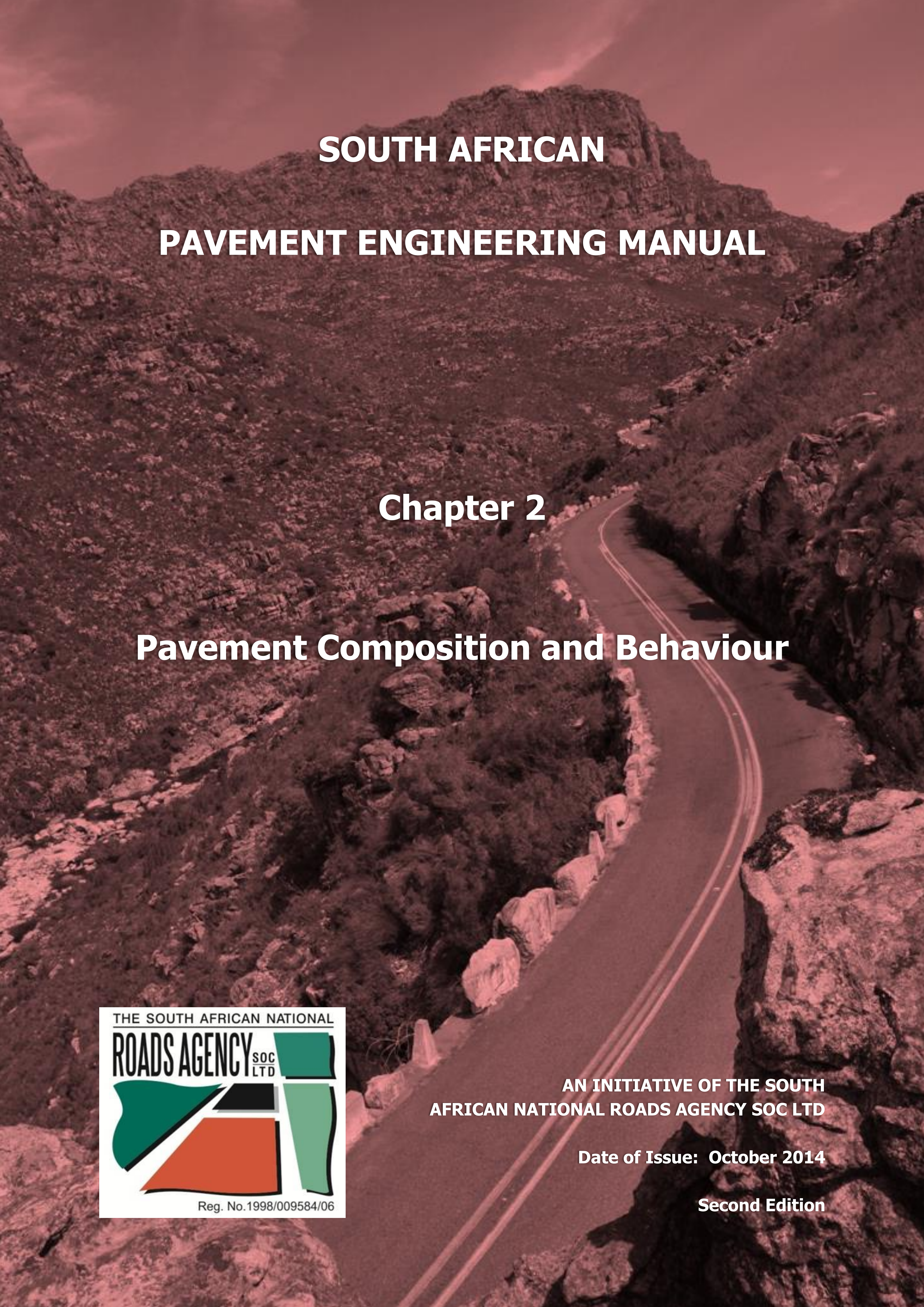

SOUTH AFRICAN

PAVEMENT ENGINEERING MANUAL

Chapter 2

Pavement Composition and Behaviour

THE SOUTH AFRICAN NATIONAL ROADS AGENCY SOC LTD

Reg. No.1998/009584/06

AN INITIATIVE OF THE SOUTH AFRICAN NATIONAL ROADS AGENCY SOC LTD

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Second Edition

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Chapter 2: Pavement Composition and Behaviour

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CHAPTER CONTEXT

The South African Pavement Engineering Manual (SAPEM) is a reference manual for all aspects of pavement engineering. SAPEM is a best practice guide. There are many relevant manuals and guidelines available for pavement engineering, which SAPEM does not replace. Rather, SAPEM provides details on these references, and where necessary, provides guidelines on their appropriate use. Where a topic is adequately covered in another guideline, the reference is provided. SAPEM strives to provide explanations of the basic concepts and terminology used in pavement engineering, and provides background information to the concepts and theories commonly used. SAPEM is appropriate for use at National, Provincial and Municipal level, as well as in the Metros. SAPEM is a valuable education and training tool, and is recommended reading for all entry level engineers, technologists and technicians involved in the pavement engineering industry. SAPEM is also useful for practising engineers who would like to access the latest appropriate reference guideline.

SAPEM consists of 14 chapters covering all aspects of pavement engineering. A brief description of each chapter is given below to provide the context for this chapter, Chapter 2.

Chapter 1: **Introduction** discusses the application of this SAPEM manual, and the institutional responsibilities, statutory requirements, basic principles of roads, the road design life cycle, and planning and time scheduling for pavement engineering projects. A glossary of terms and abbreviations used in all the SAPEM chapters is included in Appendix A. A list of the major references and guidelines for pavement engineering is given in Appendix B.

Chapter 2: Pavement Composition and Behaviour includes typical pavement structures, material characteristics and pavement types, including both flexible and rigid pavements, and surfacings. Typical materials and pavement behaviour are explained. The development of pavement distress is discussed, along with the types of distresses usually associated with particular pavement types. The functional performance of pavements is also presented. As an introduction and background for reference for the other chapters, particularly Chapter 10, the basic principles of mechanics of materials and material science are outlined. Climatic issues, variability in pavements and life cycle strategies are also covered.

Chapter 3: Materials Testing presents the tests used for all material types used in pavement structures. The tests are briefly described, and reference is made to the test number and where to obtain the full test method. Where possible and applicable, interesting observations or experiences with the tests are mentioned. Chapters 3 and 4 are complementary.

Chapter 4: Standards follows the same format as Chapter 3, but discusses the standards used for the various tests. This includes applicable limits (minimum and maximum values) for test results. Material classification systems are given, as are guidelines on mix and materials composition.

Chapter 5: Laboratory Management covers laboratory quality management, testing personnel, test methods, and the testing environment and equipment. Quality assurance issues, and health, safety and the environment are also discussed.

Chapter 6: Road Prism and Pavement Investigation discusses all aspects of the road prism and pavement investigations, including legal and environmental requirements, materials testing, and reporting on the investigations. The road pavement investigations include discussions on the investigation stages, and field testing and sampling (both intrusively and non-intrusively), and the interpretation of the pavement investigations. Chapters 6 and 7 are complementary.

Chapter 7: Geotechnical Investigations and Design Considerations covers the investigations into fills, cuts, structures and tunnels, and includes discussion on geophysical methods, drilling and probing, and stability assessments. Guidelines for the reporting of the investigations are provided.

Chapter 8: Material Sources provides information for sourcing materials from project quarries and borrow pits, commercial materials sources and alternative sources. The legal and environmental requirements for sourcing materials are given. Alternative sources of potential pavement materials are discussed, including recycled pavement materials, construction and demolition waste, slag, fly ash and mine waste.

Chapter 9: Materials Utilisation and Design discusses materials in the roadbed, earthworks (including cuts and fills) and all the pavement layers, including soils and gravels, crushed stones, cementitious materials, primes, stone precoating fluids and tack coats, bituminous binders, bitumen stabilized materials, asphalt, spray seals and micro surfacings, concrete, proprietary and certified products and block paving. The mix designs of all materials are discussed.

Chapter 10: Pavement Design presents the philosophy of pavement design, methods of estimating design traffic and the pavement design process. Methods of structural capacity estimation for flexible, rigid and concrete block pavements are discussed.

Chapter 11: Documentation and Tendering covers the different forms of contracts typical for road pavement projects; the design, contract and tender documentation; the tender process; and the contract documentation from the tender award to the close-out of the Works.

Chapter 12: Construction Equipment and Method Guidelines presents the nature and requirements of construction equipment and different methods of construction. The construction of trial sections is also discussed. Chapters 12 and 13 are complementary, with Chapter 12 covering the proactive components of road construction, i.e., the method of construction. Chapter 13 covers the reactive components, i.e., checking the construction is done correctly.

Chapter 13: Quality Management includes acceptance control processes, and quality plans. All the pavement layers and the road prism are discussed. The documentation involved in quality management is also discussed, and where applicable, provided.

Chapter 14: Post-Construction incorporates the monitoring of pavements during the service life, the causes and mechanisms of distress, and the concepts of maintenance, rehabilitation and reconstruction.

FEEDBACK

SAPEM is a "living document". The first edition was made available in electronic format in January 2013, and a second edition in October 2014. Feedback from all interested parties in industry is appreciated, as this will keep SAPEM relevant.

To provide feedback on SAPEM, please email sapem@nra.co.za.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

This chapter lays the foundation for the other chapters of SAPEM, and provides much of the background information required to understand the elements that go into pavement engineering. The rationale behind the types of structures used for pavements, and typical pavement structures are presented, including the types and characteristics of materials generally used. A section on material science is included, to explain the concepts used when analysing pavement structures. The chapter ends with sections on climate, drainage, variability and life cycle strategy.

At the outset, one of the fundamental concepts used in pavement engineering is the nature of materials included in the layers. Two primary classifications of materials can be made:

- **Unbound Materials**: This includes graded crushed stone, natural and crushed gravels, sand and soils. As traffic loads are applied, these granular materials interact with the layer beneath and respond with a stiffness that defines the extent of load spreading (stress distribution) in the structure. Only modest stress distribution is possible with unbound materials, given the moderate stiffness of their response. Repeated loads lead to an accumulation of deformation.
- **Bound Materials**: This includes hot mix or warm mix asphalt, concrete, and cemented layers amongst others, which incorporate binders that "glue" the particles together. The materials have higher stiffness that results in flexural bending under load, and wide stress distribution. The bending beam effect results in the generation of significant tensile stresses in the layer, leading to damage in the form of cracking.

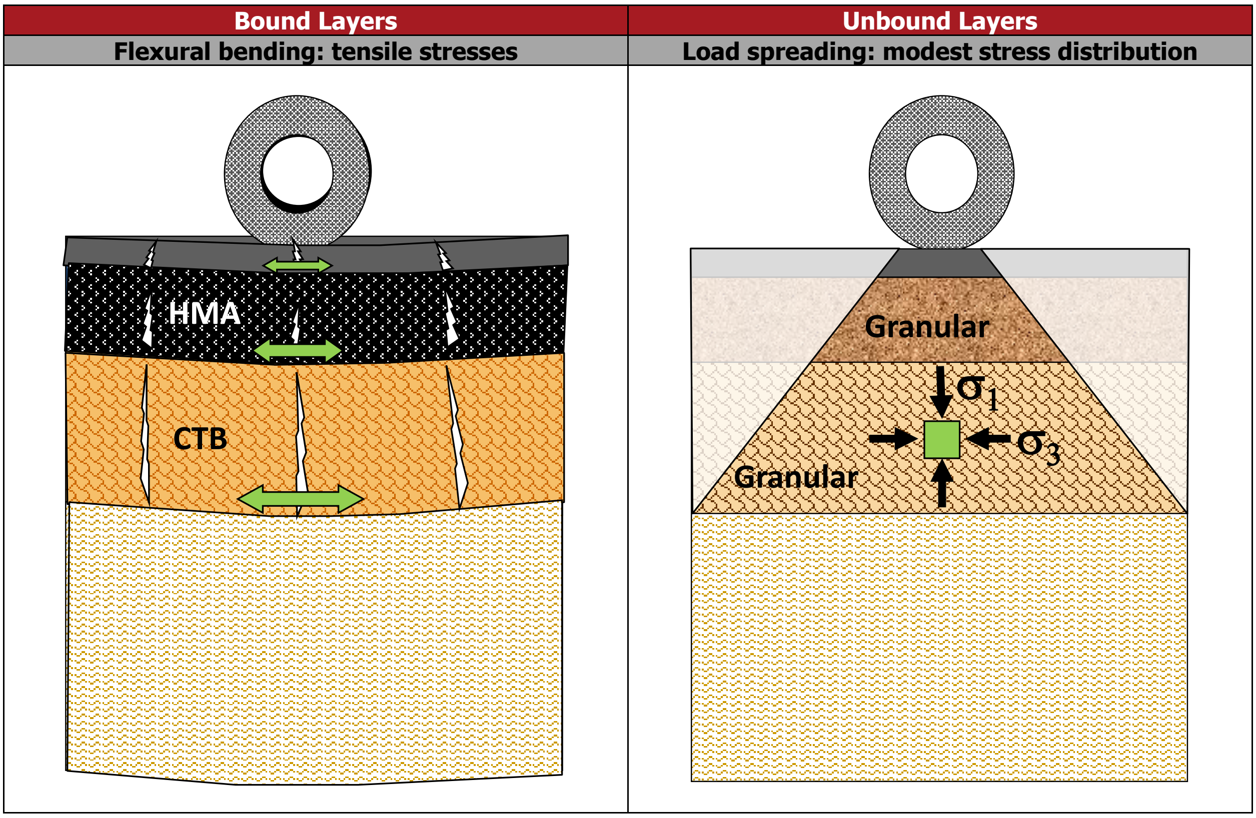


Figure 1. Two Categories of Pavement Materials and their Response to Loading

2. PAVEMENT STRUCTURE

The pavement structure is the combination of layers and the subgrade, which carries the traffic loads. Typical pavement layered structures and names for each layer used in contemporary road construction are shown in Figure 2 for flexible and rigid pavements. These pavement structures are not that different to those used in the old Roman roads, discussed in Chapter 1: 2.1, but are more refined. The pavement engineer needs to understand the particular behaviour of each layer and how this influences the layer's ability to fulfil its purpose. For example, the base layer's ability to spread loads onto the underlying layer and support the surface is of particular importance.

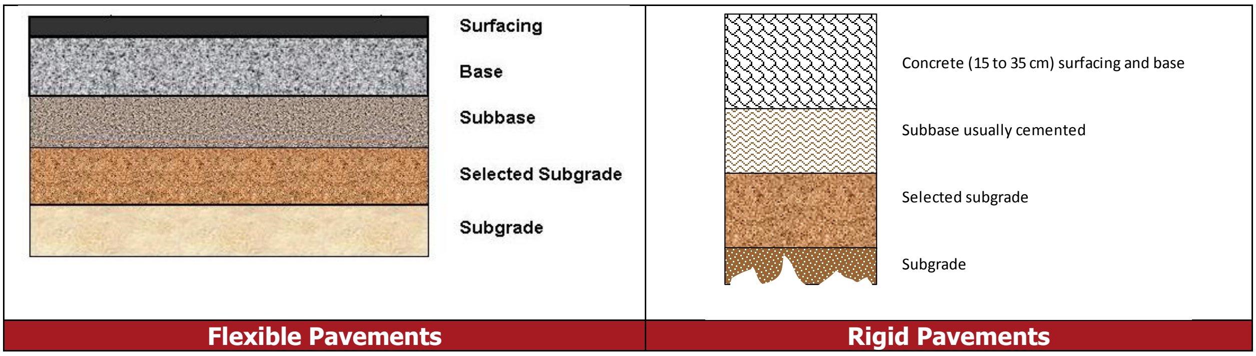


Figure 2. Typical Surfaced Pavement Structures

The purposes of the various layers in the pavement are described below:

- **Surfacing**: This is a functional wearing course that provides waterproofing, skid resistance, noise-damping, durability against the elements, visibility and drainage. For surfaced roads, the upper layer is bound, consisting of spray seals, asphalt or concrete.
- **Base**: This is a load spreading layer and is the most important structural component of the pavement. The layer must provide the required support for the surfacing and distribute the very high tyre pressures and wheel loads uniformly over the underlying layers and subgrade. The base comprises bound material, e.g., asphalt, concrete or stabilized, or it can be unbound, e.g., crushed stone or gravel base.
- **Subbase**: This layer provides support for the base as well as a platform upon which to construct a structural base layer of high integrity. It also protects the underlying selected subgrade layer by further spreading the load.
- **Selected subgrade**: These layers are primarily capping for the subgrade to provide a workable platform on which to construct the imported pavement layers. At the same time, these layers provide depth of cover over the subgrade to reduce the stresses in the subgrade to acceptable levels.
- **Subgrade**: This is the existing material upon which the pavement must be constructed. It can be modified with stabilizers to reduce plasticity, ripped and recompacted to achieve uniform support, or undercut and replaced, depending on its quality.

