volatile fluxing oils were still present in the binder.

Adhesion was also a problem for this binder due to the high viscosity. The addition of an adhesion agent, the use of clean aggregate, pre-coating and the use of a fog spray are recommended. However, the use of emulsions removes this adhesion problem.

SBS modified binders have shown reduced whip-off, no experienced aggregate embedment or bleeding after 'stabilisation' (two months service) were expected. The addition of a high content of diluent improved early adhesion, but softened the binder, leading to higher probability of bleeding, poor skid resistance and embedment. Too low diluent content resulted in insufficient early adhesion, excessive viscosity and possible brittleness.

For hot applied binder, the application period of the binder is short. SBS content should not exceed 3%, due to the viscosity and adhesion characteristics. Conversely, the setting time of SBS modified emulsion is slow, especially in cool weather, and up to 5% SBS can be used, due to the reduced viscosity of the emulsion.
Most reported failures of SBS modified seals were due to too early trafficking on unstabilised binders.

- **Air Rectification**

Marais (1979) reported that research investigations in 1959 showed that air-rectification of Middle East bitumens improved the temperature susceptibility of viscosity. These bitumens would therefore be more suitable for use in areas which experience extremes of temperature (and climate) and were expected to give improved performance. These bitumens should have been expected to give improved performance. In 1962 a full-scale asphalt experiment was laid on Umbilo Road, Durban, where air-rectified and other bitumens were used in various surfacing specifications. This experiment showed that these experimental air-rectified grades of bitumen gave poor performance. A further experiment was laid in 1964, on the National Route N3/1, Hammersdale, Natal. All binders used on the above experiments satisfied the specification for SABS 307: 1951 and the later 1966 revision, for 80/100 pen grade bitumen. It was reported that for the Umbilo sample, after 22 months of service, when tested, all ductility for the air-rectified sample had been lost, while the straight-run bitumen had retained a satisfactory value. At Hammersdale, however, both straight-run and air-rectified bitumens had maintained high ductility values, even after three and a half years of service. A strong correlation between ductility and road performance was evident for all of the bitumens on both experiments. The bitumen that lost ductility with age showed signs of cracking, and maintenance being required as the riding surface was in a poor condition. The bitumens that maintained ductility, although in places were smooth, were in a good or very good condition at the same period in service life. Thus, while the aim of the modification of the refining process was to produce a binder with lower temperature susceptibility, this process could lead to a binder, while not as sensitive to changes in ambient temperature, one that does not remain as ductile as specification or performance requires. Of note is that while all bitumens hardened to similar penetrations (from 82 to 95 pen ranges to 32 to 46 pen range) under the penetration test, ductility measurements were also required to adequately predict the behaviour of bitumen. Ductility changed from 110 to less than 5 cm/min at 25 °C (the specification) for the air-rectified binder used at Umbilo Road.
Bitumen Rubber

Potgieter et al (1999) report that bitumen rubber binder was first introduced to South Africa in approximately 1983. The authors re-examined some of the original projects. The Buccleuch interchange project, just North of Johannesburg, where the N3 joins the N1. The then existing pavement (exhibiting block cracking) required remedial treatment, and a 13.2 mm single bitumen rubber seal was used as a stress absorbing interlayer, with a bitumen rubber asphalt overlay. The bitumen rubber binder for seal and asphalt comprised 20% rubber crumbs, 78% 80/100 pen grade bitumen and 2% extender oil. These constituents were initially mixed for approximately 3 minutes, and allowed to be chemically digested in a holding tank at temperatures from 180 °C to 220 °C for 1 to 4 hours. It was reported that this wearing course still remains serviceable after 12 years of service life. Little or no oxidation had occurred (the binder was still flexible), reflective cracking minimised, and ravelling was minimal. Experience has shown that the high viscosity of bitumen rubber binders, combined with their good adhesive properties, the presence of carbon black, antioxidants, amines and aromatic oils in the binder, contribute to the binder durability, resistance to ageing and stripping. While this study comprised mainly of asphalts, the binder characteristics and performance would be expected to apply to seal binder performance as well.

2.1.4.6 Compatibility of Bitumen and Modifiers

SBS

Emery et al (1999) summarised the various definitions of compatibility, emphasizing that defined temperature at the measure of compatibility is important, as a binder may be incompatible through a certain temperature range, but compatible at another. They reported that some researchers measure compatibility as the difference in softening point between the top half and bottom half of a binder, from a defined cylindrical container, after standing for a certain time, at a certain temperature. Others defined the compatibility in terms of observation of the micro morphology of the binder. However the effect of compatibility on the binder characteristics was not always found to be deleterious to the properties of the binder, as long as separation of binder and modifier did not occur. The authors found that for successful production for example of SBS modified bitumen:

- Sufficient compatibility between the bitumen and SBS polymer is needed to accommodate the variability in conditions in production.
- SBS modified binder will be exposed to a variety of handling conditions. Although there are techniques that a manufacturer can use to accommodate a SBS binder that has separated, these are not always accessible. Sufficiently compatible binder is thus a requirement for successful production and use i.e. total incompatibility is not desired.

- Total compatibility means that the phase separation between polystyrene and butadiene does not occur. The result is low softening point and poor elasticity.

The level of compatibility affects molecular network strength, which is affected by the base bitumen and polymer characteristics. Compatibility may be adjusted by the addition of additives such as aromatic oils.

Serfass et al (1992) report that the colloidal Instability Index $I_c$ defines the compatibility between bitumen and modifier (SBS in this investigation):

$$I_c = \frac{\text{asphaltene content + saturate content}}{\text{resins + aromatics}}$$

Or the ratio of dispersed phase to dispersing phase (asphaltenes and saturates are solid bitumen at 30 °C). It should be noted that other references (www.oilanalysis.com) do not always refer to the saturates as being dispersed – they are temperature dependant.

Using the above formula for $I_c$ (colloidal instability index) of Serfass, sampling showed that fully compatible bitumen had a value of 0.13, and an incompatible bitumen had a ratio of 0.28 (where separation occurred in storage). At present there is no precise value that indicates the border between compatibility and incompatibility. A general value of 0.15 is recognised, however.

Emery et al (1999) further indicated that the molecular size distribution varies with refinery, grade and time. It is thus not possible to definitively characterise South African bitumens, but the investigated example of 60/70 pen grade bitumen suggests $I_c$ of 0.24 to 0.27, indicating that compatibility will have to be addressed with the use of aromatic oils.

2.1.4.7 Effect of Film Thickness and Contact with Aggregate

Huang et al (1998) studied the effect of film thickness on the Rheological properties of bitumen. The thin film of bitumen that has contact with the seal aggregate has been found
to exhibit different rheological behaviour than bitumen in graded aggregate asphaltic mixes.

Two aspects of their investigation are of relevance to this project:

- When a liquid is confined to a narrow gap (thin film), new behaviour was evident – viscosity was increased and greater elastic strength exhibited in the film than in the bulk material (this is more applicable to asphalts than seals).

- There was apparent adsorption of certain bitumen components on to the aggregate surface, with evidence of certain chemical reactions at the surface.

The above reference summarised the findings of various studies, including the examination of films between 20 microns and 70 microns, where the surface molecules align themselves in the direction of their polarisation, causing similar alignment to a depth of thousands of molecules within the liquid. Also summarised was the findings of a number of investigations where it was found that viscosity increased drastically with film thickness below 20 microns, and the properties of bitumen adjacent to an aggregate surface are different from the bulk bitumen. It was also speculated that large aromatic ring systems combined with polar functional groups in the bitumen have significance in the aggregate – bitumen interaction. It was also reported that mineral aggregates significantly affect the rheological characteristics of the bitumen. Adsorption was thought to be the mechanism of interaction between the aggregate and bitumen, where immobilized layers are formed at the interface. Where bitumen in bulk makes contact with aggregate, the total adsorbed bitumen is small when compared to the total amount of binder, and the properties of bitumen in thick films will thus not be affected to a significant extent. In thin films, the fractions of bitumen effecting lower viscosity are expected to be immobilised by the adsorption, subjected to ordering, which will result in obstruction to bitumen flow. For this reason the rheology of thin films was investigated further by the above authors to quantify the extent to which changes to the physical properties of thin films are induced through the contact with aggregate, and the depth to which these changes extend to the bulk aggregate.

The summary of the investigations findings are:

The authors investigated the behaviour of various types of bitumen, using the SHRP sliding plate micro viscometer (with glass plates) and a modification using polished limestone plates in order to determine the effect of aggregate on the properties of the thin bitumen films.
• **Physical Response**

It was reported that the viscosity of most bitumen in contact with the aggregate plates exhibited a substantial increase in viscosity over that in contact with the glass, especially as shear rate decreased (i.e. a move from the Newtonian behaviour exhibited by the bitumen in contact with the glass to non-Newtonian behaviour). This was taken to imply that generally the bitumen-aggregate interaction becomes more dominant as shear rate decreases, i.e. especially under low temperature or low speed traffic (low frequencies – low shear rates).

Under high pavement service temperatures the interparticle forces of the bulk bitumen binder are more important in determining bitumen behaviour than the aggregate – bitumen interface interaction.

• **Chemical Aspects**

The authors speculated that the most polar organic components present in bitumen are those that bond to inorganic aggregates (after examining the behaviour of different types of bitumen). They found that certain aggregate adsorbed bitumen components that are highly aromatic (and which contain carboxylic acid functional groups), and that the rheological properties of bitumen in the presence of aggregate are highly dependent upon bitumen composition (i.e. source dependent) and film thickness dependent.

The properties of bituminous thin films in the presence of aggregate are thus dependent on:

• Structure of bituminous binder
• Nature of aggregate surfaces
• Bitumen – aggregate interaction potential
• Pressure between the surfaces
• Direction of shear
• Shear rate

The desired binder material is thus one that demonstrates strong interactive forces between aggregate and bitumen at low shear rate (or low temperature) to resist initial external force, and also exhibits high viscosity at high shear rate (or high surface temperature) to prevent permanent deformation. The importance of the effect of
aggregate surface on the properties of thin bituminous films (and the different exhibited behaviour when compared to that of the bulk material) was emphasized by the authors.

2.2 AGGREGATE

Material types for road building include both natural and processed gravels and rock. Natural materials are primarily used in the pavement layers, but natural sands may be used in certain surfacing types. Aggregate for single and double surfacing seals are processed from rock, with desired strength, to specified shape and grading to provide the required characteristics to ensure optimal performance of the seal as a whole. Seal aggregate is exposed to severe handling, environmental and in-service conditions, and as such desired quality is high.

2.2.1 Definition

For the purposes of this study, aggregate is defined as the product of processed rock (by crushing and sieving) that is used as the load bearing and wearing course within the surfacing seal.

2.2.2 Function

Aggregate has four functions in its role as part of a road surfacing seal:

- resistance to abrasion and transfer of load
- skid resistant surface
- protection of binder from UV sun rays
- provides the structure that provides support to the visco-elastic and impervious binder, with sufficient voids (or texture) to prevent flushing

2.2.3 Behaviour and Characteristics

2.2.3.1 Wear and Degradation

Marais (1979) reported that at that time little research had been carried out on the wear rates of stone under the various types or intensities of traffic. However what was evident was that wear of aggregate did take place faster, and was more noticeable, with weaker than stronger aggregates. Not only did wear reduce the available voids (or texture), but data (Marais, 1979) suggested that initially (after 5 years’ service) the stone dimensions changed in a manner producing more ideal (spherical) shape, but in later service life, the
effect of traffic could reduce the individual stones to thin, flat particles with a high flakiness index.

Degradation primarily occurs under construction – if steel wheel rollers are used – and for this reason pneumatic-tired rollers are preferable for single seals. The net effect of degradation is to change the grading of the stone, with an increase in the finer fractions. These finer particles are then held in place by either, or a combination of, mechanical interlock or immersion in the binder film. While some of these particles are whipped off, the major effect of degradation is the reduction of voids, either by filling of the voids, or by reduction in the overall size of the original particles with associated lowering of ALD.

2.2.3.2 Absorption

Marais (1979) reports that the viscosity of bitumen at the time of wetting is so high that the probability of absorption of binder by aggregate was doubtful.

2.2.3.3 Adhesion

The composition and structure of the aggregate is widely accepted as one of the major factors affecting adhesion in a bitumen-aggregate system (Hoiberg, 1965). Aggregates are defined as being hydrophilic – silica, quartz, gravel - and hydrophobic (lacking affinity to water, tending not to be wetted) – limestone. These terms can be misleading, as both types can be wetted by water (i.e. even the hydrophobic aggregate). An alternative description – electronegative for hydrophilic, and electropositive for hydrophobic, can apply. The electrochemical property of the aggregate determines the adhesion.

Electronegative aggregates (such as siliceous materials, quartz) become negatively charged in water, due to dissociation of surface ions in the water (the ions dissolve in the water, and vice versa for electropositive aggregates (such as dolomite, limestone and other calcareous materials). Some aggregates bear mixed charges, and lie between the two extremes. Thus, when considering adhesion to bitumen emulsions, similar charges on aggregate and bitumen particles should be avoided. Anionic emulsions (negatively charged particles) should be used with electropositive aggregates (limestones, basalts), and cationic emulsions with electronegative aggregates (sandstone, aggregates, quartz, granites). Aggregates with approximately equal amount of electronegative and electropositive surface charges can usually be used with both types of emulsion. Cationic emulsions are more versatile, as they appear to be able to be used with a broader range of aggregates.
2.2.3.4 Polishing

Aggregate exposed to the surface of the road is subject to abrasion under traffic. As a result of the abrasion, the stone may attain a smooth, polished surface, and may even be polished flush to the road surface, with resultant loss of frictional resistance. The resistance of aggregate to abrasion is a function of the constituent minerals' hardness. Quartz has been shown to be the hardest of the rock-forming minerals (CSRA, 1985), with the other minerals noticeably softer. The difference in hardness of the component minerals is more important in resistance to polishing than absolute hardness. The distribution of minerals in the aggregate provides a textural property that assist in resistance to abrasion.

All of the basic crystalline rocks (little or no quartz) are liable to polish, while acidic rocks (composed of much quartz) do not polish significantly in service. High-silica rocks polish slower than the binder will abrade, due to the strength inherent from the high silica content. The quartzitic sandstone (the only member of the arenaceous group suitable for use as a surfacing seal aggregate) has a good resistance to polishing. None of the other rock groups are suitable in terms of resistance to polishing.

2.3 PAVEMENTS

A summary of the pavement issues of relevance to the study of the performance of road surfacing seals is provided.

2.3.1 Pavement Layer Behaviour

A summary of the experienced behaviour of the pavement is provided in Figure 2.2 below (CSRA, Draft 1996, TRH4).

The granular base pavements exhibit permanent (plastic) deformation arising from densification and/or shear of the untreated material.

The performance of seal and pavement, specifically base course, are interlinked. Should the seal not be properly maintained and the seal is allowed to age, the "first half life" (McManus and Metcalf, 2003) of the pavement (i.e. pavements with unbound crushed stone base) will generally be characterised by the cracking of the seal (due to loss of volatiles and bitumen oxidation, reduction in flexibility and cracking). The resulting water penetration leads to the initiation of pot holing and loss of pavement strength. The "second half life" is characterised by pavement deformation (rutting), seal ravelling and
reduction in skid resistance. The seal is required to protect the pavement, which gives support to the seal.

**Cemented layers** will exhibit block cracking caused by drying shrinkage and thermal stresses, and the subsequent breaking down of these blocks into smaller ones under traffic. If water cannot escape, pumping of fines occurs under the "rocking" movement of the blocks, accelerated by further moisture ingress. Under repeated high stress "crushing failure" of the upper part of the base can occur.

![Diagram of pavement behaviour](image)

**Figure 2.2: Generalised Pavement Behaviour (CSRA, Draft 1996, TRH4)**
The performance of seal and pavement, specifically base course, are interlinked. Should the seal not be properly maintained, and the seal is allowed to age, the "first half life" (McManus and Metcalf, 2003) of the pavement (i.e. pavements with unbound crushed stone base) will generally be characterised by the cracking of the seal (due to loss of volatility and bitumen oxidation, reduction in elasticity, and cracking. The resulting water penetration leads to the initiation of pot holing and loss of pavement strength. The "second half life" is characterised by pavement deformation (rutting), seal ravelling and reduction in skid resistance. The seal is required to protect the pavement, which gives support to the seal.

2.4 SEALS

This section provides an overview of the road surfacing seal, from examination of function, through to design and reported performance. Aspects of relevance to the project are presented under this section, while items of supplementary nature are presented in Appendix A, for completeness and ease of reference.

2.4.1 Role of Surfacing Seals

2.4.1.1 Function of a Seal

The function of a road surfacing seal is summarised in both TRH3 of 1989 (CSRA, 1989) and the draft TRH3 (CSRA, 1997) as follows:

- Providing a durable, all weather, skid resistant riding surface
- To seal and protect the structural pavement layers
- Provide strength at the road surface to resist abrasive and disruptive traffic forces and the effects of the environment
- Provide a waterproof cover

Of note is that surfacing seals are thin, and conventionally are considered to provide no contribution to the pavement's load distribution and bearing properties. Performance for seal is thus related to how it satisfies its service functions.

2.4.1.2 Historical Utilisation of Surfacing Seals

Marais (1979) summarised the popularity of bituminous surfacing seals, due primarily to the fact that they are relatively cheap, easy to place and maintain, and if properly constructed, durable.
When first utilised, no formal design method was available, and the successful implementation of the seal depended on the experience of the construction team. The then (pre-1935) low traffic volumes also ensured that minimal load was applied to the seals during their serviceable lifetime. However, with the increase in traffic, developed countries such as the USA turned to asphalt surfacing. Developing countries, then New Zealand, Australia, South Africa, still maintained seals for economic reasons. Thus, the first viable seal design method was implemented in New Zealand, by Hanson, in the 1930's. This method used the Average Least Dimension of the surfacing stone as a fundamental parameter in determining volume of the aggregate mat and voids, and related binder application rate. After the end of the Second World War in 1945, and the growth in traffic with the economic recovery, the demand for improved roads was great. Surfacing seals, single and double, were extensively applied. The shortfall in the design methodology was exposed when, due to traffic and/or environmental effects, or not fully understanding the materials used, seals failed, bleeding or other failures occurred. Several regional Roads Authorities implemented their own design methods.

Work regarding the enhancement of seal design methodology has been ongoing through the decades, and this project is part of the continuation of this historical work, with a movement towards a performance related seal design method.

2.4.1.3 Importance of Seal Utilisation on South African Roads

The South African proclaimed rural road network is estimated (TRH3, CSRA, 1997) at 200 000 km, of which 30 % are surfaced, 95 % of which are sealed or resealed with surfacing seals. Urban roads add a further 88 000 km, of which 50 % is surfaced, 75 % of which are sealed or resealed with surfacing seals.

Most rural roads are surfaced with double seals or Cape seals, and resealed later with slurries or single seals. Asphalt surfacings are usually used on highly trafficked rural roads, freeways, urban roads and intersections.

The road surfacing seal is thus an important feature of South Africa's road construction and maintenance activities, and investigation towards performance prediction and design of value to the engineering community and society.
2.4.2 Behaviour and Performance Influences

2.4.2.1 Factors Affecting Seal Performance

Literature (CSRA, 1997, TRH3) discusses the factors that affect the performance of seals. These are summarised below with comment from other authors where applicable. Roque et al (c.1989) also indicate that while much attention has been given to design procedures, much less has been given to materials, construction methods and traffic control. In their investigation, where the above procedures were varied, they reported a definite differentiation in performance of the different seal scenarios, with some seal coats outperforming others.

Oliver (1999) summarises the factors that most affect seal life (or performance), and these are in highest order:

- Design of application rates
- Traffic
- Bitumen quality
- Construction process
- Timing of work
- Climate/environment
- Aggregate quality
- Maintenance priorities

When considering a contribution to a performance related seal design method, it is imperative to be aware of the factors affecting such performance. These factors are presented below.

(i) Pavement Structure and Condition

The performance of seals is related to the structural adequacy of the pavement, to which the seal acts as a wearing course and seal against water ingress.

The base type, for new construction, affects seal performance, where resistance to penetration by the seal stone is related to material type and compaction. Where the seal stone is allowed to penetrate, there is reduction in voids, with the higher risk of fattiness, bleeding and associated danger of lowered skid resistance.
The pavement structure itself affects seal performance, where high deflection under traffic cause fatigue in both seal and layerworks. This can lead to cracking of the seal binder, with water ingress, which aggravates the whole deterioration cycle. Reflection of cracking through surfacing is related to the frequency of movement (load repetitions), and temperature and moisture changes. Seals should be selected to suit the pavement behaviour characteristics.

Rust and Hugo (c.1988) report that to prevent the recurrence of reflection of cracks through the surfacing seal, special or innovative materials such as bitumen rubber, geofabrics and low viscosity bitumen have been used in attempts to limit the reflection of these cracks through the new surfacing. They report that cracks reflect due to thermal and wheel load effects, or a combination thereof. After developing the Crack-activity meter (CAM) to measure both horizontal and vertical crack movement in relation to the wheel load position, they were able to analyse the crack movement, and simulate this in the fatigue testing of the various seal and binder types aimed at assisting in the predicting the field performance of the various binder types at various spray rates. They found that the horizontal movement was higher than the vertical movement caused by a moving wheel load. Using a Crack Movement Simulator (CMS) the fatigue characteristics of the binders were able to be investigated further under controlled laboratory conditions.

(ii) Existing Substrate

The condition of the existing surface will determine the seal type and design. The condition is determined by visual inspection and measurement (texture depth, expected embedment of stone, unevenness, permeability). Of note is that for a uniform seal design to be applied, a uniform surface is required to be sealed upon. Pre-treatment is required if the surface is not uniform, or texture depth is excessive. Pre-treatment or additional binder is required to correct permeability. Where expected seal stone embedment is high, voids in the new seal can be expected to be reduced due to stone embedment under traffic load. Where cracking is present on the surface, this indicates either reflection or brittleness of the existing seal, and applicable seal binders are required if the seal is to perform satisfactorily.

Roque et al (c.1989) found that seals placed on worn surfaces (when compared with seals placed on new or levelled surfaces) maintained the highest mean texture depth. This was due to worn surfaces being harder (i.e. better compacted under traffic load) than new surfaces and levelled surfaces. They further postulate that levelling courses should not be applied before reseal unless it is absolutely
necessary due to rutting of the existing surface being severe. Levelling courses require additional emulsion for aggregate retention (due to the porosity of the asphalt, and older surfaces usually have a lower mean texture depth due to flushing).

(iii) Traffic

The volume of traffic affects seal performance in terms of embedment, wearing, polishing, with related reduction in voids — which promotes flushing and reduced skid resistance. However, a minimum of 50 vehicles per day are required to keep the binder flexible (discussions with practitioners and researchers by Milne have sustained that this is probably due to the breaking down of the large chain hydrocarbons that form under oxidization, and the physical removal of the large oxidised materials by the traffic abrasive forces). This should be taken note of even if economic analysis suggesting single seals become justified in terms of total user costs and maintenance at 25 vehicles per day (SABITA, 1992, Manual 10).

High axle loading causes embedment of stone, and tyre inflation pressures contribute to bleeding. Tandem turning axles damage the surface during turning movements through high shear loads applied at the road surface. Low speed also results in extended loading period, fuel spillage and higher horizontal stresses due to traction.

Traffic concentrated in wheel paths, or applied too early in the seal's life before curing, will adversely affect performance.

(iv) Road Geometry

Steep gradients result in increased traction, which results in debonding between stone and bitumen, slippage and flushing. There is also greater risk due to construction difficulties, with designed binder application rates not being retained on the pavement and binder not being uniformly applied. Slower traffic speeds will also result, with the additional loading effects as indicated above. Canalised storm water, with associated erosion or stripping, especially against kerbs in hilly areas is also a potential danger.

Sharp curves lead to high horizontal (shear) stress, with associated ravelling or slippage of surfacing. Traffic on lower volume roads may cut corners, which leads to the outer part becoming dry, brittle and loosing stone. On curves, the required camber leads to higher loads on the inside, with accelerated fattiness a possibility.
Intersections often reflect the effects of deceleration forces – high horizontal (shear) stresses, with associated slippage. Fuel spillage in these areas also softens the binder.

Narrow width roadways concentrate wheel movement, causing fattiness in wheel tracks, and brittleness in the remaining areas.

(v) Design

The design process should make allowance for the different situations that may occur on and around the specific pavement. Pre-design investigation is critical to the success of the seal, to ensure proper design and maximum performance. Of note is that the design can always be amended during the construction phase should additional information become available.

(vi) Materials

- Aggregate

Aggregate related factors affecting seal performance are:

- **Shape**: this affects interlock of compacted layer and the stability of the seal, void content, and the displacement of water.

- **Nominal size**: smaller stone size is more susceptible to bleeding due to fewer voids. Larger stone is also less critical to application rates. Ball and Owen (1998) also show that seals with the larger stone are less susceptible to showing signs of distress, especially flushing.

- **Spread rate**: a uniform mosaic is required to cover underlying surface for protection. A single tight knit layer is desired, although too tight packing results in crushing, and too loose, UV damage to the binder.

- **Gradation**: single size results in good interlock, and maximum contact between road and tyre, with better rideability. Less polishing and abrasion occur (due to better distribution of the load), with related higher skid resistance.

- **Cleanliness and dust content**: dust, mud, oil and fuel, and other contaminants adversely affect the adhesion of the aggregate to the binder. Only 1% dust will result in substantial stone loss.
- **Adhesion characteristics**: moisture affects adhesion negatively, except when emulsion is used. Precoating improves adhesion, especially with binders of high viscosity. Bad adhesion between specific aggregate and binder results in an unstable seal.

- **Strength, durability and wearing characteristics**: aggregate is required to have sufficient strength (reflected by ACV or FACT test values) not to break or crush under traffic or construction. The characteristics of resistance to weathering and polishing (depends on mineral composition) are also desired.

- **Porosity and absorption**: porous aggregate absorbs the lighter bitumen fractions, thereby contributing to a brittle seal. This is unsuitable for seals required to perform for an economically acceptable design period.

- **Binder**

  Properties affecting the performance of the binder within the seal are:

  - **Binder type and properties**: the different types of binder, such as penetration grade, cut-back, emulsions and modified binders all behave differently under certain conditions, and all will affect the performance of the seal.

  - **Binder grade**: the appropriate grade for expected climatic, pavement and traffic conditions, both under construction and long term, must be selected to ensure optimal seal performance.

  - **Viscosity – temperature relationship**: each binder’s temperature – viscosity relationship will determine the optimal design performance decisions.

  - **Spray rate**: the optimal amount of bitumen is required to keep the stone on the road (through adhesion), but to maintain enough voids to prevent bleeding. The optimum amount of binder is determined by the size and shape of stone, and the volume of voids in the compacted stone layer, traffic, gradients and condition of underlying surface.

  - **Viscosity at application**: viscosity at application determines the uniformity of application, where too low temperature causes streaking
(due to high viscosity at the spray bar), and too high temperature binder degradation.

Roque (c.1989) report that on levelled surfaces (prior to reseal) the application rate had a direct relationship to retained aggregate, e.g. chip retention on the lower emulsion application rates was inadequate (due to absorption of the binder into the levelling course). However, on worn surfaces, even the minimum recommended binder was sufficient to retain the aggregate, with increase in binder only decreasing the macro texture of the seal coat. Binder application was found to be the most sensitive of all seal design variables.

(viii) Preparation, Pre-treatment and Repairs before Construction

Surface preparation is required to ensure a dense, clean surface required for a good bond between the base and bitumen. If the surface is not compacted to sufficient density, embedment under construction and traffic will result.

Pre-treatment is required if the surface texture varies, is uneven, dry or porous.

Repairs to pavement defects or failures (such as potholing) are required to prevent these defects reflecting through the surfacing.

Pre-treatment and repairs are required well before surfacing to minimize embedment (to allow the volatilises in the repair binder (fluxing agents, etc) to evaporate before sealing over).

(viii) Construction and Supervision

It has been experienced by the various South African roads authorities that in cases poor performance of seals has been due to poor construction and supervision. The correct and uniform application of binder and aggregate are required, with brooming, rolling and the use of calibrated plant to ensure the maximum possible performance from the seal. Initial traffic speed should be limited to 60 km/h while the seal develops adhesion to the base and aggregate.

Roque et al (c.1989) report that the number of roller passes under construction had no effect on the retained Mean Texture Depth (MTD) of the applied surfacing seal, either on new or worn surfaces. They also found no correlation between traffic control (delay before application of traffic) and the retained MTD of the seal.
Weather was found to have an effect on MTD of the completed seal, with greater retention of aggregate on hotter, dryer, windier construction days – aggregate embedment on rescaling may be reduced in areas that are shaded (higher embedment in hotter weather).

(ix) Maintenance

Timely maintenance through the use of diluted emulsion, patching or fine slurry will extend the seal’s serviceable life.

(x) Physical Environment

The factors affecting the seal performance through the physical environment are:

- **Climatic conditions**

  The correct type and grade of binder is required to accommodate:

  - **Hot weather**: cohesion is reduced
  
  - **Cold weather**: brittle and hard binder will accelerate aggregate loss and cracking (adhesion is reduced)
  
  - **Uncertain weather**: varying temperatures
  
  - **UV radiation**: accelerates aging of the binder
  
  - **Humidity**: affects the evaporation of volatiles, accelerating ageing

- **Drainage systems**

  Roads in urban areas carry storm water, either through their shape or against the kerbing. High speed flows and volumes erode the seal, especially with soil particles in suspension. The application of slurry, single or sand seals on steep slopes should be avoided.

- **Mechanical damage**

  Damage caused by traffic or construction plant should be repaired as soon as possible to prevent water ingress, ravelling, potholing and other forms of pavement and surfacing distress.
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

- **Dust and sand**
  
  Windblown dust and sands causes poor adhesion between aggregate and binder, and binder and base.

- **Fuel spillage and animal droppings**
  
  Fuel and animal droppings (contains acids) soften up the bitumen, and contaminated areas deteriorate, causing seal and pavement failure.

- **Developing areas**
  
  Stresses induced due to building industry vehicles, far beyond the expected vehicular and trade vehicles (axle loads), rubble spilt on the roads and punched through the seal by traffic, and other construction related activities may damage the seal and pavement prematurely.

2.4.2.2 Control over Influencing Factors

Marais (1979) classified the factors that affect seal performance in terms of the amount of control road designers have over them, as reflected in Figure 2.3:
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

Figure 2.3: Influences on Seal Performance (After Marais (1979))

2.4.2.3 Performance Measurement

Roque et al (c.1989) used five methods to report on the performance of seals.

- Sandpatch method
  The mean texture depth (MTD) was the parameter obtained.

- Skid resistance
  Skid number (SN) was the parameter obtained.
• Visual examination

Three performance ratings – overall, bleeding, aggregate retention – were evaluated. This was found to be unsuited for detailed analysis.

• Stereo Photos

No parameter was obtained. However this provided a record of visual changes with time at one location.

• Geotextiles

This method was a failure, due to the geotextile not being able to be recovered from the test sections.

2.4.3 Seal Types

A road surfacing seal is the product of the application of a bituminous binder and aggregate to the pavement. During the construction process the aggregate is rolled into a mosaic, and the binder is worked into the voids. Various types of seal construction are utilised in construction, each to suit the specific requirements of traffic, pavement and environment. TRH3 (CSRA, 1997) summarise the seal types:

• Single seal: single application of binder and aggregate, with cover spray (or precoating)
• Double seal: double application of aggregate and binder, with cover spray (or precoating)
• Cape seal: application of binder and aggregate, with slurry worked into the voids
• Slurry seal
• Sand seal
• Inverted double seal
• Geotextile seal
• Split and choked seals

Schematic representation is provided in Figure 2.4 below:
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

**SINGLE SEAL**
1. TACK COAT
2. STONE

**DOUBLE SEAL**
1. TACK COAT
2. LARGE STONE (1st Stone layer)
3. PENETRATION COAT
4. SMALL STONE (2nd Stone layer)

**CAPE SEAL**
1. TACK COAT
2. STONE
3. PENETRATION COAT
4. SLURRY

**SLURRY SEAL**
1. SLURRY

**SAND SEAL**
1. TACK COAT
2. SAND
3. PEN COAT
4. SAND

* Focus of this project

**Note:** Shoulder to shoulder stone contact in MMLS3 in Performance tests.

**Figure 2.4:** Schematic Illustrations of Various Seals (CSRA, 1997, TRH3)

It is noted that the performance testing and numerical modelling developed in this project are focused on the basic seal, i.e. the single seal, to enable the primary seal constituents to be assessed and modelled in their basic form of seal aggregate and binder.
2.4.4 Principles of Seal Design

The principles of seal design are presented below and additional supplementary information is provided in the Annexures.

2.4.4.1 Basic Design Principles

In essence, as summarised by NAASRA (1998) and TxDOT (2004), the object of sprayed seal design is to spread the single sized aggregate, one layer thick in shoulder to shoulder contact, and fill a percentage of the available voids in the mat with sufficient binder to retain the aggregate while maintaining a final surface texture for adequate skid resistance. More than one application of aggregate and binder may be utilised.