Typically, the higher up the layer is in the pavement structure, the more expensive the material to obtain or manufacture. Asphalt and concrete surfacing layers in a pavement are generally the most expensive layer in the pavement structure. It is also typical for the stiffer pavement layers to be at the top of the pavement structure. The exception to this is "inverted" flexible pavements, where the subbase layer is cement stabilized and the base layer is a good quality granular layer. These pavements are widely used in South Africa.

2.1 Pavement Types

Road pavement types can be classified according to the type of materials used to construct the upper layers, in particular the surfacing. The types of materials, whether flexible such as asphalt, or rigid such as concrete, determine the performance of a pavement in a given climate with a certain level of traffic, and the distress mechanisms that manifest in the pavement with time. The different distress types are discussed in Chapter 14: 4. An overview of different pavement types is provided in Figure 3, with cross-sections of typical pavement structures given in Figure 4.

Flexible and Rigid Pavements

Flexible pavements typically have asphalt or seal surfacings. They are flexible in that they can bend on the support.

Rigid pavements are typically concrete pavements, and the concrete layer acts in a rigid manner in that it does not bend.

See Chapter 10 for discussion on many aspects of rigid and flexible pavement design.

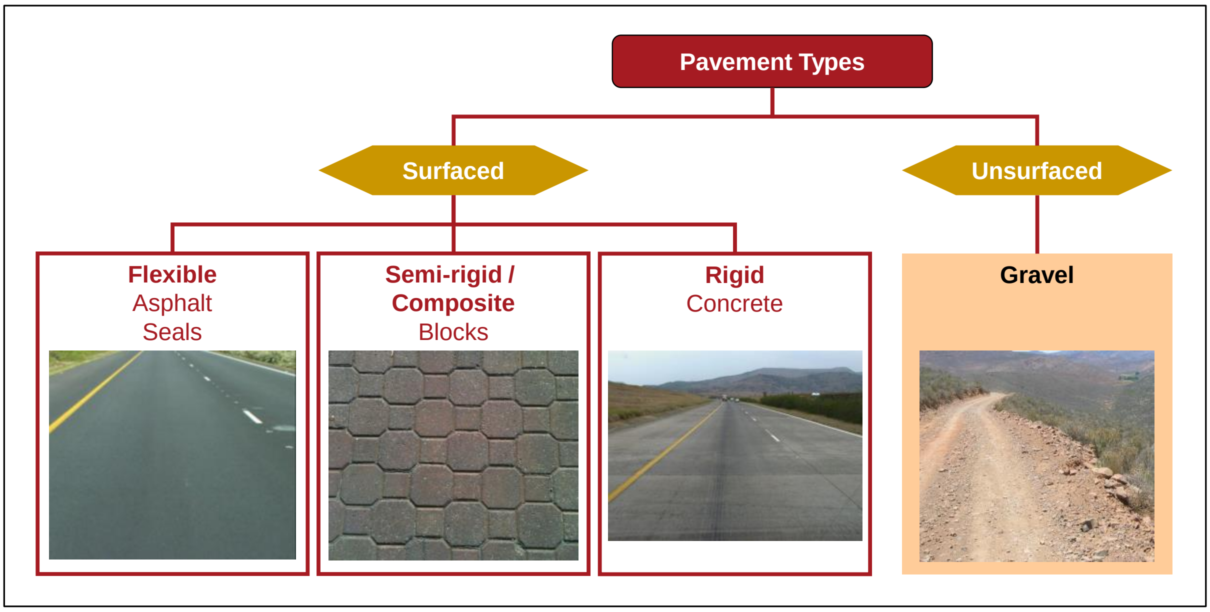


Figure 3. Classification of Pavement Types based on Materials

Figure 4. Example Cross-sections of the Typical Pavement Materials

2.2 Road Classifications Based on Function and Traffic Levels

In addition to pavement types differentiated on the materials in the upper pavement layers, they are also classified according to their applications and levels of traffic, as summarized in Table 1.

Table 1. Classification of Pavements Based on Application and Traffic

Facility	Traffic Class[1]	Loading
Freeway	Heavy, 30 to 100 MESA[2]	Light and heavy vehicles
Arterial and Main Road	Medium > 3 MESA	Light and heavy vehicles
Secondary Road	Light > 0.3 MESA	Low percentage heavy vehicles
Low Volume Road	LVR = 50 to 200 vpd[3]	Mainly light vehicles

Notes:
1. Traffic Class is also defined in TRH4 according to the upper limit of Equivalent Standard Axles (ES), e.g., ES100 = 30 to 100 million 80 kN axles.
2. MESA = million equivalent standard axles (80 kN is the standard in South Africa, even though the maximum legal axle mass is 90 kN). See Chapter 10: 4.1.3.
3. vpd = vehicles per day

Roads and their related pavements are also be classified based upon the importance of their function and the importance of the user trips made on the road. Functional classification is used to differentiate the minimum service levels for each class of road to set intervention levels with related budgetary implications. This functional classification is discussed in Chapter 1: 4 and normally entails:

- **Class 1, Primary Arterials:** High mobility between important cities, countries and transport hubs.
- **Class 2, Secondary Arterials:** Mobility links between slightly less important centres or connections to the primary road network.
- **Class 3, Minor Arterials:** Connections between districts centres or between these centres and the primary and secondary road network.
- **Class 4, Collectors:** Provide connections to the higher order network.
- **Class 5, Access Roads:** Provide access to individual properties.

Pavement Classification

In most cases, the functional classification of a road will match the pavement classification with arterial and main roads being primary roads, but this is not always the case. For example, roads to relatively remote border posts may be primary roads in view of their importance in respect of security, but only carry low traffic volumes.

2.3 Flexible Pavements

2.3.1 Types of Surfacing

2.3.1.1 Asphalt Surfacing

Asphalt surfacings provide the interface between the tyres of vehicles and the pavement, and are, therefore, one of the main structural layers of the pavement. They should meet the engineering properties and should be textured for adequate skid resistance. The following asphalt surfacings are generally used:

- Gap-graded (AG)
- Continuously graded (AC)
- Semi-gap-graded (AS)
- Open graded (AO)
- Stone mastic asphalt (SMA)
- Semi-open graded asphalt (ASO)
- Ultra-thin friction course (UTFC)

Asphalt Surfacings

Asphalt surfacings are discussed in detail in Chapter 9: 10.5.

Asphalt surfacings, or wearing coarses, can be divided into two broad categories in terms of their primary purpose:

- **Structural** layers generally have a specified thickness of more than 30 mm. They are designed to contribute measurably to the strength of the pavement and to provide adequate skid resistance for the prevailing traffic and climate conditions.
- **Functional** layers have a specified thickness of less than 30 mm and do not contribute significantly to pavement strength. They are best described as surface dressings that meet functional criteria such as:
  - Suitable surface texture for **skid resistance**, **noise reduction** and surface water **drainage,** given the traffic volumes, speed and prevailing climate.

- **Sealing** of the substratum against water penetration.
- Limited improvement of **riding quality.**

Functional layers are used in two distinct applications:

- **Thin asphalt layers** for low speed and light traffic applications, mainly in residential areas.
- **Ultra-thin friction courses** (UTFC) for high volume, often high speed, applications on major highways. See Chapter 9: 10.5 for more on UTFCs.

In South Africa, typical asphalt surfacings are between 30 and 50 mm thick.

2.3.1.2 Seals

Approximately 80% of South Africa's surfaced roads are sealed with a seal, either as the initial surfacing or as a reseal. A spray seal consists of a coat of bituminous binder sprayed onto the road surface, which is then immediately covered with a layer of aggregate, rolled and broomed to ensure close contact and thus good adhesion between the aggregate and the binder film.

There are a number of seal types available, each having specific advantages and/or disadvantages. The various seal types that are commonly constructed are illustrated schematically in Figure 5a and b. These figures are from TRH3: Design and Construction of Surfacing Seals.

Seals

A good reference for seals is **TRH3:** Design and Construction of Surfacing Seals.

In **SAPEM**, seals are discussed in:

- Chapter 3, **Materials Testing**: Section 4.4
- Chapter 4, **Standards**: Section 4.4
- Chapter 9, **Materials Utilisation and Design**: Section 11
- Chapter 12, **Construction Equipment and Method Guidelines**: Section 3.10 and 4.2
- Chapter 13, **Quality Management**: Section 7

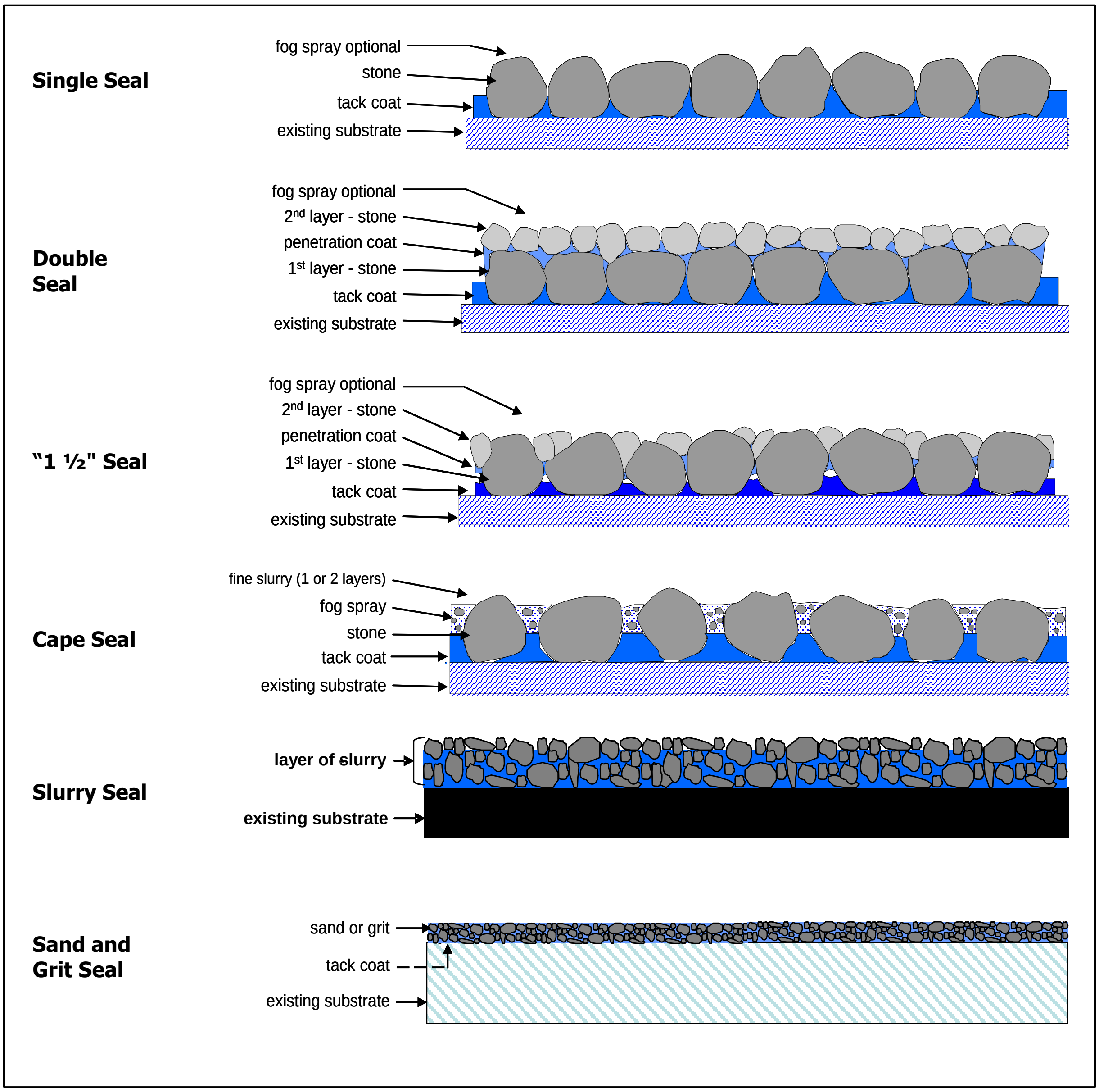


Figure 5. Schematic Illustration of Seal Types (a)

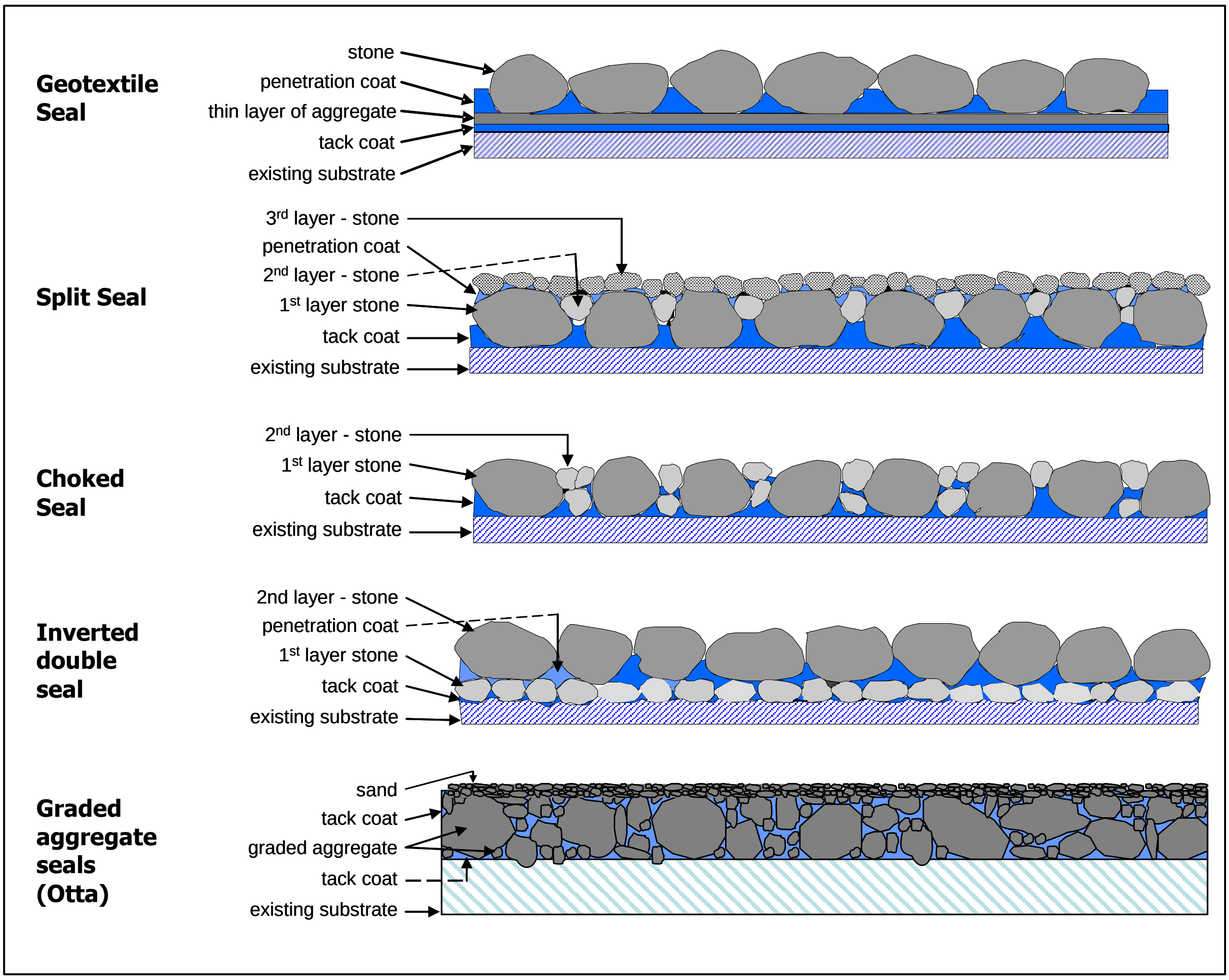


Figure 5. Schematic Illustrations of Seal Types (b)

2.3.2 Types of Bases and Subbases

There are various types of bases and subbases typically used in pavement stuctures.