Current seal design methods in South Africa have evolved from Hanson's volumetric seal design, and the concept of partially filling the voids in the seal aggregate, and that the volume of voids is controlled by the Average Least Dimension (ALD) of the aggregate (Marais, 1979). The implementation of this theory has varied over the years between the different regional South African Roads Authorities, in that different applications of aggregate or binder are possible for given design parameters, and the perception of the ideal aggregate matrix or texture depth differs. Climate and binder source also has an influence on the desired application rates for the seal. The new Draft TRH3 (CSRA, 1998) has accommodated these variations within the Hanson model, and the current basic design principles applied in South Africa are as follows:

- Minimum void space to be filled is 42 % (equates to a wetting of approximately 30 % of the aggregate) for single seals and 55 % for double seals, if no embedment is to be accommodated.

- Void (texture/texture depth) loss under traffic is dependant on aggregate hardness (minimum assumed 210 kN 10 % FACT).

- Required minimum texture depth for adequate skid resistance is 0,64 – 0,7 mm.

- Embedment under construction assumed to be 50 % of total embedment with time.
Figure 2.5: Concept of Volumetric Seal Design (CSRA, 1997, TRH3)

Figure 2.5 illustrates the concepts of volumetric seal design.

2.4.4.2 Voids (texture/texture depth)

Hanson (Marais, 1979), according to literature, was the first engineer to make a scientific study of the performance and design of single surface seals. All subsequent methods have followed his basic principles that the application of both stone and binder are controlled by the average least dimension (ALD) of the single-sized stone. Some doubts are being expressed about Hanson’s findings, due primarily to the fact that he used a soft aggregate, which crushed under the steel wheel rollers of the day, and subsequent traffic. However, the emphasis of the design method on voids in the single layer of stone in determining the quantity of binder to be applied is still accepted. From the research and findings of this project, the term “voids” is proposed not to be totally descriptive of the actual parameter being described, but that an alternative concept or description be applied: e.g. “texture” or “texture depth”, “macro-texture” or “filling ratio” - ratio of texture filled with bitumen, etc. As seal design is based on optimal filling of “voids” with binder, this custom will be followed throughout, with a recommendation under chapter 7 in the concluding remarks.

The voids in a single layer of stone placed shoulder to shoulder are of prime importance in seal design and it is necessary to quantify these for an effective design to evolve. Marais (1979) observed that when a film of binder is evenly applied to a road surface and completely covered by a single sized stone, only a single layer of stone remains bonded to the road after being exposed to traffic, all excess stone is whipped off, and the bonded stones orientate themselves into a tightly knit mosaic structure. The individual stones end
up lying with their least dimension predominantly vertical. Walker (Marais, 1979) determined in a laboratory "tray test" study that both flaky and cubical aggregate particles packed in the same manner, with the predominant factor determining the packing being the ALD, and not the other physical characteristics. When comparing tray test stone coverage, in mosaic on ALD, and the coverage of seals that performed well under traffic, it was found that the seal coverage was similar to that of the tray test. This study gave support to the use of the tray test to determine the maximum amount of stone that will be retained by the binder, after the stones have oriented themselves on ALD. This finding allowed further work to be undertaken on the design of seals in the laboratory.

Expected voids were then examined, and compared with the ALD of the stone, in order for voids to be expressed in terms of a measurable control. It was found that void content for a single sized stone covering an area was not constant, but correlated well with ALD. The relationship so obtained is:

\[ \text{Voids (as % of ALD volume)} = 100(1 - W/(ALD \times SG)) \]  \hspace{1cm} (Eq. 2.1)

where  
\[ W = \text{stone coverage in kg/m}^2 \]
\[ ALD = \text{average least dimension of stone in m} \]
\[ SG = \text{ASTM bulk density of stone @ 25°C in kg/m}^3 \]

Marais (1979) took this further, and after examining the relationships of ALD against voids in a single layer of stone (reflected as a % of ALD volume) the relationship was determined:

\[ \text{Voids} (%) = 67(0.8 - e^{-0.16ALD}) \]  \hspace{1cm} (Eq. 2.2)

When considering the factors that affect the voids in a single seal, and the above relationship, a rational design method were developed (Marais, 1979). It is noted that both wear and emulsion reduce the available voids in the seal.

2.4.4.3 Embedment

Marais (1979) believed that insufficient attention to embedment resulted in the majority of failures of single seals in practice. Although some embedment is desirable, Marais reports that the amount desired, or that expected, is still not able to be predicted in practice. Embedment has logically shown to be dependent on intensity and type of traffic, and hardness of the underlying surface. The traffic is the predominant factor.
The reduction in voids/texture depth is already evident after a short period of time (three months) in most cases, with equilibrium being reached after approximately three years. Embedment is seriously affected by surface temperature, with higher embedment occurring under the higher road temperature, especially for reseals. Hanson (Marais, 1979) assumed that under traffic compaction all stones in a single seal lie with their ALD vertical. Then the average seal thickness would equal the ALD of the stone. Embedment is therefore the difference between ALD and the actual measured thickness of the seal. Should the aggregate not lie on ALD vertical, then this method of determining embedment would lead to a negative value. This emphasizes the difficulty in determining a generalised manner of calculating embedment.

A test method - the Ball penetration test – was developed (Marais, 1979) in an attempt to quantify the expected embedment, and thereby the expected reduction in voids in the seal. Figure 2.6 reflects these findings.

Oliver (1987) records that most of the orientation of aggregate occurs during the first three roller passes, very little improvement after six passes.

Roque et al (c.1989) reported that texture depth of new reseals reduced rapidly for all test sections in their investigation in the first month, stabilising after month four. These sections included different number of roller passes during construction. Sharper drop-offs occurred in the hotter months when the aggregate embedment rate was higher.
Figure 2.6: Relationship between penetration of standard ball, traffic and equilibrium embedment of stone into underlying surface of road (Marais, 1979)

Hanekom et al (1999) emphasize the TRH3 (CSRA, 1998) postulate that the matrix formed by the aggregate with a modified binder acts as a mat, limiting penetration of the aggregate.

2.4.4.4 Change in Void Volume during Service

As discussed above, embedment occurs on the underside of the seal mat, while degradation and wear occur on the top side, both reducing the void content in the seal. The relationship between void volume and depth (or thickness of seal), with depth expressed as a fraction of ALD, was determined by Marais (1979). A curvilinear relationship evolved:

\[ V = 2.528d - 4.578d^2 + 3.058d^3 \]  \hspace{1cm} (Eq. 2.3)

where \( V \) = fractional void volume – as a fraction of depth at full ALD
\( d \) = depth (fraction of ALD) – thickness of seal
It was then possible to predict the change in voids with change in either embedment or wear/degradation (Figure 2.7 below).

Figure 2.7: Relationship between Void Volume and Seal Thickness (Marais, 1979)

2.4.4.5 Skid Resistance

One of the functions of a seal is to provide a surface with good skid resistance properties in wet weather. The Road Research Laboratory found that for high speed traffic (80 – 130 km/h), the texture depth was the determining factor in providing skid resistance under wet conditions. A texture depth of greater than 0.64 mm was required to provide effective skid resistance for these speeds. Allowance for a final texture depth of 0.64 mm at the end of an appropriate seal design life (say 10 years) is thus required. As indicated above, TRH3 (CSRA, 1997) requires a 0.7 mm minimum. For stone of ALD in excess of 7 mm, this is easily obtained, but smaller aggregates were not able to provide this. A reasonable allowance of the fraction of ALD to be available to provide skid resistance for these smaller stones was 10 % ALD (with 0.64 mm as a maximum). The minimum safe texture depth to provide skid resistance was determined as 0.4 mm (Marais, 1979).
2.4.4.6 Existing Road Surface

Allowance for the practical consideration that often surfacing seals are applied to existing road surfaces, and these surfaces are rarely smooth, must be made. Of these, coarse surfaces require more additional binder than smooth textured surfaces due to the binder filling void spaces and not being available to "wet" the applied seal stone. The different expected traffic conditions also affect the way in which the aggregate orientate themselves, which also influences the additional binder required. Suggested increases in binder quantity for each surface texture and traffic type were provided to assist the designer by Marais (1979) (ref Figure 2.8 below).

![Figure 2.8: Additional Quantity of Binder required to allow for Texture Depth of Existing Surface (Marais, 1979)](image)

2.4.4.7 Minimum Quantity of Binder

Experiments have shown that in order to retain a mat of stone in the early life of a seal, a minimum binder film thickness, dependent on the ALD of the stone, is required (Marais, 1979). A thickness of minimum 50% of the total void volume in a single stone layer is required (as indicated above, TRH3 (CSRA, 1997) requires 42%). However, during construction, embedment (estimated at a third of the penetration of a 19 mm ball – at the recommended temperature) will reduce the available void volume. The embedment assists the stone in resisting the action of traffic forces, equal in force to the volume of binder taken up by the initial embedment. But allowance must be made for binder taken up by the existing road surface. The determination of the correct binder application is required to ensure adequate design life.
2.4.4.8 Stone Application

Marais (1979) indicates that the voids in a stone mat, i.e. a single layer of stone, are related to the ALD of the stone (Hansen indicated 20% voids of the ALD volume). Marais also related the voids in a loose volume of stone to the flakiness index – the more flaky the stone, the higher the volume of voids in the bulk condition. Marais obtained the following relationship assuming an average compacted depth of stone layer equal to ALD:

\[
SR_t = \frac{1000}{ALD} \left( 100 - V_1 / 100 - V_2 \right) \quad \text{(Eq. 2.4)}
\]

Where

\[
\begin{align*}
SR_t &= \text{theoretical spread rate of stone (m}^2/\text{m}^3) \\
ALD &= \text{Average least dimension of stone (mm)} \\
V_1 &= \text{void volume in loose bulk volume expressed as percentage of total volume occupied by stones} \\
V_2 &= \text{void volume in a single layer of stone expressed as a percentage of ALD volume}
\end{align*}
\]

The recommendation is to apply an excess of stone to ensure a dense mat. Suggestions refer to between 6 and 20% excess. Marais has the following relationship:

\[
\text{Excess allowance (%) } e = -0.33 \text{ ALD} + 11.67 \quad \text{(Eq. 2.5)}
\]

with spread rate:

\[
SR_p (\text{in practice}) = SR_t - e/100. SR_t \quad \text{(Eq. 2.6)}
\]

and \( e = \text{excess allowance from above.} \)

Substituting for the volumes,

\[
SR_p = (3.3 + 883.3/\text{ALD}) \left( 57.9 - 0.22F1 / 46.4 + 67e^{-0.16\text{ALD}} \right) \quad \text{(Eq. 2.7)}
\]

2.4.5 Experienced Performance of Seal Binders and Aggregate

Literature was examined regarding aspects relating to seal binder performance, as experienced in service. Aggregate performance was also briefly expanded over the previous discussion.

2.4.5.1 Binder: Straight Bitumen

Mason (c.1986) reports that cationic bitumen emulsion used as fog spray remained tacky for up to 48 hours after application, until the tackiness arising from the fluxing agent was
lost completely. This tackiness resulted in stone loss under traffic. Also, it was found that a rubber-lined flat wheel roller yielded superior finish.

2.4.5.2 Binder: Polymer Modified Bitumen

Lewis et al (c.1999) reported the results of their examination into the performance of SBR sections of National Routes 2 and 3, where a single seal was placed as a reseal. This test section utilised 80/100 pen grade base bitumen, with SB contents varying from 2 to 6%, and varying binder application. Evaluation was made using TRH12 visual assessment. It was found after 4 years service that “ghosting” of the cracks sealed before application of the reseal was evident, and the section was still in a better condition than prior to the reseal. At that stage (1990) there was no visual indication of the difference in performance for the three different SBR latex contents.

The recommendation is that modified binders be sealed as late as possible into the dry season, to limit the sealing-in of moisture content.

Mason (c.1966) reported that the initial tackiness of the RMB binder utilised on trial sections had pickup resulting from the tackiness of the binder. Mason utilised aggregate with precoat that was applied while still damp.

Roque et al (1991), in their investigation over 13 months, found no evidence to indicate difference in behaviour between straight (control) bitumen binder, and modified binder, seals when using Mean Texture Depth as a measure of performance. They postulated that the patterns of aggregate wear and embedment were similar for straight and modified binders, and that modifiers were unsuccessful in preventing embedment in hot weather.

In Rust and Hugo’s investigations (c.1988) of the performance of various binders under fatigue testing (with the Crack Movement Simulator), various binders were tested, including modified binders with a range of polymer added from 2 to 5%. These were compared with bitumen rubber and straight binder control. The fatigue performance varied markedly between the modified binders, whose performance fell far short of that of the bitumen rubbers. The straight control bitumen had the weakest performance in this regard, with bitumen rubber performing the best in general, but the addition of polymer modifiers added to the performance of the binder.

Emery et al (1999) researched the factors affecting production of SBS modified binder. Oxidation problems could be avoided by keeping mixing time to 2 hours, with temperature not exceeding 180°C. They reported that branched polymers had a greater effect on increasing softening point than linear polymers. Base bitumen also affected the effect of
modifier on improvement of characteristics, especially the balance of asphaltenes, saturates, aromatics and resins. This can vary daily at the refineries, and large scale batching is required to limit variability. They also report that there is also an increase in softening point and viscosity with time when the binder is stored at 180 °C (oven aged), due to gelation. Shell recommends an increase of 2.5 °C in normal mixing and compaction temperatures for every 1% SBS added, to counter this increase. Degradation (shearing) by gear pumps in the asphalt plant was investigated. When using low shear stirrers with SBS powder, higher values of softening point and viscosity were evident when compared with the same modified binder after high shear circulation. Full scale manufacture uses generally high shear stirrers, which are more effective in dispersing the SBS in the bitumen, although network chains are cut and properties changed. The authors report that in the manufacture process the binder will pass through many pumps, thus at each stage a reduction in the properties the modification process has enhanced in the binder. Shell postulate that laboratory measured viscosity of SBS modified bitumen cannot be compared with that measured after the production process.

Hanekom et al (1999) investigated various experimental seals including the N1 North of Pretoria, constructed in 1988, the Provincial Road 823 near Secunda, constructed during 1990, and Road P88/1 near Vereeniging (resealed in 1983). Seals included double seals using combinations of modified binders, including SBR, and bitumen rubber. They report that the both modified and bitumen rubber application rate previously considered adequate, of 2.0 m²/l to 2.5 m²/l, is not sufficient to prevent reflective cracking should the base be brittle, exhibiting extensive cracking with high deflections. The authors also reported that the seals performed satisfactorily, but where the roads were sealed over base requiring remedial action (such as Road 823) the seal and pavement were showing severe signs of distress after three years of service. Also punching had occurred on Road P156/2 (also near Vereeniging) where texture treatment in the form of slurry was applied prior to reseal. In general it was reported that the straight bitumen (MC3000) became brittle and dry when compared with the modified binders (Road 823) after seven years of the double seals being in service.

2.4.5.3 Binder: Bitumen Rubber

In the investigation by Lewis et al (1999), a Bitumen Rubber (20% rubber) modified binder was included as well. By four years service, there was no real difference in behaviour or appearance between the latex (SB) modified binder and the rubber bitumen. There was incidence of "plucking" of the bleeding modified seal on one section of the test section. The supposition that moisture retention in the pavement (at time of construction) has led to
the situation where the pore pressure of the water under an impermeable seal, is occurring (c. 1999) was raised. The pore pressure thus forces the bitumen onto the surface, causing fattiness and later bleeding. The binder then adheres to the vehicle tyres. On further trial sections (seals also four years old) the incidence of cracking reflecting through the surface was found to be reduced.

Mason (c.1986) reports that the current recommended factor of 1.7 applied to convert current seal designs to bitumen rubber cold application were considered too high. Existing rubber and modified reseals tended to show bleeding for the modified binder sections. Also the report reflects that the present rational method of seal design provides too much binder, and the seals designed in this manner can be expected to show signs of bleeding. Precoated aggregate is recommended, to allow for proper orientation of the aggregate, and to prevent pick-up. A factor of 1.53 were considered satisfactory, after the test sections (36 variations) were evaluated. Due to the high viscosity of the rubber modified bitumen, good lateral distribution of binder during construction is imperative to ensure efficient performance. Precoating is recommended.

Blending requires two hours, and effective life of the stored binder is four hours, after which the beneficial properties decrease rapidly through digestion of the rubber. Due to the high viscosity of the bitumen rubber, a uniform transverse distribution is required.

A minimum binder thickness is required to prevent reflection cracks appearing on the surface.

Mason (c.1986) further reports that of all possible combinations of rubber bitumen, RMB, straight and modified slurry, the most cost effective combination was the bitumen rubber/65 % cationic emulsion double seal, especially if the existing road surface and pavement was showing distress.

2.4.5.4 Aggregate Performance

Woodside et al (c.1999) indicated that in the United Kingdom there has been a noted increase in the premature failure of road surfacing layers, due primarily to loss of skid resistance, and deformation or rutting. Of relevance to seals is the loss of skid resistance, which was difficult to explain in light of aggregate being specified with high levels of skid resistance.
2.4.6 Mechanisms and Modes of Bituminous Seal and Surfacing Failure

In this section the actual modes of failure are discussed, while actual criteria against which the performance of bitumen and seals are measured are discussed in Chapter 3.

From the work by Robertson et al (c.1990) it is believed that bitumen is comprised of an internal multi-molecular matrix that consists of polar molecules dispersed in a less-polar to non-polar phase. The result is a material that has elastic properties as a result of the network formed by the polar molecules, and viscous behaviour due to the ability of the network to flow or creep under prolonged stress. The relative contributions of the elastic and viscous behaviour vary with composition.

2.4.6.1 Deformation

Robertson et al (c.1990) reported that bitumen with large proportion of dispersing phase will not be very elastic in character, and insensitive to oxidation. This bitumen would not be expected to harden well, and would deform, especially at high temperatures. This type of bitumen has little of the large molecules that would give it elasticity. The dispersing phase however is made up of non-associated material, which would organize and harden at low temperature, where it would be very stiff and thus susceptible to cracking at low temperature. Bitumen with a large amount of associated material would have a higher elastic modulus at high temperature, reducing the potential of deformation. Bitumen with a higher proportion of large molecules would be expected to be less susceptible to failure at low temperature. The relationship of composition to performance is thus evident. Deformation of the seal is in terms of rotating of the seal stone, affecting available voids for the binder and the texture depth, and flow of binder causing bleeding.

2.4.6.2 Thermal and Fatigue Cracking

If the molecular network – the associated/dispersed phase – becomes too rigid, the ability of the bitumen to deform elastically will be reduced. The asphalt would behave in a brittle manner, and fracture of the material would occur once the materials strength is exceeded. The constant working of a material would also cause fatigue and associated cracking. Compounding this tendency is that at low temperatures the dispersing – or non-associated- phase becomes organised in a more structured form. A very brittle material susceptible to cracking results. This reorganization also results in shrinkage where the low-polarity and non-polar components organize (particularly the aliphatic materials), again initiating cracking.
2.4.6.3 Adhesion and Moisture Damage

Adhesion and moisture were discussed by Robertson et al. (c.1990). The authors report that adhesion of bitumen to aggregate is governed at molecular and inter-molecular level. Certain functional groups (molecular types) appear dominant, particularly polarity displayed by the functional groups. Separation of charge within the organic molecules (i.e. polarity) promotes attraction between the bitumen and the polar surface of the aggregate. It was reported that aggregates differ in polarity, and some showed variation in change with temperature and moisture. Adhesion arises through the interaction of the polars in the bitumen and aggregate. The capacity to absorb water varies with bitumen composition. Apart from the physical damage water has the ability to inflict upon the bitumen, seal and pavement, water has the ability of invading the bitumen due to its polar nature, and the corresponding attraction to the polar molecules in the asphalt. The effect of water on the bitumen properties is to usually soften the bitumen, with the similar effect of diluting the bitumen with a low molecular mass solvent. Resulting performance is reduced strength, greater susceptibility to rutting and deformation. Aged or oxidised bitumens incorporate water to a greater degree than fresh bitumen, due to polarity considerations. Older bitumens are also harder than new bitumens, so the effects of oxidation and moisture somewhat counter each other. Again, behaviour varies with composition.

2.5 FORCES OF TRAFFIC ON SEALS

Traffic considerations will be included in both the numerical modelling and performance testing. Aspects of relevance to both numerical modelling and performance testing are presented under this section, while the interpretation specific to each of the numerical or performance testing components are presented under the respective chapters.

2.5.1 Equivalency Factor

From observations of the performance of seals (Marais, 1979), the equivalency factors used in structural pavement design for converting light axle loads to heavy equivalent axles do not apply for seal design. Light vehicles are practically of no consequence in pavement design, but are important in the performance of seals, as are heavy vehicles. Marais reports that little quantitative data is available equating heavy vehicles to light vehicles for seal design, but a factor of 25 is suggested, although figures vary from 20 to 100. TRH 3 (CSRA, 1997) recommends a factor of 40. This equivalency factor still requires refining.
2.5.2 Footprint

De Beer (1995) investigated the tyre-pavement interface stresses using a prototype Vehicle-Road Surface Pressure Transducer Array (VRSPTA) system. This was used to measure the interface stresses of a moving wheel load. As de Beer notes, the correct estimation of expected traffic loading is one of the key elements in the design process.

Two major components of traffic loading are axle loads and tyre pressures. As indicated above, one of the most commonly used design methods are based on the principle of equivalent loads (estimated through the "equivalency factor"), where axle loads are represented by an equivalent design load on the pavement. The simplification of this approach is that dynamic vehicle loads are simulated by a static, uniform tyre contact stress distribution. De Beer indicates that this approach is adequate for relatively thick (>75 mm) asphaltic surfacing, but is highly inaccurate for thinner layers, where horizontal tensile strains resulting from non-uniform stress distribution can be up to 100% higher than stresses induced by a uniform distribution.

Using the above system, De Beer (1995) found the following for this initial investigation (the VRSPTA was being improved to ensure more accurate results):

- Due to the imperfect tyre geometry, free rolling wheels did apply a transverse force (magnitude is less than 2% of vertical load).
- Transverse load for a driving wheel (i.e. with shear) appears to increase with increase in vertical load at constant tyre inflation pressure and constant wheel velocity (magnitude is less than 3% of vertical load).
- Resultant longitudinal force appears to increase with wheel load and decrease with increase in tyre inflation pressure (magnitude is also less than 3% of vertical load).
- Results indicated that within the tyre, sidewall stresses are 100 to 150% higher than inflation pressure, and maximum vertical stresses in the centre of the tyre are up to 27% higher than inflation pressure.
- Transverse stresses are up to 72% of inflation pressure.
- Maximum longitudinal stresses are at maximum only 30% of inflation pressure.

Woodside et al (1992) investigated the distribution of stresses at the tyre-road interface, and specifically their effect on a textured seal aggregate surface. Vertical (normal) and transverse and longitudinal (tangential) contact stresses induced at the tyre-road interface have a deleterious effect on the wearing course (surfacing), and as indicated previously,
may cause polishing, abrasion and reduction in performance (i.e. the provision of skid resistance to vehicles and protection of the pavement layers). Pavement and seal design is based on standard axle load and assumed uniform load distribution, with resulting constant contact stresses acting on the road surface.

Texture depth is required for adequate skid resistance – 1.5 mm for major roads in the United Kingdom, 0.64 mm in South Africa (the greater texture depth in the UK postulated to be due to wetter climate, lower average road and thus tyre temperatures, and aggregate characteristics). In practice this results in the tyres of vehicles being supported by pinnacles of course aggregate chips which protrude above the surfacing matrix. This results in the surface aggregate bearing higher contact stresses than estimated using the assumed uniform load contact area. Woodside et al indicate that due to these excessive contact stresses, premature failures occur, characterised as:

- Initial damage to the aggregate chips
- Early disintegration of the combined aggregate/binder matrix
- Premature polishing of the aggregate with reduced skid resistance

The above authors examined the stresses imposed by both truck and car tyres (all radial) with various pressures and tyre loadings, with different texture depths. Static measurement using contact stress transducers was used in the determination of the stresses of the treaded tyres on the aggregate chips. It was found that as the height of the transducers increased, so did contact stress (the applied stress doubled when transducer height was increased from 0 to 1 mm above the rest of the contact surface, and trebled when the height was increased to 2 mm. It was also found that the highest contact stress was up to 10 times average contact stress (at 2 mm high transducers). Also, change in tyre pressure and wheel load have little influence on the highest value of the contact stress when compared to the influence of height of transducer. Magnitude of tangential forces was also highly dependent on the position of transducer. The transducers that had full contact with the tyre had lower tangential forces than those with partial contact. Tangential forces under this static test were not significant. Again, the height of transducer had more influence on tangential contact force than tyre pressure or load. Under dynamic wheel load it was found that distribution of normal contact pressure was relatively constant under greatest wheel load, or lowest inflation pressure. Inflation pressure had a greater effect than actual wheel load. Under different contact stress distributions under the dynamic tyre load, tangential forces changed direction as the contact patch length varied, demonstrating the rocking effect imposed on the aggregate.
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

Figure 2.9: Contact Forces on the Transducer Surface (Woodside et al, 1992)

Figure 2.10: Analysis of Interface Stress between Surface Chipping and Binder (Woodside et al, 1992)

In order to determine the magnitude of the forces on the individual chip, the authors determined the following relationship, when considering the moment balance around the bearing point D (the rotation centre under the wheel load) (Figures 2.9 and 2.10 above):
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

\[ F_{xy}(L + L_1) = F_t \frac{2}{3} L_1 + F_c \frac{2}{3} L_1 + F_{bt} \frac{2}{3} \frac{a}{3} \]  
Eq. 2.8

Where
- \( F_t \) is the side resultant tensile force
- \( F_c \) is the resultant compressive force
- \( F_{bt} \) is the bottom resultant tensile force

Assuming:
- maximum value of distributed resisting tensile stress will first reach its limit \( f_t \) (2 to 4 kgf/cm²), and that the resisting compressive force \( F_c \) has triangular distribution,

\[ F_c = \left(3 \cdot F_{xy}(L + L_1) - af_1 L_1^2 - a^2 f_1 L_1^3\right) / 2 L_1 \]  
Eq. 2.9

Woodside et al (c.1999) in later work emphasized the effect surface macro texture has on stress imposed by dynamic wheel load. Distribution of tyre contact stress is not uniform, greatly influenced by macro-texture. During dynamic loading contact stress is generated in three directions: vertical, longitudinal and lateral (transverse). Under static loading, stress is generated in the vertical plane. This further study confirmed:

- Dynamic stress greatest in the vertical plane, maximum effect occurring approximately 75% along the contact length.
- Longitudinal contact stress considerably less than vertical contact stress.
- Lateral contact stress has parabolic shape, and is the lowest stress magnitude.

The dynamic vertical contact stress was a maximum at the edge of the contact patch, suggesting that the tyre wall has a significant effect on the contact stress distribution, up to a 233% increase in vertical contact stress at the edge when compared to the centre. Confirmation was obtained during their analysis that stress distribution is not constant through the contact patch and that the maximum applied stress occurs on the edge, while the lowest applied stress occurs close to (or at) the centre of the contact patch. The greater the mean texture depth, the higher the applied contact stress in the vertical direction. It was also noted that increased road camber and turning movements would greatly increase applied stresses.

The increase in tyre pressure resulted in an increased maximum vertical stress, as expected. The above authors emphasized that aggregate located at the edge of the wheel path would experience greater vertical contact stress, would polish, wear away and suffer permanent deformation at a much faster rate.
Woodside *et al* (c.1999) showed further that the distribution of maximum vertical contact stress is not constant across the contact patch, and even at low inflation pressures there is significant increase in maximum dynamic vertical stress at the edge of the contact patch. The change in dynamic vertical contact stress with increase in tyre inflation pressure varies with distance from the centre, and the rate of change is not constant. The effect of texture depth was also simulated through the use of transducers at differing heights – the increase in maximum vertical contact stress with increasing transducer height was linear, thus indicating that increase in texture depth would have a resulting increase in applied stress under wheel load.

In summary, texture depth has the greatest effect on generation of vertical stress, and applied load is transferred to the pavement through the aggregate chippings. Deeper surface texture would imply that the applied load would be carried on the exposed chipping tops, resulting in the high applied stress. This, in practice, may accelerate aggregate wear or polishing, with the premature loss in skid resistance. Maximum vertical contact stress occurs for 75% of the contact duration within the contact patch.

### 2.5.3 The South African Traffic Trends

Traffic patterns vary throughout South Africa. However, the experienced high tyre pressures and overloading problems impose high stresses on the pavements and surfacings. Super single tyre axles have not been introduced in any significant form to date, although their effects on overseas pavements will no doubt be monitored. Heavy vehicles constitute 15% of the Average Annual Daily Traffic (AADT) (CSRA, 1997, TRH3). Traffic volumes vary from less than 50 vehicles per day (vpd) on rural access roads, to a small percentage of roads that carry in excess of 10 000 vpd.

### 2.6 ENVIRONMENT

A summary of environmental aspects is provided to enable consideration of the temperature and moisture effects on seals. Bitumen is temperature and moisture sensitive, and these aspects will be taken into account in the experimental phase.

#### 2.6.1 South African Environment

The average annual temperature ranges for South Africa are from less than 13 °C in the Central Mountains to 17 °C in the central and Southern coastal areas and 22 °C in the Western, Northern and Eastern Parts. Minimum temperatures occur in June and July.
Rainfall regions are: summer, in Centre and East, winter in the South West, and all seasons in the Southern Coastal belt. Average annual rainfall ranges from 125 mm in the West to 1000 mm in the East, Central Mountains and South Western Coastal Area.

Duration of sunshine ranges from 60% in the Coastal areas, to 70% in the Central region and 80% in the North Western Parts.

2.6.2 Pavement Temperatures

Williamson and Marais (1975) reported on the range of temperatures to which pavements in South Africa are subjected. Ambient and pavement temperature have an influence on the seal binder’s behaviour under load.

These researchers gathered data at four sites distributed between the various climatic regions of Southern Africa, recording minimum and maximum pavement surface temperatures. In addition to this, the new Hot Mix Asphalt Guide (HMA Design Project, draft 2000) provides an updated indication of the time period per year that the pavements are at these extremes as reflected in Table 2.3.

Table 2.3: Average Pavement Temperatures

<table>
<thead>
<tr>
<th>Average Pavement Surface Temperature</th>
<th>Max Summer (Measured)</th>
<th>Min Winter (Measured)</th>
<th>Estimated hours per year surfaces</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Above 50 °C</td>
</tr>
<tr>
<td>Cape Town (Mediterranean Climate)</td>
<td>49 °C</td>
<td>10 °C</td>
<td>250-500</td>
</tr>
<tr>
<td>Durban (Subtropical)</td>
<td>44 °C</td>
<td>15 °C</td>
<td>250-500</td>
</tr>
<tr>
<td>Pretoria (Highveld)</td>
<td>53 °C</td>
<td>5 °C</td>
<td>250-500</td>
</tr>
<tr>
<td>Queenstown (Semi-Arid Steppe)</td>
<td>46 °C</td>
<td>5 °C</td>
<td>250-500</td>
</tr>
</tbody>
</table>

It was found that all sites experienced large variation around the mean in summer (large range between daily maxima and minima, of up to 31 °C) especially inland from the coastal areas, and a reduced variation in winter (of up to 23 °C). Practice has shown that pavement temperatures exceed 67 °C in the mid summer months in the eastern, Lowveld areas, and must reach below 0 °C in the high lying mountainous areas of the central areas. The designer should thus be aware that not only should averaged maximum or minimum temperatures be considered, but the high and low extremes could be potentially catastrophic in terms of effect on binder characteristics. Road surfacing seals will thus be...
exposed to a large temperature range and extremes, which makes the correct choice of binder imperative.

Dumas (1999) emphasizes the unpredictable effect high ambient temperatures and related road temperatures have on the behaviour of the seal and aggregate retention, especially on freshly applied surfacing, and if initial exposure to traffic is not regulated. The sun is the main source of heat, and the black surfacing seal is an ideal heat absorber. High binder temperature of freshly placed seals and unregulated traffic will result in probable aggregate loss through whip-off. A formula relating sun's apparent ecliptic longitude, road surface temperature and solar light intensity has been developed to predict the maximum road surface temperature (for cloudless days). After examining different types of bitumen (Cat 65 % emulsion, pen 80/100, and pen 60/70), it was found that there was no difference in temperature sensitivity between the bitumen grades. Maximum day time temperatures of the binders, during their study, were in the order of 30 °C above maximum air temperature. During the night, binder temperature is below that of ambient temperature. Aggregate whip-off due to the traffic is related to the degree of adhesive strength between aggregate and the road surface. Road surface temperature has a major affect on the aggregate retention. When comparing the force required to move aggregate chips 5 mm without making contact with another chip, for the different binder types, it was found that the emulsion (no volatiles) had a high risk of losing aggregate, followed by 80/100-pen bitumen, and finally 60/70 pen.