- **Granular** layers range from well graded natural gravels to crushed gravels and crushed stone bases.
  - G1 crushed stone bases are a unique form of crushed stone base, and have specific gradings and construction methods to ensure the layers have a high density. See more in Chapter 12: 3.8.
  - Waterbound macadam is another unique type of crushed stone base. It consists of large particles of stone (37 mm) in a matrix of non-plastic sand that is washed and vibrated in between the large stones with large amounts of water.
- **Cemented** layers range from weakly cemented natural gravels to strongly cemented, durable crushed stone.
  - The addition of small amounts of cement to a natural gravel reduces the material's moisture susceptibility.
  - Lightly cemented layers are used to provide a good support to high quality crushed stone and BSM layers.
  - Strongly cemented, durable crushed stone layers act as a support for concrete or thick bituminous layers.
- **Bituminous** bases normally have large aggregates and bituminous binders that are less moisture susceptible than granular materials.
- **Bituminous Stabilized Materials (BSM)** are gravels and crushed stone materials stabilized with bitumen and small amounts of cement or lime, to provide some strength but primarily to reduce moisture susceptibility, while retaining more flexibility than a purely cementitious layer.

Testing of Component Materials

Information on the appropriate standards and testing of the component materials for all pavement materials are covered in Chapters 3 and 4.

2.4 Rigid Pavements

In South Africa and overseas, a number of concrete pavement types have been constructed, and are illustrated in Figure 6. The following types, which differ only by the crack control criteria, are the most common concrete road pavements in South Africa.

- **Jointed** unreinforced (plain) concrete that can be doweled or undoweled
- **Jointed reinforced** concrete pavement with light reinforcement to increase joint spacing
- **Continuously** reinforced concrete pavement (CRCP)
- **Ultra-thin** concrete pavement (UTCP)

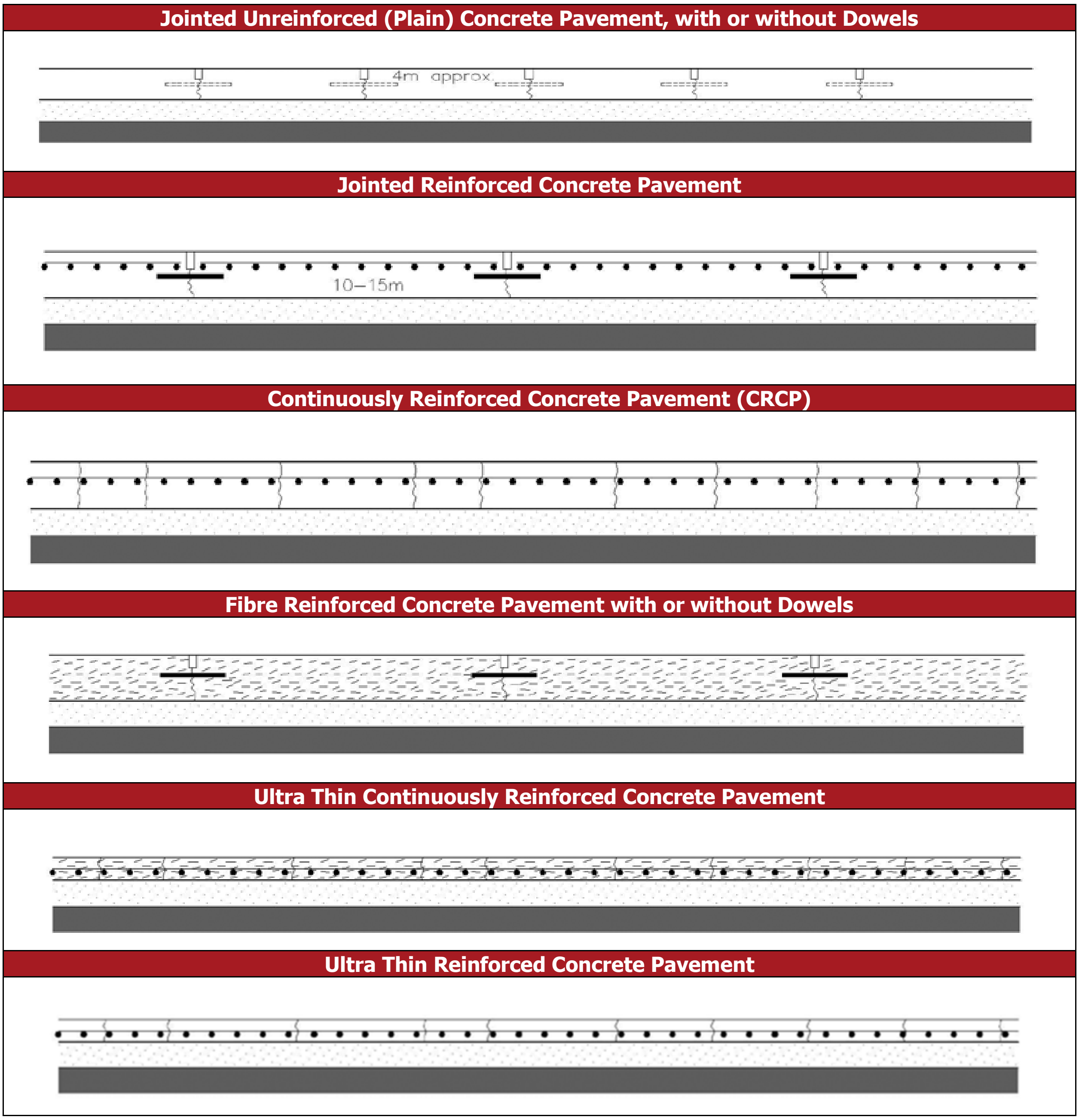


Figure 6. Schematic Illustrations of the Types of Rigid Pavements

Concrete Pavements

Good references for concrete pavements are:

- **Fulton's** Concrete Technology. 2009. 9th edition, Cement & Concrete Institute.
- **Concrete Road Construction**. 2009. Cement and Concrete Institute (C&CI).

These references are available from The Concrete Institute, www.theconcreteinstitute.org.za.

In **SAPEM**, concrete pavements are discussed in:

- Chapter 3, **Materials Testing**: Section 5.1
- Chapter 4, **Standards**: Section 5.1
- Chapter 9, **Materials Utilisation and Design**: Section 12
- Chapter 10, **Pavement Design**, Sections 2.2 and 8
- Chapter 12, **Construction Equipment and Method Guidelines**: Sections 2.9, 3.12 and 4.7
- Chapter 13, **Quality Management**: Section 8
- Chapter 14, **Post-Construction**, Section 4.2

2.4.1 Types of Support Layers

While the subbase provides the primary support to the base, lower layers such as selected subgrade layers in turn support the subbase. The specifications for these layers depend primarily on the subgrade conditions and need to provide adequate cover to the subgrade to support the subbase. The quality and strength gradually improves towards the surface, to provide a balanced structure.

2.5 Gravel Roads

Unpaved roads require a competent wearing course to carry the required loads when wet and also provide adequate cover to the underlying subgrade. As gravel roads are easy to re-shape when deformed, the material requirements in terms of strength are less stringent. The material, does however, need to be resistant to erosion when exposed to traffic and the environment.

Gravel Roads

Gravel roads are not extensively covered in this manual as they are adequately addressed in other references. The principles and material tests involved with the provision of gravel roads are the same as for paved roads.

A good reference for gravel roads is:

- TRH20. **Unsealed Roads: Design, Construction and Maintenance.** Technical Recommendations for Highways.
- **Towards Appropriate Standards for Rural Roads**: Discussion Document (SARB, 1993)

3. MECHANICS OF MATERIALS (STRESSES AND STRAINS)

To further understand how pavements and materials behave, and how this behaviour is modelled in mathematical terms to enable design predictions, it is necessary to understand the concepts of stress and strain in these materials. This section discusses these concepts, and their application to pavement engineering.

3.1 Definitions of Stress and Strain

Consider an element of material, with an original length L as shown in Figure 7 with a normal tensile force F applied to it. The force F divided by the cross-sectional area A is defined as the stress, called sigma (σ), as shown in Equation (1).

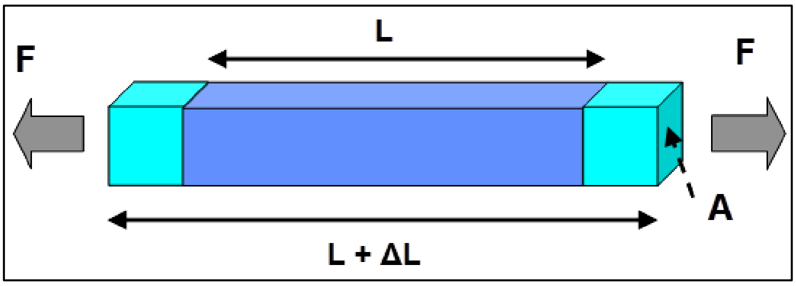


Figure 7. Force Applied to an Element of Material

$$\text{Stress} \quad \sigma = \frac{F}{A} \quad (\text{N/m}^2 \text{ or Pascal}) \qquad (1)$$

The units of stress are the same as for pressure. In other words, the element of material is experiencing an internal "pressure" when a force is applied to it. Normal stresses can either be tensile, causing extension, or compressive, causing shortening of the element. In the example in Figure 7, the material is subjected to a tensile stress.

> **Units for Stress**
> We typically use the unit kPa for tyre pressure and MPa for stiffness.

The applied stress results in some elongation of the block. In this case, the total elongation is ΔL. This elongation is represented as strain ε, called epsilon, which is defined as the unit linear change in length, and is calculated in the manner shown in Equation (2). Strain is dimensionless. Sometimes microstrain, $\mu\varepsilon = 10^{-6}\ \varepsilon$, is used as a dimensionless unit for strain, because this gives more understandable and manageable values.

$$\text{Strain} \quad \varepsilon = \frac{\Delta L}{L} \qquad (2)$$

3.2 Normal and Shear Stresses and Strains

The definitions of stress and strain were limited to one-dimension. Materials, however, exist in three dimensions. Imagine a small cube of material, subjected to stresses at any point within a pavement structure, as illustrated in Figure 8 with a Cartesian x-y-z coordinate system. The figure illustrates stresses, but the definitions and discussion are also relevant for strains. Normal stresses are defined as the stresses that act perpendicular to a particular face of the cube. For example, the stress acting in the z-direction, perpendicular to the z-face (the face perpendicular to the direction, in the x-y plane) is called σ_{zz}. Similarly, σ_{xx} and σ_{yy} are the other normal stresses. Normal stresses can be tensile or compressive.

The stresses that act parallel to a face are called shear stresses. For example, $\sigma_{zy,}$ is the shear stress acting on the z-plane in the y direction. Normal stresses invoke volume changes in the cube, whereas shear stresses invoke shape changes, as illustrated in Figure 9. Generally however, normal and shear stresses act on a material simultaneously, invoking both volume and shape changes.

In total, there are 3 normal stresses and 6 shear stresses that are needed to quantify the stress state. The value of each of these 9 stresses depends on the chosen coordinate system. Fortunately, it is always possible to rotate the cube until a position is reached where there are no shear stresses, and only normal stresses. This rotated position is known as the principal axes, and the normal stresses are the principal stresses. In the principal axes space, the maximum stress is known as the first principal stress, or σ_1. The smallest stress is known as the third principal stress, or σ_3. The principal stress space is useful as only three stresses are required to quantify the full stress state, and the values of the three stresses are not dependant on the chosen coordinate system.

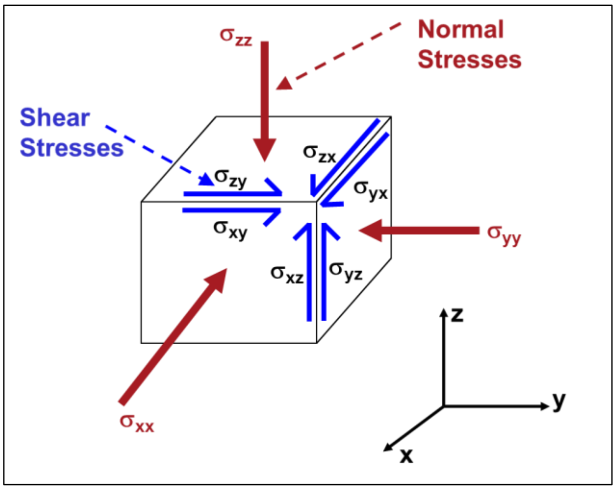


Figure 8. Normal Stresses

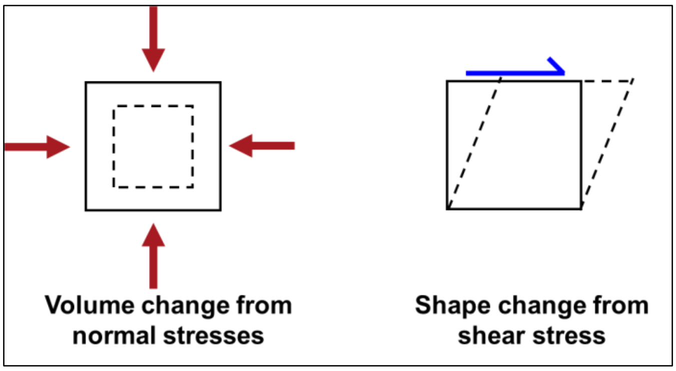


Figure 9. Volume and Shape Changes

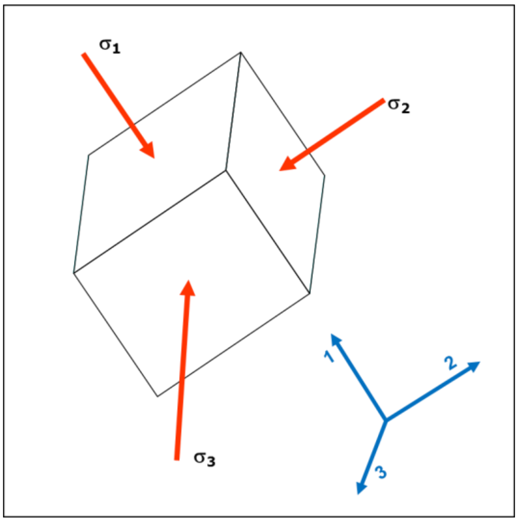


Figure 10. Principal Stresses

4. PAVEMENT DESIGN CONSIDERATIONS

Pavement design is the process to decide on the pavement structure, in terms of the type of structure, the materials and the layer thicknesses. The basic objective of pavement design is to combine materials of sufficient strength in a layered system to provide the desired functional and structural service levels over the design period, subject to the applicable traffic demand and the particular environment. Protection of the subgrade, through sufficient cover with the appropriate qualities, is the essence of pavement design.