The above authors determined that the contact area of an aggregate chip is approximated by measuring only the two linear dimensions – length (a) and perpendicular dimension breadth (b), both reflected in mm. The approximate area of contact is calculated using the following expression:

\[ A_{\text{contact}} = 49 - 7.66b + 0.9ab \]  
\( \text{(Eq. 2.10)} \)

The authors determined the temperatures at which various seal binders begin exhibiting the risk of losing aggregate due to the action of traffic. Cationic emulsion reaches this point at 32 °C, pen grade 80/100 at 40 °C and pen grade 60/70 at 46 °C. These results reflect the indication that for road surface temperatures in excess of 46 °C and beyond, there is equal risk of aggregate loss for all binders. From this information, and the ability of determining the maximum road surface temperature for a certain time of year, a contour graph reflecting certain warning zones will be able to be compiled.

The maximum road temperature is more dependant on the intensity of the black colour, and only to a lesser degree the bitumen type. The risk of whip-off reduces as the binder
cures and later ages, changing from a liquefiable phase to a more solid state at the prevailing maximum road surface temperature. With fresh bitumen, this high risk period is from 10 to 12 weeks for cationic 65% bitumen emulsion.

Roberts and Roper (1998) indicate that (specifically for unbound bases), the main effect of temperature on pavement performance is on the performance of the seal. Sustained high temperatures and wide daily variations lead to the ageing of the bitumen through oxidation, with resulting brittleness enabling cracking under the imposed traffic load. Should this cracking not be repaired, water ingress leads to pavement performance deterioration. Figure 2.11 reflects the impact of climatic temperature and moisture ranges on crack initiation.

![Predicted Surface Crack Initiation Time in Years](image)

**Figure 2.11:** Predicted Surface Crack Initiation for Climatic Zones (Roberts and Roper, 1998)

### 2.6.3 Humidity and Water

Humidity and water were found to accelerate the rate of bitumen degradation, with similar effect as heat on the rate of weathering. This is through the loss of water soluble degradation products, with resultant exposure of fresh bitumen surfaces. Hoiberg’s summary (1965) indicates that the effect on bitumen is primarily physical, rather than chemical. High exposure to sunlight and humidity or water results in accelerated weathering, with associated reduced durability.

Surfacing seal failures have been found to be caused by hardening of the bitumen (Hoiberg, 1965), or bitumen brittleness, due to volatisation and oxidation. Mechanical
stress imposed by traffic (at low temperatures) was considered the main cause of crack formation in the bitumen binder.

Oliver (1987) indicates that the life of a seal depends on the life of the binder, if properly constructed. A common distress mode of bitumen is its hardening with time, when movement under thermal variation results in consequent cracking through failure of the bond between aggregate and binder. Ingress of water through the cracks or gaps where aggregate is lost leads to premature pavement failure, unless efficient maintenance is implemented. Hardening of the bitumen is caused by either the loss of volatiles (depending if the bitumen has a high content of cut-off or volatiles), and by the oxidation of the bitumen. The rate of aging depends on: temperature of surfacing, thickness of bitumen film, and the intrinsic resistance of the specific bitumen to oxidative hardening.

Robertson et al (c.1990) indicate that bitumen is susceptible to oxidation at molecular level, especially at higher road temperatures. The formation of additional polar molecules through oxidation, with the original polar molecules, lead to additional molecules in the dispersed phase (matrices weakly bonded to each other), which in turn decrease the dispersing phase/dispersed phase ratio indicating brittleness and potential to crack.

2.6.4 Light and Heat

As indicated in Chapter 2 bitumens durability and hardness is changed after exposure to the effects of oxidation, elimination of the volatile components, and polarisation.

The physical reaction occurs when the radiation photons (Rosenthal et al, 1971) have sufficient energy when interacting with a particular bitumen molecule to excite it enough into a higher energy level. This may result in the breaking of the covalent bonds with the rejection of the valence electron. The polymer structure changes, often with the addition of hydrogen, carbon dioxide, and the formation of cross – linking or chain scission of the remaining radical ion. With cross-linking, a stronger, stiffer and more viscous product is formed, which may become brittle under large doses of radiation. The above results in larger molecules, which raise viscosity and affects temperature susceptibility.

When scission occurs, a weaker product results with the degrading of the polymer. Which of the two reactions occur is still only able to be determined empirically, although the presence of oxygen promotes scission due to the inhibition of cross-linking.

Light (solar radiation) has been shown to cause photo-oxidation in bitumen. The radiant energy is absorbed by the bitumen and is utilised by oxidation reactions. Oxygen is
absorbed into bitumen in the presence of incident light. Hoiberg (1965) summarised the findings of various researchers.

Heat was found to accelerate the oxidation reaction (Hoiberg, 1965), a rise of 10 °C was found to double the rate of oxidation (although the effect is not linear through the temperature range).

2.7 NUMERICAL MODELLING: MATERIALS PARAMETERS

Specific aspects relating to the numerical modelling of the road seal's material components, in Chapter 5, are discussed in this section. Further background is provided in terms of the bitumen behaviour and rheology in Appendix A (section A2.5).

2.7.1 Supporting Pavement Layers Materials Modelling

The prototype numerical model (as developed in Chapter 5) was focused on the seal geometry and component materials behaviour (aggregate and bitumen binder). The bitumen binder is orders size softer than the aggregate, and temperature and load dependant. As such bitumen was the focus of the material modelling. However for completeness, and to allow comparison of an example of the parameters of granular material of the pavement layers, a brief summary is provided:

The resiliant modulus is the elastic modulus used with elastic theory when considering imposed stresses on granular material. Figure 2.12 (Huang, 1993) reflects the behaviour of granular materials, with both elastic and plastic behaviour. The Resilient Modulus is defined as:

\[ M_R = \frac{\sigma_d}{\varepsilon_r} \quad (Eq. 2.11) \]

\( M_R \) = Resilient Modulus

\( \sigma_d \) = Deviator Stress (applied axial (restraint) stress minus confining stress)

\( \varepsilon_r \) = elastic (i.e. recoverable) strain
Figure 2.12: Visco-elastic-plastic Strains under Repeated Loads (Huang, 1993)

The current prototype FEM model assumes a fixed horizontal plane on the "surface" of the "base", where the degrees of freedom on the bottom mesh nodes are fixed.

2.7.2 Bitumen Parameters for Prototype Numerical Model

The various relevant models that enable visco-elastic and viscous bituminous behaviour to be modelled are summarised below, with expanded detail with specific reference to this project. The examination of literature has shown that there are various methods available to the researcher to model bitumen, from the use of the resilient modulus to the use of visco-elastic models developed from specifically designed experimental methods and related mathematical models. This project, as it was breaking ground in terms of modelling seal binders, involved the examination of existing tools, and broke ground in terms of combining different historic research results to enable the mathematical representation of prototype seal binders. This chapter examines the literature for available tools, while the development of the model parameters is provided in chapter 5.

2.7.2.1 Resilient Modulus

Huang (1993) reports that the resilient modulus $M_r$ as defined above is appropriate to model a visco-elastic bituminous material. This concept is noted for completeness, as the complex modulus and DSR measurements were utilized under this project, as described below and in chapter 5.
2.7.2.2 Visco-Elasticity

Collop and Khanzade (1999) investigated the behaviour of bitumen with the objective of characterizing the material beyond the elastic range of behaviour. They report the findings of Cheung and Cebon, where the steady state behaviour of bitumen (in this case pen 50) is in the form:

\[
\frac{\sigma}{\sigma_0} = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \left( \frac{1}{1 + \left( \frac{\varepsilon}{\varepsilon_0} \right)^\eta} \right) \quad \text{(Eq. 2.12)}
\]

where

- $\sigma$ and $\varepsilon$ are the uni-axial stress and strain rate respectively
- $\sigma_0$ and $\varepsilon_0$ and $\eta$ are material constants for the grade of bitumen (in this case pen 50)

In this model:

- Low strain rates (stress levels) give linear viscous flow ($\dot{\varepsilon} \propto \sigma$).
- High strain rates (stress levels) give non-linear viscous flow ($\dot{\varepsilon} \propto \sigma^n$) with a power law creep exponent of $\eta = \left( \frac{1}{1 - \eta_c} \right)$

For the purposes of modelling the bituminous material, equivalent viscosity is represented by:

\[
\lambda_{eq} = \frac{\Sigma}{\varepsilon} \quad \text{(Eq. 2.13)}
\]

where

- $\lambda_{eq}$ is the equivalent extensional viscosity
- $\Sigma$ is the deviation stress (uniaxial if in a uniaxial test)
- $\varepsilon$ the uniaxial strain rate.
In the above references, Collop et al also provide an indication of permanent deformation:

\[ \delta = \frac{F}{V} \int_{-\chi_0}^{\chi_0} I(y)dy \]  

(Eq. 2.14)

where

\[ \delta \] is the permanent deformation

\[ V \] is the speed of applied static load

\[ I(y) \] is the rate of permanent deformation influence function

\[ F \] is the applied load

\[ \chi_0 \] is the position where the rate of permanent deformation influence function is negligible (i.e. \( I(y) = 0 \) for \(|y|>\chi_0\))

Collop and Khanzada (2001) further indicate that in bituminous mixtures the deformation process of the asphalt mix is determined by the deformation profiles of the binder, and that the experimental stress level tests may not be sufficient to characterise the properties of the binder. To further this concept of modelling, Collop, Scarpas et al (2003) examined a stress dependent visco-elastic (in their terms, a elasto-visco-plastic) constitutive model, with damage determination, for an asphalt mix.

Due to the proposition above that the deformation process of bituminous mixtures are dependent on the binder properties, this reference provided the model for the bitumen in terms of implementation of visco-elasticity and permanent damage for this project.

The model is summarised by the above authors as:

- **Visco-Elastic Model**

The visco-elastic (in the authors' structural mechanics terms, an elasto-visco-plastic model) models are developed from the spring and dashpot elements arranged in series and parallel, as defined in the multiple element Burgers Model (Figure 2.12).
Figure 2.13: Burgers Model as Applicable to the Visco-Elastic Model

For a linear material, in the generalised Burger's model the strains are additive and the stress is the same for each element. The generalised Burger's model is used as it shares the same framework as classical viscous (visco-plasticity) models and allows non-linearities based on stress to be more easily modelled. Figure 2.12 shows that the generalised Burger's model comprises an elastic element (spring) \( (E_0) \) in series with a number of visco-elastic (Voigt) elements \( (E_1 \text{ to } E_\infty \text{ and } \lambda_1 \text{ to } \lambda_\infty) \) and a viscous (dashpot) \( (\lambda_\infty) \) element (permanent flow, or visco-plastic in the authors' terms). In this type of model the stress is transmitted through each element and the strains (and strain rates) are additive such that:

\[
\varepsilon(t) = \varepsilon_{el}(t) + \varepsilon_{ve}(t) + \varepsilon_{vp}(t) \tag{Eq. 2.15}
\]

where \( \varepsilon, \varepsilon_{el}, \varepsilon_{ve}, \varepsilon_{vp} \) are the total, elastic, visco-elastic and permanent viscous strain components and \( t \) is time.

The elastic component can be calculated using:

\[
\varepsilon_{el}(t) = \frac{\sigma(t)}{E_0} \tag{Eq. 2.16}
\]

where \( \sigma \) is the stress and \( E_0 \) is the modulus of elasticity of the elastic element. The visco-elastic and viscous components can be calculated using the Hereditary Integral formulation:

\[
\varepsilon_{ve}(t) = J_{ve}(0)\sigma(t) + \int_0^t \frac{dJ_{ve}(t-t')}{dt} \sigma(t') dt' \tag{Eq. 2.17}
\]
\[ \varepsilon_v(t) = J_{ve}(0) \sigma(t) + \int_0^t \frac{dJ_{vp}(t-t')}{d(t-t')} \sigma(t') dt' \]  

(Eq. 2.18)

where \( J_{ve}, J_{vp} \) are the visco-elastic and viscous (permanent) creep compliances and \( t' \) is a "dummy" integration variable. The authors show that the visco-elastic and permanent viscous (visco-plastic) creep compliances and the initial creep compliances for the generalised Burger's model shown in Figure 2.12 are given by:

\[ \frac{dJ_{ve}(t-t')}{d(t-t')} = \sum \frac{1}{\lambda_i} e^{-t'/\tau_i}, \quad \tau_i = \frac{\lambda_i}{E_i} \]  

(Eq. 2.19)

\[ \frac{dJ_{vp}(t-t')}{d(t-t')} = \frac{1}{\lambda_w} \]  

(Eq. 2.20)

\[ J_{ve}(0) = J_{vp}(0) = 0 \]

where \( \lambda_i \) is the viscosity of the \( i \)th Voigt visco-elastic element, \( E_i \) is the modulus of elasticity of the \( i \)th Voigt visco-elastic element and \( \lambda_w \) is the viscosity of the viscous element.

- **Viscous (visco-plastic) Stress Dependence**

The authors reflect that research has shown that at high stress levels, the steady-state (visco-plastic) strain-rate follows a power law relationship of the following form (2.21):

\[ \frac{d\varepsilon}{dt} = K \sigma^n = K \sigma^{n-1} \sigma \]  

\[ = \frac{\sigma}{\lambda_w} \]  

(Eq. 2.21)

where \( K \) and \( n \) are material constants. Results from triaxial experiments have also shown that, in addition overall stress level, the steady-state strain rate also depends on the test temperature and the degree of confinement. Based on these results, a model of the following form was formulated for determining the equivalent viscosity of the viscous element as a function of the stress conditions, temperature and degree of confinement:
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

\[ \lambda_\infty = \lambda_{un}(T) \left( \frac{\sigma_y}{\sigma_0} \right)^{1-n} 10^{n(\sigma+\eta^2)} \quad (\sigma > \sigma_0) \]  
\[ = \lambda_{un}(T) 10^{n(\sigma+\eta^2)} \quad (\sigma \leq \sigma_0) \]  

(Eq. 2.22)

where \( \sigma_y \) is the Von Mises equivalent stress \( \sigma_y = \left\{ \frac{3}{2} s_{ij} s_{ij} \right\}^{1/2} \), \( s_{ij} \) is the deviatoric stress tensor \( s_{ij} = \sigma_{ij} - \frac{1}{3} \delta_{ij} \sigma \), \( \delta_{ij} \) is the Kronocker delta, \( p \) is the mean stress \( (p = 1/3 \sigma_{ii}) \), \( \eta \) is the stress ratio \( (\eta = p/\sigma_y) \), \( \lambda_{un} \) is the uniaxial viscosity measured from a uniaxial compression test (where \( \eta = -1/3 \)), \( T \) is temperature, and \( n, \sigma_0, B \), are material constants. Equation (2.22) isimplemented numerically into CAPA-3D using the values of \( \sigma_y \) and \( \eta \) calculated at the beginning of the time step (i.e. at time \( t \)).

This formula was used in the initial visco-elastic runs, with permanent damage, to determine the suitability and stability of the model.

The damage determination, i.e. permanent deformation, evolved to:

\[ \Delta D = \left( 1 - 10^{-\lambda_{un} (1 - T_0)} \right) - \left( (1 - T_0) \right) - \left( \mu + 1 \right) \left( \frac{10\sigma + \Delta \sigma}{c} \right) \Delta t \]  

(Eq. 2.23)

where \( c, B, \mu, \sigma_0 \) and \( \lambda_{un} \) are independent constants for a specific material.

2.7.2.3 Modelling Visco-Elastic Behaviour of Modified Bitumen Binders

- **Burgers Model for Modelling Visco-Elastic Behaviour with Dynamic Shear Rheometer Input Parameters**

A Burgers model is a combination of Maxwell and Kelvin models in as indicated in Figure 2.13(a). Under a constant stress,

\[ \varepsilon = \frac{\sigma}{E_0} \left( 1 + \frac{1}{T_0} \right) + \sum_{i=1}^{n} \frac{\sigma_i}{E_i} \left[ 1 - \exp \left( -\frac{1}{T_i} \right) \right] \]  

(Eq. 2.24)
The total strain is composed of three parts: an instantaneous elastic strain, viscous strain, and a retarded elastic strain, as shown in Figure 2.13 (a). Quantitatively, a Burgers model represents the behaviour of a visco-elastic material. A single Kelvin model is usually not sufficient to cover the whole period of time over which the retarded strain takes place and a number of Kelvin models may be needed.

Under a constant stress, the strain can be written as:

$$\varepsilon = \frac{\sigma}{E_0} \left( 1 + \frac{1}{T_0} \right) + \sum_{i=1}^{n} \frac{\sigma}{E_i} \left[ 1 - \exp \left( -\frac{t}{T_i} \right) \right] \quad \text{(Eq. 2.25)}$$

In which \( n \) is the number of Kelvin models (see Figure 2.13 (a)). This model explains the effect of duration on pavement responses. Under a single load application, the instantaneous and retarded elastic strains predominate. However, under large number of load repetitions the accommodation of viscous strains is the cause of large permanent deformation.

![Figure 2.14 (a): Application of Burgers Model](image)

Hagos (2002) determined the complex modulus \( G^* \) and phase angle \( \gamma \) for the various bitumen modified binders (SBS, EVA modified and 70/100 per grade bitumen) using the Dynamic Shear Rheometer.

From literature he proposed the determination of the visco-elastic parameters required from the Burgers model (see Figure 2.14 (b)).
Figure 2.14 (b): Burger’s Model as applied to Determination of Modified Bitumen Binders Model Properties

Using the differential equation that describes the static and dynamic behaviour of the Burgers Model:

\[
\frac{d^2 \varepsilon}{dt^2} + \frac{E_2}{\eta_2} \frac{d \varepsilon}{dt} = \left[ \frac{E_1}{\eta_1 \eta_2} \right] \sigma_0
\] (Eq. 2.26)

The static linear visco-elastic creep is described by the boundary value conditions below:

\[
\begin{cases}
  \varepsilon(0) = \frac{\sigma_0}{E_1} \\
  \sigma(0) = \sigma_0 \left( \frac{1}{\eta_1} + \frac{1}{\eta_2} \right)
\end{cases}
\]

The resulting relationship for the linear visco-elastic model is given by equation:

\[
\varepsilon(t) = \frac{\sigma_0}{E_1} \ln \left( 1 + \frac{\sigma_0 \eta_2}{E_2} \right) + \frac{\sigma_0}{E_2} \left( 1 - e^{-t/\lambda} \right) \quad ; \quad \lambda = \frac{\eta_2}{E_2}
\] (Eq. 2.27)

From which, it follows that:

\[
\dot{\varepsilon}(t) = \frac{\sigma_0}{\eta_1} + \frac{\sigma_0}{\eta_2} e^{-t/\lambda}
\] (Eq. 2.28)

And at large value of \( t \), i.e. as \( t \to \infty \):
\[ \dot{\varepsilon}(t) \rightarrow \varepsilon_m = \frac{\sigma}{\eta_1} \quad \text{(Eq. 2.29)} \]

where:  
- \( \varepsilon(t) \) = strain as a function of time  
- \( \dot{\varepsilon}(t) \) = shear strain rate as a function of time  
- \( \sigma \) = applied stress  
- \( \lambda \) = relaxation time  
- \( E_1, E_2, \eta_1, \eta_2 \) = parameters in the Burgers model

The creep curve shown in Figure 2.15 illustrates the link between the creep and relaxation and the parameters of the Burgers model. The immediate response to loading is reflected by the elastic property of the material \( E_1 \), followed by visco-elastic response as a function of time. The tangent line to the visco-elastic response depends on the dash-pot parameters \( \eta_1 \) and \( \eta_2 \). Large values of \( \eta_1 \) and \( \eta_2 \) imply that the strain will be small, indicating resistance to flow or delay to viscous condition. During relaxation, the visco-elastic response depends on \( \eta_2 \) and \( E_2 \). Hence, the effect of delayed elasticity is expressed by the increase of \( \eta_2 \) and decrease of \( E_2 \).

\[ \text{Slope } \dot{\varepsilon}(t) = \sigma \left( \frac{1}{\eta_1} + \frac{1}{\eta_2} \right) \]

\[ \varepsilon = \sigma / E_1 \]  
\[ \varepsilon = \sigma / E_2 \]

Figure 2.15: Representation of the Creep and Relaxation Response of a Visco-elastic Material as a Result of an Applied Stress (Load) at \( t = 0 \) to \( t = t_1 \)

The dynamic linear visco-elastic behaviour is described by the equation below:
Elastic components are determined by:

\[
E' = \frac{\Xi \eta \omega^2 - \left( \frac{\eta_1 \eta_2}{\eta_2} \right) \left( 1 - \frac{\eta_1 \eta_2}{\eta_2} \right) \omega^2}{\Xi^2 \omega^2 + \left( 1 - \frac{\eta_1 \eta_2}{\eta_2} \right)^2 \omega^2}
\]  
\text{(Eq. 2.30)}

Viscous components are determined by:

\[
E'' = \frac{\Xi \omega^3 \left( \frac{\eta_1 \eta_2}{\eta_2} + \eta_1 \omega \left( 1 - \frac{\eta_1 \eta_2}{\eta_2} \right) \omega^2 \right)}{\Xi^2 \omega^2 + \left( 1 - \frac{\eta_1 \eta_2}{\eta_2} \right)^2 \omega^2}
\]  
\text{(Eq. 2.31)}

where:

\[
\Xi = \frac{\eta_1}{E_1} + \frac{\eta_2}{E_2} + \frac{\eta_2}{E_2}
\]  
\text{(Eq. 2.32)}

And, phase loss by:

\[
\tan \delta = \frac{G' \left( G_1^2 + \eta_2 (\eta_1 + \eta_2) \omega^2 \right)}{\eta_1 \omega \left( G_1^2 + G_2^2 + \eta_2^2 \omega^2 \right)}
\]  
\text{(Eq. 2.33)}

applicable to binders associated with this project.

Results of the dynamic measurement on DSR such as the \(G^*, \delta, \text{ and } \omega \) (frequency) values were used in determining the parameters of the model, \(E_1, E_2 \) and \(R_1, \eta_2 \) indicated in Figure 2.13 (b) as spring and dashpot configuration.

Accordingly, the corresponding model parameters for the entire PMB samples were determined using the equations (above) to fit the measured data with the predicted values by the model. The outcome of the trial and error determination by Hagos of the parameters is presented in Table 2.4.
Table 2.4: Burgers Model Parameters from $G^*$, $\omega$ and $\delta$ (Hagos, 2002)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Polymer Content</th>
<th>$E_1$ (Pa)</th>
<th>$E_2$ (Pa)</th>
<th>$\eta_1$ (Pa)</th>
<th>$\eta_2$ (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70/100</td>
<td>0 %</td>
<td>2.00E+08</td>
<td>1.50E+06</td>
<td>3.00E+05</td>
<td>3.00E+04</td>
</tr>
<tr>
<td>EVA</td>
<td>3 %</td>
<td>2.00E+08</td>
<td>1.50E+06</td>
<td>4.00E+05</td>
<td>2.50E+04</td>
</tr>
<tr>
<td>Linear SBS</td>
<td>3 %</td>
<td>8.00E+08</td>
<td>8.00E+05</td>
<td>7.00E+05</td>
<td>3.50E+04</td>
</tr>
<tr>
<td>Radial SBS</td>
<td>3 %</td>
<td>4.00E+08</td>
<td>4.00E+06</td>
<td>5.00E+05</td>
<td>2.00E+04</td>
</tr>
</tbody>
</table>

The parameters of the model were determined by fitting the points predicted by the Burger's model to match the observed complex modulus master curve measurements. However Hagos (2002), indicates that the model is not actually simulating the storage and loss components of the complex modulus. Therefore, although changes in the parameters can be observed that demonstrate the delayed effect in elasticity of the modified samples from the results, the model is not perfectly suitable to fully illustrate the effect of visco-elastic behaviour. These were however used in an initial assessment of the different binder types to ascertain whether the prototype numerical model of seal performance was able to distinguish between the different binder types.

2.8 CONCLUDING REMARKS

The subject literature review has focussed on establishing the basis of factors that affect the performance of road surfacing seals, from the component constituents, to external influences and design aspects. Background and supporting information is provided in Appendix A. It is evident that the bitumen binder is a major factor in determining seal performance, and that the performance characteristics of the base bitumen can be modified to satisfy certain in service performance criteria.

Aggregate, although relatively less affected by loading and environment than bitumen, also contributes to the performance of the seal, as does the base surface the seal is applied to in terms of embedment under construction and load.

Current seal design is volumetric based and performance assessment primarily empirical. There has been research into the environmental and traffic loading effects on the performance of the seal, and this will be extrapolated further when determining the basis
of the numerical model, and in assessing the performance test (APT) tools for examination of the different seal types.

The literature review has also examined the different seal types, and the most commonly available bitumen modifiers, which will be used in the research process. These binders are: bitumen binder modified with, in turn, SBS (3 % by mass), SBR (3 % by mass), EVA (3 % by mass) and bitumen rubber (20 % by mass). The base and control binder will be the most commonly applied penetration (road) grade binder, 80/100 pen. In addition, the theory related to numerical modelling of the material parameters was presented for utilization in the numerical modelling phase.

The seal that will be examined is a single seal (13,2 mm), to allow examination of the main seal components, and to allow performance assessment of aggregate and binder interaction free of interlock effects of a double or Cape seal.

The influencing factors on the seal, with related numerical modelling aspects, as discussed in this chapter, will be prioritized in Chapter 3. Indication from literature and trends arising from the study enabled seal performance parameters to be developed. These will be used as the basis for initiating performance tools and numerical modelling.
REFERENCES


Committee of State Road Authorities, 1985 reprinted in 1989 (Draft 1996), Technical recommendations for Highways 4 Structural Design of Interurban and Rural Road Pavements, Department of Transport (RSA) for CSRA.

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


Lewis AJN, Rossman DR, 1999, a *Review of the Performance of Modified Binders used in Surface Treatments in Natal*, CAPSA.

*Lubrication and Oil Analysis Determining* (www.oilanalysis.com/dictionary).


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

3. **SEAL PERFORMANCE PARAMETERS FOR EXAMINATION**

Within the blacktop industry in South Africa, the current seal design guide TRH3 (CSRA, 1998) is continually being critically examined. In broader context, an example of the continued quest for refinement of design and pavement performance prediction is the Strategic Highway Research Project undertaken under the auspices of the Transportation Research Board in the United States. Under this study, between 1988 and 1993 intensive research was undertaken in seven technology areas, including "Superpave" (TRB, 2004). The Superpave programme included the preparation of the foundation of predictive performance models usage for hot asphalt mixes. In the area of surfacing seal design, there are currently only empirical seal design methods available using experience for the assumption of in-service seal performance. TRH3 (CSRA, 1998) provides only a table in its Appendix B giving life expectancy for the different seal and binder types. The stated aim of this project (see section 1.2) is to "contribute to the development of a performance related seal design method for bitumen and modified seal binders". To this end, under this chapter the existing theory and practice is collated, and analysed, with the objective of identifying seal performance parameters for prioritisation for the research phase. This analysis has two purposes: enabling focus on the seal design criteria, and identifying performance parameters for research through experimental performance testing and numerical modelling. The influencing factors included in literature (and the applicable theory and practice) have been identified, analysed and developed in this chapter, also to enable comparative assessment and verification of the numerical model and performance testing.

3.1 **PERFORMANCE CRITERIA AND INFLUENCING FACTORS**

3.1.1 Performance Criteria

To enable the influencing factors to be evaluated in terms of performance, performance criteria are required. Robertson et al (c.1990) defined performance criteria for surfacing as a whole as avoidance of certain failure criteria, these being:

- Permanent deformation/displacement/embedment (loss of surface texture, this project includes punching, rotation of stone to reduce voids)
- Early rutting
- Fatigue cracking
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

- Low temperature cracking
- Moisture damage
- Adhesion failure

The performance criteria applicable to seals were expanded (under this project) to:

- Permanent deformation/displacement/embedment

  This should include loss of surface texture due to punching/embedment, rotation of stone in binders with higher viscosity to least dimension thereby reducing voids, flow of binder laterally under load and flushing/bleeding.

- Fatigue cracking
- Low temperature cracking and brittleness
- Moisture damage
- Adhesion failure

Loss of aggregate (stripping) under dynamic load. This should include low temperature loss of aggregate.

The above authors further simplified their definition of failure situation to:

- Bitumen that is too soft and have relatively high viscous (loss) modulus compared with elastic modulus (expected permanent deformation under load)

- Bitumen that is too brittle and stiff, expected to crack under a variety of loads (traffic, thermal, etc.)

- Bitumen that is affected by moisture

They further maintain that while ageing is often described as a factor contributing to failure of the binder, it is an inevitable conditioning step in the serviceable lifetime of the bitumen. Ageing should however be taken into account in predicting the performance of the bitumen. The rolling thin film oven procedure can be used to predict this occurrence.

From the analysis of seals in practice, it is postulated that the life of a seal is dependant on the performance of the base regarding:
- Permanent deformation/embedment: punching (associated with bleeding and rutting)

- Moisture damage to the base

and dependant on the fundamental seal material components for:

- Permanent seal deformation: rotation of seal stone (reducing voids associated with bleeding)

- Embedment into the base (due to viscosity of seal allowing this under load)

- Fatigue cracking (cohesive failure of the binder, i.e. the binder cracks as the chemical structure is inadequate for the imposed loads (Whiteoak, 1991). Repeated loads inducing tensile stresses above the tensile strength of the bitumen lead to crack propagation and failure).

- Low temperature/brittle cracking (when the bitumen is cold or stiff through ageing, and brittle, the binder stiffness constrains deformation, and brittle failure under load results if yield stress is reached (Whiteoak, 1991).

- Adhesion failure (stripping), where the adhesive strength of the aggregate-bitumen bond is exceeded under imposed load, usually in cold or wet, i.e. extreme, conditions, or due to ageing of the binder).

3.1.2 Influencing Factors

The identification of influencing factors from theory and practice for inclusion in the numerical behaviour and experimental performance models of seal performance was an interactive process. Theory was examined to initiate the respective models, and in the development of the models the need for confirmation, determination or explanation of parameters arose which in turn required further investigation into literature.

Marais (1979) classified the factors that affect seal performance, and TRH3 (CSRA, 1998) provides a summary of the factors influencing a road seal, as discussed under Chapter 2. Utilising the above, a comprehensive determination of influencing factors on a seal was made under this section, addressing all components of the seal, through its serviceable life.

Table 3.1 has been compiled from assessment and interpretation of the literature review, as a comprehensive list of influencing factors that should be considered when modelling...
seal performance. The determinable parameters for both numerical and experimental performance models have been provided. The influencing factors have also been linked to the functional aspect of the seal. Experimental performance modelling will utilise accelerated pavement testing methods to determine seal behaviour on a scaled down level, in terms of a representative service environment. The numerical seal behaviour model will be developed using FEM methods to examine performance of the seal at micromechanic scale.

Controllable (material and design) and non-controllable (external) factors have been described by Marais (1979), and discussed in this document under 2.4.2.2. These influencing factors will thus be able to be assessed, after a sensitivity assessment, included in the models' development on a phased basis.
<table>
<thead>
<tr>
<th>INVESTIGATION FIELD</th>
<th>NUMERICAL MODEL</th>
<th>PERFORMANCE MODEL</th>
<th>FUNCTION</th>
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</thead>
<tbody>
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<td>CONTROLLABLE FACTORS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bitumen</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| • Binder type (SBS, BR, EVA, SBR, 80/100 pen) | • $G^*$ (complex modulus), $G', G^*$  
  $G' = G \cos \gamma$ (storage/elastic modulus)  
  $G^* = G \sin \gamma$ (loss/viscous modulus)  
  $\gamma = \text{phase angle}$  
  $E_n$, $\eta$: Visco-elastic rheological components  
  $\eta$: (temperature and frequency/time of load)  
  Temperature dependent  
  • Below 10 °C: brittle  
  • 10 °C – 25 °C: elastic solid  
  • 25 °C – R&B: visco-elastic solid  
  • R&B above 90 °C: (Non-Newtonian fluid)  
  • Above 135 °C: (Newtonian fluid)  
  Time dependent  
  • $S = \text{Stiffness Modulus}$  
  = tensile stress/total strain | • Temperature Susceptibility ($T_{\text{RSE}}$)  
  • Viscosity  
  • Adhesion  
  • Cohesion  
  • Ductility | • Flexibility  
  • Durability  
  • Waterproof |
| Aggregate           |                |                   |          |
| • FI  
  • Resistance to abrasion (PSV)  
  • Adhesion ($R&W$)  
  • Grading  
  • ALD  
  • Strength (ACV) | • Strength  
  • Adhesive properties  
  • Wear properties  
  • Texture | • Transfer of Load (shear and vertical forces)  
  • Durability of surface  
  • skid resistance  
  • Protect bitumen |
<table>
<thead>
<tr>
<th>INVESTIGATION FIELD</th>
<th>NUMERICAL MODEL</th>
<th>PERFORMANCE MODEL</th>
<th>FUNCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CONTROLLABLE FACTORS (cont)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Seal | - Single seal  
- Seal design:  
  - applications  
  - aggregate,  
  - binder  
  - void volume | - Seal design:  
  - type  
  - applications  
  - aggregate,  
  - binder | - Provides a structure to carry the waterproof elastic layer without damaging bitumen  
- Durable, all weather protection of pavement  
- Strength at surface to resist traffic force |

| **NON-CONTROLLABLE FACTORS** | | | |
| Traffic | - Equivalency factor  
- Actual measured contact stress  
  - Foot print  
  - Pressure  
  - Load  
  - Time and frequency of loading | - Tyre pressure  
- Load  
- Traffic volume | - Apply vehicle load to surface  
- Provide driving force |
| Environment | - $E$, $\eta$ temperature variation  
- $G^*$ and $\gamma$ (complex modulus) per 4 temperature zones | - Effect of temperature (4 temperature zones)  
- Ageing  
- Effect of moisture | |
| Pavement, substrate | - Plastic deformation  
- Support/strength CBR, E  
- Surface hardness (ball penetration) | - Density  
- strength  
- embedment | - Load distribution to sub-grade/bearing capacity |
Table 3.1 allows consideration of the influencing factors that should be considered when modelling seal behaviour, or when determining a comparative seal performance assessment.