The design commences with investigations aimed at developing an adequate understanding of the properties of the subgrade and other materials in the road prism to determine the expected long term performance of the pavement structure, as well as the locally available materials to be cost-effectively used in the pavement. This is covered in detail in Chapters 6, 7, 8 and 9.

Although the final design decision is dictated by the most economically viable design, the process of ensuring that a pavement with adequate strength is provided is critical. The economic validity of a design is determined by several factors:

- Functional and structural **service levels**
- Rates at which **service levels deteriorate**
- **Costs** associated with the provision and maintenance of these service levels
- **Savings** by the road users resulting from improved service levels

The philosophy, principles and details of several different design methods, applicable to new pavements and pavements requiring rehabilitation, are included in Chapter 10, Pavement Design.

This section provides information on pavement material characteristics and behaviour for pavement engineers to develop an understanding of fundamental pavement material's behaviour and related thinking. This needs to be applied to make optimal use of available materials and achieve good designs that provide the necessary functionality and performance. It is essential for pavement engineers to understand how pavement materials behave, so they can predict performance in general terms, and seek appropriate mathematical models for more specific design predictions. Unthinking and irresponsible application of design methods, without considering fundamental behaviour must be avoided. All design outputs must be backed up by a rational understanding of the potential causes and mechanisms of distress that are likely to occur over time.

Role of the Pavement Engineer

It is essential for pavement engineers to understand how pavement materials behave, so they can predict performance in general terms, and seek appropriate mathematical models for more specific design predictions. Unthinking and irresponsible application of design methods, without considering fundamental behaviour must be avoided.

4.1 Material Characteristics and Behaviour

Material characteristics and their influence on behaviour must be thoroughly understood when carrying out pavement analyses and designs. All road materials comprise mineral aggregates as their main component. Some materials have binders added to improve performance, such as cementitious binders, bituminous binders or mineral fillers. The fundamental types of materials that are used in road pavements are:

- **Granular** or **unbound:** natural gravels or crushed rock
- **Modified:** mechanically or chemically
- **Cemented (bound):** concrete or lightly cemented aggregates
- **Bituminous (bound):** hot mix asphalt, seals or bitumen stabilized

The primary function of pavement materials is to spread the traffic load induced stresses to all the underlying pavement layers. It is important to note that there are a number of fundamental properties that influence the behaviour of a material, regardless of its situation, while there are also several situational properties that influence behaviour. These can be summarized as follows:

- **Fundamental properties** (nature of materials)
  - Grading or particle size distribution
  - Inter-particle friction

Art of Pavement Engineering

The art of pavement design is to ensure that materials within the pavement layers are not overstressed at any time during the course of these changes in the pavement's life.

- Clayeyness/cohesion, or the degree to which particles are stuck together when wet or soaked
- Elasticity, plasticity and viscosity
- Particle hardness
- Durability
- Porosity and absorption

- **Situational properties**
  - Density: increased packing and reduced permeability
  - Moisture content: includes issues such as adsorbed moisture in clays and apparent cohesion when unsoaked, as well as soil suction due to capillary action between finer soil particles
  - Temperature
  - Support, which influences the stress situation, which in turn influences the stiffness of stress-sensitive materials
- **Engineering Properties**
  - Ultimate strength in terms of shear, tensile and compressive strength
  - Elastic modulus: stiff to spread loads, or flexible to allow lower layers to carry the loads and to bend without breaking
  - Resistance to deformation
  - Fatigue: number of movements or loads required to cause permanent damage in the form of cracking

The stress situation and materials characteristics of the entire pavement change continuously over time with environmental changes, and also as material stiffness changes and transfers loads to lower layers. The art of pavement design is to ensure that materials within the pavement layers are not overstressed at any time during the course of these changes in the pavement's life.

It is useful to consider the fundamental, situational and functional properties in more detail.

4.1.1 Fundamental Properties

Figure 11 shows the typical packing of particles in a granular layer as a background to the fundamental properties discussed below. The blue background represents voids between the particles that can be partially filled with water or stabilizer.

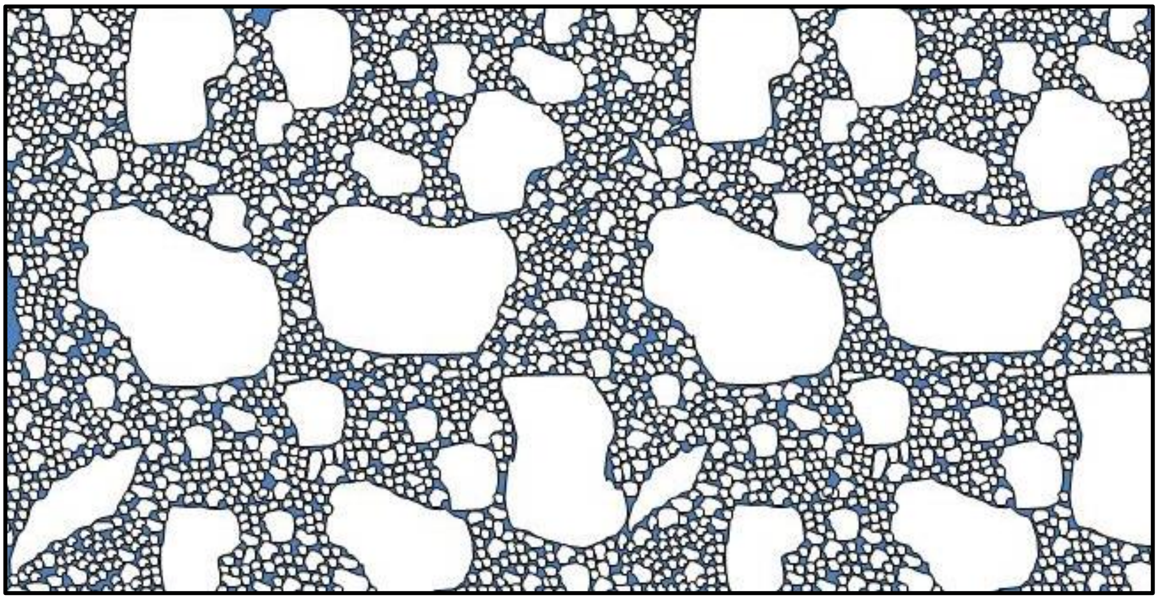


Figure 11. Typical Particle Packing in a Granular Material

- **Grading or particle size distribution.** Figure 11 illustrates a grading or particle size distribution**,** with several coarse stones in a finer matrix, which is typical of most naturally occurring road-building materials or crushed rock. In this type of material, the behaviour of the finer material dominates the behaviour of the layer. As the material gets coarser, the coarse particles begin to dominate the behaviour of the material. The grading modulus (GM) (Chapter 3: 2.3.2) provides an indicator of the relative quantity of fine material, and whether the coarse or fine material dominates the behaviour. Many material classification systems (Chapter 4: 2.3) use the particle size distribution as one of the primary classification elements. Specifications and classifications (Chapter 4) normally also have limits on the Grading Modulus of layers, depending on their position in the pavement and the stresses they bear.

Examples of the influence of the grading on performance for coarse materials include the G1 crushed stone base. In a G1, the particles are carefully graded to ensure optimal packing, and the material has low permeability and a high resistance to deformation. Any variation in the grading results in an increase in permeability, allowing water to enter the layer with a significant reduction in deformation resistance. Construction of G1s is discussed in Chapter 12: 3.8. Another example for finer materials are non-plastic sands classified as A3 in the AASHTO Classification (Chapter 4: 2.3.2). This class of material is a non-plastic sand, typically with rounded wind-blown particles and has less than 10% fine material passing the 0.075 mm sieve. This material is loose, cannot easily be compacted and has very little resistance to deformation. As soon as the percentage passing the 0.075 mm sieve exceeds 10%, the material becomes compactible and classifies as an A2-4 material, which can achieve very high resistance to deformation when well compacted.

Typically, a material with a single particle size will have around 40% voids between the particles. As the particle size distribution improves with a blend of most particle sizes, the material has fewer and fewer voids. The minimum possible void content in a granular material, is typically obtained in a well compacted crushed stone base with a density of 88% of solid density, or 12% voids. This can only be achieved in a stony material, where all the particles are hard and cannot be broken down during compaction.

- **Harder particles** provide greater stability and do not break down under compaction, thus retaining the grading of the material. Softer particles often break down during compaction, resulting in a finer material in the pavement layer than was originally placed.

- **Durability**. Some particles break down or weather in the road and have poor **durability**. These include almost all materials that can disintegrate when exposed to the atmosphere.

- **Roughness and angularity**. The surface roughness or rugosity of the material, as well as the degree of angularity affects inter-particle friction and the compactibility of the material. Flaky particles can also resist compaction by creating voids underneath the particles.

  While compactibility is reduced with increased inter-particle friction, the strength of the material in terms of its resistance to shear failure and deformation is increased. Moisture is added to facilitate compaction and non-plastic materials compact best when saturated.

Materials Properties

The material properties discussed here are all described in detail in Chapters 3 and 4, along with the tests used to measure the properties and standards used to assess them.

- **Plasticity Index**. The presence of fine plastic materials or clay helps the particles slide over one another and improves compactibility, but also reduces its shear strength, particularly when wet. For this reason the plasticity index (PI) is normally limited in materials used in pavements, particularly in the upper layers.

- The **clay content** and **activity** of the clay is a very important parameter in road-building materials. This is due to the ability of the clays particles to adsorb water on their surfaces due to the electron imbalances. Highly active clays swell substantially when adsorbing water, and shrink again upon drying out.

- **Cohesion**. When a cementitious or bituminous stabilizing agent is added to the material, this helps to bond the particles together when soaked, which is termed the cohesion. In most cases of cementitious stabilization of natural gravels, the stabilizer reacts with the clay in the material, reducing its plasticity and increasing inter-particle friction. This reduces the densities that can be achieved.

4.1.1.1 Material Models

To be able to model material and pavement behaviour in any detail, fundamental response models are used. There are three fundamental types of theoretical material responses used to model material behaviour applicable to pavement engineering:

- Elasticity
- Plasticity
- Viscosity

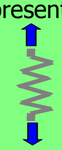
There are very few road building materials that follow one discrete mode of response. The response models often need to be combined to model material behaviour more accurately, as shown in the examples below:

- **Elastic** behaviour: cement or concrete
- **Elasto-plastic** behaviour: granular materials
- **Visco-elastic** behaviour: bituminous materials
- **Visco-elasto-plastic** behaviour: asphalt

The basics of these response models are described below. Thereafter, their application to granular, cemented and bituminous materials is explained.

Elasticity Symbol

Elasticity is represented by a spring.



(i) Elasticity

Elasticity, represented by a spring, is explained in Figure 12, where a material responds immediately to loading and deforms. With a sustained load the material does not change, i.e., it is not time dependent. Upon unloading, the deformation is fully recoverable.

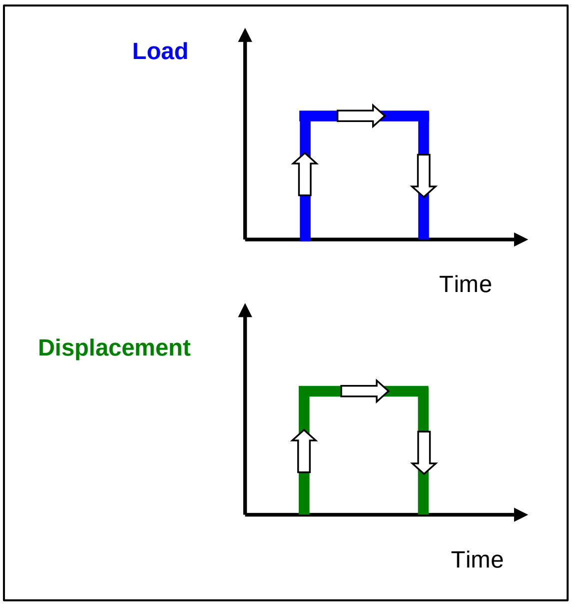


Figure 12. Elastic Response to a Load, Sustain, Unload Cycle

Linear elastic behaviour implies that the relationship between stress and strain is linear. According to Hooke's Law, a simple relationship exists between stress and strain for linear elastic behaviour. This law states that the slope of the stress-strain relationship reflects the material stiffness or Elastic Modulus, also known as Young’s Modulus, see Figure 13, and Equation (3).

Elastic (Young’s) Modulus: $$E = \frac{\sigma}{\varepsilon} \qquad (3)$$

Where
E = Elastic modulus, usually in MPa
σ = Stress
ε = strain

The point at which this relationship deviates from the linear form for a specific material, is called the linear elastic limit. If loading is removed before the elastic limit is reached (whether linear or non-linear), the strain is recoverable or elastic, which means that the material recovers completely with no residual stress and strain. If loading continues beyond the elastic limit, some materials experience a reduction in stiffness as the material begins to yield, up to the ultimate strength. The maximum stress that a material can withstand is also known as an ultimate stress, which can be either compressive or tensile, depending on the nature of the stress applied. The ultimate stress is a measure of the material’s strength.

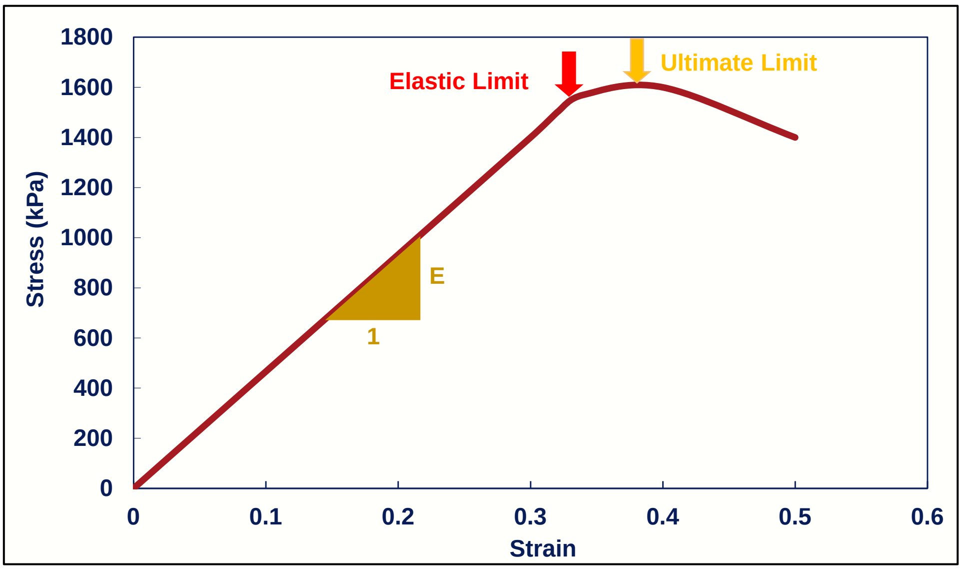


Figure 13. Elastic Modulus as a Function of Stress and Strain

(ii) Poisson's Ratio

Poisson's Ratio is an important element in elastic theory. Elastic theory only requires the elastic stiffness and Poisson's Ratio to fully characterise a material and its response to loading.

Poisson's Ratio is the ratio of lateral to vertical deformation of a material when it is loaded vertically, as illustrated in Figure 14. The method of calculating Poisson's Ratio for the unconfined case is given in Equations 5, 6 and 7.