3.1.3 Interaction of Influencing Factors for Seals

Each influencing factor influences another. As such the behaviour of a road seal on the pavement, under changing environmental conditions, under variable load, provides a complex system to study and model.

The influence of the controllable factors on the non-controllable factors is considered from literature assessment, and summarised in table 3.2
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

Table 3.2: Influence of Non-Controllable Factors on Controllable Seal Factors

<table>
<thead>
<tr>
<th>INVESTIGATION FIELD</th>
<th>NUMERICAL MODEL</th>
<th>PERFORMANCE MODEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>NON-CONTROLLABLE FACTOR</td>
<td>EFFECT ON CONTrollable FACTORS (DESIGN, CONSTRUCTION)</td>
<td></td>
</tr>
</tbody>
</table>
| Traffic Geometrics (load application) | Seal
  • Contact stress: Applied on stone contact surface
  • Change shear and vertical stresses footprint
  • Time and frequency of loading | Apply load through MMLS
  • Aggregate: Can vary stress and load
  • Observe crushing/polishing |
| Environment               | Bitumen
  • Vary $E_n$ and $\eta$, i.e. visco-elastic parameters with temperature
  • Cohesion and adhesion
  Aggregate model
  • Adhesion
  • Model effect of adjacent stones | Bitumen
  • Observe flow under load
  • Observe brittle behaviour
  • Observe behaviour under moisture
  Aggregate
  • Observe effect of adjacent stones
  • Observe if rotation under heat regime
  • Observe stone loss under cold regime
  • Observe stripping under moisture |
| Pavement                  | Aggregate
  • Embedment modelled through plastic base deformation | Aggregate
  • Observe ball pen hardness
  • Visual assessment of setting/embedment/punching
  Bitumen
  • Measure texture depth/visual assessment of flushing
  • Observe if “mat behaviour” occurs
  Seal
  • Visual assessment of performance (bitumen application rate)
  Monitor base failure
  • Visually assess seal behaviour |
The Influencing Factors in Tables 3.1 and 3.2 are examined to enable the definition of the parameters required to model the seal behaviour, identify performance criteria and enable contribution towards seal performance prediction.

3.1.4 Matrix of Influences on Seals

From the above assessment of factors that influence seals, a matrix of influences on seals was compiled to enable prioritization of the factors or influences that should be focused on, and enable a phased approach to the project.

Bitumen, as the active component of the seal, when considering the relatively inert aggregate in comparison (it is acknowledged that aggregate does have influence on adhesion, abrasion, etc.), the focus is on the binder, its characteristics under the non-controllable elements, and changes to the binder characteristics.

Research observation and expert opinion from literature (Olivier, 1999; TxDOT, 2004; Marais, 1979; CSRA, 1998) have been used in the development of the matrix. A multiplication of expert ratings of influences has been developed to enable objective assessment of the effect of multiple influences on the performance of the seal. Adding of these expert multiplied ratings will provide an accumulative assessment of effects.

For ease of reference, the influencing factors on seal performance as listed in design guides (CSRA, 1998; TxDOT, 2004) and seal assessment of design issues (Olivier, 1999) are given in Table 3.3. The rankings in this table were determined by taking the order of importance each factor was listed in each of the respective design guides, and dividing by the total number of factors, to get a weighted ranking with "1" as the worst extreme. The influence of each authority's service environments and perceptions is made evident through the comparative prioritization of the influencing factors. Local conditions thus play a major part in the influence of the various influencing factors on seal design and performance. The average ranking is thus an initiation of a mechanism of enabling assessment of the effects of multiple influences on seal performance:
Table 3.3: Expert Opinion Ratings: Influence on Seal Performance

<table>
<thead>
<tr>
<th>Factor</th>
<th>Australasia (Ollvier, 1999)</th>
<th>South African (TRH3, CSRA, 1996)</th>
<th>Texas (TxDOT, 2004)</th>
<th>Average</th>
<th>Rating to Table 3.4 (in order of Avg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design/application rates/ stone size &amp; shape</td>
<td>1/8 (0.125)</td>
<td>5/10 (0.5)</td>
<td>3/8 (0.375)</td>
<td>0.33</td>
<td>1/12 (0.08)</td>
</tr>
<tr>
<td>Traffic</td>
<td>2/8 (0.25)</td>
<td>3/10 (0.3)</td>
<td>7/8 (0.875)</td>
<td>0.475</td>
<td>5/12 (0.42)</td>
</tr>
<tr>
<td>Bitumen quality/ property /type</td>
<td>3/8 (0.375)</td>
<td>6/10 (0.6)</td>
<td>2/8 (0.25)</td>
<td>0.4</td>
<td>2/12 (0.17)</td>
</tr>
<tr>
<td>Construction</td>
<td>4/8 (0.5)</td>
<td>8/10 (0.8)</td>
<td>1/8 (0.125)</td>
<td>0.474</td>
<td>4/12 (0.33)</td>
</tr>
<tr>
<td>Timing of work</td>
<td>5/8 (0.625)</td>
<td>Incl. in specs</td>
<td>Incl. in specs</td>
<td>0.625</td>
<td>8/12 (0.67)</td>
</tr>
<tr>
<td>Climate/environment</td>
<td>6/8 (0.75)</td>
<td>10/10 (1.0)</td>
<td>8/8 (1.0)</td>
<td>0.92</td>
<td>10/12 (0.83)</td>
</tr>
<tr>
<td>Aggregate quality</td>
<td>7/8 (0.875)</td>
<td>6/10 (0.6)</td>
<td>2/8 (0.25)</td>
<td>0.575</td>
<td>7/12 (0.58)</td>
</tr>
<tr>
<td>Maintenance</td>
<td>8/8 (1.0)</td>
<td>9/10 (0.9)</td>
<td>Incl. in pavement influence</td>
<td>0.95</td>
<td>11/12 (0.92)</td>
</tr>
<tr>
<td>Drainage</td>
<td>Incl. in pavement influence</td>
<td>Incl. in pavement influence</td>
<td>Incl. in pavement influence</td>
<td>1.0</td>
<td>12/12 (1.0)</td>
</tr>
<tr>
<td>Pavement condition</td>
<td>1/10 (0.1)</td>
<td>6/8 (0.75)</td>
<td>0.425</td>
<td>3/12 (0.25)</td>
<td></td>
</tr>
<tr>
<td>Pre-treatment of base</td>
<td>7/10 (0.7)</td>
<td>Incl. in pavement influence</td>
<td>Incl. in pavement influence</td>
<td>0.7</td>
<td>9/12 (0.75)</td>
</tr>
<tr>
<td>Substrate</td>
<td>2/10 (0.2)</td>
<td>Incl. in pavement influence</td>
<td>Incl. in pavement influence</td>
<td>0.4</td>
<td>2/12 (0.17)</td>
</tr>
<tr>
<td>Geometry</td>
<td>4/10 (0.4)</td>
<td>Incl. in pavement influence</td>
<td>Incl. in pavement influence</td>
<td>0.625</td>
<td>7/12 (0.58)</td>
</tr>
<tr>
<td>Intertock</td>
<td>5/8 (0.625)</td>
<td>Incl. in pavement influence</td>
<td>Incl. in pavement influence</td>
<td>0.5</td>
<td>6/12 (0.5)</td>
</tr>
<tr>
<td>Maturing/adhesion</td>
<td>4/6 (0.5)</td>
<td>Incl. in pavement influence</td>
<td>Incl. in pavement influence</td>
<td>0.5</td>
<td>6/12 (0.5)</td>
</tr>
</tbody>
</table>

Notes:
1. Ranking: Order listed in design guide/study/ number of RANKED fields.
2. *: same fields/collective assessment.
3. The table illustrates the effect of service environments and experience in the ranking of influences on seal design and performance. The "average" ranking should thus be considered as a guide and academic tool, as this is the "average" experience crossing different service environments.

From this summary, it is evident that the experience of different authorities reflects the unique characteristics and focus of the service environments or seal design and performance assessment.

The Table 3.4 thus provides a "living matrix", that can be refined under future work, especially considering the differences in perceived or measured importance of the factors on seal performance.
The Matrix "Controllable Factors" reflect the Seal Design, Material choice, and Construction and Maintenance aspects. Construction can in effect be modelled through variation (statistically as required) in the material parameters and application rates from the design or specified values.

Non-controllable factors reflect the Environment, Geometrics, Loading and Pavement Structure and Substrate. These factors are discussed in detail in Chapter 2, and their mutual interaction is also reflected in the matrix.
### Table 3.4: Matrix of Influences on Seals (use in context of Table 3.3)

<table>
<thead>
<tr>
<th>INFLUENCES</th>
<th>NON-CONTROLLABLE FACTORS</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GEOMETRY</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TRAFFIC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ENVIRONMENT</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ROAD</td>
<td></td>
</tr>
<tr>
<td></td>
<td>REMARKS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expert</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>Ranking</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>(Table 3.3)</td>
<td>0.83</td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CONTROLLABLE FACTORS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AGGREGATE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardness (void loss and crushing)</td>
<td>0.58</td>
<td>0.10</td>
</tr>
<tr>
<td>Adhesion</td>
<td>0.6</td>
<td>0.21</td>
</tr>
<tr>
<td>Size</td>
<td>0.08</td>
<td>0.03</td>
</tr>
<tr>
<td>Shape</td>
<td>0.08</td>
<td>0.03</td>
</tr>
<tr>
<td>Application</td>
<td>0.08</td>
<td>0.03</td>
</tr>
<tr>
<td>BINDERS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>0.17</td>
<td>0.14</td>
</tr>
<tr>
<td>Penetration/grade</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modified</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td>(SBR, SBS, EVA, Bit. Rubber)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Application</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td>SEAL TYPE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Single, double, cape, slurry)</td>
<td>0.08</td>
<td>0.03</td>
</tr>
<tr>
<td>Voids</td>
<td>0.08</td>
<td>0.03</td>
</tr>
<tr>
<td>Interlock</td>
<td>0.58</td>
<td>0.24</td>
</tr>
<tr>
<td>AGE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curing</td>
<td>0.5</td>
<td>0.21</td>
</tr>
<tr>
<td>Hardening</td>
<td>0.5</td>
<td>0.21</td>
</tr>
<tr>
<td>CONSTRUCTION</td>
<td>0.33</td>
<td>0.14</td>
</tr>
<tr>
<td>MAINTENANCE</td>
<td>0.92</td>
<td>0.76</td>
</tr>
</tbody>
</table>

**NOTES:**

- Weighting: proposed greatest influence on the model behaviour.
- Greatest influence: Lowest total columns when added
- Least influence: Highest total when columns added

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T I Milne 102 7/26/2004
3.2 PERFORMANCE CRITERIA FOR EXAMINATION

In Chapter 2, the actual behaviour of binders is discussed, while actual criteria against which the performance of bitumen and seals are measured against are discussed in this section, with the identified need for further examination.

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 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 cost of construction, traffic load, environment, substrate, pavement type, and many other factors. Definition of failure can thus be in terms of performance criteria relating to the pavement (and seal) materials.

As indicated in the prelude to this chapter, there is currently no available tool to assess the above performance parameters in service for different seals, 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 assessment of these factors in terms of new experimental performance tests and in terms of the postulated need for an analytical tool (numerical behavioural model) for seal behavioural assessment.

The performance parameters requiring examination arising from the above section on performance criteria and influencing factors are:

- Deformation: rotation and punching
- Fatigue/cohesive cracking
- Brittle cracking
- Loss of adhesion (of stone to bitumen, and bitumen to base)
- Aggregate crushing/polishing

The performance criteria for each seal model type are summarised in Table 3.5:
Table 3.5: Performance Criteria for Examination

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Performance Testing Model</th>
<th>Numerical Behavioural Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deformation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Rotation</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>• Punching and flushing</td>
<td>√</td>
<td>√ (limited)</td>
</tr>
<tr>
<td>Cracking</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Brittle/cold temperature</td>
<td>√</td>
<td>*</td>
</tr>
<tr>
<td>• Fatigue/Cohesive</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Adhesion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Bitumen-base</td>
<td>√</td>
<td>*</td>
</tr>
<tr>
<td>• Stone-bitumen</td>
<td>√</td>
<td>*</td>
</tr>
<tr>
<td>Crushing/polishing</td>
<td>√</td>
<td>*</td>
</tr>
</tbody>
</table>

- Model designed to be expandable to include these factors.
- Aggregate assumed very stiff (no abrasion modelled). Crushing is a factor of aggregate strength and binder resistance to the seal stone's rotation (allowing stones contact). As such it is an integral part of seal behaviour.

The performance of the specific seals under accelerated pavement testing (experimental) phase (Chapter 4), and the behaviour of the different seals in the numerical behavioural model (Chapter 5) will be assessed in terms of the above performance criteria.

3.3 CONCLUDING REMARKS

The influencing factors and seal performance criteria that have been extrapolated under this chapter, form the basis for the design of the experimental performance test protocols and the development of the numerical model of the seal behaviour. The synthesis in Chapter 6 of the numerical model and performance tests will also be undertaken with reference to these performance criteria.
By design, accelerated pavement testing models as close as possible a service environment. As such all critical seal performance criteria will be examined. During the development of the numerical behavioural model, as this project involved the initiation of a prototype, all influencing factors could not be considered, and thus not all performance criteria be included in the assessment. The development of the numerical model focussed on the most critical seal controllable (design) factors (bitumen and aggregate), and the most influential non-controllable factors (environment: temperature, moisture and traffic). As indicated, Table 3.4 reflects the performance criteria focussed on in these studies. The design of the performance test protocols including influencing factors and the parameters the seal is measured against are summarised in Figure 3.1.

<table>
<thead>
<tr>
<th>Seal Influencing Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Controllable</strong></td>
</tr>
<tr>
<td>• Binder</td>
</tr>
<tr>
<td>• Aggregate</td>
</tr>
<tr>
<td>• Seal (design &amp; construction)</td>
</tr>
<tr>
<td><strong>Non-Controllable</strong></td>
</tr>
<tr>
<td>• Environment (temperatures and moisture)</td>
</tr>
<tr>
<td>• Traffic</td>
</tr>
<tr>
<td>• Pavement</td>
</tr>
</tbody>
</table>

**Figure 3.1: Seal Performance Testing and Assessment**

The controllable influencing factors with highest rating on expert opinion (design/application rates and bitumen quality) will be examined under the performance testing and modelling. The non-
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

controllable factor with highest rating (pavement condition) is also considered. As environment influences the bitumen characteristics, and the design code assumptions regarding specifically the modified binder's behaviour, is also considered a crucial aspect for assessment under this project.
REFERENCES


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

Oliver J, 1999, The Performance of Sprayed Seals, ARR 326, ARRB.


TxDot, 2004, Seal Coat and Surface Treatment Manual, Texas DoT.

4. DEVELOPMENT OF NEW PERFORMANCE TEST METHODS

The objective of this component of the project is to improve the confidence between design prediction and performance of seals, through comparative performance assessment of the different seals and seal binders. An Empirical Test Method was developed to enable accelerated performance testing of the seals. This chapter describes the evolution of the methodology, the actual test process and the results of the empirical performance testing.

4.1 MATERIALS AND PAVEMENT TESTING

In practice, the testing carried out at seal pre-design stage is aimed at the selection of the most appropriate seal, and at gaining as much information on the seal components and pavement to which the seal is to be applied to determine the required application rates of the seal components.

Design investigation and construction quality control tests are suggested by literature (TRH3, CSRA, 1998) for the pavement on which the seal is to be constructed, and on the seal component materials to be utilised in the construction process. The applicable tests applied on this project’s materials and pavements are discussed below.

4.1.1 Tests on the Pavement

4.1.1.1 Ball Penetration

Ball penetration is used to predict the possible embedment of the aggregate into the pavement base under traffic. TMH6 (CSRA, 1984), Test ST4 is the test procedure. This value is required in the design process to determine the reduction in binder application due to expected embedment of the seal stone under construction and traffic. A ball penetration of in excess of 3 mm usually indicates that embedment can be expected, and adjustment in binder application is recommended (TRH3, CSRA, 1998). The development of this test method is provided by Marais (1979). In this project the ball penetration value was used in the assessment of the behaviour of the seals for varying base conditions

4.1.1.2 Texture Depth

Texture depth is measured in terms of the procedure ST1 in TMH6 (CSRA, 1984), where this value is used to evaluate whether pre-treatment or additional binder is required in the seal design. A texture depth of between 0.25 mm and 0.6 mm requires additional binder, while in excess of 0.6 mm, pre-treatment is required.
Roque et al (1991) report that the mean texture depth was the best method used to compare the performance of seal coats on a relative basis. Other methods were skid resistance, geotextiles (failed method) and visual assessment.

Hammoum (1999) reported on their contribution to the evolution of macro-texture measurement. Macro-texture affects the ability of the seal to evacuate water from the space between the tyre and the pavement, and affects the development of friction forces in the contact area. Micro-texture enables the tyre to break the residual film of water until a dry contact is maintained, and also contributes to the friction between tyre and pavement. Texture depth is usually used to provide an indication of the macro-texture state of the wearing course. The authors evaluated texture depth by sand patch and compared this with Tridim laser measurement on various surfaces. They found that the sand patch method did not provide a clear indication of the change in macro-texture after up to 5000 wheel passes, and that the TRIDEM LASER (Fractal method) was able to do so, although continued work was required to increase the accuracy of this method. The sand patch method provides a volumetric average depth, rather than a measured mean distance from a datum, which the laser provides, and from which a texture depth can be mathematically determined.

Jooste et al (1999) compared the friction and texture measurements in practice in South Africa. They report that the methods used to measure skid resistance vary considerably. In 1995 an experiment conducted in Spain and Belgium (the PIARC experiment) compared the measurements obtained from various devices evaluating skid resistance and surface texture. It was found that substantial differences existed between uncalibrated instruments. The authors investigated 11 test sections, for both friction and texture. The surface texture was determined by Mini Texture Meter (MTM) and the sand patch method. The macro-texture definition of surface amplitudes between 0.5 mm and 50 mm in height was emphasized (micro texture being the deviation in surface texture with peak to peak amplitude of less than 0.5 mm). Currently, in South Africa, the sand patch method is used to measure macro texture, expressed as average i.e. Mean texture depth (MTD) (measured by calculation of the average of the distance to bottom of surface voids and top of aggregate particles). The TRRL Mini Texture Meter is also used, which operates through electrical and optical devices attached to a trolley. The unit results are expressed in are Sensor Measured Texture Depth (SMTD). Good correlation was obtained between SMTD and MTD when comparing measurements on eleven road surfaces. The authors note that the sand particles of the sand patch test penetrate voids or cavities not seen by the SMTD laser eye, and it is for this reason the sand patch reports a slightly higher MTD than the MTM for surfaces with open structures.
In this project the Texture depth and its measurement was considered as an avenue where additional development and research is required, in terms of seal performance measurement (refer to the Texture Indication Meter). As the seals were constructed in the laboratory, texture of the base was not a construction issue.

4.1.1.3 Visual Assessment

The assessment of pavement visual appearance (TMH9, 1992) provides information regarding the most suitable seal, or re-seal based primarily on pavement management data on a network level. Experience is required to provide insight on the type of seal, especially with regard to the identification of uniform sections, and to provide confirmation of the design process on a project basis.

Current practice provides no definitive visual assessment or electronic road surveillance data to the detail required at project level to assess the comparative performance of road seals. As such, under the descriptions of the Performance Test Methods, a supplementary assessment system will be further developed, as a tool for further refinement by practitioners.

4.1.2 Tests on the Seal Materials

4.1.2.1 Seal Aggregate

The tests as traditionally recommended for testing of suitability of aggregate for seal application, and as applied to this project for design purposes are:

- Gradation: grading (sieve analysis, fines content and dust content (TMH1, 1986, Test TMH1/B4)
- Hardness: (Test TMH1/B1 or B2) Aggregate Crushing Value and 10 % FACT or Polished stone value
- Flakiness Index
- Average least dimension

4.1.2.2 Seal Binder

The following tests are required on the seal binder:

- Penetration
- Softening point
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

- On modified binders: ball penetration

Emery et al (1999) report that traditional binder tests are poor predictive tools for field performance. They use as example Rogue et al (1992) findings that SBS modified binders that had poor ductility values at 25 °C was in that case in contradiction to field performance, and that none of the normal tests could be used to predict the performance of, in their case, SBS modified binders. The emphasis was for performance based testing.

Approaches to performance related testing, for example relating to SBS modified binders, were summarised by the above authors. They reported Srivastave et al (1992) approach at relating deformation energy (product of force and displacement during tensile testing). Boudin and Collins (1992) described the overall resistance of bitumen to deformation in terms of the complex modulus:

$$G^* = (G''^2 + G'^2)^{1/2}$$  \hspace{1cm} (Eq. 4.1)

where

- $G^*$ is the complex modulus describing the overall resistance to deformation
- $G'$ is the storage modulus (portion of deformation energy that is stored elastically)
- $G''$ is the loss modulus (portion of deformation energy dissipated as viscous flow)

Experience has shown that for modified binders (SBS in particular) $G^*$ remained constant through a large temperature range.

4.1.3 Performance Testing

Pavement performance testing has been a tool which the Pavement Engineer has used to ascertain both failure mechanisms and expected pavement serviceable lifespan through determination of performance and fatigue relationships. Accelerated pavement testing is able to provide both economic (in terms of time and expenditure on resources) and timeous solutions to the Pavement Engineers design related questions. These “trafficking tests” are used to improve the understanding of pavement behaviour. The ultimate goal of this understanding is to improve the efficiency of design and provision of road infrastructure (including its cost effectiveness (Hugo, 1997)). Due to the expense of Full Scale APT, scaled down APT was developed as a tool to examine the testing and prioritising of influencing variables prior to conducting full scale tests, but was also shown to be a performance test in itself. Scaled down pavement testing is a development that further addresses the economic factors associated with accelerated testing.
This section examines the choice of performance testing apparatus and scaling questions applicable to the road surfacing seal.

The types of performance test regimes available to the researcher are summarised below, with indication of those applicable to this project:

![Diagram]

**Figure 4.1: Types of Pavement and Surfacing Accelerated Performance Test Regimes**

In terms of full pavement or surfacing serviceable lifespan, the performance tests carried out on the seal and test bed (MMLS APT) were aimed at an averaged expected lifetime (i.e. the fresh seal susceptible to a single event failure seal as stripping under front wheel load in cold regimes and the brittle, aged (i.e. end of lifespan) regimes are not modelled).
The objective of the project is to undertake and assess comparative seal performance, with the object of developing a new test method to assess service regimes (i.e. the expected performance of the seal). Modelling of single catastrophic events, such as fresh seals and cold weather or fast traffic, or brittle old seals where adhesive capacity of the brittleness is being lost, are postulated to form part of the possible extended "supplementary" test regime (i.e. extremes) at not the performance test regime.

4.1.3.1 Use of the Scaled Down Model Mobile Load Simulator

The feasibility of using scaled down APT was established (Hugo, 1997, pg B251) for quantitative comparison of performance prediction of pavements, within the laws of the theory of similitude.

The University of Stellenbosch has developed a series of Scaled Down Accelerated Pavement Testing devices. At time of commencement of this project, the Model Mobile Load Simulator MM3 (MMLS) was developed and available for testing.

Literature (Van de Ven et al, 1997, and Seong Min et al, 1998) has shown that the Model Mobile Load Simulator is an economically and technically viable testing apparatus for assessing pavement and surfacing performance.

The use of the Model Mobile Load Simulator was thus decided upon four major reasons:

- The focus of the project is on the surfacing seal, and the tyre contact patch. This will be able to be effectively tested using contact pressure of the tyre, thus having a scale factor of 1:1 tyre stress application at the surface. This substantiates the decision to utilise the MMLS for scientific and economic reasons. In the hierarchy of performance tests, full scale APT tests simulate as close as possible reality. Scaled down tests are an economically viable test alternative to prioritise the test variables, and to simulate a scaled down reflection of reality. In the case of seals, where the contact patch of tyre on seal stone is to be examined, the contact stress has similitude and this reflects a model of reality. For this project, scaled down APT is thus utilised for examination as a new tool for comparative seal performance assessment.

- Accelerated testing could be carried out in a controlled laboratory and field environment, due to its mobility and simple operational requirements.

- The use of a scaled down pavement and accelerated Pavement testing device made testing within limited funding possible.
The MMLS has a successful research application record.

4.1.3.2 Dimensional Analysis applied to this Project

Dimensional Analysis is used to determine dimensionally correct equations among the research variables being investigated, calibrated or verified through a scale modelling process. It is also used to determine the scale factors required to which the pavement components have to be constructed to, in this case with the scale of the MMLS being a given. The need for scaling, or not, and the variables affected by the scaling was examined using the dimensional analysis tool.

Model studies are usually undertaken to study the performance of a scaled down version of the prototype for economic reasons, or to aid in obtaining information that will assist in design of the prototype. For this project, the prototype can be considered the full scale version of a pavement and its seal, and the model testing as a means of obtaining data to assist in the design (or verification thereof) of pavement seals. The model must adequately represent the prototype in order for the results to be correctly interpreted.

- Stresses and Strains

In stress analysis, two dimensions are involved: force and length, although under the mass system of dimensional analysis, this amounts to three: mass, length and time through the relationship: \( [F] = \{MLT^{-2}\} \). If two geometrically similar structures have similar loading (i.e. same constant ratio), then they are said to have the same type of loading.

In elastic theory, large loads are those considered to result in a non-linear load-deflection relationship. Membrane action introduces a nonlinear load-deflection relationship, which may occur in the seal component of a pavement, but not necessarily in the layer works component. Dimensional analysis for large deflections requires no special consideration (Langhaar, 1951). The stress equation will be a function of:

\[ \sigma = f(F,M,L,E,v) \]  where E is Young's Modulus, and v is Poisson's Ratio

Loading beyond the yield point causes permanent deformation. There is thus no unique relationship between stress and strain in the in-elastic range. In modelling, two materials are said to have the same type of stress-strain relationship if their dimensionless stress-strain curves are identical. This is determined by E and v. In so far as dimensional analysis is concerned, when materials of the same type of
stress-strain relationship are used, i.e. the same materials are used, the distinction between elastic and plastic materials is eliminated. The following law is then valid:

If the linear dimensions of a structure are changed by a factor \( k \), the applied forces are changed by \( k^2 \), the deflections by \( k \), and the stresses are unchanged (Langhaar, 1951).

- **Pavement**

Kim *et al* (1997) indicate that when material properties in the prototype and scaled are similar, engineering is produced to scale, and materials are linear elastic similitude will be maintained as long as the scale factors are used. The length scale factor is \( 1:N \), materials properties \( 1:1 \), pressure on surface \( 1:1 \), time rate of loading \( 1:N \), load \( 1:N^2 \). However, the authors found that even if sub-grade characteristics were not identical – prototype and model, the surface stresses and strains were similar, as long as the material characteristics had similitude. This is the case in this project.

For this reason a base and sub-base of two 100 mm layers (i.e. 200 mm thick pavement) was used and as the interest is in the performance of the seal, and in the immediate contact zone of the base, no scaling of the pavement was determined necessary.

- **Seal**

From the stress – strain law highlighted above, it is evident for stresses to remain unchanged in a scaled down model, and application of an axle load onto a seal must be determined by the tyre pressure, not applied axle load. In effect, all that varies will be the contract area between tyre and road surface. Due to the seal being a non-structural part of the pavement, and load transferred to the individual stones, with layer of bitumen applied, edge effects were postulated as minimal, no scale factor was used in the construction of the seal, i.e. the 1:3 scaled model was able to apply seal contact pressure, and real load of up to 2.7 kN.

The performance testing of the SEAL, and the immediate context with the bitumen binder and top ± 50 mm of base, on un-scaled model seal was particulated to provide comparable and competitive seal performance indication.

As the performance of the seal was required to be evaluated and not full base or sub-base layer depth, the model mobile load simulator with un-scaled contact
stress, and with un-scaled seal was considered as being the ideal tool for empirical performance testing, as a 1:1 model of the prototype of only seal comparative performance was to be modelled.

Should displacements be required to be modelled, and scaled up, the scale factor on the load would have to be considered. However, the dimensions of the seal and base are unchanged, i.e. \( k = 1 \). Should displacements wish to be extrapolated to full scale, the effect of the smaller wheel load would have been considered, and using measured stress in the pavement. Contact stress, however, is not scaled, and it is postulated that seal displacement would be similar.

4.1.3.3 MMLS

(a) Specifications

The Model Mobile Load Simulator (MMLS) utilised for this project was developed by the Institute for Transport Technology, University of Stellenbosch. The MMLS mark 1 was a 1:10 SCALE MODEL, while the newer Mk 3, a 1:3 scale model was available for use on this project, being completed during 1998. The MMLS Mk 3 (MMLS3), this model, was designed to perform tests in the laboratory and tests on full scale pavements in the field, and due to its larger scale, was decided to be utilised on this project (Figure 4.2 (a) and 4.2 (b)).

The MMLS3 is capable of trafficking at a rate of 7 200 real axle loads per hour. The machine has four bogies, linked together to form an endless chain moving around a set of looped rails mounted in a vertical plane on a fixed frame. Each bogie contains an axle with suspension springs and a single rubber tyre. The bogies are loaded by the fixed frame, at constant load, while the tyres are in contact with the pavement. The loading complies with a 1:10 scaled wheel load of an 80 kN axle, with a 300 mm diameter tyre. Maximum inflation pressure is 600 kPa at the maximum wheel load of 2700 N, enabling the simulation of E80 tyres. Tyre footprint area is 34 cm² with nominal speed 3 m/s.

Detail regarding the further development of the MMLS3 as an empirical road seal testing apparatus is discussed below.
Figure 4.2 (a): MMLS3 Schematic View (from Technical Brochure)

Figure 4.2 (b): MMLS3 in Operation

(b) Load Application

The load application was determined using required constant stress. The 600 kPa contact stress of the MMLS3 was considered an acceptable representation of a heavy vehicle (E80 inflation pressure is usually between 600 to 700 kPa, while an "elv" contact stress is 200 kPa to 250 kPa. The wheel load of 2,1 kN, was used as a representation of one of the dual axle wheels on an E80 (the maximum load application of the MMLS3 is 2,7 kPa). The 1/3 scale factor in terms of size provides a contact patch of 1/3 x 1/3 area of an E80 tyre. Using this factor, this equates
approximately to a 1:9 scale factor of area and load while application stress has similitude.

(c) Development of the MMLS3

At initiation of the project, the MMLS3 was used primarily for laboratory and field tests on asphalt and block paving in the vicinity of an experienced workshop.

The test trial sections and use of the MMLS3 on abrasive seals, away from the available workshop resources highlighted the complicated maintenance requirements of the MMLS3. As such various modifications were implemented as part of the evolution of the MMLS3 to an acceptable research and in-service performance determining tool.

The major areas requiring attention were:

- Punctures and the time taken/work required to remove the wheel bogies to repair punctures;
- Difficulty in replacing the drive belts due to their not being easily accessible;
- Reliance on external power supply (generator);
- No driven wheels;
- Difficulty in loading and transporting the MMLS3;
- No weather protection.

Developments on the MMLS3 to make it more suitable to the project, and to improve it for field service on other projects in terms of performance testing were:

- Different source of tyres, to improve serviceable lifespan and reduce punctures;
- Drive belts were relocated outside the MMLS3 frame, on extended drive shafts. This enabled easier assessment of belt condition, faster replacement time, and easier maintenance;
- Future models of the MMLS3 may have an integral power supply (generator) included;
- Future models may have driven wheels and adjustable wheel angle from direction of travel;
• A possible consideration to reduce weight and ease loading and transport in
the replacement of solid ballast by water tanks. This will enable decreased
deaf weight for travel, and enable easier maneuvrability in the field;

• Waterproof wheel bearings were included in the upgrade during the course of
the project.

These developments have enhanced the efficiency of the MMLS3 for use in practice
and in future research projects. Climate chambers and heating/cooling facilities
were also developed by the manufacturer, in parallel to this project.

4.1.4 Development of Texture Indication Meter

The development of a performance related seal design method for road surfacing seals
includes the development of the empirical model.

From the test trials using trial seal manufacture methods, and the performance testing
apparatus (the MMLS3), it became evident that measurement of surface texture (and if
possible the actual seal store orientation and changes to both of the above parameters
under load) was necessary, to enable comparison of different seal type behaviour and
performance. To this end the Texture Indication Meter (TI Meter) evolved. However
development was concurrent to the performance tests, and further work is required to
develop the prototype and collate the laser readings to Mean Texture Depth.

4.1.4.1 Surface Texture as a Measure of Performance

The South African seal design code, TRH3 (CSRA, 1998) utilizes desired surface texture
as the definitive design parameter. The design charts for seal design utilize texture depth
categories for the determination or selection of binder application.

Minimum texture depth for skid resistance, as discussed above, is 0.7 mm (TRH3, CSRA,
1998).

Texture depth is also an indication of void content in the seal. As void content will be a
determination of the performance of the seal, this parameter is a major means of
measuring performance in road seals (TRH3, CSRA, 1998). The measure of rotation or
punching of the seal stones would also be of great value in describing the behaviour of the
specific seal under traffic load and specific environmental conditions.

Of note is the difference between texture and roughness, as a measure of performance.
Seal design is aimed at achieving a minimum texture depth, or macro-texture, required for
skid resistance. Roughness, as an input to network level pavement management, is a measure of pavement unevenness or "condition index" (i.e. terms of "roughness counts"), for example measured in the NRM method as accumulated vertical movement between the vehicles unspung mass (vehicles differential for example) and the sprung mass (the body) (Hunt and Bunker, 2003).

4.1.4.2 Proposed Method of Measuring Texture

To enable utilisation of current algorithms and surveillance data, the current electronic road surface surveillance methods in South Africa were examined.

The laser for enabling measuring as reflected depth was sourced from practice (Specialised Road Technologies (Pty) Ltd, South Africa). The operating range of the laser was 200 – 300 mm height. Software development was contracted out, and in 1999 the prototype Texture Indication Meter (TI Meter) was manufactured. The operation consists of:

- Rented laser device
- Stand and datum bar
- Software (processing the laser readings to determine height from datum bar)
- Power pack
- Linear position control
- Laptop computer

The prototype had a hand operated mechanism (i.e. laser in bracket pulled or pushed) along the datum bar. Later a chain and gear mechanism and upgraded bracket were manufactured at the Workshop of Africon Engineering Materials Laboratory, to enable smoother and controlled operation.

The use of a laser or other electronic texture device to measure texture was proposed, as the projects seal patches are too small for conventional sand patch texture assessment. However to date the TI Meter (Figure 4.3) is still in development. The project indicated the need for a more refined method of measuring texture depth, both in terms of actually measuring depth as opposed to a volumetric averaged depth (as in the sand patch), but also in terms of a portable, repeatable test method which will give results not only for seal design, but also in terms of texture for skid resistance.
Figure 4.3: Texture Indication Meter

4.1.4.3 Proposed use of the TI Meter

The TI Meter has the following envisaged uses:

- Determination of SMTD and conversion to Mean Texture Depth;
- Enable analysis of either rotation, punching, i.e. variation of seal texture depth under traffic;
- Enable skid resistance to be determined cheaply with a repeatable, portable device;
- Assistance in determining road surfacing texture for Pavement Management Systems;
- Enable objective (measured) comparison and assessment for seal performance.
- Measuring rutting.

Further proposed development is:

- Mechanisation of the laser movement along the datum bar;
- Development of the road texture software to enable convenient plotting of the cross section and texture;
- Development of algorithms for conversion of TI Meter measured texture (i.e. SMDD) to Mean Texture Depth (MTD) from the sand patch method.
While this device was not developed sufficiently for utilisation on this research project, further commercial development will be considered.

4.2 EXPERIMENTAL PERFORMANCE TESTING

Performance testing is utilised in this project for the comparative assessment of the various seal types.

4.2.1 Performance Testing: Objectives

Following from the needs and performance criteria postulated in Chapter 3, experimental performance tests were designed and implemented with the following objectives:

- Determination and verification of the new performance test method as a research tool, not only for this project, but for field and laboratory testing in practice.

- Examination of the relationships between the factors that influence seals.

- Examination of the "mat" behaviour in terms of vertical displacement (i.e. embedment) (CSRA, 1998, TRH3) of modified binders (that limits penetration of aggregate into the base under traffic). Of special emphasis will be the behaviour of the binder film at high service temperatures (beyond softening point).

- The influence on seal design and performance (due to base softness using the ball penetration as guide).

- The rotation of aggregate to average least dimension (i.e. reduction in voids due to rotation of stones to least dimension, without embedment in to the base) (or possibly not, when higher viscosity modified binders are used), especially the behaviour at high service temperatures.

4.2.2 Apparatus

4.2.2.1 Test Bed and Pavement

The choice and construction of a suitable test bed evolved from the initial laboratory test bed, to an external test bed (with use of climate box), and full scale field sections.
• Laboratory test bed

A test bed was constructed in a laboratory at the University of Stellenbosch to enable the desired accelerated testing to take place within a controlled environment. A variable width frame (300 mm to 900 mm width), 2000 mm long was constructed, with piping below the floor. Water at variable temperatures is able to be circulated through the pipes (and later a test bath), thereby enabling variation of pavement and surface temperature through radiation of heat without the application of direct heat. A pavement of up to 200 mm thick (of any required material) is able to be constructed within the frame, using a purpose made vibrating steel drum roller. The prefabricated seal tiles were then able to be applied for testing. This method was revised due to the pavement only able to be used for a single test, due to the destructive test regime.

• External test bed

A frame 3.0 m by 3.0 m, 200 mm high was constructed in the Civil Engineering Courtyard, University of Stellenbosch. A 200 mm crushed stone, G5 sub-base quality layer was constructed within the frame, and primed. Seal patches were placed on this revised test bed, and a series of 33 tests were carried out.

Pavement thickness of 200 mm (exceeding the material depth of influence of the 2,1 to 2,7 kN wheel load: for a 1/10 scaled tyre load, the 200 mm model depth is more than adequate for a 1/10 scaled 1,2 m maximum required depth for a high class pavement). G5 quality base was constructed on a concrete slab floor, of size 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 levels.

4.2.2.2 Accelerated Pavement Tester

The Model Mobile Load Simulator Mk3 (Figure 4.2 (a) and (b)), (originally used as a ¼ to \( \frac{1}{2} \) scaled down accelerated pavement tester) is being used in this project. The MMLS3 has a treaded pneumatic tyre footprint of up to 34 cm\(^2\), and is able to place up to 7200 wheel loads per hour. Both load and tyre pressure can be varied to enable the examination of the traffic related influencing factors. The MMLS3 can be used in the laboratory and the field was refurbished during the course of the project to enable easier
field maintenance and wet weather operation. In the research described in this paper, the seal was not scaled down. It was considered that the MMLS3 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.

4.2.2.3 Seal Components

Seals were constructed using the different binder types, namely 80/100 penetration grade bitumen, bitumen modified with EVA, SBS, SBR and bitumen rubber.

13.2 mm aggregate single seal was used, as this is a typical common seal type as used in practice.

4.2.3 Methodology

4.2.3.1 Development of a New Test Method for Seals

A method for the accelerated testing of road surfacing seals was developed to enable the serviceability and performance of seals to be evaluated and compared 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 in this project to reflect the TRH3 (CSRA, 1997) influences on seal behaviour). There are three components to the test method.

- The method of constructing seals in the laboratory (on small scale).
- The test bed with pavement.
- The accelerated pavement tester.

Field testing also took place, with seals being applied in full-scale construction on existing pavements, and the MMLS3 being used in accelerated testing.

4.2.3.2 Seal Construction Method

For the test bed series, 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. Three options were examined:

- Applying the binder by pouring the desired volume onto a silicon lined tray mould, and adding the aggregate. When cold the binder was then removed from the
mould, and applied to the pavement. It was, however, found that with low binder applications (especially with 80/100 pen grade bitumen), that the bitumen film lost its integrity. Also the seal tended to distort when the binder adhered to the steel tray, and a measure of force had to be used to extract the seal.

- Direct application to the pavement. Due to the rapid cooling, and related increase in binder viscosity, uniform application was not possible when pouring the binder onto the pavement in this manner.

- The method of placing silicon paper into the tray mould, preheating the tray, and decanting the heated binder onto the paper was the method that provided the best result. After adding aggregate, tamping, and cooling to below 10 °C, the seal could be peeled off the paper without distortion and applied directly to the pavement. In this manner seals for both laboratory and field tests were able to be prepared. This is the method that was used for the manufacture of seals for test bed testing on this project. Of special note is that the preparation trays with silicon paper were preheated to 180 °C. The binder was heated in an over to specified application temperature, decanted into the tray placed on a scale, to enable control of application by mass. The tray was agitated to ensure the binder was distributed uniformly, and aggregate applied to desired application (in this project’s case, shoulder to shoulder) (reflected in Figure 4.4). The seal tiles were placed into refrigeration and stored for later use.

![Figure 4.4: Test Tiles Being Prepared](image-url)
4.2.3.3 Test Method

The three components: seal, test bed and accelerated pavement tester, were combined to enable the testing of different seals (with variation of binder type and application, aggregate application rates and base composition). The MMLS3 was utilised to apply a traffic load, and the test bed and climate box used to simulate different environmental conditions (especially road surface temperature). Traffic load was applied, and varied on the full scale pavement, to examine the performance of the various seals and pavements, and thereby contributing to the comparative assessment of seal performance in practice. The empirical testing was part of this project to be aimed at contributing towards a performance related seal design method through examining the relationships between the various influencing factors. The test process is reflected in the Figures 4.5 (a) to (c) and 4.6 below.

Figure 4.5 (a): Test Mosaic: Test Trials

Figure 4.5 (b): 80/100 Pen Patch before Load
TOWARDS A PERFORMANCE RELATED SEAL DESIGN METHOD FOR
BITUMEN AND MODIFIED ROAD SEAL BINDERS

by

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December 2004
Figure 4.5 (c): 80/100 Pen after Loading

Figure 4.6: MMLS3 Footprint on Seal Tiles

4.2.4 Scope: Performance Testing

The scope of work included in the Empirical component and Performance Testing is discussed in detail under this section.
4.2.4.1 Test Variables

The test variables of the empirical test programme were compiled after examination of literature, and in particular the current design methodology used in South Africa as reflected in the TRH3 (CSRA, 1998).

From Chapter 3, the influencing areas on the seal behaviour and identification of test variables were collated. From the matrix of influences on seals, determination of the scope of work for the empirical testing is enabled from the tabulation of the controllable factors against the non-controllable factors. In this manner each of the respective controllable factors was examined against the non-controllable factors, to enable relationships with each other to be determined.

The controllable factors included in the test variables include aspects of:

- Aggregate
- Binder (including application and type)
- Age at loading

Non-controllable factors include:

- Traffic
- Environment
- Existing road surface and pavement type and condition

Due to the large amount of testing required to examine all the factors, it was decided to concentrate on those factors where the current seal design practice (as summarised in TRH3 (CSRA, 1998) required additional research.

The decision of which of the matrix of variables to include in the experimental tests is explained as follows:

- Binder Type and Application

This was identified through the assessment process in Chapter 3 as having greatest proposed influence on seal behaviour. Literature provides sufficient justification expanded in Chapter 2, that this aspect of seal design factor is the major test variable.
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

- Environment

  Temperature greatly affects the characteristics of bitumen. As such the test regime includes temperature as a major variable.

  Moisture was included in the further development of empirical seal performance testing.

- Road Surface

  The assessment of the influence of road surface was identified in Chapter 3 as a critical parameter, due to road surface providing the support for the seal stone, and in effect the transfer of applied load through the seal stone to the pavement.

- Age of Seal

  Age of seal was considered during supplementary performance tests, age affecting binder characteristics.

The above variables provide for the assessment of the critical seal design components, and for comparative seal performance assessment, as well as the validation of the empirical test method.

4.2.4.2 Scope of Empirical Testing

  Testing was scheduled as:

  - Binder

    The external test bed was used for tests on the binders, due to the need to accommodate sufficient basic data for analysis. All identified binder types were tested, with different applications, based of the TRH3 (CSRA, 1998) design code.

    Field testing also contributed to this examination.

    The following binder types were tested:

    - 80/100 penetration grade bitumen
    - 3% modified by mass (80/100 per grade bitumen as base)
      - EVA
- SBR
- SBS

- 20% modified by mass (80/100 per grade bitumen as base)
  - Bitumen rubber (COLAS manufacturing method)
  - Bitumen rubber (TOSAS manufacturing method)

**Environment**

The external test bed was again utilised, with focused testing on a range of the binder type and application for the assessment of the influence of temperature on seal performance.

The temperature test ranges were decided upon as follows:

- Road temperatures:
  - 10 °C (border of brittle range of bitumen behaviour)
  - Ambient (25 – 35 °C) (visco-elastic range) and to enable assessment of typical conditions in practice
  - 50 °C (viscous range)

Moisture was the focus of supplementary performance testing.

**Road Surface**

The field test comparisons with external test bed, and reporting of surface hardness enabled assessment of this variable.
Diagrammatically, the test programme evolved as follows (Figure 4.7):

**TEST REGIME**

**TRIALS**
- Methodology finalised

**FIELD TESTS: EAST LONDON**
- Dry weather control: Completed 1999
- Selected Binders (3 types)
- High traffic repetitions

**EXTERNAL TEST BED**
- Tests: all binders (6 types) all application rates
- All 6 binder types, two application rates, 3 repetitions on each
- Ambient temperature
- Completed December 2000

**EXTERNAL TEST BED**
- All binder types, one application rate (BR repeat), 3 repetitions
- 50°C : Climate box
- Completed December 2001

**EXTERNAL TEST BED**
- All binder types, one application one repetition
- Below 10°C: Climate box
- Completed August 2002

**LABORATORY (SUPPLEMENTARY PERFORMANCE)**
- 3 binder types
- Different ageing
- Completed May 2003

**VARIABLE EXAMINED**
- Binder type
- Base hardness
- Binder application
- Base hardness
- Environment (temperature)
- Binder type
- Environment (temperature)
- Binder type
- Aggregate
- Moisture
- Ageing

**APT**
- MMLS
- MMLS
- MMLS
- MMLS
- Wheel Tracker

*Figure 4.7: Performance Test Programme*
4.2.4.3 Applied Traffic Loading

The number of load applications determined for the comparative performance tests were as follows:

TRH3 (CSRA, 1998) indicates that single seals can accommodate 750 to 2000 elv/lane/day, increasing to up to 2000 – 5000 elv/lane/day with the use of modified binders. Life expectancy of seals is provided from in TRH3. 13.2 mm single seal on a new base (a single seal used in this project to ensure the assessment of individual variables, avoiding the interlock of a second layer of aggregate) is:

- 6 years at in excess of 10 000 elv/lane/day: 21,9 million elv’s, or 547 000 E80’s
- 9 years at 2000 – 10 000 elv/lane/day: 6,5 to 32,8 million elv’s or 164 000 to 821 000 E80’s
- 12 years at 2000 elv/lane/day: 8,8 million elv’s or 219 000 E80’s at 40 elv’s per E80 axle load

The use of bitumen modifiers is expected to increase life expectancy as follows:

- 8-10 years at in excess of 10 000 elv/lane/day: up to 36,5 million elv’s or 912 000 E80’s
- 10–13 years at 2000 – 10 000 elv/lane/day: from 7,3 million elv’s or 182 500 E80’s
- 14–16 years at 2000 elv/lane/day: from 10,22 million E80’s or 255 500 E80’s at 40 elv’s per E80 axle load

The above indicated life expectancies range from 6,5 million elv’s to 32,8 million elv’s (164 000 to 821 000 E80’s) to for straight bitumen binders and 7,3 million to 36,5 million elv’s (182 000 to 912 000 E80’s) for modified binders.

However on a fatigued base or of lower quality (e.g. G5 sub-base quality), reseal lifespan is expected to be reduced from the above expectancies on new pavements to 50% of design life (a five year lifespan for "re-seal" being a realistic expectation) to enable comparison of performance of the seal types and application rates. Initial load applied was 200 000 wheel loads at 2,1 kN with tyre pressure of 600 kPa to simulate a heavy (E80) contact stress. Lateral Wander was not used, and channelised traffic facilitated concentration of the applied load (rutting is not a performance criteria in seal behaviour), equating to 1,5 to 3 times normally distributed traffic. Seal performance was evaluated in
terms of number of axles and applied surface stress. This amounts to 50 000 to 82 000 E80’s minimum to 200 000 to 450 000 E80’s.

The number of applied loads was thus determined as:

200,000 repetitions of load of single wheels 600 kPa and 2.1 kN per wheel were applied (with no "lateral wander"). This equating to an equivalent five year traffic load, using an equivalency factor of 40 elv’s per E80 and a conservative factor of 3 increase due to the effect of lateral wander in practice.

4.2.5 Performance Test Results

4.2.5.1 Test Trials: Method Ratification

The test trials undertaken in December 1998 to examine the feasibility of the empirical test method and ratify the test methodology, although of little scientific value due to the limited environmental control and test duration. The test trials illustrated the feasibility of the test method.

(a) Seals Tested

Four binders were tested: 80/100 penetration grade bitumen and modified binders (3% addition by mass per binder type: SBR, SBS and EVA).

For feasibility test purposes, two different application rates were used.

Due to the higher expected ball penetration on the trial pavement surface (existing asphalt), the TRH3 (CSRA, 1998) applications were low. It was therefore decided to utilise a higher "typical" application for trial purposes as the seal tile preparation was also to be tested.

Binder application rates were 0.76 and 1.3t/m² for the 80/100 penetration grade bitumen, and 1.25 and 1.5t/m² for the modified binders. Aggregate was applied at a rate to ensure shoulder to shoulder distribution.

(b) Traffic Load

Traffic load of single wheels at 600 kPa and 2.1 kN per axle was applied, with 50,000 applications applied (with no "lateral wander").
(c) Pavement

The seal tests were applied to an existing asphalted pavement, in the parking area adjacent to the Civil Engineering Laboratory, University of Stellenbosch.

(d) Climate

On average, the road temperature varied between 20 - 30 °C throughout the two days of testing, although it dropped to 16 °C due to rainfall. Testing was done throughout the day and night, but no undue low temperatures were experienced that resulted in extension seal stone loss or brittle failure.

(e) Lessons Learned: Trial Results

The following results were of value to this project:

- All seal applications performed satisfactorily. No undue stripping of aggregate under the MMLS3 wheel loads occurred, confirming that the method of seal tile application was feasible.

- The 80/100 penetration grade seals stripped slightly (these had the lowest binder application). Under the limited traffic load, and supported by a strong base, no punching or bleeding of any of the seals was evident. The SBS modified binders had the best appearance, in terms of limiting seal loss, and aggregate settling on a shoulder to shoulder orientation, rotating slightly (although probably not to ALD).

- There was sufficient difference in behaviour, between the seal types, and observed behaviour under the applied traffic load under the environmental conditions to enable confirmation of the validity of the test method as a research tool.

- The MMLS3 was ratified as an acceptable accelerated seal performance tester.

4.2.5.2 Field Testing

The field testing occurred chronologically between the trial tests and the external test bed.

(a) Motivation for Field Testing

The initial objective was to test a range of seals on an existing pavement, to:
• obviate the need to construct a test bed;
• to enable a full range of seals to be tested under conventional construction techniques (i.e. full scale seal construction);
• to test economically, as the test bed was in situ.

(b) Location

Full scale beds were constructed on Trunk Road 45, Settlers Way, East London, during October 1999.

East London was decided upon as:
• place of residence of author;
• weather is consistently moderate i.e. no cold extremes;
• willing Contractor and municipality, enabling the test sections to be constructed.

(c) Seal Designs

The Table 4.1 reflects the TRH3 seal design. Of note is that two seal stone applications were made, one an open texture allowing seal stone to move, and the other a tight, shoulder to shoulder texture, as used with the seal tile construction.

(d) Seal Tests

The 80/100 pen grade bitumen and SBR modified binders were tested.

All seals accommodated the 200 000 axles without distress and the test 1, SBR modified seal, had 1 million axles placed on it, without distress.

(e) Results

The following results are of value to this project:
• The MMLS3 accelerated pavement tester is of value when considering seal behaviour.
• This is evidence that seal lifetime under good climatic conditions, is greatly dependent on the base and pavement construction and behaviour.
- The abrasion suffered by the MMLS3 wheels and mechanics resulted in part to the MMLS3 being modified as discussed previously.

- To enable the full range seal performance criteria to be assessed, a base that will allow penetration and stone embedment or settlement (i.e. to test postulated "MAT behaviour", etc.) is required, rather than testing on a G1 quality, strong base.
Table 4.1: Field Test Section: Seal Design

SETTLERS WAY: EAST LONDON

Date Sealed: 8 October 1999

<table>
<thead>
<tr>
<th>SECTION</th>
<th>CHAINAGE</th>
<th>TACK COAT</th>
<th>DESIGN</th>
<th>TEST SECTION</th>
<th>FOG SPRAY</th>
<th>AGGREGATE</th>
<th>TEMPERATURE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>APPLICATION</td>
<td>L/S/QM</td>
<td>DESIGN CURVE</td>
<td>Cat 30% Cat 60%</td>
<td>APPLICATION</td>
<td>AMBIENT (AIR)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cat 30% Cat 60%</td>
<td></td>
<td>°C</td>
</tr>
<tr>
<td>1</td>
<td>0-75</td>
<td>1.3 Cat 70,3% SBR</td>
<td>1.33</td>
<td>Minimum</td>
<td>1.0</td>
<td>100</td>
<td>25.2</td>
</tr>
<tr>
<td>2</td>
<td>75-150</td>
<td>1.3 Cat 70 3% SBR</td>
<td>1.33</td>
<td>Minimum</td>
<td>1.0</td>
<td>100-</td>
<td>25.2</td>
</tr>
<tr>
<td>3</td>
<td>150-225</td>
<td>1.7 Cat 70 3% SBR</td>
<td>1.733</td>
<td>0.7 texture</td>
<td>1.0</td>
<td>100</td>
<td>25.3</td>
</tr>
<tr>
<td>4</td>
<td>225-300</td>
<td>1.7 Cat 70 3% SBR</td>
<td>1.733</td>
<td>0.7 texture</td>
<td>1.0</td>
<td>100-</td>
<td>25.3</td>
</tr>
<tr>
<td>4A</td>
<td>300-375</td>
<td>2.0 Cat 70 3% SBR</td>
<td>2.0</td>
<td></td>
<td>1.0</td>
<td>100</td>
<td>24.6</td>
</tr>
<tr>
<td>4B</td>
<td>375-450</td>
<td>2.0 Cat 70 3% SBR</td>
<td>2.0</td>
<td></td>
<td>1.0</td>
<td>100-</td>
<td>24.6</td>
</tr>
<tr>
<td>5</td>
<td>450-525</td>
<td>1.16 B-100 pen Cat 65%</td>
<td>1.2</td>
<td>Minimum</td>
<td>1.0</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>525-600</td>
<td>1.16 B-100 pen Cat 65%</td>
<td>1.2</td>
<td>Minimum</td>
<td>1.0</td>
<td>100-</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>600-675</td>
<td>1.36 B-100 pen Cat 65%</td>
<td>1.33</td>
<td>0.7 mm texture</td>
<td>1.0</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>675-750</td>
<td>1.36 B-100 pen Cat 65%</td>
<td>1.33</td>
<td>0.7 mm texture</td>
<td>1.0</td>
<td>100-</td>
<td></td>
</tr>
</tbody>
</table>
4.2.5.3 Performance Testing: External Test Bed Series

From 1998 to 2002 a test regime using five different seal binders, and three temperature regimes, was implemented for performance based empirical comparative testing using the MMLS3. A method of evaluating seal performance was developed to enable assessment of the seals’ behaviour.

The test results of the external test bed series are presented, which provides a comparative performance of the different binders under similar imposed loads and environment. Insight is provided for the identification of critical seal performance influences and criteria, which will be included in the verification of the numerical seal performance prediction model.

(a) Seals Tested

The Comparative Performance Test Method is summarised below for the test series.

Single seals with five binder types (with variation of the rubber bitumen manufacture process, making a series of six binders) were tested:

- 80/100 penetration grade bitumen
- 3 by mass % modified bitumen:
  - SBS
  - SBR
  - EVA
- 20 % by mass modified bitumen rubber
  - Colas; and
  - TOSAS manufacturing methods

For comparison purposes, two different application rates were used, based on TRH3 (1997) design parameters.
Seal details are shown in Table 4.2:

**Table 4.2: Test Bed Seal**

<table>
<thead>
<tr>
<th>Binder Type</th>
<th>Modifier</th>
<th>Net Binder Application</th>
<th>Higher Application</th>
<th>Base Bitumen</th>
<th>Aggregate Size (Hormela ACV 10,6 %)</th>
<th>Penetration (dmm) (needle at 25°C)</th>
<th>R&amp;B Softening Point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3% SBS (Radial) (COLAS)</td>
<td>Pellets</td>
<td>1.2 l/m²</td>
<td>1.5 l/m²</td>
<td>80/100 pen</td>
<td>SAPREF (Durban)</td>
<td>13,2mm</td>
<td>80</td>
</tr>
<tr>
<td>3% SBR (COLAS)</td>
<td>Latex</td>
<td>1.2 l/m²</td>
<td>1.5 l/m²</td>
<td>80/100 pen</td>
<td>SAPREF (Durban)</td>
<td>13,2mm</td>
<td>85</td>
</tr>
<tr>
<td>3% EVA (COLAS)</td>
<td>Pellets</td>
<td>1.2 l/m²</td>
<td>1.5 l/m²</td>
<td>80/100 pen</td>
<td>SAPREF (Durban)</td>
<td>13,2mm</td>
<td>63</td>
</tr>
<tr>
<td>80/100 pen (COLAS)</td>
<td></td>
<td>0.9 l/m²</td>
<td>1.1 l/m²</td>
<td>80/100 pen</td>
<td>SAPREF (Durban)</td>
<td>13,2mm</td>
<td>90</td>
</tr>
<tr>
<td>20% Bitumen Rubber (COLAS)</td>
<td>Crumbs</td>
<td>2.0 l/m²</td>
<td>2.4 l/m²</td>
<td>80/100 pen</td>
<td>SAPREF (Durban)</td>
<td>13,2mm</td>
<td>-</td>
</tr>
<tr>
<td>20% Bitumen rubber (TOSAS)</td>
<td>Crumbs</td>
<td>2.0 l/m²</td>
<td>2.4 l/m²</td>
<td>80/100 pen</td>
<td>NATREF (Sediburg)</td>
<td>13,2mm</td>
<td>44</td>
</tr>
</tbody>
</table>

The modified binders were manufactured in the quality control laboratories of COLAS (Epping) and TOSAS (Wadeville) as indicated in the table above. Specifically the compatibility of the SBS modifier is continually examined, bitumen by bitumen, by COLAS. The laboratory test reports are provided in Annexure C to this chapter.

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

(b) Test Bed

The test bed was constructed with sub-base (GS) quality natural gravel, to 200 mm thick. This layer was placed within a steel test frame, on top of a concrete slab. The bed was compacted with hand operated compaction tools until a smooth surface was "slushed" (stone moisture surface). Surface hardness was measured as the performance control (ball penetration).

(c) Traffic Load

Traffic load was applied by the MMLS3: single wheels at 600kPa and 2,1kN per axle, with 200,000 applications applied (with no "lateral wander"). The application stress equates to an equivalent 5-year traffic load, using an equivalency factor of 40
elv's (equivalent light vehicle) per E80 (80KN axle load) and a conservative factor of 3 increases due to the effect of lateral wander in practice.

(d) Temperature Regimes

- Ambient Temperature

On average, the road temperature varied between 20 - 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 release the seal temperature to 10 % for full test duration.

(e) Development of Performance Evaluation Model

In practice, currently the pavement assessment methodology (CSRA, 1992, TMH9 for granular pavements) is determined for describing the condition and performance of the pavement and is NOT detailed regarding the seal. In terms of assessment for Road Management Systems, there is no detailed guide for the assessment of seal surfacing performance. As current philosophy assumes that the seal does not contribute to the structural capacity of the pavement, assessments are generally focussed on criteria that will affect the base, e.g. cracking. Thus, to enable assessment of seal performance, a system for evaluation of the seal was developed.

Seal texture measurements are based on texture depth, using the sand patch. This measurement would provide an indication of the general performance in terms of texture depth. However, the sand patch test regimes utilised the specification of a certain quantity of sand spread over one area that would exceed the size of the seal patches. The wheel track is the critical area for assessment, a small area compared with conventional sand patch methodology. This method alone would in any event not provide sufficient information regarding assessment of distress types.
As indicated in TMH9 (CSRA, 1992), current pavement condition is assessed using different visual ratings. This philosophy was established for the seal assessment in conformance with practice.

TMH 9 (CSRA, 1992) indicates that road engineers use visual assessments as a tool to assess the condition of a pavement, based on functional descriptions, recording the pavements distress characteristics. The "attributes" of distress are described in terms of type, degree and extent. For this project, the seal performance will thus be described in terms of the distress (or "performance criteria"), with a "performance rating" combining degree and extent (due to the small scale of the APT patches test these attributes were combined). In TMH 9, a five point scale is used. This was initially evaluated, but with a seal, conventionally when 5 % area has failed, a reseal is required. The 5 % area refers to the whole road area, but effectively the failure will occur only in the trafficked way. In order to distinguish between good and bad, and taking cognisance of the limited distress inflicted on a seal (its life is being determined also by the pavement base strength), a more focussed "3 point" scale was used. On the "3 point scale", the "0" rating reflects no distress, "1" initiation of distress, "3 severe" as indicated in Table 4.3, and "2" a visual distinction between these ranges.

As with any visual assessment in practice, where the visual assessors are trained, and "calibration" sections evaluated, each of the seals tested on the test bed for the comparative tests remained on the test bed, and were able to be compared with each other. Table 4.3 has been developed to describe the ratings per performance criteria, based on the principles of TMH 9.

The seal performance was measured in terms of the method being developed in terms of assessment parameters. These parameters are:

- stone loss
- embedment
- rotation to average least dimension (ALD)
- flushing/bleeding
- base distress
- crushing
- general performance (visual)
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

For initial development of a repeatable comparison method of performance, the following rating system (ref Table 4.3) was used:

### Table 4.3: Seal Performance Parameters: Ratings

<table>
<thead>
<tr>
<th>Performance Criteria</th>
<th>Performance Parameter (Rating)</th>
<th>Performance Rating</th>
<th>Poorest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adhesion</td>
<td>stone loss ($R_{sl}$)</td>
<td>0: none</td>
<td>3: stripping (5% of trafficked area or more)</td>
</tr>
<tr>
<td>Deformation</td>
<td>embedment ($R_{e}$)</td>
<td>0: none</td>
<td>3: flush (embedded to zero texture depth)</td>
</tr>
<tr>
<td></td>
<td>rotation ($R_{r}$)</td>
<td>0: as laid</td>
<td>3: ALD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>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.</td>
<td></td>
</tr>
<tr>
<td>flushing/bleeding ($R_{fb}$)</td>
<td>0: none</td>
<td>3: bleeding – severe</td>
<td></td>
</tr>
<tr>
<td>Aggregate</td>
<td>crushing ($R_{c}$)</td>
<td>0: none</td>
<td>3: severe</td>
</tr>
<tr>
<td></td>
<td>polishing</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td>general performance</td>
<td>(includes cracking) ($R_{a}$)</td>
<td>0: good visual appearance</td>
<td>3: poor</td>
</tr>
<tr>
<td>(visual assessment)</td>
<td></td>
<td>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)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>base distress*</td>
<td>0: none</td>
<td>3: failure</td>
</tr>
<tr>
<td>* record only</td>
<td></td>
<td>Note: when distressed base occurred the overall rating was reduced to &quot;credit&quot; 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</td>
<td></td>
</tr>
<tr>
<td>** note taken only, not visible on these tests</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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:

\[
\text{Performance Index} = \left[ \frac{(R_{sl} + R_{e} + R_{r} + R_{fb} + R_{c} + R_{a}) \times 100}{18} \right] \quad (\text{Eq. 4.2})
\]

Where:

\[
R = \text{Performance Rating (0-3)}
\]

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

SL = Stone Loss
E = Embedment
R = Rotation to ALD
F/B = Flushing or bleeding
C = Crushing
A = Appearance

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

The determination of the performance indeces for each test is provided in Annexure A to this Chapter. 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.

(f) Performance Testing Evaluation

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

Analysis of the performance tests in terms of performance index is provided in terms of performance plots in the figures of series 4.8.