Typical Poisson's Ratios

In Mechanistic-empirical analysis we usually use Poisson's Ratios of 0.35 to 0.45 for asphalt, 0.35 for granular and 0.30 for stabilized materials.

Strongly bound materials will have less perpendicular strain relative to the parallel strain, due to the inhibiting bonds created by the binder, hence Poisson's Ratio is higher. The Poisson's ratio of engineering materials generally ranges between 0.2 and 0.5. Typical values for different materials are given in Table 2.

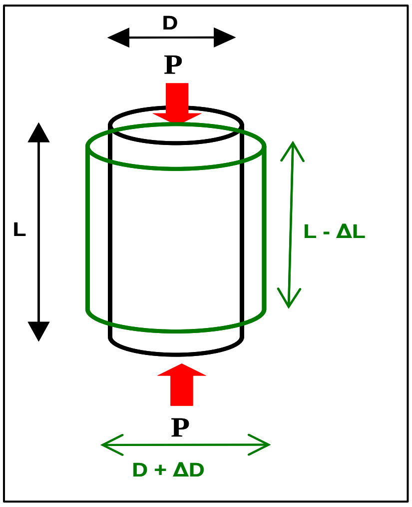


Figure 14. Poisson's Ratio (ν)

Poisson's Ratio: $$\upsilon = \frac{\varepsilon_D}{\varepsilon_L} \quad (4)$$

where $$\varepsilon_D = \frac{\Delta D}{D} \quad (5)$$

$$\varepsilon_L = \frac{\Delta L}{L} \quad (6)$$

Table 2. Typical Poisson's Ratio Values

Material	Poisson's Ratio
Steel	0.25 to 0.30
Aluminium	0.33
Concrete	0.15 to 0.25
Asphalt	0.35 (cold) to 0.45 (warm)[1]
Crushed stone	0.35 to 0.50
Soils (fine-grained)	0.35 to 0.45

Note
1. 0.44 typically used in South Africa for asphalt

Plasticity Symbol

Plasticity is represented by a slider.

(iii) Plasticity

Plasticity refers to permanent deformation of a material when stressed, but non-time dependent behaviour. Plasticity is represented by a slider. Most pavement materials undergo plastic deformation when the shear stresses exerted upon them result in some minor shear movement that cannot be recovered. For example, if a load is applied to a material and only non-recoverable deformation occurs, i.e., when the load is removed, there is no recovery, then the material is completely plastic. This is illustrated in Figure 15. Plastic response models apply to materials that accumulate non-recoverable deformation or plastic strain when a load is applied to them. Plastic strain is typically denoted as ε_p.

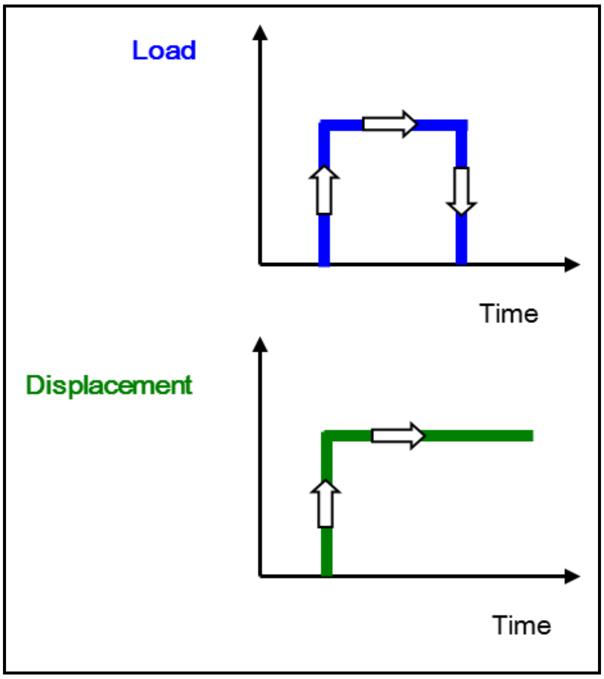


Figure 15. Plastic Response to a Load, Sustain, Unload Cycle

(iv) Elasto-Plasticity

Elasto-plastic behaviour occurs in materials that show some elasticity, which extends into plastic behaviour when the elastic limit is reached. With each load cycle in the plastic zone, some plastic strain accumulates, resulting in the accumulation of non-recoverable or plastic strain. This manifests as permanent deformation in the material after repeated load cycles. This is called elasto-plastic behaviour, and is illustrated in Figure 16. Elasto-plastic behaviour is often used to model granular materials under repeated loading.

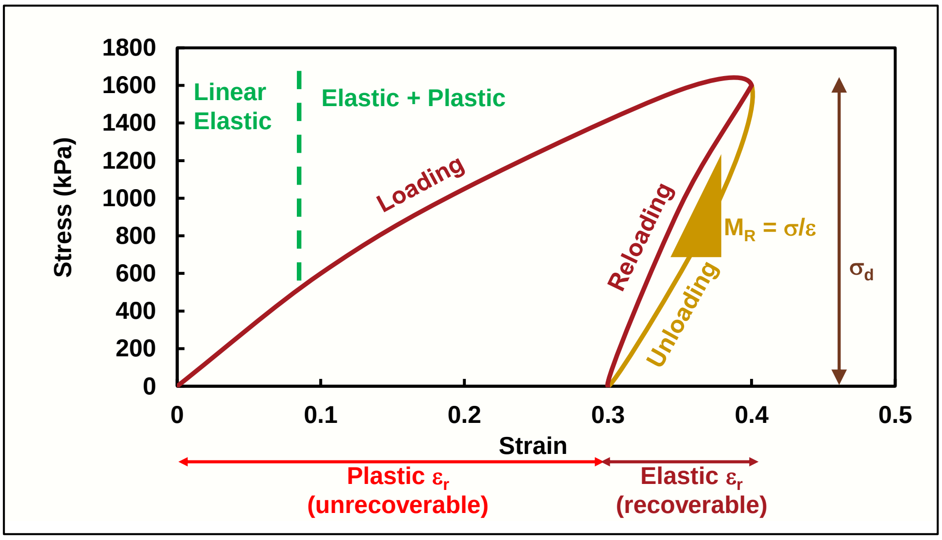


Figure 16. Elasto-plastic Behaviour and Resilient Modulus

Granular materials cannot actually withstand any tensile stress. However, linear elastic layer theory predicts tensile stresses. Typically, if the models show tensile stresses occurring in granular materials then the material is at risk of de-compacting and loosening, and ultimately deformation and failure could occur. This is why it is essential to ensure a gradual progression of stiffness modulus in successive granular layers to minimise the prediction of tensile by the theoretical models using elastic layered theory.

(v) Viscosity

Viscosity refers to the degree to which a "fluid" material resists shear forces being exerted upon it as its molecules continuously slide over one another. Bitumen is a viscous material, with reduced viscosity as temperature increases.

Viscosity gives an indication of how "syrupy" or "watery" a material is. For example, toffee is hard and brittle at low temperatures (high viscosity) and flows at higher temperatures (low viscosity). The viscosity of a material also depends on how fast a load is applied; and the viscosity increases as the speed of loading increases. Consider a shock absorber on a car: If you sit down slowly on the bonnet, the shock absorber displaces. However, if you hit a bump at high speed in the car, the shock absorber gives a stiff, immediate response and does not displace much, thus damping any oscillation of the springs.

Viscosity is measured either dynamically by applying a shear stress to the viscous material, or, kinetically by measuring the flow of the viscous substance through known apertures. The units of the different measures of viscosity are:

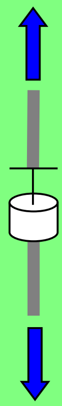
- **Dynamic:** Pascal seconds (Pa.s) or Poise (P) where 1 Pa.s = 10 P
- **Kinematic:** mm^2 per second (mm^2/s) or centistokes (CSt) where 1 mm^2/s = 1 Cst

The measurement of dynamic viscosity requires applying a shear stress and measuring the strain and time response, as illustrated in Figure 17. For viscous materials, the stress and strain response is dependent on the time of loading and temperature, which must therefore be measured.

Rheology is the science of deformation and flow in materials.

Viscosity Symbol

Viscosity is represented by a dashpot.



Bitumen is very stiff (glassy) and elastic at low temperatures, i.e., it has a high viscosity, and becomes a fluid at higher temperatures with a much lower viscosity. This behaviour is referred to as bitumen rheology.

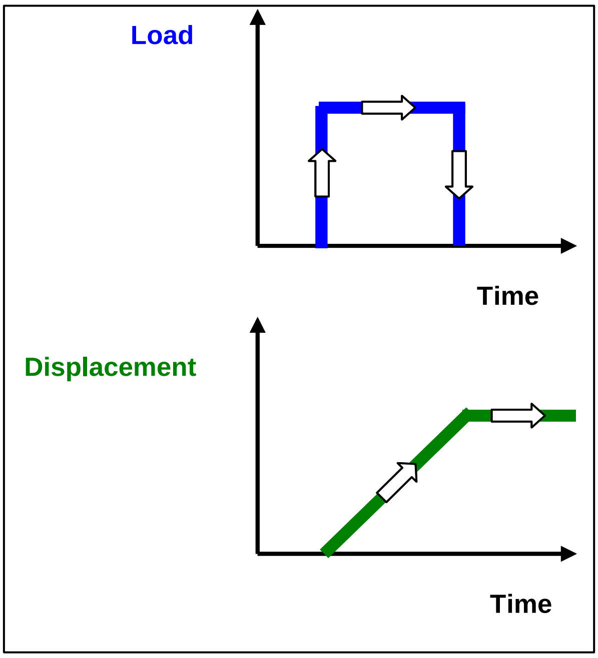


Figure 17. Viscous Response to a Load, Sustain, Unload Cycle

4.1.2 Situational Properties

Several situational properties have a big influence on materials and pavement behaviour.

- **Density**. Increased density is almost always beneficial to road building materials as it results in increased packing, reduced permeability and increased strength. An exception is in asphalt materials where a too high density is indicative of all the voids being filled with binder and the stone particles losing contact with one another as they "float" in the binder. At that stage, the strength of the material depends primarily on the viscosity of the bitumen and not the strength from the aggregate interlock and the particles packing together.

- **Moisture Content**. While a high moisture content assists with compaction during construction, it also facilitates particles sliding over one another, resulting in a weakened material. Moisture is the "*Number One Enemy*" of the pavement engineer, as moisture ingress into a pavement, either from above or from below, reduces its structural capacity. Where pavements have very thick bound materials, such as well cemented materials or thick bituminous layers, this effect is less than on granular materials, but is still significant.

Moisture in a Pavement

Moisture is the "**Number One Enemy"** of the pavement engineer, as moisture ingress into a pavement, either from above or from below, reduces its structural capacity. Where pavements have very thick bound materials, such as well cemented materials or thick bituminous layers, this effect is less than on granular materials, but is still significant.

- **Soil suction**. An important contributor to the strength of partially saturated granular materials is **soil suction**. This is the capillary action of the moisture between fine particles that appears to "suck" them together. There are two components to soil suction: capillary suction, which is more applicable to pavement materials, and osmotic suction, which is applicable to clay mineralogy that has significant ionic bonds. Capillary suction is therefore focussed on here. Where the moisture in a pavement material dispersed in thin films with particles close together, the meniscus is steep and results in a large suction force, as shown in Figure 18 and Figure 19. This force is greater than with a thicker film of water (and small radius of meniscus). Smaller soil particle sizes lead to smaller voids, with small radii of moisture menisci, creating powerful suction forces. As a result, soil suction can make dry, silty and clayey materials seem very strong. However, the strength disappears with the addition of moisture as the moisture breaks down the menisci. For this reason, soil suction is also known as apparent cohesion.

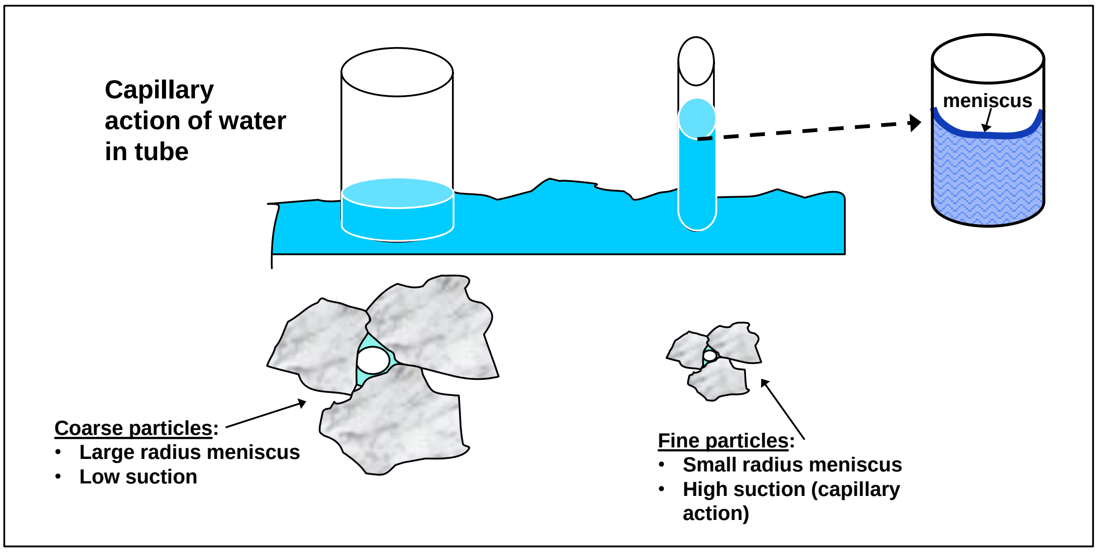


Figure 18. Principles of Capillary Action

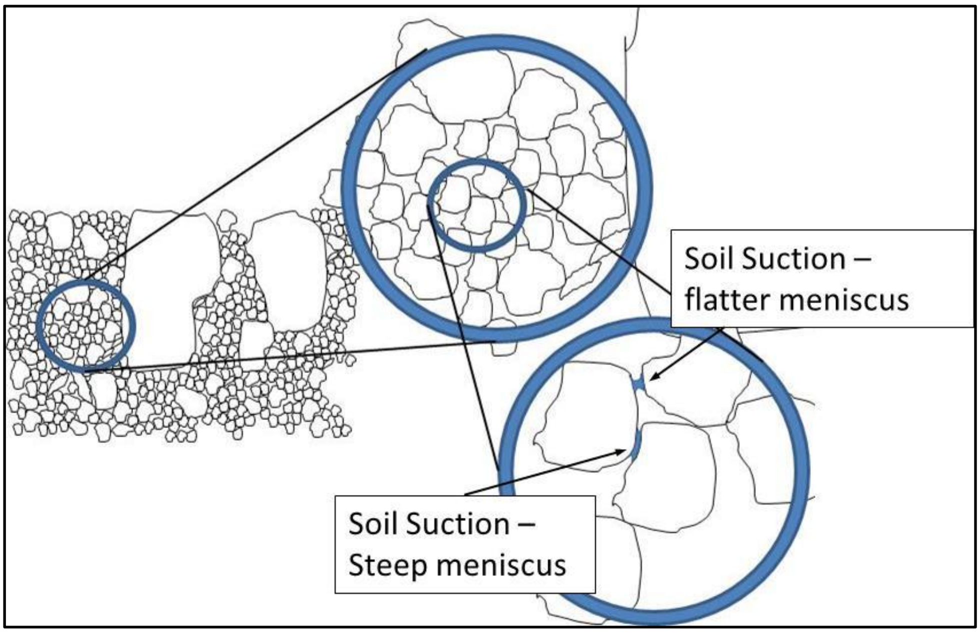


Figure 19. Capillary Action in Partially Saturation Soils Creating Suction Forces

- **Temperature** variations generally only affect the strength of temperature susceptible materials, such as bituminous materials.