On the performance index scale of "0" best (i.e. no visible distress) and "100" extreme distress for the cumulative rating of all functional performance factors, the overall performance of the binders can be assessed. The Performance Index was plotted against two variables:

- Base hardness (measured in "mm" ball penetration)
  The design code TRH3 (CSRA, 1998) has surface hardness as a critical parameter in the design of seal binder applications.

- Temperature (Road)
  Due to the critical influence of temperature on bitumen behaviour the performance of the seal was assessed in terms of road temperature.
Figure 4.8 (a): Performance Indices: 80/100 Pen Bitumen

When considering the performance of the 80/100 penetration grade bitumen, lower binder rate showed improved performance for all surface hardness, i.e. in overall terms the binder was able to hold the aggregate in place, and the distress types associated with higher binder contents (flushing, bleeding) were averted. Performance decreased with temperature increase.

In terms of surface hardness, the harder the surface, the better the performance, for same temperature and application rates.
Figure 4.8 (b): Performance Indices: Bitumen Rubber (COLAS)

Bitumen rubber modified bitumen showed decreased performance (i.e. increased performance index) with rising temperature and higher application rates. Performance for same application rates improved with harder surface.
Figure 4.8 (c): Performance Indices: Bitumen Rubber (TOSAS)

The TOSAS bitumen rubber reflected the same trends as the COLAS bitumen rubber, i.e. better performance with harder surface, lower temperature and lower binder application rates.
Figure 4.8 (d): Performance Indices: EVA Modified Bitumen

Performance for the EVA modified binder was more sensitive in cold temperatures, but showed similar trends for application for rates and surface hardness as the pen grade binders (i.e. better performance for lower application rates and harder surfaces).
SBR modified binder showed similar trends to the EVA modified binder, in terms of better performance at higher temperatures. Higher surface hardness and lower application rates improved performance at same temperatures.
For SBS modified binders, performance improved in certain cases with decrease in temperature. Performance increased with surface hardness and reduced binder application.
The trend was as follows:

Penetration grade and the higher application rate bitumen rubber modified binders showed decreased overall performance with increasing service temperatures. The SBS, EVA and SBR modified binders showed increased performance at higher temperatures. In all cases, performance improved with higher surface hardness.

Aggregate was applied shoulder to shoulder – thus the viscous binders have higher application of aggregate than those less viscous at application temperature - due 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 related higher binder contents, as flushing was reduced, with minimal stone loss. The elevated test regime, i.e. high temperatures, allowed the modified binders to settle under traffic, and the modified binders' higher viscosities prevented excessive rotation or flow.

Specific performance characteristics are discussed in Table 4.4 below:

### Table 4.4: Description of Performance Test Results

<table>
<thead>
<tr>
<th>Influencing Factor</th>
<th>Binder and Temperature</th>
<th>Binder and Surface Hardness</th>
<th>Binder and Application Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Penetration</td>
<td>This binder performed better overall at ambient temperature than elevated or cold in most cases. 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</td>
<td>Slight affect on performance (embedment) but visible distress limited due probably to low binder content.</td>
<td>The higher application rate allowed better performance (limited stone loss).</td>
</tr>
<tr>
<td>High Penetration</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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7/26/2004
<table>
<thead>
<tr>
<th>Influencing Factor</th>
<th>Binder and Temperature</th>
<th>Binder and Surface Hardness</th>
<th>Binder and Application Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3% EVA modified bitumen</strong></td>
<td>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 temperature, more stone loss and visually unsettled, i.e. not bedded under traffic, than ambient.</td>
<td>Surface hardness had slight detrimental effect on performance under these tests, slight embedment evident.</td>
<td>The binder application rate was not a major influence on performance.</td>
</tr>
<tr>
<td><strong>3% SBR modified bitumen</strong></td>
<td>The binder performed slightly better at higher temperature, although 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</td>
<td>Surface hardness slight effect. Higher resistance to embedment.</td>
<td>-</td>
</tr>
<tr>
<td><strong>5% SBS modified bitumen</strong></td>
<td>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.</td>
<td>Binder performed better on harder surface.</td>
<td>Better performance at higher application rate, based on appearance (i.e. stone settled, surface texture visually as desired).</td>
</tr>
<tr>
<td><strong>20% rubber (GOLAD)</strong></td>
<td>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.</td>
<td>Surface hardness affected seal performance, due to embedment</td>
<td>Better performance for lower application rates (less flushing displayed)</td>
</tr>
<tr>
<td><strong>20% rubber (TORSAD)</strong></td>
<td>Better performance at ambient temperature (less flushing)</td>
<td>More embedment for softer surface, better performance on harder surface</td>
<td>Lower binder application rate performed slightly better (less flushing), better appearance</td>
</tr>
<tr>
<td><strong>Summary</strong></td>
<td>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.</td>
<td>Surface hardness a major effect on performance, especially at ambient and elevated temperature</td>
<td>For modified binders, better performance at lower binder application at elevated temperatures</td>
</tr>
</tbody>
</table>

A general assessment of "best performance" was made by comparing the range of performance indices, shown in Table 4.5.
Full details are available in Annexure A.

### Table 4.5: Summary of MMLS3 Seal Performance (MMLS3 Test Results)

<table>
<thead>
<tr>
<th>Binder</th>
<th>Overall Performance (Performance Index –Eq 4.2)</th>
<th>Test Regime</th>
<th>Performance Index (Eq 4.2) Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10 °C (Cold)</td>
<td>Ambient</td>
</tr>
<tr>
<td>Binder modified 80/100 pen grade with:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3% SBR</td>
<td>0 - 22</td>
<td>19</td>
<td>17 - 22</td>
</tr>
<tr>
<td>3% SBS</td>
<td>0 - 28</td>
<td>28</td>
<td>0 - 16</td>
</tr>
<tr>
<td>3% EVA</td>
<td>11 - 28</td>
<td>17</td>
<td>11 - 28</td>
</tr>
<tr>
<td>20% Bitumen rubber BR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- COLAS</td>
<td>11 - 56</td>
<td>17</td>
<td>11 - 33</td>
</tr>
<tr>
<td>80/100 Penetration grade</td>
<td>22 - 56</td>
<td>22</td>
<td>31</td>
</tr>
</tbody>
</table>

Each binder type has a specific regime where, for the tested base type, performance is enhanced. This is summarised in Table 4.6. The five binder types were ranked in order of performance "1", being the best, "5" the worst performing.

### Table 4.6: Binder Performance Ranking under MMLS (MMLS3 test results)

<table>
<thead>
<tr>
<th>Regime</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>20 % BR</td>
<td>3 % EVA</td>
<td>3 % SBR</td>
<td>80/100</td>
<td>3 % SBS</td>
</tr>
<tr>
<td>Ambient</td>
<td>3 % SBS</td>
<td>3 % SBR</td>
<td>3 % EVA</td>
<td>20 % BR</td>
<td>80/100</td>
</tr>
<tr>
<td>Elevated</td>
<td>3 % SBR</td>
<td>3 % EVA</td>
<td>3 % SBS</td>
<td>20 % BR</td>
<td>80/100</td>
</tr>
<tr>
<td>Overall</td>
<td>3 % SBR</td>
<td>3 % SBS</td>
<td>3 % EVA</td>
<td>20 % BR</td>
<td>80/100</td>
</tr>
</tbody>
</table>

* Binder modified 80/100 pen grade as indicated.

(g) Summary

It is evident, that the empirical test method using the MMLS3 APT apparatus is able to assess the performance of each different binder type. What is evident is the
subjective manner of assessing seals, in terms of "visual appearance", plays a
definite role in assessing seal performance.

The rich, flushed appearance of the bitumen rubber binders, when compared to a
well seated 80/100 penetration grade seal is an example of such a distinction.

Each binder type has its unique contribution to seal performance, e.g.:

- Rubber bitumen performs well in a cold regime

- The modified binders performed well under elevated temperatures, due to the
  viscosity reduction allowing the seal stone to seat, while binder application was
  not high enough to give the flushing appearance, and the high softening point.

- The role of the base is determining ultimate failure of a seal is evident, when
  examining the effect of base on failure criteria such as punching, embedment,
  bleeding and flushing.

Further work outside of the limitations of this project, and by practice, is required in
refining the visual assessment method of seal performance. The contribution of this
research to seal performance prediction will be in the verification of the prototype
model being developed.

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

4.2.5.4 Supplementary Performance Test: Wheel Tracking Device

To supplement the MMLS3 based comparative seal performance tests, a Supplementary
Performance Test was developed. As indicated in Figure 4.1, the role of the supporting
performance test is designed to examine the extremes of the service environment, in this
case severe moisture and ageing. These tests do not simulate or model results as the
MMLS3 does, but have value in comparative performance evaluation of the seals in
extremes.

Aschenbrenner (1995) examined the ability of the Hamburg Wheel Tracking device to
predict moisture damage in asphalt. The device and tests were found to be very sensitive
to quality of aggregate and asphalt stiffness. He also found that ageing increased the resistance of the sample to moisture damage including stripping. Izzo et al (1999) found, however, that the steel wheels test was not very repeatable, and the rubber coated wheels caused less comparative damage. In terms of this research project, the Hamburg Wheel Tracking device was selected for the demonstrated ability to evaluate different seals under ageing and moisture, in a controlled environment. However cognisance is taken of the test constraints.

A device based on the Hamburg wheel tracking test was used to enable comparative tests of seals with different binders under moisture. The following aspects were examined:

- Seal under moisture
- Moisture and aged binder
- Aggregate: Acidic and basic aggregate

These tests were aimed at undertaking an economical, fast test to enable assessment of the comparative performance of different seal and binder types under moist conditions.

This test, however, does not have the benefit of simulating actual wheel contact on the stones, as the MMLS3 is able to, but it is of value to practice, in terms of comparative performance.

(a) Objective

The MMLS3 Empirical Test Model was developed as a performance test method, where seal performance could be compared under conditions replicating a service environment. At the time of testing, the MMLS3 had not been upgraded to enable testing under wet trafficking conditions. In order to supplement the MMLS3 data, especially regarding moisture and ageing, a supplementary comparative performance test was developed.

(b) Apparatus

- Wheel Tracking Device

The Hamburg Wheel Tracking Device was identified, due to its ability to simulate a heavy vehicle, in wet conditions, with results available in a shorter test period.
The wheel is steel, with hard rubber coating, of diameter 204 mm, width 47 mm, applying a force of 705 N ± 22 N to the seal to be tested (Figure 4.9).

Speed is 0.305 m/s. The wheel is driven by electric motor. Literature (Colorado DoT, 1993) shows that the Hamburg test provides satisfactory indications of stripping in practice. However, Jyozo et al (1999) findings regarding repeatability should be considered before drawing absolute conclusions.

![Hamburg Wheel Tracking Device](image)

**Figure 4.9: Hamburg Wheel Tracking Device**

- **Test Bed**

  Concrete prisms were cast to fit the test apparatus, which enabled a set of three samples to be tested at one time. Concrete was chosen to eliminate base effects when testing the seal performance under water (i.e. no punching or rutting would be able to occur). Seals are conventionally constructed on granular or stabilised bases, which would be susceptible to moisture ingress. The wheel tracking test would then be examining the seal and base, and not just the extreme aspects of seal behaviour that is desired to be examined (moisture and ageing of the binder).

  The concrete prism with seal was soaked for 12 hours, prior to testing, submerged in the water bath. Test was at 40 °C.

- **Test Methodology**

  The following test regime was decided upon:
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

- **Seals**

  Single seals were constructed in similar method to that for the MMLS3, and the seal then applied to the prisms. The objective was to assess a bitumen rubber, elastomer modified binder and straight pen grade binder. The following binders were used:

  - 80/100 pen grade
  - 3% RMB (SBR)
  - 20% bitumen rubber (COLAS)

  The following variables were used (Table 4.7):

<table>
<thead>
<tr>
<th>Binder</th>
<th>Applications l/m²</th>
<th>1.1</th>
<th>1.5</th>
<th>1.1 aged RTFO</th>
</tr>
</thead>
<tbody>
<tr>
<td>80/100</td>
<td>1,1</td>
<td>1,5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3% RMB</td>
<td>1,5</td>
<td>1,5</td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>20% BR</td>
<td>2,4</td>
<td>1,5</td>
<td></td>
<td>2,4 aged RTFO</td>
</tr>
<tr>
<td></td>
<td>• Aged RMB too viscous and adhesive to extract for seal construction</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

  The applications decided were as MMLS3 for the comparative testing, then equal binder application to determine whether the binder properties and/or application rate was the critical factor in determining stripping, and the 24 hours RTFO aged binder (3% SBR modified binder to viscous and adhesive to extract from the RTFO vessels in sufficient quantities to construct the seal).

- **Moisture**

  The seals-on-prism were tested in water. One test was designed to determine the effect of moisture quantity, in terms of differentiation in pre-soaking.

  Soaking of seal-on-prism for 12 hours was standard, with one test at 8 hours soaking only, for comparison.

- **Stone Type**

  Acidic (quartzite) and basic (dolerite) aggregate was used. Both aggregate types were of good quality (ACV of the quartzite was 11% and dolerite 13%).

- **Temperature**

  40 °C was selected to add heat to the aggressive humid/soaked environment.
Performance

Performance of the seals was measured at intervals (to 5,000 repetitions) in terms of stone loss. The ranking is provided in terms of a five point scale, as used in Table 4.6, in line with the MMLS. Performance was measured at design binder applications.

(d) Results

Full results for each test run are presented in Annexure B of this section. Results are summarised in Table 4.8 in terms of stone loss.

**Table 4.8: Assessment: Moisture and Ageing under Hamburg Testing**

<table>
<thead>
<tr>
<th>Test Run</th>
<th>PERFORMANCE (performance ratings valid across the row, i.e. comparative for each specific test only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 hrs soaked @ 40 °C</td>
<td>80/100 @ 1.1 ℓ/m³</td>
</tr>
<tr>
<td>1: Best (least stone loss) - 3: Worst (most stone loss)</td>
<td>5</td>
</tr>
<tr>
<td>Remarks</td>
<td>Comparing runs 1 and 7, binder types as designed, performed in order: BR best, 3% RMB, then 80/100 worst under soaked conditions, for both stone types. Acidic stone stripped volume wise, in excess of 100% more than basic stone, under moist conditions.</td>
</tr>
<tr>
<td>Avg 3, 4, 6</td>
<td>80/100 @ 1.5 ℓ/m³</td>
</tr>
<tr>
<td>12 hrs soaked @ 40 °C</td>
<td>1</td>
</tr>
<tr>
<td>Remarks</td>
<td>Comparing avg 3, 4, 6 and 1 with high binder application and quartzite stone, 80/100 pen performed better than all binders, at same application and stone type, i.e. binder quantity has a direct influence on performance and preventing stripping especially under moist conditions, noting that stone penetration into the concrete was not possible.</td>
</tr>
<tr>
<td>Avg 2 &amp; 5</td>
<td>80/100 @ 1.5 ℓ/m³</td>
</tr>
<tr>
<td>8 hrs soaked @ 40 °C</td>
<td>5</td>
</tr>
<tr>
<td>Remarks</td>
<td>Comparing avg 2, 5 with run 1, results suspect due to weight influenced by water still being soaked up by sample (see negative loss for 3% RMB).</td>
</tr>
<tr>
<td>8</td>
<td>80/100 @ 1.1 ℓ/m³</td>
</tr>
<tr>
<td>12 hrs soaked, aged as RTFO @ 40 °C</td>
<td>3</td>
</tr>
<tr>
<td>Remarks</td>
<td>Comparing runs 7 and 8, bitumen rubber (BR) performed best after ageing, when comparing design applications and same stone types. Ageing slowed stone loss, for same binder and stone type and application.</td>
</tr>
</tbody>
</table>
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

(e) Summary

- Bitumen rubber performed the best under design (i.e. 2.4 ℓ/m²) application under all test regimes. This is expected, due to better adhesive properties.

- Basic aggregate (electropositive) strips less under moisture (this is expected).

- Ageing/hardening enable better resistance to moisture damage, due to (postulating) that the softening effect of the water has on the polar molecules is slower, as the aged binder will be harder.

- Increased binder application reduces stripping, and stripping increasing proportional to reduction in binder application rate.

- Soaking time influenced the results, and importance of saturation of samples required before testing is emphasized.

The strength of both aggregates was evident in the lack of crushing observed under the wheels. Aggregate that stripped was examined, and the individual stones were each coated in bitumen, to a greater or lesser extent.

Overall, bitumen rubber, then RMB, followed by 80/100 for design binder applications is the order of performance. Ageing enhanced resistance to stripping.

4.2.5.5 Summary: Empirical Performance Component Results

To enable contribution to the better understanding of seal performance under the various simulated operating or service conditions, the results of the performance and supplementary tests are collated under a single reporting regime. It should be noted however that the MMLS3 results are performance based, i.e. the tests were carried out under conditions modelling as close as possible to seal service environments. The wheel tracking tests on the other hand, are comparative tests, and the testing environment does not simulate actual service conditions, but is designed to enable supplementary comparative testing under extreme, and aggressive parameters (e.g. completely saturated and rigid wheel load).

A subjective assessment of the performance of seal binders is provided, with two objectives:

- Providing consolidated results for consideration by practitioners;
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

- Providing a base for verification of trends of the prototype Numerical Model.

With reference to tables 4.6 and 4.8, a summary of the results of the performance and supplementary tests is provided in Table 4.9.

Table 4.9: Summary of Consolidated MMLS3 and Hamburg Seal Performance Results

<table>
<thead>
<tr>
<th>Regime</th>
<th>Best</th>
<th>Worst</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>BR</td>
<td>EVA</td>
</tr>
<tr>
<td></td>
<td>SBR</td>
<td>80/100</td>
</tr>
<tr>
<td>Ambient</td>
<td>SBS</td>
<td>BR</td>
</tr>
<tr>
<td>Elevated</td>
<td>SBR</td>
<td>EVA</td>
</tr>
<tr>
<td>Wet</td>
<td>BR</td>
<td>•</td>
</tr>
<tr>
<td>Aged</td>
<td>BR</td>
<td>•</td>
</tr>
</tbody>
</table>

Note:

- Not included in the test series.

** Note prototype Performance Index and Rating system used to initiate this comparative evaluation requires refinement through future research. However the value of the comparative research is to enable identification of unknowns and critical aspect requiring further investigation.

When considering the performance of the seals and different binders under all test regimes (through assessment of the rating score of averaged performance on the MMLS3 tests from Annexure A), and using the results of the wet tests in Annexure B, the rankings per performance test are provided in Table 4.10. As an added check, the aggregate rankings for all criteria were compared and provide the same ranking as the overall assessment summary in Table 4.5. The average of performances through all regimes, per performance criteria, provides a further objective assessment of the performance of the various seal types by averaging all test regimes.
Table 4.10: Summary of Performance by Binder per Criteria under MMLS3 and Hamburg (at design applications, all regimes)

<table>
<thead>
<tr>
<th>Binder</th>
<th>Critical Performance Criteria******</th>
<th>Ranking (1 best, 5 worst) (BR consolidated) (based on the MMLS3 tests and prototype)</th>
<th>Performance Index – Eq 4.2, Hamburg tests and rating system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Deformation****</td>
<td>Cracking</td>
<td>Adhesion</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dry</td>
</tr>
<tr>
<td>20 S 180</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>50 S 130</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>50 S 80</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3 S 180 A</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>50/50</td>
<td>4</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>

* Aggregate polishing not evident
** Binder modified 80/100 pen grade as indicated
*** No test
**** Including flushing
****** Note prototype Performance Index and Rating system used to initiate this comparative evaluation requires refinement through future research. However the value of the comparative research is to enable identification of unknowns and critical aspects requiring further investigation.

The rubber modified and modified binders out-performed the straight binders in almost all service environments. However, bitumen rubber out-performed all binders in the extreme environment of moisture and cold regimes. At elevated temperatures lower binder design applications would limit detrimental bleeding, specifically with the high bitumen rubber design applications.

Detailed assessment results are available in the Annexure A to this chapter.

4.3 CONCLUDING REMARKS

4.3.1 Performance of Seals in Terms of Fundamental Requirements

In Chapter 2 the functions of the binder were defined as:
Provision of adhesion between binder and aggregate, provide flexibility and durability of the seal, and waterproofing the pavement.

The modification of the binder was aimed at:

Reducing temperature susceptibility, in providing cohesion and adhesion, resistance to ageing and increased flexibility and ability to recover after release of load.

The function of the seal is summarised as:

Providing a durable, skid resistant surface, protecting the pavement layers, resisting adhesive traffic forces and providing a waterproof cover to the pavement.

Under the performance tests, it was found that the various seal binders performed differently under varying environmental and pavement scenarios.

The modified binders, overall, out performed the straight penetration grade binders. When compared with the fundamental requirements, all binders provided adhesion and flexibility, the seal protected the base from the traffic load. From Tables 4.9 and 4.10, the modification process is seen to improve performance over that of the straight binder.

4.3.2 Performance of Seals in terms of Performance Criteria

The performance test results were related back to the critical performance criteria, as reflected in Table 4.10. Again, each specific seal offers unique performance under each of the criteria. The benefits of assessing seal performance in terms of critical performance criteria have been determined, providing techniques that could be extended in practice.

4.3.3 Seal Design Performance Consideration

The TRH3 seal design (CSRA, 1998) has been tested. Regarding the contribution to a performance related seal design method, 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 (i.e. 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. Tables 4.9 and
4.10 summarise the different behaviour of the binders under different service environments.

- The desired and postulated (CSRA, 1998) "mat behaviour" of modified binders should be carefully assessed. The designer should consider the changing behaviour of binder types with changing temperatures (especially where road temperature reaches softening point of the binder). Careful reconsideration of the assumed elastic "mat" behaviour of seal stone with modified binder, and the TRH3 (CSRA, 1998) postulation that seal aggregate embedment does not occur in service, after the initial construction compaction, is recommended. With high temperature (above $T_{RMB}$) these assumptions could be questionable.

- Orientation of stone, and shoulder to shoulder application to prevent rotation of seal stone to ALD was assessed. The assumption that seal stones would not fail to ALD is made in the design guide (CSRA, 1998), 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 rational if the seal stones are prevented from rotation under traffic (and the seal stones do not crush) or punching in to the base.

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

- Carefully consider the desired aggregate application rate, especially aiming at preventing seal stone in modified seals rotating once service temperatures have exceeded $T_{RMB}$. However, seal stone hardness should be high enough to prevent crushing as the stones rotate against each other.

- 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.

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


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

CSRA, 1986, TMH6, RSA DoT, Pretoria.


Langhaar HL, 1951, Dimensional Analysis and Theory of Models (University of Illinois), John Wiley & Sons.

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

Seong-Min K, Hugo F, Roesset JM, 1998, Small Scale Accelerated Pavement Testing, Accepted for Publication: Journal of Transportation Engineering: The Development and Application of the Texas Mobile Load Simulator as an Accelerated Pavement Testing Tool (Hugo F, University of Stellenbosch, 1998), ASCE.


ANNEXURE A

TO CHAPTER 4

MMLS3 SEAL PERFORMANCE TESTS
## Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

### MMLS3

**US Test Bed: Performance Tests**

**Load:** 200,000 Axles, 600kPa, 2.1kN  
**December 1999 to September 2002**

**SUMMARY: AVERAGED ALL TESTS**

<table>
<thead>
<tr>
<th>Test No</th>
<th>Description</th>
<th>Applicator (deg)</th>
<th>Penetration (mm)</th>
<th>Test Regime</th>
<th>Performance Index Determination</th>
<th>Performance Index Excl. Base</th>
<th>Performance Index Corrected for Base Distress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only 60100</td>
<td>1.1</td>
<td>3.0</td>
<td>44</td>
<td>10 deg C</td>
<td>2.0</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Ave 60100</td>
<td>0.9</td>
<td>2.87</td>
<td>44</td>
<td>50 deg C</td>
<td>2.5</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Only 60100</td>
<td>0.9</td>
<td>3.0</td>
<td>44</td>
<td>Ambient</td>
<td>2.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Ave 60100</td>
<td>0.9</td>
<td>2.87</td>
<td>44</td>
<td>Ambient</td>
<td>2.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Only 60100</td>
<td>1.1</td>
<td>3.4</td>
<td>44</td>
<td>Ambient</td>
<td>2.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Ave 60100</td>
<td>1.1</td>
<td>3.4</td>
<td>44</td>
<td>Ambient</td>
<td>2.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Ave BR</td>
<td>2.4</td>
<td>4.85</td>
<td>53</td>
<td>10 deg C</td>
<td>0.0</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Only BR</td>
<td>2.0</td>
<td>4.85</td>
<td>53</td>
<td>50 deg C</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Only BR</td>
<td>2.0</td>
<td>4.85</td>
<td>53</td>
<td>50 deg C</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Only BR</td>
<td>2.0</td>
<td>4.85</td>
<td>53</td>
<td>50 deg C</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Ave BR</td>
<td>2.0</td>
<td>4.85</td>
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<td>2.0</td>
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<td>61</td>
<td>50 deg C</td>
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<tr>
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<td>50 deg C</td>
<td>0.0</td>
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</table>

**Description**

- less stone loss at ambient, than 50 deg
- Better appearance at ambient
- some stone loss, definite signs of embedment, no punching, good visual performance
- some stone loss, not on ALD, no rotation to ALD, same orientation as 1st, but not as good adhesion
- In all cases, 50 deg binder more flushed
- In all cases, 50 deg binder more flushed no stone loss, no ALD, good performance, settled nicely, slight embedment
- embedment, no stone loss, no rotation, good performance
- no stone loss, slight embedment, no rotation, slight flushing, no base distress, good performance
- less embedment, less flushing

---

**TILline**

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7/28/2004
## Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

<table>
<thead>
<tr>
<th>Test No</th>
<th>Description</th>
<th>Binder</th>
<th>Application (kg/m^2)</th>
<th>Penetration (mm)</th>
<th>Ring &amp; Ball (mm)</th>
<th>Test Regime</th>
<th>Performance Index Determination</th>
<th>Base Distress</th>
<th>Crushing</th>
<th>Appearance</th>
<th>Performance Index excl Base</th>
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<td>Embedment</td>
<td>Relation to ALD</td>
<td>Flushing / Rich</td>
<td>Base Distress</td>
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**Indices**
- **Excellent**: 0
- **Very Good**: 1
- **Good**: 2
- **Fair**: 3
- **Poor**: 4
- **Worst**: 5

**Notes**
- 0.0 indicates no distress.
- Distress values are based on visual inspection and laboratory testing.

---

T: Mline

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7/26/2004
## MMLS3

**US Test Bed : Performance Tests**

**Load : 200 000 Axial, 600kPa, 2.1kN**

**December 1999 to September 2002**

**PERFORMANCE INDEX (by TEST)**

<table>
<thead>
<tr>
<th>Test No</th>
<th>Description Binder</th>
<th>Application /g m</th>
<th>Pertraction (Ball)</th>
<th>Ring &amp; Ball (mm)</th>
<th>Test Regime</th>
<th>Stone Loss</th>
<th>Embedment</th>
<th>Rotation to ALD</th>
<th>Flushing/Rich</th>
<th>Base Distress</th>
<th>Crushing</th>
<th>Appearance</th>
<th>Corrected for Base Distress</th>
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<td>56 (Excellent - 100 : Poorest)</td>
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<td>0</td>
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<td>56 (Excellent - 100 : Poorest)</td>
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<td>44</td>
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<td>0</td>
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<td>10 deg C</td>
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<td>0</td>
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<td>17 (Excellent - 100 : Poorest)</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>11 (Excellent - 100 : Poorest)</td>
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</tbody>
</table>

- less stone loss at ambient, than 10deg.
- Better appearance at ambient
- in all cases, 50deg test binder more flushed
- in all cases, 50deg test binder more flushed
- some stone loss - definite signs, embedment, no punching, good visual performance
- some stone loss, on ALD, low binder content, but no stripping, good performance
- stripping (<40% loss)
- some stone loss, not on ALD, no rotation to ALD, same orientation as "1", but not as good adhesion
- good rotation, no stone loss, no punching, nice bedding, good performance
- some to slight stone loss, did rotate but not nice rotation to settle, definite embedment
- heavy stone application, little or no stone loss at 10deg
- more stone loss at 10deg
- in all cases, 50deg test binder more flushed

T: Milne

668

7/26/2004
<table>
<thead>
<tr>
<th>Description</th>
<th>Performance Index Description</th>
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<tbody>
<tr>
<td>in all cases, 50deg test binder more flushed</td>
<td>Performance Index Description</td>
</tr>
<tr>
<td>no stone loss, no ALD, good performance, settled nicely, slight embedment</td>
<td>Performance Index Description</td>
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<tr>
<td>base settled - i.e. rutting, no stone loss, slight signs of initial crushing, settled + on ALD</td>
<td>Performance Index Description</td>
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<tr>
<td>embedment, binder visible, base rutted, stone loss</td>
<td>Performance Index Description</td>
</tr>
<tr>
<td>in all cases, 50deg test binder more flushed</td>
<td>Performance Index Description</td>
</tr>
<tr>
<td>in all cases, 50deg test binder more flushed</td>
<td>Performance Index Description</td>
</tr>
<tr>
<td>embedment, no stone loss, no rotation, good performance</td>
<td>Performance Index Description</td>
</tr>
<tr>
<td>rutting slightly, no punching, definite embedment, on ALD, one stone lost</td>
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</tr>
<tr>
<td>embedment, slight punching, base rutted, base settled, binder visible</td>
<td>Performance Index Description</td>
</tr>
<tr>
<td>in all cases, 50deg test binder more flushed</td>
<td>Performance Index Description</td>
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<tr>
<td>in all cases, 50deg test binder more flushed</td>
<td>Performance Index Description</td>
</tr>
<tr>
<td>base rutted, definite flushing, stone embedment, no stripping flushing not as bad as &quot;62, 85,88&quot; and look better for same base condition, base rutted, definite embedment, 1/2 of stone on ALD</td>
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<tr>
<td>slight flushing not as bad as &quot;61, 94&quot; and look better for same base condition, base rutted, definite embedment, 1/2 of stone on ALD</td>
<td>Performance Index Description</td>
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<tr>
<td>no stone loss, slight embedment, no rotation, no flushing, no base distress, best performance of three BR</td>
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</tr>
<tr>
<td>no stone loss, slight embedment, no rotation, slight flushing, no base distress, Ok performance</td>
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<table>
<thead>
<tr>
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<td>1.5</td>
<td>4.85</td>
<td>54 Amb. 0.0 2.0 0.0 0.0 1.0 0.0</td>
<td>16.7</td>
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<tr>
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<td>SBR</td>
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<td>4.85</td>
<td>54 Amb. 0.5 1.0 0.5 0.0 1.0 0.0</td>
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<tr>
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<td>16.7</td>
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<tr>
<td>Ave</td>
<td>SBS</td>
<td>1.2</td>
<td>2.87</td>
<td>46 Amb. 0.5 0.5 0.0 0.0 0.0 0.5</td>
<td>11.1</td>
</tr>
<tr>
<td>Only</td>
<td>SBS</td>
<td>1.5</td>
<td>3.4</td>
<td>46 Amb. 0.0 0.0 0.0 0.0 0.0 0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1</td>
<td>SBS</td>
<td>1.5</td>
<td>3.9</td>
<td>46 Amb. 1.0 0.0 1.0 0.0 0.0 0.0</td>
<td>16.7</td>
</tr>
<tr>
<td>2</td>
<td>SBS</td>
<td>1.5</td>
<td>3.9</td>
<td>46 Amb. 1.0 0.0 1.0 0.0 0.0 0.0</td>
<td>16.7</td>
</tr>
<tr>
<td>Ave</td>
<td>SBS</td>
<td>1.5</td>
<td>3.9</td>
<td>46 Amb. 1.0 0.0 1.0 0.0 0.0 1.0</td>
<td>16.7</td>
</tr>
</tbody>
</table>

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ANNEXURE B

TO CHAPTER 4

WHEEL TRACKING TEST RESULTS
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

**Wheel Tracking Test 1 (soaked)**

<table>
<thead>
<tr>
<th>Bitumen Type:</th>
<th>80/100</th>
<th>Colas BR</th>
<th>RMB 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application (l/m²):</td>
<td>1.1</td>
<td>2.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Stone Size (mm) &amp; Type:</td>
<td>13mm Quartz</td>
<td>13mm Quartz</td>
<td>13mm Quartz</td>
</tr>
</tbody>
</table>

Images showing wheel tracking test results for different materials and conditions.
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

Wheel Tracking Test 2 (reduced soaking)

<table>
<thead>
<tr>
<th>Bitumen Type</th>
<th>80/100</th>
<th>Colas BR</th>
<th>RMB 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application (l/m²):</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Stone Size (mm) &amp; Type:</td>
<td>13mm Quartz</td>
<td>13mm Quartz</td>
<td>13mm Quartz</td>
</tr>
</tbody>
</table>

0 80/100 BR20 RMB3 1000 80/100 BR20 RMB3 3000 80/100 BR20 RMB3 5000 80/100 BR20 RMB3
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

<table>
<thead>
<tr>
<th>Wheel Tracking Test 3 (soaked)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bitumen Type:</td>
</tr>
<tr>
<td>Application (ℓ/㎡):</td>
</tr>
<tr>
<td>Stone Size (mm) &amp; Type:</td>
</tr>
</tbody>
</table>

![Graph showing stripping loss over wheel passes](image)

![Images of test samples](image)
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

![Graph showing Wheel Tracking Test 5 (reduced soaking)]

<table>
<thead>
<tr>
<th>Bitumen Type</th>
<th>80/100</th>
<th>Colas BR</th>
<th>RMB 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application (l/m²):</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Stone Size (mm) &amp; Type:</td>
<td>13mm Quartz</td>
<td>13mm Quartz</td>
<td>13mm Quartz</td>
</tr>
</tbody>
</table>

0 80/100 BR20 RMB3
1000 80/100 BR20 RMB3
3000 80/100 BR20 RMB3
5000 80/100 BR20 RMB3

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

Wheel Tracking Test 7 (soaked)

<table>
<thead>
<tr>
<th>Bitumen Type</th>
<th>80/100</th>
<th>Colas BR</th>
<th>RMB 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application (L/m²)</td>
<td>1.1</td>
<td>1.5</td>
<td>2.4</td>
</tr>
<tr>
<td>Stone Size (mm) &amp; Type:</td>
<td>13mm Quartz</td>
<td>13mm Quartz</td>
<td>13mm Quartz</td>
</tr>
</tbody>
</table>

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ANNEXURE C

TO CHAPTER 4

BINDER TEST RESULTS
## COLAS LABORATORY TEST REPORT

**PRODUCT: 80/100 PEN BITUMEN**

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>TEST RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring and Ball Softening Point (°C)</td>
<td>44.0</td>
</tr>
<tr>
<td>Viscosity @ 60 °C (Pa.s)</td>
<td>140</td>
</tr>
<tr>
<td>Viscosity @ 135 °C (Pa.s)</td>
<td>0.31</td>
</tr>
<tr>
<td>Penetration@ 25 °C (0.1 mm)</td>
<td>89</td>
</tr>
</tbody>
</table>

**PRODUCT: RMB 3 (CLASS S-E1)**

**RESULTS:**

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Softening Point (R&amp;B) (°C)</td>
<td>64</td>
</tr>
<tr>
<td>Dynamic Viscosity @ 165 °C (Pa.s)</td>
<td>0.45</td>
</tr>
<tr>
<td>Ductility @ 15 °C (cm)</td>
<td>115</td>
</tr>
<tr>
<td>Elastic Recovery @ 15 °C (%)</td>
<td>58</td>
</tr>
<tr>
<td>Stability (R&amp;B) diff @ 160 °C</td>
<td>0.6</td>
</tr>
</tbody>
</table>

**PRODUCT: POLYMOD S (EVA)**

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>TEST RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring and Ball Softening Point (°C)</td>
<td>53</td>
</tr>
<tr>
<td>Dynamic Viscosity @ 165 °C (Pa.s)</td>
<td>0.21</td>
</tr>
<tr>
<td>Ductility @ 15 °C (cm)</td>
<td>41</td>
</tr>
<tr>
<td>Elastic Recovery @ 15 °C (%)</td>
<td>47</td>
</tr>
</tbody>
</table>
### PRODUCT: BITUMEN RUBBER (CLASS S-R1)

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>TEST RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring and Ball Softening Point (°C)</td>
<td>61,0</td>
</tr>
<tr>
<td>Dynamic Viscosity (Haake @ 190 °C) (dPa.s)</td>
<td>35</td>
</tr>
<tr>
<td>Compression Recovery: 5 minutes (%)</td>
<td>92</td>
</tr>
<tr>
<td>Compression Recovery: 1 day (%)</td>
<td>89</td>
</tr>
<tr>
<td>Compression Recovery: 4 days (%)</td>
<td>45</td>
</tr>
<tr>
<td>Resilience (%)</td>
<td>21</td>
</tr>
<tr>
<td>Flow (mm)</td>
<td>26</td>
</tr>
</tbody>
</table>

### PRODUCT: COLFLEX S (CLASS S-E2) SBS

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>TEST RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring and Ball Softening Point (°C)</td>
<td>64,0</td>
</tr>
<tr>
<td>Dynamic Viscosity @ 165 °C (Pa.s)</td>
<td>0,27</td>
</tr>
<tr>
<td>Ductility @ 15 °C (cm)</td>
<td>105</td>
</tr>
<tr>
<td>Elastic Recovery @ 15 °C (%)</td>
<td>80,0</td>
</tr>
</tbody>
</table>
5 DEVELOPMENT OF A PROTOTYPE NUMERICAL BEHAVIOURAL MODEL OF SEAL PERFORMANCE

In this chapter, following from the postulated needs for an analytical tool to enable assessment of the behaviour and performance of different seal types as discussed in Chapter 3, the detailed needs statement and development of a prototype numerical model of seal performance is described.