- **Supporting layers**. The support beneath the layer influences the stress conditions in the layer, which in turn influences the stiffness response of stress-dependent materials. For example, if a competent material is confined with a strong underlying layer, it experiences enhanced compressive stresses, which force the particles against one another. This increases their zones of contact inter-particle friction, resulting in an increased stiffness modulus. Alternatively, when a wet plastic material is subjected to stresses, instantaneous pore pressures develop, resulting in particles losing their packing structure, causing stress-softening and weakening behaviour.

4.1.3 Engineering Properties

These are properties that are needed to provide solutions to engineering problems. Think of a beam with known dimensions, somewhat like a pavement layer. To estimate the deflection of a beam under a given load, certain engineering properties are required. Some examples of engineering properties include:

- **Stiffness** or elastic modulus
- **Strength**, either compressive or tensile
- **Shear strength**
- **Poisson's ratio**

In most cases, engineering properties can only be determined accurately and reliably using sophisticated tests. Therefore, alternate, simple tests that are indirectly linked to fundamental properties, are developed. Based on experience, their results provide an empirical indication of performance. Consider the example of bearing capacity of a granular base layer, supported by a competent subbase. As illustrated in Figure 20, a wheel load applies a normal stress, resulting in shear stresses along the idealised planes, depicted by the red curves. This requires knowledge of the shear strength of a material. The shear strength is best determined with triaxial, from which the shear parameters cohesion (C) and friction angle (ϕ) are acquired. The triaxial test is a complex, expensive and time consuming test. As a result, the roads industry uses the Californian Bearing Ratio CBR Test, to get an indication of shear strength rather than actually measuring the properties with the triaxial test. The CBR cannot explicitly provide the cohesion and friction angle, but it serves to classify the bearing capacity of materials. The CBR uses a small plunger that is forced into a compacted specimen of the granular material after soaking. The CBR and triaxial tests tests are discussed in detail in Chapter 3: 2.8 and 4.6 and Chapter 4: 2.

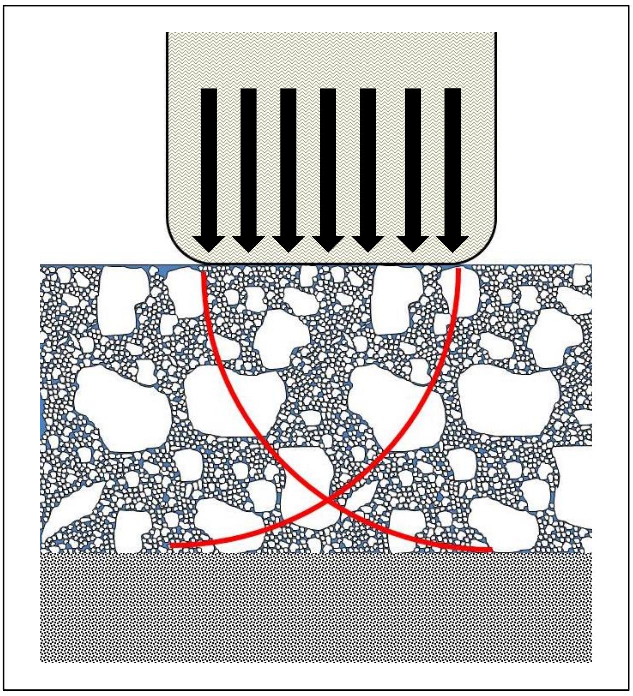


Figure 20. Loading on a Granular Base Layer

Some of the factors influencing the shear properties of a material can be understood from Figure 20:

- **Grading**. The maximum particle size, packing characteristics, number of contact points, and the irregular paths that the shear plane has to navigate through influence the shear strength. Larger particles, e.g., 40 to 50 mm, increase the shear path length, thereby increasing the shear strength.
- **Aggregate strength** is measured with the aggregate crushing value (ACV). This measures if an aggregate is soft and friable and therefore not resistant to crushing. The more a particle can resist crushing, the higher shear resistance it provides.
- **Particle shape.** Rounded particles offer less shear resistance than angular particles.
- **Particle texture**. Rough particles with a coarser texture generate higher friction than smooth particles.

- **Compaction**. The number of contact points and inter-particle friction increase as the density of a material increases.
- The **degree of support** provided by the underlying layer strongly influences the **stiffness modulus** that a granular material develops. It is this stiffness modulus that defines the degree of load spreading in each layer, i.e., the slope of the green line in Figure 21.

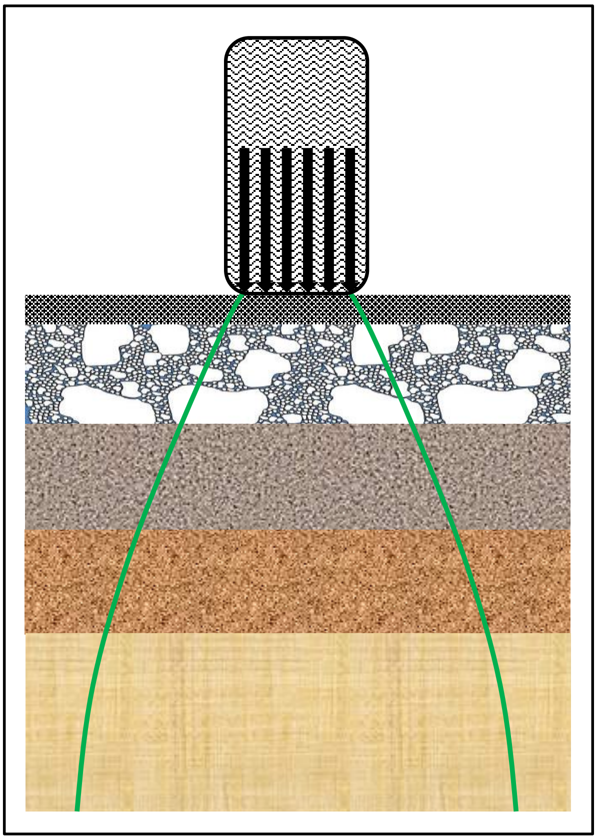


Figure 21. Load Spreading in a Pavement Structure

- **Supporting layer**. A weak support with a low stiffness modulus, causes a loss of inter-particle contacts, especially in the lower part of the granular layer, with a consequent reduction in stiffness and strength under loading. Strong and stiff support, e.g., a cemented subbase, enhances the particle contacts and increases the strength and stiffness of a granular layer.
- **Compressive forces** are exerted by traffic loads onto the surfacing of the pavement, and apply compressive stresses of the same order of magnitude as the tyre pressure applied at the surface. These stresses are distributed in the pavement structure, based on the ratio of stiffnesses of the layers. This is called the modular ratio, which is the ratio of the stiffness of one layer and the layer immediately underneath. High modular ratios, e.g., above 3, are an indication of an unbalanced pavement. Layers with a high modulus attract significant tensile stresses in the bending mode, which results in damage. This reduces the modular ratio and creates a balanced pavement. In bound layers, such as cement stabilized and asphalt materials, this form of damage typically manifests in fatigue damage.
- **Load spreading**. Some pavement layers, such as thick bituminous surfacings, must be stiff enough, i.e., have a high elastic modulus, to **spread loads** and reduce the stresses on the underlying layers. Alternatively, thin surfacings must be **flexible** enough with a low elastic modulus, to allow the lower layers to carry the stresses and to bend and accommodate this **deflection** without breaking.

The balance between load spreading and flexibility is achieved through a balance of the amount and type of binder added to the material, as summarised in Figure 22. Materials that are formed from combinations of the three fundamental materials, i.e., aggregate, bitumen and cement, such as Bitumen Stabilized Materials (BSMs), are complex as they have a combination of granular and bituminous characteristics, but also show the influence of small quantities of cement.

Modular Ratio

The ratio of the stiffness of the upper layer and the stiffness of the lower layer is known as the modular ratio.

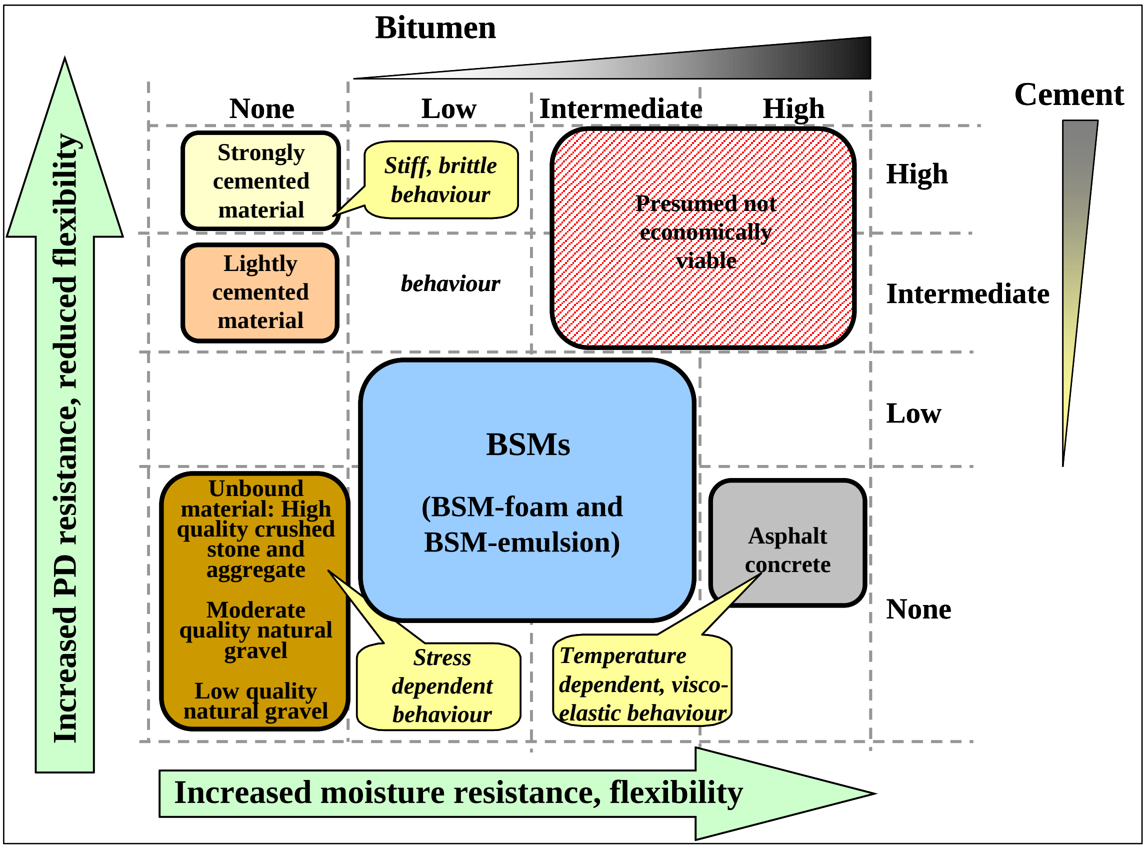


Figure 22. Expected Behaviour of Material Types as a Function of Bitumen and Active Filler Content

4.2 Mechanistic Pavement Analysis

Pavements are often analysed mechanistically. That is, the pavement structure is considered as a mechanism that is subjected to loading. Although this is discussed in great detail in Chapter 10: 6, 7, 8 and 9, this section is intended to give a brief introduction to this type of analysis.

In a mechanistic analysis, the material in each layer is described by the stiffness and Poisson's Ratio. Stiffness provides a good indication of the load spreading capacity of the layer. Stiffness is a generic term for this property, and is an approximation of Young's modulus and the material's resilient modulus. These terms are defined and discussed in Section 4.1.1.1.

Two examples are given to illustrate mechanistic pavement analyses.

Example 1: **Bound Upper Layer on Unbound Support**

In this example, the upper layer is bound, i.e., a stabilized or HMA base layer, and the lower layer is unbound, i.e., a granular support layer. This conceptual pavement is illustrated in Figure 23, along with some of the idealized linear-elastic compressive and tensile stresses (σ) in the upper layer. In this type of model, the loading causes the upper layer to bend. The following stress or strain parameters are useful:

- The **stiffness** of the layers is denoted E.
- The vertical **deflection** (δ) directly under the wheel load. Vertical deflection is the integral of the vertical strains.
- Directly under the wheel, **compressive stresses** are introduced, denoted σ_{zz} (vertical) and σ_{yy} (horizontal). Not shown, but introduced, are σ_{xx} horizontal stresses.
- At the bottom of the upper layer, **tensile stresses** and strains are introduced, illustrated only by σ_{yy}.
- At the top of the bottom layer, vertical **compressive stresses** (σ_{zz}) and strains are introduced.

Granular materials cannot typically carry any tensile stresses. One of the fundamentals of pavement engineering is to ensure that such "tensile" stresses do not actually occur in granular layers by avoiding high stiffness ratios (modular ratios) between any two consecutive pavement layers. If such a situation actually occurs in practice, the layer decompacts and becomes less stiff, and results in more stress transferring to the underlying layer. However, if the layer is well supported, the stresses at the bottom of the layer are compressive and the materials in the layer could easily exhibit stress-stiffening behaviour due to the confining effects of the underlying layer.

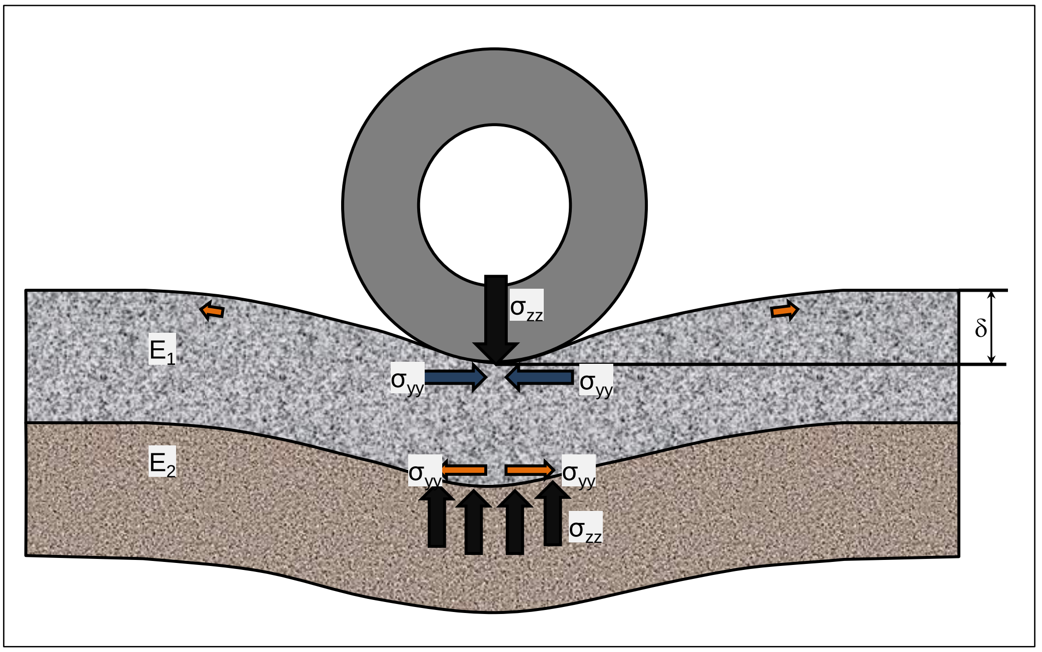


Figure 23. Conceptual Bending Model for a Bound Layer on Unbound Support

Example 2: **Unbound Upper Layer on Unbound Support**

In this example, illustrated in Figure 24 both layers are unbound, i.e., granular materials. In this case, the upper layer cannot bend, therefore the load is carried through shear forces and shear stresses. The figure shows the greater spread of shear forces in the upper layer that has a higher modulus (E) than the lower layer. The concept involves ever decreasing vertical stresses and strains as the load is spread over an increasing area so that the load or stresses imposed on the weaker lower layer are restricted to acceptable levels.

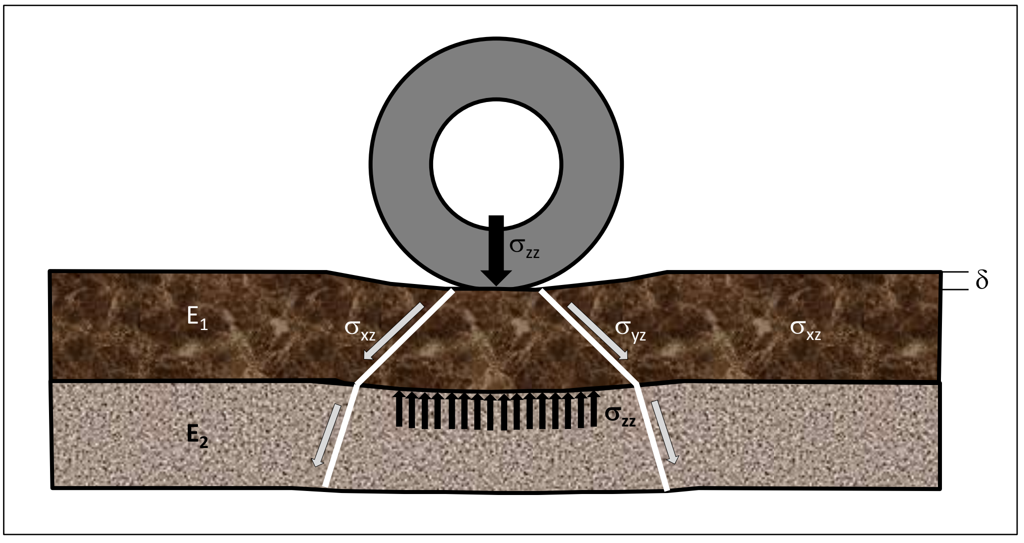


Figure 24. Conceptual Model of Stress-Distribution for Unbound Layer on Unbound Support

5. PAVEMENT DISTRESS

The loading on pavements consists of millions of relatively small magnitude loads from vehicles, which cause the gradual or incremental deterioration of the pavement, until the level of service becomes unacceptable. The stress imposed by the external load is normally well below the strength of the material and causes the gradual deterioration of the functional and structural levels of service provided by the road.

There are many types of distress that manifest in pavements. Distress of the surfacing is relatively easy to observe. Typical surfacing distress examples are listed below. While surfacing defects are generally confined to the surfacing, pavement structural defects related to problems deeper within the pavement also occur and must be recognised. These defects are divided into those that are caused by traffic, and are normally confined to the wheelpaths, and those caused by other stresses in the pavement such as drying shrinkage, thermal stresses and deep-seated underlying movements. Examples of the types of distress in **flexible** pavements are:

- **Surfacing distress**
  - Surface cracking
  - Bleeding
  - Binder condition
  - Permeability
  - Aggregate loss/ravelling
  - Surface failure
  - Surface texture
- **Traffic associated distress**
  - Crocodile cracking
  - Rutting
  - Deformation
  - Pumping
  - Potholes
  - Patching
- **Environmentally induced distress**
  - Block cracking
  - Longitudinal cracking
  - Transverse cracking
  - Undulations

Pavement Distress

Pavement distress is discussed in **Chapter 14: Post-Construction**. Pictures of the different types of distress are also given.

Examples of the types of distress in **rigid** pavements are:

- Cracking (centre-slab, longitudinal, corner-slab, diagonal, star)
- Punch-outs
- Spalling at joints
- Faulting at joints
- Curling
- Shrinkage
- Shattered slabs

Examples of the types of distress in **block** pavements are:

- Permanent deformation
- Shoving
- Pop-outs (loose blocks)
- Block failures (cracking or spalling)

In addition to the structural distresses, there are functional distresses that affect the ability of the pavement to carry traffic comfortably and safely:

- Functional distress in **flexible** pavements:
  - Riding quality
  - Edge drop
  - Edge break
  - Reserve encroachment
  - Skid resistance

Pavement Failure

Pavement failure does not mean the road has failed and cannot carry traffic. Failure is therefore not the same as structural failure, for example, when a bridge collapses! Rather, it means that the condition of a road is terminal in that the severity and extent of distress have reached specified limits, and the road needs maintenance or rehabilitation.

  - Potholes
  - Bush encroachment
- Functional distress in rigid pavements:
  - Riding quality
  - Skid resistance
  - Edge break
- Functional distress in block pavements:
  - Riding quality
  - Potholes (pop-outs and loose blocks)
  - Edge break (instability)

5.1 Accumulation of Distress

Pavement distresses occur at different rates. For example, rutting may occur rapidly initially and diminish exponentially as materials densify, whereas cracking can follow a cumulative normal distribution or "S curve", as shown in Figure 25. "Failure" is said to occur when the severity and extent of distress reaches a terminal condition before the design life of the pavement expires. The combination of several distress mechanisms is collectively measured as the Pavement Condition.

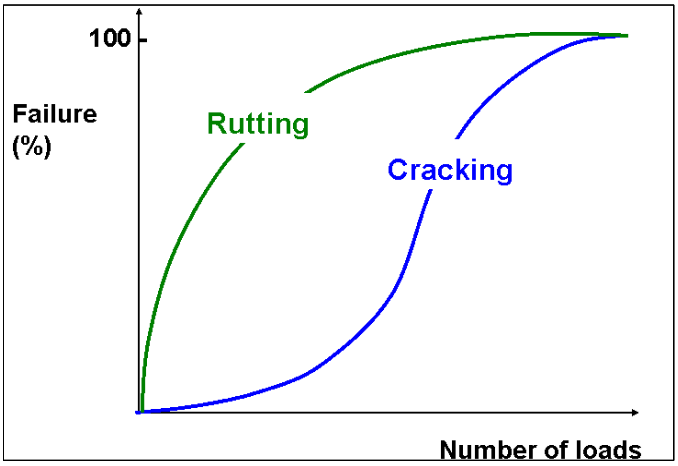


Figure 25. Evolution of Failure Mechanisms with Time and Loading

It is important to note that the terminal condition, shown as in Figure 26, is defined as end of useful life. It is identified in terms of safety, road user costs, rate of deterioration and cost of rehabilitation of a pavement. If a pavement has reached a terminal condition, it does not mean that traffic cannot drive on it. It means that the pavement can no longer fulfil the function for which it was originally intended, such as, high speeds, safe mobility for Class 1 to 3 roads, or its maintenance cost has become prohibitive for class 4 and 5 roads. At that stage it may be more cost effective to rehabilitate the road.

Figure 26 shows the structural performance of two roads, one of poor quality (red) that deteriorates relatively uniformly until it starts to deteriorate very rapidly, and another with a longer life and better structural performance (green).

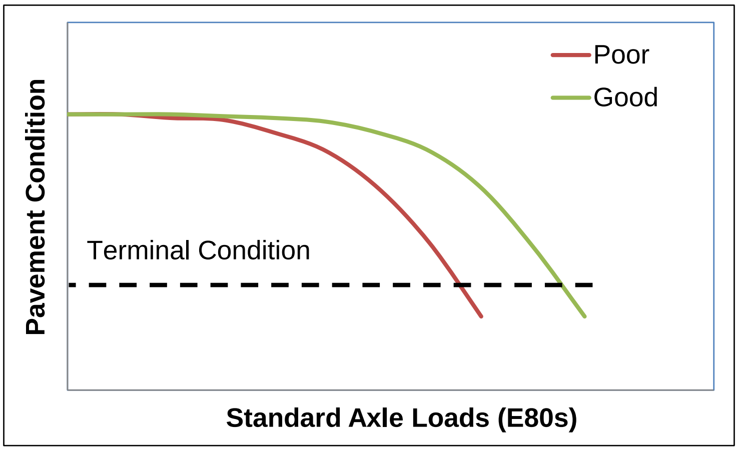


Figure 26. Structural Performance Incorporated into Pavement Condition

6. FUNCTIONAL PERFORMANCE

Performance can be described as: *"the manner in which, or the efficiency with which, something fulfils its intended purpose".* The pavement engineer needs to be aware of how the distress types result in functional problems and the consequent effect on road users. Table 3 shows the links between the road user needs, functional parameters and behaviour measurements.

Table 3. Road User Needs, Functional Parameters and Behaviour Measurements

Road User Needs	Functional Parameters	Behaviour Measurements
Safety	Skid resistance Potholes Rutting	Texture depth Number and age of potholes Rut depth
Comfort	Riding quality	Roughness
Environment	Noise pollution	Noise levels

For example, safety translates into skid resistance that is assessed by measuring texture depth. Potholes may also cause swerving of vehicles with resulting accidents. To mitigate dangerous potholes, SANRAL specifies in all its maintenance contracts that potholes are repaired within 24 hours.

Comfort involves smoothness or riding quality, measured with various devices such as non-contact laser profilometers. The values measured are expressed as International Roughness Index (IRI) units. The pavement engineer compares the measured values with the functional requirements and terminal conditions for that class of road. The requirements are established measures that define the boundaries between acceptable and unacceptable functional conditions. When a road's condition crosses such a boundary, then some maintenance measure needs to be triggered. See Chapter 14 for more on triggering maintenance and rehabilitation activities.

The appropriate maintenance action depends on the pavement type and layer strengths, as well as traffic loads and environmental conditions. For example, Figure 27 shows pumping of a stabilized base and relatively rapid development of roughness. Any crack sealing has to accommodate fairly active crack movements to prevent further moisture ingress and associated roughness development.

Figure 27. Pumping of Stabilized Base

Figure 28 shows extensive surface cracking and surface potholes, but little development of deeper seated rutting, deformation and roughness. If this road surfacing could be repaired and sealed, the pavement may provide many years of life before its serviceability drops below acceptable levels.

Figure 28. Surface Cracking and Potholing

As a road's purpose is to carry traffic with an acceptable degree of comfort and safety over its design life, its functional performance is a measure of how well it achieves this purpose. It is normally represented by a serviceability – time graph, with the area under the curve representing functional performance. This is illustrated in Figure 29 for a good and a poor road, and, shows how functional improvements are required at different times, on roads with differing functional performance.

The benefit of different levels of performance is also illustrated Figure 29. It is the pavement engineer's job to ensure that the designed pavements not only reach their design lives, but also perform well during this time as illustrated by the performance of the "good" road compared to the "poor" road. The performance of a "good" road (area A_2) is significantly higher than the performance of a "poor" road (area A_1).

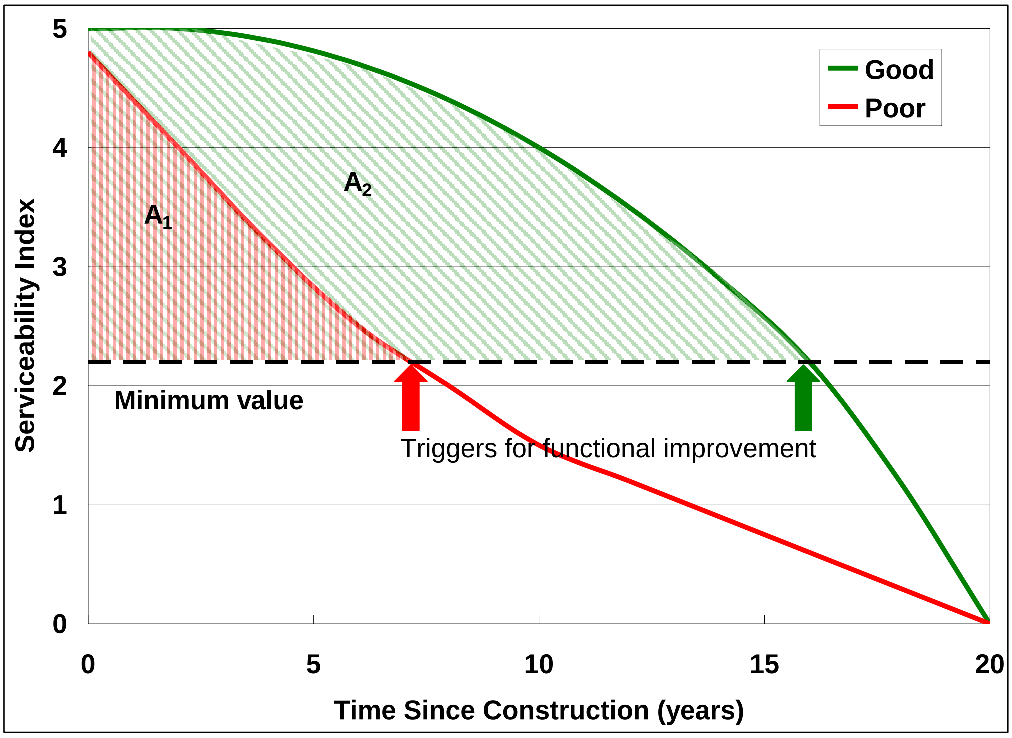


Figure 29. Functional Performance for Different Road Structures

7. CLIMATE

Climate is a critical consideration for pavement engineering as it has a significant influence on construction, pavement behaviour and performance. Climate has two primary components: temperature and moisture. The role of climate and related issues in pavement engineering is covered in Chapters 5, 6, 9, 10, 12 and 13 of SAPEM.

7.1 Temperature

Temperature has a major influence on many pavement materials. These effects include:

- Cracking
- Permanent deformation
- Warping
- Curling
- Evaporation
- Weathering
- Speed of reactions
- Drying out of materials
- Ageing

The South African Weather Service (SAWS) collects and keeps temperature and rainfall data at many weather stations across South Africa. These can be purchased through the SAWS webstore: www.weathersa.co.za. Temperature maps for South Africa, which, for example, show the minimum and maximum design temperatures for asphalt are shown in Figure 30 and Figure 31 (O'Connell, 2012).

7.2 Moisture

Moisture ingress into a pavement, either from above or from below, reduces its structural capacity. In this way, climate is directly linked to performance of a road. The manner in which the moisture content of each layer impacts of the performance of that layer, is explained in the pavement design methods outlined in Chapter 10. Moisture has a significant effect on pavement materials and pavement behaviour, including:

- Permeability
- Drainage
- Safety
- Material strength
- Material selection

Moisture in a Pavement

Moisture is the "**Number One Enemy"** of the pavement engineer, as moisture ingress into a pavement, either from above or from below, reduces its structural capacity.

For example, in a wet region, materials are selected that are more resistant to moisture damage. Subgrades generally have higher moisture contents in wetter areas, provide less bearing capacity, requiring a thicker pavement structure and highlight the need for good drainage systems. In addition, climate considerations also need to be taken into account during construction. For example, the prediction of material moisture contents for compaction, and asphalt temperature loss during laying and compaction.

In South Africa, the Thornthwaite Moisture Index Im, is used to classify climatic zones for moisture (Thornthwaite, 1948; Paige-Green, 2012). Two maps of the index are shown in Figure 32 and the zones and index values are given in Table 4. Thornthwaite's Im is a function of evapo-transpiration, which is dependent on vegetation and rainfall. Im provides a measure of the soil water storage, and indicates a moisture surplus or moisture deficit.