The examination of the type of model, material components and geometry, loading and service environment, and results of the prototype model are provided, with recommendations and conclusion.

5.1 IDENTIFIED NEED FOR MODELLING BASED ON MECHANISTIC PRINCIPLES

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, viscoelasticity), rather than empirical methods (based on experience or index properties – such as difference in CBR, limiting deflections, etc.) (Desai, 2002).

The modelling of road surfacing seals using mechanistic principles with determined failure and fatigue criteria would enable assessment of the seal’s expected lifetime, inclusion of different component material characteristics and variations, varying traffic and environmental conditions. In current practice there is no available mechanistic analysis tool to assist the design in the determination of loads imposed or carried by thin layer surfacing, and certainly not for road surfacing seals.

It was with the above in consideration, that the feasibility of the development of a performance model for seal design and assessment was examined, with the use of finite element analysis tools, an initial prototype numerical model of seal performance was developed.

The Finite Element Method (FEM) Analysis was selected for the purpose of modelling seal performance and the development of a prototype numerical model for the following major reasons:

- The seal components and geometry is 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 from the determined displacements using the applicable elastic and visco-elastic methods).

• The availability of proven existing modelling software.

The application of the Finite Element Method methodology and development of the prototype model based on the micro-mechanics of road surfacing seals' behaviour are provided in this chapter.

5.2 MODELLING TOOL: FINITE ELEMENT METHODS TO MODEL MICRO-MECHANICS

Finite element analysis began as a numerical method of stress analysis (Cook, 1995). This method enabled the analysis of complex stress analysis problems, where mathematical solution is difficult. FEM utilises the tools provided through numerical methods, and often uses the technique of replacing the continuous element with a substitute structure or framework comprised of elements with a finite number of degrees of freedom (the number of directions each element is free to be displaced under load). Each of the material characteristics are approximated by the collective behaviour (such as displacement) of all of the elements having the same combined displacement as the original structure. This displacement is modelled as occurring at the points where the elements are connected to each other. By using the displacements so determined, the stresses and strains the elements are subjected to are then able to be determined using the applicable elastic and visco-elastic or plastic relationships.

Thus, the finite element method uses a substitute structure whose parts are pieces of the actual structure. The structure so modelled is termed the finite element structure or "mesh", and each separate area in 2-D or element in 3-D is the finite element. Points where the elements are connected to one another are termed nodes. Finite elements are not simply pieces of the actual structure, in the sense of many small plates or blocks connected to each other at the nodes by pins at their corners. As load is applied, these plates would be expected to distort more at the corners than elsewhere, with the element sides becoming curved and gaps appearing between some elements. This would clearly not be representative of the actual structure, and accordingly certain element distortions must be excluded in the analysis, while others must be permitted. Element properties must thus be carefully formulated.
(c) A finite element model "mesh", support (constraints) and load

Figure 5.1: Example of Finite Element Model (Cook, 1995)

The above Figure 5.1 provides an example of the implementation of the finite element method in 2-D to enable the analysis and resolution of structures with complex, stress-strain relationships.

For the above problem, where each element making up the structure is a flat plate, connected by pins at the corners. Constraints would be placed on the displacement or distortion of the plates on their sides, to prevent curving of the edges and gaps appearing between the elements.

Using the technique of the "element stiffness matrix" with stiffness coefficients and an applied force resulting in a displacement, the system is analysed using numerical methods, by interaction to determine the response of the system to a load.

The Finite Element Method allows:

- The use of elements of various types, sizes and shapes, to model a structure of arbitrary geometry.
- The accommodation of arbitrary support conditions, loading (including thermal loading).
- Modelling of composite structures involving different structural components, stiffness and strength.
- The finite element structure closely resembles the actual structure.
Erkens *et al.* (2002), Airey *et al.* (2002), Huang (2003) and Molenaar (2003) summarise, that in general, the linear-elastic techniques currently used to evaluate a pavement structure and assess pavement deterioration, do not fully describe the complex behaviour of asphaltic materials.

They further emphasize that in other engineering fields, such as pavement engineering, soil and rock mechanics, and concrete technology, use of Finite Element Methods (FEM) have enabled an improved understanding of the influence of individual material properties on the overall response of a structure.

For bituminous materials, a constitutive model capable of describing the elastic, visco-plastic and temperature and stress (rate) dependant nature of the material is required. The above authors, and others including De Bondt (1999) have shown that FEM packages provide the versatility and responses based on the fundamental material characteristics included in the material models, to satisfy the requirements of modelling a road surfacing seal.

The finite element method thus provides a tool where the modelling of a road seal can be undertaken by:

- analysing the seal through modelling the behaviour of individual components;
- using the FEM tool to allow assessment of Micro Mechanics, i.e. the study of relative movement (and thus effects of stress and strain) on a micro (SMALL) scale, i.e. the behaviour of each stone and the bitumen around it, under an imposed traffic load;
- the inclusion of different material parameters at Micro level to enable assessment of comparative expected behaviour of the different seals at Micro, and hence, macro or full scale levels.

From consideration of the above, the use of Finite Element Method (FEM) to model numerically the behaviour of a road surfacing seal, at micro-mechanical scale, was considered favourable as multiple material, thin seal layer, could be developed.

### 5.3 BASIS OF A PROTOTYPE NUMERICAL MODEL OF SEAL BEHAVIOUR

Basic structure of the Finite Element Method Model applicable to the development of a numerical model of seal behaviour under applied load is discussed under this section,
which provides an overview of the objective and resulting modelling process. The detailed development of the prototype, with each phase, is discussed under subsequent sections.

The development of the model from scratch is a process, with substantial work required for not only the fundamental basis of the model, but for future refining the specific material parameters required for ultimate calibration of the model to enable accurate prediction of each specific seal's performance. As such, a framework had to be determined through which a prototype will evolve in phases, under this project and in future initiatives.

5.3.1 Ultimate Requirements from the Model

The ultimate objective of the numerical model is to predict seal performance. Performance will be measured by the seal's response under load to the failure criteria. The ultimate requirements of the model are proposed:

- Prediction of the serviceable life expected (in terms of traffic load) until one or more failure criteria are reached.

- Assessment of the seal performance under different material components or types.

- Assessment of the behaviour of the seal under different traffic loads (time dependent and applied stresses).

- Assessment of the effect of environment (especially temperature and moisture) on the seal behaviour (through the influence on material parameters).

It is stressed that these are the ultimate requirements of the model. As the model is initiated under this research project, the scope of work is such that a prototype will be developed within the model framework, and further research outside of this project will be required to expand and refine the model, also to enable inclusion of further new modelling techniques, material characteristics and tools.

5.3.2 Model Parameters for Measurement of Seal Performance

Based on the ultimate seal performance requirements, and the performance criteria discussed in Chapter 3, the following parameters are applicable to modelling the behaviour of a seal as summarised in Table 5.1:
### Table 5.1: Seal Performance Parameters

<table>
<thead>
<tr>
<th>Model Component</th>
<th>Parameter</th>
<th>Failure criteria</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>Punching (associated with bleeding)</td>
<td>Texture depth below that required for desired skid resistance</td>
<td>Number of elv’s to texture depth &lt; 0.56 mm (TRH3)</td>
</tr>
<tr>
<td>Seal</td>
<td>Rotation of seal aggregate to ALD (associated with bleeding)</td>
<td>Void reduction to that below which texture depth not adequate</td>
<td>Number of elv’s to volume of voids reduced to less than that required for texture depth</td>
</tr>
<tr>
<td>Seal</td>
<td>Cracking, or stripping fatigue (loss of cohesion)</td>
<td>Seal cracks under dynamic load, or stone and bitumen sheath dislodged</td>
<td>Performance curve for number of elv’s to cracking, stress determination at yield</td>
</tr>
<tr>
<td>Seal</td>
<td>Cracking or stripping of stone, brittle cracking (loss of cohesion in the bitumen)</td>
<td>Seal cracks under load when tensile stress exceeds yield value (temperature dependant) or stone and bitumen sheath dislodged</td>
<td>Number of elv’s to yield stress reached (including fatigue relationship)</td>
</tr>
<tr>
<td>Seal</td>
<td>Loss of adhesion: stripping/ravelling</td>
<td>Seal stone dislodged under wheel load</td>
<td>Number of elv’s to yield stress being reached (including fatigue relationship)</td>
</tr>
<tr>
<td>Seal</td>
<td>Loss of adhesion to base: bitumen pick-up</td>
<td>Bitumen comes into contact with wheel (i.e. after punching, rotation), adhesion with base soils</td>
<td>Number of elv’s to zero texture depth, yield stress on bitumen adhesion</td>
</tr>
</tbody>
</table>

**Notes:**

1. Bitumen material characteristics are temperature, time of loading and age dependant, which will ultimately have to be accommodated in the future modelling of fundamental material parameters.

2. Bitumen behaves in elastic, visco-elastic viscous/plastic or brittle manners, depending on time of loading and temperature.

### 5.3.3 Model Components

The modelling of a seal must include:

- Seal stone;
- Bitumen;
- Applied traffic load; and
- Base support
Work published by Woodside et al (1992) reflects (refer Figure 5.2 (a)) the simplicity of the model components, on micro scale.

![Diagram of seal model components before and after embedment.

Figure 5.2 (a): Seal Model Components (from Woodside et al, 1992)

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

5.3.4 Model Development Framework

The development framework of the model has evolved from consideration of the components of the seal, and their interaction, utilising finite element methods, and is summarised as:

- Examination of the interaction of individual components (i.e. stone, bitumen and later base), i.e. micro-mechanics (the study of micro-elements and their movement or behaviour under an imposed load).

- Generation of an element of a single stone and the related seal components, thereafter multiplying the elements to generate a composite of adjacent seal stones.

- The seal foundation will be comprised of:
  - The base
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

- Embedment
- Support
- The individual seal stone
  - Bitumen layer
  - Load
    - Applied to simulate rubber tyre in contact with the stone.
    - Dynamic loading and the vertical and horizontal stresses associated with wheel loads on a textured surface.
  - Interfaces
    - Interface elements will be included between stone and bitumen, and between bitumen and base.
    - These interfaces will allow interaction between the different materials (such as adhesion) to be accommodated.

The setting-up of the FEM model will occur in two stages, to allow changing of physical seal parameters without the necessity of requiring reconfiguration of the entire model mesh:

1. The generation of the Mesh

   - To enable accommodation for changing stone size and binder application, and other parameters, the mesh generation should be "parametised". This is implemented using a mesh generating spreadsheet based system, where element node coordinates are entered using formulae linked to the input parameters. In this manner the model framework has been initiated that can include:

   - Average least dimension (ALD) of the seal stone
   - Aggregate (seal stone) nominal sizes
   - Bitumen (binder) application rate
   - Distance between the seal stones
   - Initial texture depth
• The finite element analysis

  - This includes the input of material parameters and load cases.
  - In the finite element analysis itself, the actual material parameters will be able to be varied, allowing assessment of differing materials, loads and environmental effects without influencing the mesh generation.

5.4 DEVELOPMENT OF PILOT NUMERICAL MODEL

From assessment of literature and the theory included in this thesis, the numerical model was developed for analysis by a finite element method, after considering the suitability of the applicable FEM program.

A pilot model was made using commonly available 2-D FEM software tools. This was the first step that lead to the introduction to the powerful CAPA 3-D FEM research tool developed at TUDelft. A pilot 3-D model at micro-mechanic based was also examined to determine feasibility of the development of the full analytic model of seal performance. These steps in the assessment and development process are discussed below.

5.4.1 Micro-Mechanic Dimensions: Pilot Run

The empirical performance testing utilised a 13.2 mm nominal size aggregate single seal stone with an ALD of 8 mm. The numerical model was developed utilising the corresponding dimensions to enable later comparison and verification.

![Diagram of Trial Numerical Model Seal Stone Dimensions]

Figure 5.2 (b): Trial Numerical Model Seal Stone Dimensions
The dimensions were determined as follows (as illustrated in Figure 5.2 (b)):

- The **height of the aggregate** was determined as the average least dimension (ALD), the average height the aggregate will rotate to under construction rolling, if applied at not more than allowing shoulder to shoulder orientation. For the 13 mm stone, ALD (and thus model stone height) of 8 mm as determined.

- The **thickness of the bitumen** was determined directly from the application. For an average application of 1.2t /m², thickness equates to 1.2 mm if there is no displacement of bitumen by stone. As indicated previously (Marais, 1979) 30 % of the aggregate (42 % of void space) needs to be wetted to retain the aggregate. For the ALD of 8 mm, 2.4 mm “void” height or texture depth will be filled if no embedment occurs. It is also noted (Marais, 1979) there are formula for the determination of voids, once aggregate coverage and specific gravity are known).

- For the initial purposes of developing a basic model, the dimensions are determined before punching of the aggregate occurs into base.

- Note is made that the TRH3 design code (CSRA, 1998) assumes 50 % of predicted embedment occurs under construction.

- **Distance between aggregate** (i.e.: stones) was determined by averaging the void volume dimensions. Assume the aggregate is applied shoulder to shoulder. In order to determine an average distance between aggregate applied “shoulder to shoulder,” Marais (1979) relationship between depth and void volume between spheres as described in Chapter 2 was used. This relationship is thus also available for further refinement as the model is developed.

From Marais (1979):

assume aggregate as spheres shoulder to shoulder is thus

\[ h = \sqrt{(2r)^2 + (2r)^2} \text{ less } 2r \text{ if } r = \frac{1}{2} \text{ ALD} \]

(Eq. 5.1)

thus for ALD = 8 mm, maximum distance apart is:

22.5 mm - 2(8) = 6.63 mm

i.e.: distance varies between 0 and 6.6 mm (see Figure 5.2 (b))
5.4.2 Collation of the Parameters of the FEM Components for Trial Model

In order to enable initial assessment of feasibility of the model, basic assumptions have been made, based on literature researched.

- **Stone**

  Assume the stone is rigid (infinitely stiff), for the model. From Chapter 2, Marais (1979) indicates that voids in the seal are only reduced due to wear of the aggregate and embedment (i.e.: no internal stone deflection under load).

- **Base**

  The design code TRH4 (CSRA, 1996) indicates that granular and gravel materials deform through shear and densification under repeated stress. The use of a mechanistic design package to analyse the material depth of the applied loads by the MMLS3 during the empirical testing assumed a historical Elastic (Young's) Modulus (E) value of 400 Mpa.

  Additional determination of applicable approximations of E values described previously has been made for additional input for development of the model. Semmelink's K - mould E values (Semmelink, 1991) for granular material ranging from E = 60 MPa minimum to 330 Mpa maximum have relevance. To enable assessment of embedment in the pilot model, an elasto-plastic hyperbolic material model with friction hardening plasticity was utilised to allow simulation of elasto-plasto behaviour of the base.

- **Bitumen**

  As an indicative value for Elastic modulus, an assumed value for the pilot assessment of 1000 times less than that of the base was used.

5.4.3 Applied Loads

The applied wheel loads identified for the pilot model assessment were derived from the actual loads used under the empirical testing.

Vertical applied load is 690 kPa simulating to E80 tyre pressure, 2.1 kN wheel as used on the empirical tests.

i.e.: \( \sigma_v = 690 \text{ kPa} \)
Transverse and longitudinal stresses were obtained from literature analysed under Chapter 2. (De Beer, 1995):

Transverse stress = up to 72% of $\sigma_v$, inflation pressure (magnitude less than 3% of $F_v$).

Longitudinal stress = 30% maximum of inflation pressure (magnitude less than 3% of $F_v$).

Shear due to inclines, braking and driven wheels were not included in the trial model.

5.4.4 Failure Parameters

The assessment of the performance of the seal will be repetitions of applied load until failure criteria are reached.

Chapter 3 expands on the failure parameters: failure in the model would ultimately be determined by number of equivalent light vehicles (i.e.: E80 – elv factor of 40) to:

- deformation (punching stone to less than 0.7 mm to texture depth)
- cracking of bitumen (if cold, fatigue)
- loss of adhesion

The model will be developed to reflect the above parameters. At trial stage, however, the focus is on feasibility of the FEM method to enable development of the mathematical model.

5.4.5 Summary of Numerical Parameters

Future development was postulated to include the additional parameters in the model as summarised in Table 5.2:

Table 5.2: Model Parameter Scope

<table>
<thead>
<tr>
<th>Bitumen</th>
<th>Pavement</th>
<th>Seal</th>
<th>Aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G^*$ (complex modulus)</td>
<td>E and CBR Ball penetration</td>
<td>Binder aggregate application</td>
<td>ACV, PSV, R &amp; W (adhesion), FI, ALD</td>
</tr>
<tr>
<td>$\eta$ (viscosity)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S (stiffness modulus)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variation of the above with temperature</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.4.6 2-Dimensional Pilot Model

The commercial FEM programme PLAXIS was used for the 2-D pilot model (Figure 5.3 below). The initiation model was implemented in partnership with Africon: Structural Services Division using the material parameters discussed above:

![Diagram showing AGGREGATE, BITUMEN, and BASE layers.

Figure 5.3: Basic FEM Model Components]

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 numerical 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
- Cracking of the bitumen

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 or cracking of the bitumen). 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, i.e. texture depth is reduced). Failure would then be evaluated by the TRH3 (CSRA, 1998) texture parameters (Point A in Figure 5.3).
Figure 5.4: FEM 2-D Pilot Run: Plaxis Output: Trend Line of Displacement of Point A under Load

Figure 5.4 is an output from Plaxis of the first FEM run, indicating that for the base material characteristics, there is initial large plastic deformation in to the granular base material (confirmation by experience – 50% of total penetration occurs under construction) with gradually reduced plastic deformation, as the base consolidates. The PLAXIS base material choice for this pilot assessment utilised the Hardening Soil Model, an elasto-plastic hyperbolic material model with friction hardening plasticity.

Figure 5.5: Maximum Displacement of Points A (bottom of seal stone) under 4 Load Cycles (refer to Figure 5.3)
Figure 5.5 depicts the elastic nature of the displacement of the stone under load. Figure 5.6 indicates the relative displacement of stone and adjacent bitumen under load. The fact that the bitumen is also displaced downwards 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 5.4, a scale a magnitude smaller indicates slightly plastic deformation of the end of the repeated load cycle was modelled using the material parameters in the commercial package.

![Chart 1](image)

**Figure 5.6: Displacement at Peak Load – Point A and Point B (refer Figure 5.3)**

Figure 5.6 indicates the small increase in displacement of the seal stone during the applied load, under peak load (690 kPa) while Figure 5.4 indicates permanent or plastic deformation (small magnitudes) at the end of the cycles of loading.

The value of this 2-D Plaxis study to the project is not in terms of absolute values, but in the demonstration of the ability of finite element methods to model a seal at micromechanic (i.e. single stone) level. From this indication evolved the examination of a 3-D research package pilot study. In terms of scientific value, this 2-D study gave an indication of the research direction.

The PLAXIS Model was limited in terms of 2-Dimensions, and to the material models included in the package. The move to a pilot study using the research programme, CAPA, enabled customising and in fact modelling of new materials using current research results. The bitumen in the PLAXIS Model is an elastic material where the permanent deformation was accommodated in the top of the base. CAPA would enable a "visco-elastic" material model to be used and further developed. Further to this, the 3-D CAPA programme would
enable examination of the seal at micro-mechanic level (i.e. individual stone) level, in 3-D, better simulating the effect of an imposed tyre load on a seal stone (surrounded with other stones, in a bitumen bed).

5.4.7 3-Dimensional Pilot Model

The original initiation of a 3-dimensional pilot seal model was undertaken at Technical University Delft during March 2002, using the CAPA research programme, and the TU Delft computer resources of required computational ability.

5.4.7.1 Philosophy of Model

The philosophy of the model evolved from consideration of the components of the seal, and their interaction.

The model philosophy as summarized is:

- Generation of an element of a single stone and the related seal components, thereafter multiplying the elements to generate a seal of adjacent seal stones.

- The seal foundation is comprised of the base, modelled in two layers:
  - Thin (soft) contact layer to allow embedment.
  - Thick rigid (high stiffness compared with the bitumen) support layer.

- The individual seal stone
- Bitumen layer
- Load
  - Applied also in two layers: soft elastic layer to simulate rubber type in contact with the stone.
  - Stiff layer above this to apply the load uniformly. Dynamic loading, and the vertical and horizontal stresses associated with wheel loads, will be included.
- Interfaces
  - Two interface elements will be included between stone and bitumen, and between bitumen and base.
  - These interfaces will allow interaction (such as adhesion) to be modelled.
5.4.7.2 Parametised Model

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

- The generation of the Mesh.

To enable accommodation for changing stone size and binder application, and other parameters, the mesh generation was undertaken using a spreadsheet based input file where element node coordinates are entered using formulae linked to the input parameters. In this manner a model has been initiated that can include changing parameters without the total mesh being redesigned. Included is the ability to vary:

- Average least dimension (ALD) of the seal stone
- Aggregate (seal stone) nominal sizes
- Bitumen (binder) application rate
- Distance between the seal stones
- Initial texture depth

- 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 dependant items) without influencing the mesh.

5.4.7.3 Single Stone Element

The 3-D initiation model of a single stone element was developed during March and April 2002. Output is provided as an example of the feasibility of the model and a basis of the further development of this model. The parameters included in the stone element are:

- Aggregate: ALD 8 mm, nominal size 13.2 mm
- Texture depth: 0.7 mm
- Bitumen application: rate determined by texture depth
- Interface - bitumen – stone (0.1 mm)
- Interface - bitumen – base (0.1 mm)
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

- Base – contact layer (20 mm)
- Base – support layer (130 mm)
- Load

The element cross section is as follows (Figure 5.7) (printouts not to scale):

Load application layers (green & lt blue) Stone (blue) with bitumen (red)
Base layers (brown-soft, and dark blue-hard)

Figure 5.7: Provides the One Quarter View through a Seal Stone, with the Load and Support Layers

Under 0.7 kPa wheel load, single pass, the stress distribution is indicated in Figure 5.8:

Figure 5.8: Stress through Quarter Stone and Bitumen: \( \sigma_{zz} \)
The deflection of the model with fixed base, away from centre line is indicated in Figure 5.9:

Figure 5.9: Displacement of Quarter Model under Load: $\varepsilon_{xx}$

This 3-D model at micro-mechanic level illustrated the ability of the CAPA 3-D FEM research program to model the individual seal stones, and to give output in terms of stresses and strains. Again, this pilot study should not be assessed in terms of values of stress or strain output, but in terms of indication the research methods for the initiation of a prototype numerical behavioural model.

5.4.8 Outcome of Pilot Models

The development of the Pilot Models has the following value to the scientific contribution of the project:

- Using FEM methods to model micro-mechanics, it is possible to model, and gets output in terms of displacements, stresses and strains for single stone elements of a seal.
- The 3-D CAPA programme will be able to accommodate the modelling of single stone micro mechanic elements, and enable the development of a model of multiple stone elements.
The 3-D CAPA programme will be able to provide indication of stresses and strains under load, on the seal stone elements.

The FEM model will be able to accommodate the various components and behaviour of the micro-elements of the seal.

With much further development of the required material parameters, plastic and visco-elastic behaviour will be able to be modelled. The refinement of these parameters may take place under separate focused projects, due to magnitude of the research and development involved.

From the assistance of these pilot runs, the further development of a multi-element 3-D seal numerical model was approved, and assistance committed by TUDelft, which is highly appreciated.

5.5 NUMERICAL MODEL APPLIED LOADS FOR PROTOTYPE MODEL

For the development of a multi-element prototype numerical model, the determination of applied loads representing as real a reflection as possible of actual traffic loading on seals was required. A detailed assessment and interpretation of current available data, focused on the geometry of the textured FEM model, is based on the study in section 2.5 made under this section with the objective of defining a prototype model traffic load.

This chapter examines the determination of loads on the seal surface specifically in terms of load imposed to a textured surface, and relevant to the numerical model. The loads summarized under this chapter will be used on the prototype models to enable comparative examination of the effect of material parameters under load.

5.5.1 Consideration of Load Types

The imposed load types are of different type and characteristics:

- Dynamic or static tyre loading
- Rolling or driven wheel loading

Various authors as discussed in Chapter 2 (section 2.5) have examined aspects of these on simulated road surfaces, and the detail from literature relevant to the model will be considered further.
Of importance to a seal model is the load on:

- A textured surface, as represented by the seal aggregate
- Contact stresses, tangential and vertical, imposed by the vehicle tyre

The determination of load application type, and implementation, for FEM modelling, allows inclusion of all the above load types, e.g.:

- Dynamic "single wave" load application or modelled static load imposed a number of times to simulate dynamic effects.
- Differentiation will be made in the model between loading applied to a smooth surface and textured surface, and texture of different depths. Focus on the seal model will be on the affect of texture on the transfer of bulk stresses through the seal to the supporting base course.

5.5.2 Base Data for Interpretation of Loads on FEM Elements

The applied traffic load on a seal is transferred to the pavement through the individual stones. As texture depth increases, the raised elements providing the texture, in the seal numerical model's case, the seal aggregate, are loaded with higher stresses in order to provide equilibrium in the transfer of the bulk load imposed by the wheels to the road surface. In practice the vastly different stiffness between stone and bitumen will affect how the load is transferred by each seal component.

The Figures 5.10 below illustrate the forces imposed on the individual stones, as interpreted from Woodside et al (1992). The figure shows the different seal stone scenarios, before and after embedment. This will be taken into account during the modelling of the seal performance, and in future models the effect of embedment could be considered.
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

Figure 5.10: Interface Stresses and Induced Load (from Woodside et al, 1992)

Within the above philosophy, the actual expected representative stresses be imposed on a seal will be determined for use in the FEM model.

5.5.3 Summary of Traffic Imposed Loads for Interpretation for Application with Numerical Model

The traffic imposed loads for the CAPA FEM seal model have been interpreted from literature, for specific application to this project. The summary of the applicable studies from literature are summarised under this section.

Literature was used to determine the load distribution and magnitude.

As discussed in Chapter 2, Marais (1979), De Beer (1995) and Woodside et al (1992 and 1999) have analysed the traffic loading, and their approaches vary from equivalency factors to actual measures stresses.

Woodside et al (1992) dynamic 3-D stresses are useful for the FEM model, as they also include the height of seal stone i.e. texture. Their 5 mm x 5 mm transducer system reflects similar geometry to the FEM mesh (although the FEM mesh also is able to utilise
random shapes and heights, with stone sizes distributed around a nominal size), and an effective texture depth was generated in their test (in practice minimum texture depth in the UK 1.5 mm, while South African Authorities require measured 0.64 mm for texture depth required, for minimum skid resistance). Different load types were used – heavy and light vehicles being simulated and treded tyres were used. Using contact stress transducers, lateral, longitudinal and vertical stresses were measured under a moving wheel.

This study shows that for an increase in transducer height, representing seal stone height or texture depth, contact stress was greatly increased, even under static conditions.

The following table (5.3) summarises contact stress that will be used as reference in the determination of applicable stresses for the model.

Table 5.3: Load Application for FEM Model

<table>
<thead>
<tr>
<th>WOODSIDE et al (1992)</th>
<th>Pressure distribution on different stones of texture depths</th>
</tr>
</thead>
<tbody>
<tr>
<td>700 kPa Tyre Pressure</td>
<td></td>
</tr>
<tr>
<td>Measured pressure in kPa (% increase over tyre inflation pressure)</td>
<td></td>
</tr>
<tr>
<td>VERTICAL</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stone texture depth</th>
<th>0 mm</th>
<th>1 mm</th>
<th>2 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (kPa) at centre of tyre</td>
<td>513</td>
<td>912</td>
<td>1453</td>
</tr>
<tr>
<td>700 kPa tyre inflation pressure</td>
<td>(73 %)</td>
<td>(130 %)</td>
<td>(207 %)</td>
</tr>
<tr>
<td>Pressure at edge of tyre</td>
<td>0</td>
<td>0</td>
<td>494</td>
</tr>
<tr>
<td>700 kPa tyre</td>
<td>(0 %)</td>
<td>(0 %)</td>
<td>(71 %)</td>
</tr>
</tbody>
</table>

| DE BEER (1995) |
| Maximum pressure under tyres |

<table>
<thead>
<tr>
<th>Direction</th>
<th>Pressure % of inflation</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>127 %</td>
<td></td>
</tr>
<tr>
<td>Longitudinal</td>
<td>30 %</td>
<td>3 % of vertical</td>
</tr>
<tr>
<td>Transverse</td>
<td>72 %</td>
<td>2 % of vertical</td>
</tr>
</tbody>
</table>

Woodside et al (1999) dynamic stresses compare well with De Beer above, and the reference provides distribution of stress through cross section of contact area. For the FEM model, maximum stress values in the above table will be considered for worst case
scenarios. Dynamic stresses will be increased with texture depth, as indicated in Woodside table above. As an addition, the following formulae are available:

- The applicable mathematical models for prediction of applied stresses were developed, taking texture depth into account (Figure 5.11 provide axes and applied stress directions):

\[
\sigma_v = 407.71P + 6.396Pi + 1105.251H + 184.141R - 4245.734 \quad (Eq. 5.2)
\]
\[
\sigma_x = 113.979P + 1.235Pi + 102.628H - 801.273 \quad (Eq. 5.3)
\]
\[
\sigma_y = 151.159P + 1.297Pi + 107.375H - 959.087 \quad (Eq. 5.4)
\]

Where:

\( \sigma_v \) = dynamic vertical contact stress across contact width
\( \sigma_x \) = dynamic longitudinal contact stress at the centre of the contact patch
\( \sigma_y \) = dynamic lateral contact stress at the centre of the contact patch
\( P \) = load in kN*
\( Pi \) = tyre inflation pressure in kPa
\( H \) = height of transducer in mm (extrapolate: macro texture depth?)
\( R \) = distance from the centre of contact patch in cm*

*(Changes by Milne to original text of paper (Woodside et al, 1999))

A summary of determined values are provided in Table 5.4.

Texture depth has the greatest effect on generation of vertical stress, and applied load is transferred to the pavement through the aggregate chippings. Deeper surface texture would imply that the applied load would be carried on the exposed chipping tops, resulting in the high applied stress. Thus, in practice, texture depth may accelerate aggregate wear or polishing, with the premature loss in skid resistance. Maximum vertical contact stress occurs for 75% of the contact duration within the contact patch.
Figure 5.11: Summary of x, y and z Contact Stress Directions (Woodside et al, 1999)

Table 5.4: Comparison of Predicted Vertical Contact Stress (from Woodside et al, 1999)

<table>
<thead>
<tr>
<th>Test conditions</th>
<th>Predicted value (kPa)</th>
<th>% of inflation Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (kN)</td>
<td>PI (kPa)</td>
<td>H (mm)</td>
</tr>
<tr>
<td>3.5</td>
<td>276</td>
<td>3</td>
</tr>
<tr>
<td>6.0</td>
<td>483</td>
<td>3</td>
</tr>
<tr>
<td>7.0</td>
<td>557</td>
<td>5</td>
</tr>
</tbody>
</table>
Figure 5.12: Distribution of Dynamic Vertical Contact Stress across the Contact Width for Different Tyre Inflation pressures (3 mm – transducer height and a load of 3.5 kN)

Woodside et al (1999) also provide graphic representation illustrated in Figure 5.12 and 5.13 of the edge effects for different tyre pressures of the tyre, i.e. how a vertical contact stress increases towards the edge of the contact patch.

Figure 5.13: Change in Dynamic Vertical Contact Stress with Tyre Inflation Pressure for a 3 mm Transducer and 3.5 kN Load
Supplementing the formulae and tables, graphic inclusion of the different load scenarios is the plot showing the effect of tyre inflation pressure to tyre contact stress.

5.5.4 Evolution and Simulation of Applied Loads for the FEM Model

This section summarises the process through which the measured stresses imposed on a textured surface by a wheel are translated into FEM Model input to simulate an applied load. Specific reference is given to the practical determination of input for the respective models, and the motivation for each decision. The actual response of the model to the load will be discussed in detail under the respective sections in this thesis.

In the extrapolation of stresses, shear due to inclines or braking is not considered at prototype stage. Shear due to driven wheels is however included through the introduction of the respective load functions, as discussed in this section.

5.5.4.1 Determination of Aggregate/"Stone" (Micro) Stress from Bulk Stress for Loading of the FEM Mesh

Woodside et al (1999) reported on the measurement of bulk stress, i.e. stress imposed onto the surface under the tyre contact patch. The FEM Mesh requires that individual stones are loaded, i.e. micro-stress must be extrapolated from the bulk stress. From examination of the behaviour of trial FEM meshes and loading input, it was found that the determination of the full influence of tyre load, and the stress measurements made on textured surfaces, is not complete. Specifically the geometry of the measuring device is not well documented in the Woodside (1999) study. Regarding this study, it was determined that the modelled "stone" or aggregate size was area 5 mm x 5 mm, with a 25 mm² surface area. It was also postulated that the modelled "stone" is embedded in a square of 13.18 mm x 13.18 mm, i.e. a 174 mm² square. The simulated FEM "stone" in the FEM mesh has a round "stone" embedded in a binder "column" of 139.5 mm². The FEM "stone" surface sticking out of the binder column takes 37.4 mm² of this column. This implies that one modelled "stone" in the Woodside study's measurement represents a bulk area that is 7 times larger than the modelled "stone" surface itself. In the FEM model this ratio is 3.7. This shows that the geometry of the measured modelled "stone" differs strongly from the FEM model and also from reality. Figure 5.14 reflects this geometric difference between the studies and Figure 5.15 the concept of bulk and micro scales. Measurements in the Woodside study were made on "stones" that protruded 0, 1 and 2 mm from the free surface. The FEM "stone" in the Prototype FEM model protrudes 2.5 mm from the surface.
The “stones” in the FEM model rise out of the binder for 2.5 mm. In the modelled measurements this was 1 mm and 2 mm.

The bulk measurements show that vertical stresses on a stone can be >200% of the tyre pressure. In Woodside et al measurements a vertical micro stress of >1000% of the tyre pressure was measured on the modelled stone.

Figure 5.14: FEM and Measured Modelled Stone Geometry
Figure 5.15: Bulk to Micro Stress (Textured Seal Surface)

Given the strong difference between the geometry of the measurement device and the FEM Mesh the results of the measurements cannot be used without correction from bulk stress to micro stone stress. The limited description of the measurements required interpretation and extrapolation for the determination of stresses for the FEM mesh.

The approach was to conform to the principles of the physical model for the measurements and use this to define the applied stresses for the load time functions for moving loads. A moving load was applied to allow assessment of the viscous/plastic behaviour of bitumen, where "relaxation" periods were required between wheel loads. Measured absolute values of applied stresses are independent of the load time function and are reflected in the actual values of "stone" forces applied to the model. A typical "heavy vehicle" was measured, to allow the "time" function to be determined, and associated with each load magnitude, for driven and un-driven wheels. The "time functions" were determined for the moving wheels, and the bulk behaviour utilised to determine the micro stresses.

Time functions were used for each load type to allow simulation of application and release of the rolling loads, and the modelled measurements used to allow distinction between
vertical stress (z-direction), lateral stress (x-direction) and longitudinal stress (y-direction). A "typical heavy vehicle load" was numerically modelled using the above principles.

5.5.4.2 Basic Wheel Load Time Functions

From the above assessment, Basic Wheel Load Time Functions were determined, and when applied to the magnitudes of Maximum Applied Stresses, the micro/stone stresses were determined. Figure 5.16 reflects the basic time functions, taken from Woodside et al, and Groenendijk (1998). 

![Basic time functions](image)

Figure 5.16: Basic Time Functions #1 and #2: Stress imposed by a Rolling Wheel

- **Basic Time Function #1 and #3**

  Function #1 is the shape of the load application through the tyre for a rolling wheel due to vehicle weight (i.e. vertical load due to vehicle mass) and the lateral force (due to tension in the tyre from restraining the inflation pressure) and driving wheel load due to engine output. Basic function #1 is used to cumulatively add stresses that result from rolling resistance and function #3 the engine output.

- **Basic Time Load Function #2**

  Function #2 is applicable to represent the stresses that develop in the transverse direction, due to the forces in the rubber tyre for a free rolling wheel.
5.5.4.3 Basic Wheel Load Ratios and Modelled Bulk Stresses

The time functions used for loading the model are based on measurements as extrapolated above. With respect to absolute values of stress no directly applicable measurements are available for direct application to the numerical model. For that reason an interpolation approach is used:

From the measurements, ratios between the various stresses in the principal axes for a unit load as defined in the time functions are are determined. The following holds for the FEM numerical model for a free rolling wheel (Figure 5.22 shows the x, y and z axes in relation to the tyre direction, as used by the FEM simulation):

\[ \text{max } \sigma_{xx}, \text{ basic time function } #1: \quad 15\% \text{ of } \sigma_{zz} : \text{lateral (90° to travel) load due to lateral tyre pressure} \]

\[ \text{max } \sigma_{yy}, \text{ basic time function } #2: \quad 30\% \text{ of } \sigma_{zz} : \text{rolling wheel in direction of travel} \]

\[ \text{tyre tensions in circumference} \]

\[ \text{max } \sigma_{yy}, \text{ basic time function } #1: \quad 2.5\% \text{ of } \sigma_{zz} : \text{rolling resistance} \]

\[ \text{max } \sigma_{zz}, \text{ basic time function } #1: \quad 100\% \text{ of } \sigma_{zz} : \text{weight} \]

To limit variable influences, and due to practice or research not able currently to provide directly applicable data to the contrary, it was decided to keep these ratios constant for all possible types of rolling wheel loadings, independent of axle load, tyre tread or axle geometry or vehicle type. The total load to be applied was thus able to be controlled by defining \( \sigma_{zz} \). From measurements by Groenendijk (1998) it is known that the maximum bulk \( \sigma_{zz} \) (so not measured on "stones" of micro scale) might easily achieve 300% of the inflation pressure at the edge of a tyre. In the middle of the tyre lower \( \sigma_{zz} \) values are found. The distribution of bulk \( \sigma_{zz} \) heavily depends on the profile of the tyre.

It can however be concluded that a maximum bulk \( \sigma_{zz} \) of 200% of the inflation pressure is within realistically expected values.

In analogy with the SA design code an equivalent 80kN axle load, or E80, is used as a starting point for the determination of the loading. It is assumed for this model that this load is applied to the surface via a tyre with a 8 atm = 0.8 MPa inflation pressure, making \( \sigma_{zz} 1.6\text{Mpa} \) for this model for the "Stone" or Micro loading.
For a free rolling wheel the following bulk stresses are thus applied to the model:

max \sigma_{xx}, basic time function #1: 0.24 MPa
max \sigma_{yy}, basic time function #2: 0.48 MPa
max \sigma_{yy}, basic time function #1: 0.04 MPa
max \sigma_{zz}, basic time function #1: 1.6 MPa

It is assumed that the tyre will have a contact length of 300 mm. On the basis of the inflation pressure only this results in a tyre width of 167 mm. The tyre now carries a 40,000 N load.

No measurement with respect to driven wheels is available. The longitudinal shear force (engine output) on the driven wheels is therefore applied via an assumed distribution following time function #1. It is assumed that a linear superposition principal will hold.

The force applied by the engine to the driven wheels is calculated as follows:

Net engine output: 275,000 Watt
Loss in gearbox and drive shafts: 20%
Engine operational output: 80%
Output on the axle: 

\[(100\%-20\%)*80\%*275,000 \text{ Watt} = 176,000 \text{ Watt}\]

Since the net output on the axle should equal the (driving force x driving speed) the driving speed becomes a factor of importance. A speed of 22 m/s is assumed (about 80 km/h). At this speed the 176,000 Watt generates a 8000 N force on the driven wheels.

The force on the driven wheels thus equals 10% of the axle load. Since it is assumed that the engine output is applied to the roadsurface on the same way as the vertical load, the forces of the engine, i.e driving wheel in addition will result in a maximum bulk \sigma_{yy} of - 0.16 MPa applied via time function #1.

- Unloaded time

Within real trucks the front (free) and rear (driven) wheels are placed about 4 m apart due to wheel base. This distance is roughly 13 times larger than the length of the load pulse determined at the speed of 22 m/s. In a computation this implies that a lot of computational effort is put into calculating what happens when the system is not loaded. During the unloaded period the relaxation will occur in the system.
Due to the visco-elastic part of the model this relaxation will take place on an exponential basis. The largest part of the relaxation takes place directly after unloading.

To make the calculations economic, yet realistic it was decided that a relaxation time that is equal to twice the load pulse time will give accurate results at relatively low computational time.

- **Time step for FEM**

The width of a load pulse is 300 mm, followed by the "unloaded time" distance of 600 mm between wheel pulses. The combination of a free wheel followed by a driven wheel thus equals 1800 mm. At a driving speed of 22 m/s this total cycle including rest period will pass in 0.8181 sec. In order to have at least 10 points in a load pulse the timestep should be 0.001363636 sec at maximum. This was rounded to 0.0014 sec reflecting a revised modelled speed to 21.43 m/s or 77.14 km/hr.

### 5.5.4.4 Summary of Bulk Stresses for FEM Model

The above results are summarised in Table 5.5.

#### Table 5.5: Summary of FEM Model Bulk Stresses in Principal Axes

<table>
<thead>
<tr>
<th></th>
<th>Free wheel</th>
<th>Rest period</th>
<th>Driven wheel</th>
<th>Rest period</th>
</tr>
</thead>
<tbody>
<tr>
<td>length [mm]</td>
<td></td>
<td>300</td>
<td>600</td>
<td>300</td>
</tr>
<tr>
<td>duration [s]</td>
<td>0.014</td>
<td>0.028</td>
<td>0.014</td>
<td>0.028</td>
</tr>
<tr>
<td>( \sigma_{xx} )</td>
<td>max bulk stress [MPa]</td>
<td>0.24</td>
<td>0</td>
<td>0.24</td>
</tr>
<tr>
<td>Transversal stress</td>
<td>time function [-]</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>( \sigma_{yy} )</td>
<td>max bulk stress [MPa]</td>
<td>0.48</td>
<td>0</td>
<td>0.48</td>
</tr>
<tr>
<td>Longitudinal stress</td>
<td>time function [-]</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>( \sigma_{yy} )</td>
<td>max bulk stress [MPa]</td>
<td>0.04</td>
<td>0</td>
<td>0.04</td>
</tr>
<tr>
<td>Longitudinal stress</td>
<td>time function [-]</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>( \sigma_{zz} )</td>
<td>max bulk stress [MPa]</td>
<td>0</td>
<td>0</td>
<td>-0.16</td>
</tr>
<tr>
<td>Vertical stress</td>
<td>time function [-]</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>( \sigma_{zz} )</td>
<td>max bulk stress [MPa]</td>
<td>1.6</td>
<td>0</td>
<td>1.6</td>
</tr>
<tr>
<td>Vertical stress</td>
<td>time function [-]</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
For the ease of manipulating input 3 time functions as depicted in Figure 5.17 have been based on the above interpolations:

**Function #1**

**Function #2**

**Function #3 (function #1 for driven wheel): Engine output**

<table>
<thead>
<tr>
<th>Maximum applied stresses:</th>
<th></th>
<th></th>
<th>Weight &amp; Tyre Contact &amp; Friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction</td>
<td>Driven</td>
<td>Rolling</td>
<td></td>
</tr>
<tr>
<td>XX</td>
<td></td>
<td></td>
<td>0.24 MPa #1</td>
</tr>
<tr>
<td>YY</td>
<td>0.16 MPa #3</td>
<td>0.48 MPa #2</td>
<td>0.04 MPa #1</td>
</tr>
<tr>
<td>ZZ</td>
<td></td>
<td></td>
<td>1.6 MPa #1</td>
</tr>
</tbody>
</table>

With these time functions the following input is applicable:

<table>
<thead>
<tr>
<th>Time Function</th>
<th>Stress Direction</th>
<th>100 % of Maximum Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time function #1</td>
<td>Weight and tension in tyre surface:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• vertical stress zz</td>
<td>1.6 MPa</td>
</tr>
<tr>
<td></td>
<td>• lateral stress xx</td>
<td>0.24 MPa</td>
</tr>
<tr>
<td></td>
<td>• rolling friction stress yy</td>
<td>0.04 MPa</td>
</tr>
<tr>
<td>Time function #2</td>
<td>Free rolling longitudinal: stress yy</td>
<td>0.48 MPa</td>
</tr>
<tr>
<td>Time function #3</td>
<td>Engine output: stress yy</td>
<td>0.16 MPa</td>
</tr>
</tbody>
</table>

Figure 5.17: Summary of Time Load Functions
5.5.4.5 "Stone" Micro Stresses for FEM Model

The project facilitated the examination of Bulk to Micro or "Stone" stresses, and Huurman et al (2003) has assisted in identifying areas for continued development of the FEM model input data.

On micro scale, the model of the seal surfacing consists of stone grains and bituminous binder. A bulk stress as calculated in above should thus be distributed over the stone grains and the binder. The various papers about measured grain stress were not detailed specifically enough to enable categoric determination of the micro stresses to the extent the FEM model required. The papers however did show that grain stresses may be several times larger than the tyre inflation pressure, which on its turn will roughly equal the bulk stress. This is a result of the fact that the grains rise about 2.225 mm out of the surface and thus make contact with the wheels.

For the translation of the bulk stress to stone grain/micro stress first the force on each individual grain is computed. This force is equal to the bulk stress multiplied with the surface area in which the grain is sitting. In the model as it is now this surface area equals 139.5 mm². The bulk stresses $\sigma_{xx}$, $\sigma_{yy}$ and $\sigma_{zz}$ are in this way translated to grain forces $F_x$, $F_y$ and $F_z$.

Since the stone grain is a very stiff element sitting in a soft environment it may mechanically be seen as completely rigid. This implies that the system of grains sitting in binder reacts as a function of the forces on the grains. The distribution of these stone grain micro forces over a certain area as stone grain micro stress is not of importance (since the grains do not deform).

As described, the forces $F_x$, $F_y$ and $F_z$ can be determined. The further issue problem is that the numerical model presents a 3-D problem. This implies that the forces will also introduce a moment to the stone grain. This moment will induce grain rotation, which in turn depends on the location where the forces are introduced. In principal this is shown for a 2-D situation in the Figure 5.18. The figure shows that the moments that are acting on the grains reduce as the level at which shear forces are applied on a textured surface moves into the road surface texture.
Figure 5.18: Micro forces and moments on a textured surface

It is not currently known at micro-scale how the applied bulk forces are transferred to the stone or bituminous surface. Further investigation into this area of research will be recommended and discussed under the applicable section of this project, as this is a detailed investigation in itself. This project has thus identified the limitations of current knowledge, and provided tools and indication of where the research should focus. For this FEM numerical model the translation of bulk to stone grain/micro force (distribution) is largely based on engineering judgement. The applied forces are balanced in equilibrium between applied load and the contact seal response.

In the model a grain has an ALD of 6 mm. Of this 6 mm 2.225 mm is rising above the binder. Forces to the stone grain can only be applied to that part of the grain that sticks out. The lever arm to the grain centre may thus vary from 3 mm (force applied to stone grain summit) to 0.775 mm (force applied to stone grain at binder level). This roughly gives a factor of four in difference with respect to the applied moment.

Since it is clear that both extremes in terms of force application will not be realistic it can well be argued that the forces acting on a stone grain should be applied over an average distributed area at the upper half of that part of the grain that comes out of the binder. It was decided to introduce the grain forces as a stress acting on the upper 0.406 mm of the stone grain, the height at which the upper half of the stone FEM elements begin. In the model a ring of nodes is sitting at that level, it is these nodes that carry the main load. A single node at the grain summit is also loaded. In total the nodal forces put on a single stone grain add up to be equal to the earlier described grain forces $F_x$, $F_y$, and $F_z$. 
In Figure 5.19 below (not to scale) the loaded nodes are indicated. Given the high density of modelled stone.

Note: Highlighted nodes accommodate APPLIED FORCES

**Figure 5.19: Micro scale: Seal Stone and Binder Nodes**

For these stone grains it is postulated that this method of translating bulk to micro/stone grain scale forces is an accurate reflection of reality. As the empirical scale model uses applied contact STRESS at 1:1 full scale: model STRESS, the applied forces were desired to be converted to a stress. Also, STRESS in the CAPA FEM program is applied at LOCAL “Z” or vertical (in terms of X and Y tangential to the element surface). The stone/grain load was required to be applied at GLOBAL “Z” to simulate the correct application directions of the “tyre” load in the GLOBAL direction X, Y and Z, even on a curved surface. This has the advantage that the correct tyre load can be applied to any shape of stone, using the same load functions.

5.5.4.6 Loading of the FEM Mesh : Prototype Model Data Input

This section describes the actual loading of the nodes.

- **Load Magnitudes**

The loading of the nodes is based upon the shape function nodal weights as determined for a square surface. This gives a good estimate of force per node in a simple manner because with no relation with the actual stone geometry. Small errors are a result, but these only effect micro grain stress and not the stress and strain in the binder, as there must be global equilibrium. The Force magnitude is
determined as described above, where the TOTAL micro/stone grain accommodates the force, reworked into a simulated STRESS by applying the force across the element’s nodes. A spread sheet based program was used to filter the nodes above the set distance from the binder, and these nodes were identified as loaded nodes for the FEM data input file. The simple formula of:

\[
\text{Area per grain/Force} = \text{Applied Stress} \quad \text{is used to generate Force per stone grain (Newtons)}
\]

The force per grain is applied in a manner simulating stress, in the GLOBAL axes directions.

- **Load Application**

The force was applied to the element by distributing the FORCE across the 8 nodes describing the respective elements of the stone using a mathematical simulation, using a push and pull on the nodes to create a simulated area load as illustrated in Figure 5.20 below.

![Diagram of FEM Element: Nodal Force Distribution](image)

*Figure 5.20: FEM Element: Nodal Force Distribution*
FEM Load Function Input

The load is applied to the FEM seal stone as follows:

- The absolute magnitude of each $F_{zz}$, $F_{yy}$, $F_{xx}$ is determined per load in the above manner, and entered in to the FEM data input as nodal number, and the absolute value of the force applied, coupled with a load time function number;

- The load time functions were defined in terms of ratio of actual load to absolute value, and the time of application, as USER DEFINED FUNCTIONS as defined in the combined load time functions;

- In this manner the moving wheel can be applied row by row of stones.

The series of plots in Figure 5.21 (a) – (g) below shows the tyre imposed vertical loads, as an example of the simulation of the traffic loading in the manner described above. The series of plots 5.21 (a) to (g) show the contact patch of the tyre passing over the stones at approximately 2.2 m/s. The colour shading reflects vertical stress schematically.
(a) ZZ vertical stress on mesh of 19 stones, fully loaded under one tyre

(b) Time step 0.007 sec later, showing position of tyre off first stone

(c) 0.014 sec start of unloading as wheel contact patch rolls off the seal stones

(d) 0.021 sec's from start of unloading

(e) 0.028 sec from start of unloading

(f) 0.035 sec's from start of unloading

(f) 0.042 sec from start of unloading. Wheel passed over all stones in mesh

Figure 5.21: Illustration of Traffic Contact Patch: Vertical ZZ Stress under Truck Tyre
The FEM seal stones are situated adjacent to the centre line, as reflected in Figure 5.22 below:

![Diagram of FEM seal mesh](image)

*Figure 5.22: Position of FEM Seal under Tyre*

### 5.6 FEM MATERIAL PARAMETERS

#### 5.6.1 Bitumen Binder

From the literature review, specifically Hagos (2002), the material parameters for the bitumen have been 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.

Using Hagos parameters and the correcting factors provided, plus the Time Temperature Supposition Principle (TTSP),
Towards a Performance Related Seal Design Method for Bitumen and Modified Bitumen Seal Binders

\[ \log \alpha(T) = -c_1(T - T_R) \frac{1}{(T - T_R) + C_2} \]  \hspace{1cm} (Eq. 5.5)

A full range of data is obtained for use in this and future numerical modelling of the seal binders.

The bitumen data for the bitumen material parameters was worked from Hagos (2002) (Annexure A to Chapter 5). For the simulation of the straight binder, the results for the 70/100 pen grade bitumen was selected (to allow later comparison with the performance tests 80/100 pen binder and seal). For the modelling of a modified binder, the 3% SBS (linear) modified binder was selected (to allow comparison with the 3% SBS modified binder and seal in the performance tests). The linear (L) rather than radial (R) SBS was selected with the Burgers model (linear spring and dash pot) material simulation in the FEM program) consideration. The temperature ranges considered were in line with the performance tests at 10°C, 25°C and 50°C.

The Hagos (2002) Burgers model featured one Kelvin element and one Maxwell element in parallel (ref Figure 2.13 (b)). Table 5.6 reflects the elastic and viscous parameters as used by the FEM model in this project.

**Table 5.6: FEM Material Parameters for Prototype FEM Model**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>10°C</th>
<th>25°C</th>
<th>50°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Pa) E₁</td>
<td>2x10⁵</td>
<td>2x10⁵</td>
<td>2x10⁵</td>
</tr>
<tr>
<td>(Pa) E₂</td>
<td>5,3x10⁴</td>
<td>5,3x10⁴</td>
<td>5,3x10⁴</td>
</tr>
<tr>
<td>(Pa) λ₁</td>
<td>2x10⁴</td>
<td>8,67x10⁴</td>
<td>8,67x10⁴</td>
</tr>
<tr>
<td>(Pa) λ₂</td>
<td>2x10⁴</td>
<td>6,98x10⁴</td>
<td>6,98x10⁴</td>
</tr>
<tr>
<td>(Pa) λ₃</td>
<td>2x10⁵</td>
<td>2x10⁵</td>
<td>2x10⁵</td>
</tr>
</tbody>
</table>

With reference to the selected parameters, the spring stiffness of the binder remained constant (reflecting the time of loading function, i.e. bitumen binder's elasticity under rapid loading), while the dash pot viscosity showed order size reduction with increase in temperature. This reflects the physical nature of bitumen.
5.6.2 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, sourced from internet literature on research on concrete aggregate.

Of note is that the stiffness moduli for crushed stone layers is order size less than for solid aggregate, as indicated in the previous sections K-mould tests.

The E moduli for aggregate are thus $10^3$ order sizes greater than bitumen.

5.6.3 Interface

The CAPA FEM numerical model interface will be used ultimately to model adhesion, amongst other parameters. The interface parameters are required in terms of stiffness, units N/mm$^2$.

This was derived from dividing the assumed E modulus of the interface by the interface thickness. Due to the interface numerical parameters still being the subject of current research, the extremes of the interface stiffness was decided after discussion with the CAPA group and Project Committee at TU Delft. The two extremes are:

- Using $E_{\text{bitumen}}$ in interface thickness
- Using $E_{\text{aggregate}}$ in interface thickness

The lower range of interface stiffness thus changed for each binder type, where applicable, based on the $E_{\infty}$ of the Burgers model simulation of bitumen visco-elastic behaviour (the "series" E modulus, not affected by the dashpot viscosity or viscous behaviour of bitumen).

The interface stiffness vened was the local "z" direction, i.e. stiffness perpendicular to the stone surface. Interface stiffness thus ranged from

$$1 \times 10^3 \text{ N/mm}^2 \text{ (series } E_{\text{bitumen/IF thickness}) \text{ to } 1 \times 10^6 \text{ N/mm}^2 \text{ (E_{aggregate/IF thickness})}$$

The local x and y interface stiffness are kept $10^5$ order sizes higher than the z parameter to reduce resulting deformation in these directions, to enable the effect of one variable (i.e. the stiffness) to be examined.
Through examination of the behaviour of the prototype model with two extremes of interface behaviour, the following will be determined:

- The role or necessity of the interface in the model;
- The sensitivity of the model to changing interface parameters.

5.7 DEVELOPMENT PHASES: NUMERICAL PROTOTYPE MODEL

The original initiation of a 3-dimensional seal model was undertaken in 2002 at Technical University Delft, using the CAPA research programme, and the TU Delft computer resources of required computational ability. Work continued in 2003, and currently development is continuing beyond the scope of this project.

5.7.1 Prototype Seal Surfacing Model: Test Trial

A prototype model was developed to enable the assessment of FEM mesh effectiveness, and to undertake an "elastic" run to ensure the basic structure and composition of the mesh model was sound.

5.7.1.1 Basic Layout of Model

In Figure 5.23 the basic layout of the prototype model is presented (Huurman, Milne et al, 2003). Various shades refer to different materials. As is shown by Figure 5.24, the model is made up of modules that consist of individual stones encompassed by bitumen. By adding modules together, the model can easily be made as large as can be handled by the available computers.

Figure 5.23: Basic Layout of the FEM for Seal Surfacing with Interface Elements
Given the importance of the adhesion between stone and binder, for both cracking and stripping/ravelling damage, each grain is placed in a bowl of interface elements. These elements, also shown in Figure 4.23, may be used to model the bond between stone and binder.

It is expected that grain shape and grain orientation may affect the behaviour of the seal surfacing. For that reason the model is parametrised, as indicated above. The model parameters may be used to alter the basic topology of the model:

- Average grain size in three directions (grain orientation);
- Number of grains per unit area;
- Thickness of the binder layer below the grains; and
- Volume of binder.

Apart from these fixed parameters the model is made so that a random generator may be used to vary the above parameters per grain. Grains with various sizes may be placed in the model as a result of this. Since grain shape is also considered to be an influencing parameter, a random generator may also be used to affect the grain shape. This random generator acts on the radius of the grain. Figure 5.24 shows the effects of these random generators on the topology of the mesh. For the mesh parameters used to generate the meshes in Figures 5.25, reference is made to Table 5.7.

![Mesh of the Seal Surfacing Generated with the Use of Random Generators](image)

**Figure 5.24:** Mesh of the Seal Surfacing Generated with the Use of Random Generators
5.7.1.2 Some Results

The randomly generated geometry makes it possible to do some low-level probabilistic analysis and furthermore distinguish between physical/chemical adhesion (to be modelled in the behaviour of the interface) and mechanical adhesion (to be modelled in the random grain geometry).

To get an indication of the behaviour of the mesh, two computations were made. Both computations refer to exactly the same situation. In one of the calculations the grains are all the same size and have a perfect shape (i.e. all st.devs are 0%) in the second calculation the grain size shows a st.dev. of 2% and the radius of the grains has a st.dev. of 5%. In the Table 5.7 more details about the meshes, the loading and material properties are provided.

Table 5.7: FEM Model parameter input

<table>
<thead>
<tr>
<th></th>
<th>Calculation #1</th>
<th>Calculation #2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>nominal</td>
<td>St.dev</td>
</tr>
<tr>
<td>grain length</td>
<td>12 mm</td>
<td>0%</td>
</tr>
<tr>
<td>grain width</td>
<td>8 mm</td>
<td>0%</td>
</tr>
<tr>
<td>grain height</td>
<td>6 mm</td>
<td>0%</td>
</tr>
<tr>
<td>grain radius</td>
<td>n.a.</td>
<td>0%</td>
</tr>
<tr>
<td>IF thickness</td>
<td>0.2 mm</td>
<td></td>
</tr>
<tr>
<td>IF shear stiff</td>
<td>100 N/mm³</td>
<td></td>
</tr>
<tr>
<td>IF normal stiff</td>
<td>500 N/mm³</td>
<td></td>
</tr>
<tr>
<td>Binder E</td>
<td>100 MPa</td>
<td></td>
</tr>
<tr>
<td>Binder Poisons Ratio</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>Load on central grains</td>
<td>z = 139.5 N</td>
<td>z = 1 Mpa</td>
</tr>
<tr>
<td></td>
<td>y = 139.5 N</td>
<td>y = 1 Mpa</td>
</tr>
</tbody>
</table>

The load is applied as a force on the upper node of each loaded grain. This force is based on an assumed average contact pressure between tyre and road surface.

In Figure 5.25 the deformed meshes are shown.
Figure 5.25: Deformation (50x) of the Meshes as Per Table 5.7

In Figure 5.25 the interface elements become visible. This is a result of the properties of these elements which in these calculations are such that stones may rotate within their shell of physical/chemical adhesion. This property of the model may prove to be of importance to explain loss of adhesion and thus loss of stones (ravelling). It may also help to understand stone rotation.

In Figure 5.26 the deformed mesh is shown in combination with strain. The figure shows concentration of strain around the stones in the direction of the shear load component, and that tensile and compressive strains are located close to each other. Figure 5.27 shows the stresses that develop.

Figure 5.26: Strain as it Develops in the Binder between Stones
Figure 5.27: Stress as it Develops in the Binder between Stones

Both Figures 5.26 and 5.27 show that stress and strain in the surfacing binder are not homogenous. Compression may exist directly adjacent to areas of tension and areas of highly stressed binder emerge. This type of information may prove to be of vital value when seal cracking is an issue.

Of course the discussed plots only enable qualitative insight into the computations. A further impression of the effects of grain shape is shown in Figure 5.28. In this figure a cross-section of the model is provided, where the rotations are shown for a mesh with the smooth stones, and the randomly shaped stones. The figure clearly shows that stone shape has an effect on stone rotation. This of course is again a strong indication that the model will be able to distinguish between physical/chemical adhesion (interface - behaviour) and mechanical adhesion (grain shape).

Figure 5.28: Comparison between Smooth and Randomly Shaped Stones