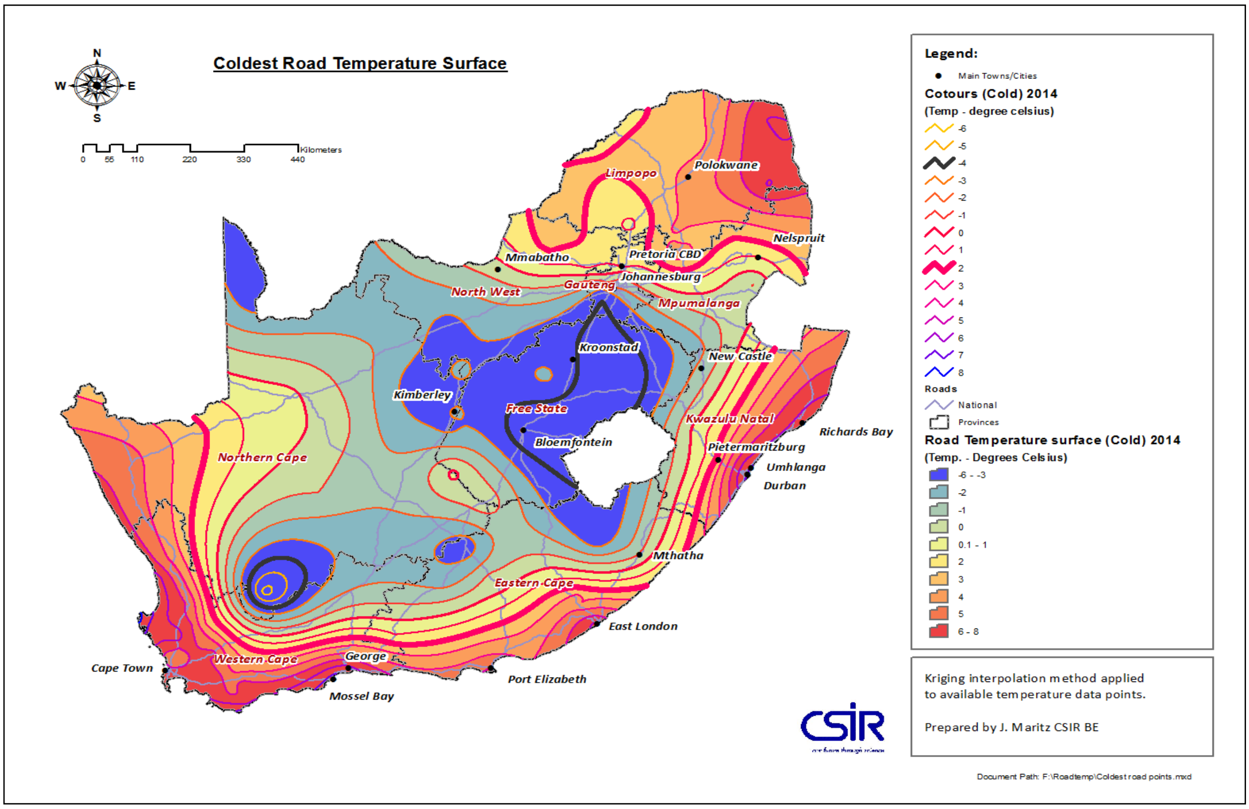


Figure 30. Minimum Asphalt Design Temperature on Surface

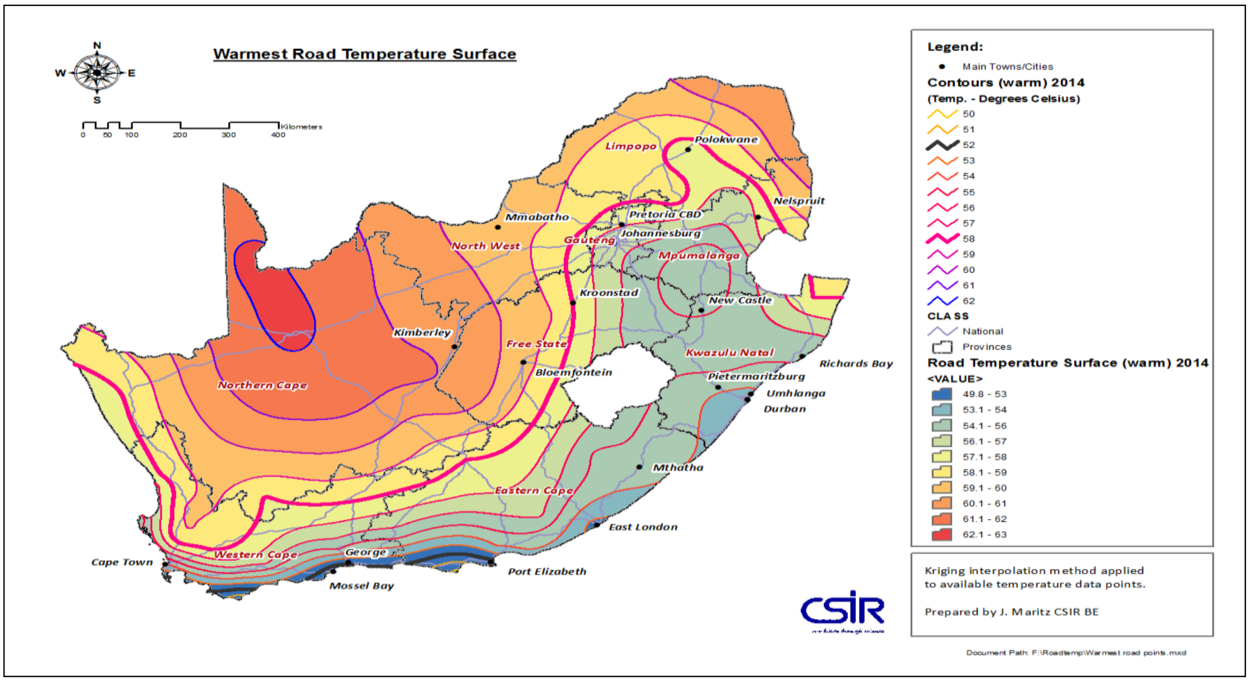


Figure 31. Maximum Asphalt Design Temperature at 20 mm Below Surface

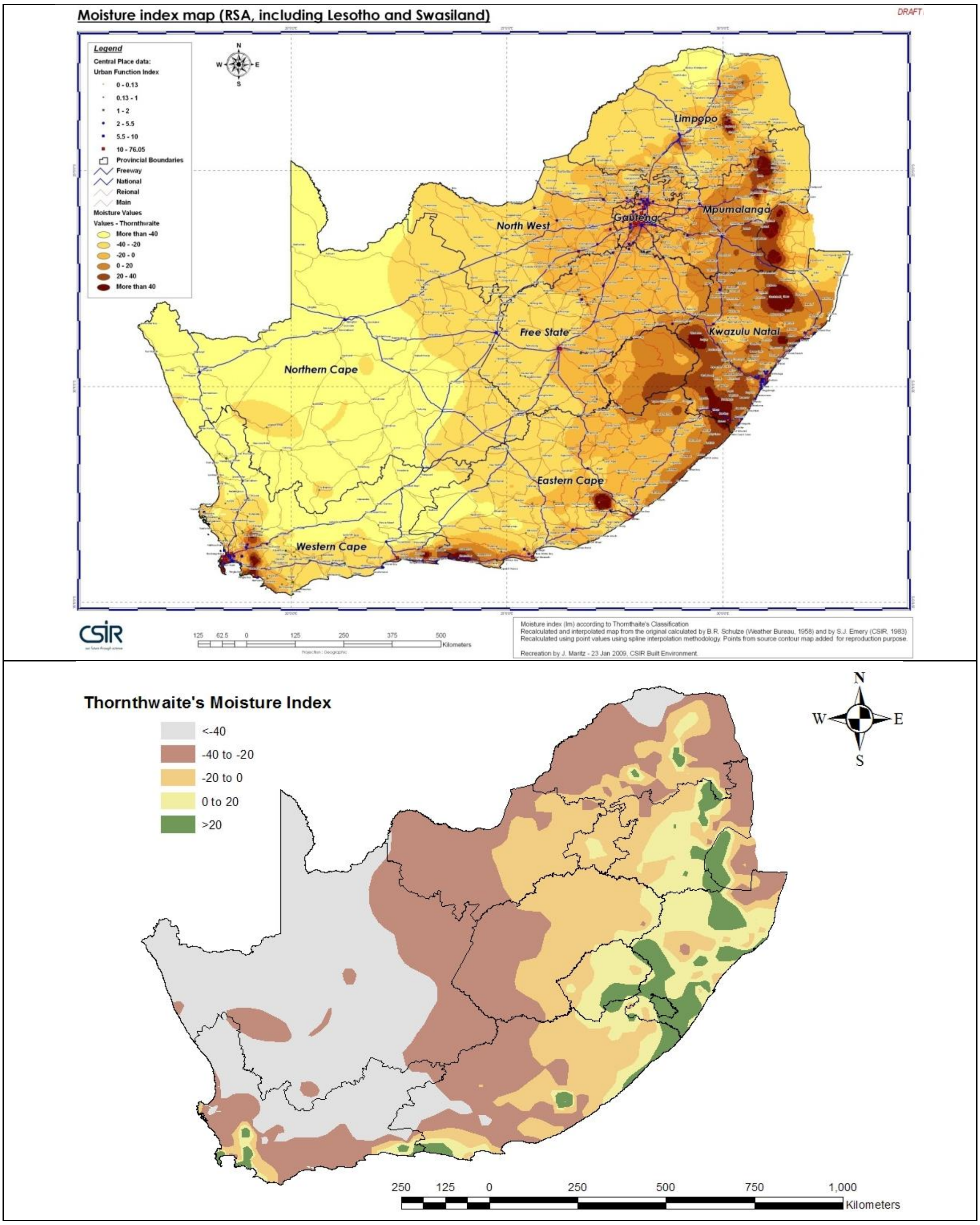


Figure 32. Thornthwaite's Moisture Index for Southern Africa

Table 4. Thornthwaite's Moisture Index for Climatic Areas

Index Range	Climatic Region	
< – 40	Arid	Dry
– 40 to – 20	Semi-arid	
– 20 to 0	Dry Sub-humid	Moderate
0 to 20	Moist Sub-humid	
20 – 100	Humid	Wet
> 100	Perhumid	

Equilibrium Moisture Content (EMC) is the long term field moisture in a pavement layer, with some allowance for seasonal variation. EMC has a significant influence on the performance of the pavement and is therefore an important parameter. Research in South Africa has shown that the EMC in a pavement is a function of the optimum moisture content (OMC) of the material itself and of Thornthwaite's Im (Emery, 1988). This m oisture relationship is shown relative to depth in a pavement structure for various climates in Table 5. Considering that a granular base layer must be dried back to < 50% of OMC after construction, before a surfacing layer can be placed on top of it, the figures provided in the table show that the base layer regains moisture after surfacing. This process is commonly known as hydrogenises.

Table 5. Thornthwaite's Index and Moisture Ratio for Pavement Layers in South Africa

		Moisture Ratio: Equilibrium Moisture Content / Optimum Moisture Content		
Climatic Area	**Im**	**Subgrade**	**Subbase**	**Base**
Arid	< -40	0.71	0.7	0.53
Western Cape	< -20	0.75	0.78	0.63
Gauteng	< 0	0.94	(0.8)	(0.65)
Southern Cape	-20 to 0	0.98	0.83	0.57
Gauteng	≥ 0	0.96	(0.81)	(0.65)
KwaZulu Natal	> 20	1.05	(0.89)	(0.72)

Note:
() denotes interpolated values

Another moisture index is Weinert's N-value (Weinert, 1980; TRH4). This index is a measure of weathering forces on materials. Using Weinert's N-value, South Africa was divided into 3 areas macro climatic regions: Wet (N < 2), Moderate (N = 2 to 5) and Dry (N > 5). Historically Weinert's N-value was used as a climatic indicator. However, Thornthwaite's Index is now considered to be am improved indicator of climatic regions for South African conditions, because of its focus on soil water storage rather than Weinert's weathering forces.

Moisture in the Pavement

The primary consideration in pavement design and maintenance is keeping water out of the pavement.

8. DRAINAGE

Moisture is the "Number One Enemy" of the pavement engineer. However, good drainage can combat the negative effects of water ingress. Drainage of road prisms is a primary consideration to ensure the longevity of a pavement structure. It includes interception and removal of surface and subsurface water to enhance safety for road users, reduce water erosion in the road prism, and prevent water ingress into the pavement structure and subgrade.

Some examples of facilities used effectively and ineffectively for drainage are shown in Figure 33 and Figure 34, respectively.

Figure 33. Poor Surface Drainage (from SANRAL Drainage Manual)

Drainage is a very important factor in pavement engineering. However, because all aspects of drainage are comprehensively covered in SANRAL's Drainage Manual, drainage is not discussed in detail in SAPEM.

> **Drainage**
>
> Drainage is an extremely important consideration for pavements! Water is the primary cause of premature failure, accelerated distress and reduced structural capacity.
>
> All aspects of drainage are comprehensively covered in SANRAL's Drainage Manual and not repeated in SAPEM. Download the Drainage Manual from www.nra.co.za.

Good Surface Drainage (Crossfall and Side Drain)	Wide Side Drain gives Flexibility for Maintenance	Side Drain with Free-flow Link to Channel
		
Grid Inlet at Low Point	**Combined Grid and Kerb Inlet**	**Surface Drainage to Vegetated Bank. Side Drain Invert 1 m below Road**
		
Open Rectangular Stormwater Channel (Intercept Cutting Water)	**Open Trapezoidal Stormwater Channel**	**Toe of Fill Trapezoidal Stormwater Channel**
		
Erosion Protection via Lined Side Drain	**Down-chute on Embankment**	**Installation of Sub-soil Drainage**
		
Pipe Culvert Outlet with Gabion Lining and Wing Walls	**Box Culvert with Wing Walls**	**Box Culvert with Trapezoidal Stormwater Channel (Urban)**
		

Figure 34. Effective Drainage Mechanisms and Structures from SANRAL Drainage Manual

In SANRAL's Drainage Manual there are different objectives for designs for unpaved (gravel) roads and paved roads, as outlined in Table 6. Competent drainage design requires knowledge of hydrology (rainfall, catchment areas and concentration times) and hydraulics (flow in and through drainage structures). Effective drainage leads to the reduction of moisture content in the pavement layers and subgrade. Dysfunctional drainage can accelerate the distress in pavement layers, beyond the norm catered for in the design performance functions.

Table 6. Drainage Design for Unpaved and Paved Roads

	Unpaved (Gravel) Roads	Paved Roads
Surface Drainage	Primary failure mechanisms • Erosion of surface • Gravel loss	Safety at higher speeds • Spray and skid resistance • Prevent aquaplaning
	Reduce infiltration into structure • Maintain bearing capacity • Unsoaked CBR	Surfacing mixtures • Macro-texture • Stripping resistance
	Maintain passability, reduce erosion • Side drains below final road level • Vegetation for lining	Interception of surface runoff, e.g., above cuttings, alongside roads, down-chutes on embankments
	Landscaping • Interception of surface water • Shape	• Side drains with invert lower than grade level • Maintain moisture levels in subgrade and pavement layers as low as possible
	Using the road as a drain is disastrous	Durability of materials with time: infiltration of cracks, ravelling of seals
Sub-surface Drainage	Prevent accelerated failure, specifically in wet/saturated areas	Extends structural life in the long term: enhance stiffness, strength and reduce permanent deformation
	Enhance strength of materials	Prevent stripping
	Budget generally does not usually allow for sub-soil drains	Reduce frost damage in cold areas
		Intercept lateral infiltration into lower pavement layers

9. VARIABILITY

Designing a pavement is not an exact science because of variability, which occurs in four predominant areas:

- **Materials:**
  - Random variability exists in all materials, which is apparent when viewing quality and strength results.
  - Behaviour of materials is complex, resulting in variability in the form of random error.
  - The tests that are used do not entirely simulate field conditions and follow simplified protocols, thus introducing more variability in the form of systematic error.
  - Material models are simplified for expedience and thus unable to fully capture complex material behaviour, resulting in more variability and uncertainty.
- **Climate:**
  - Temperature varies diurnally and seasonally, and prediction models are not exact.
  - Moisture varies seasonally and regionally, and prediction models are also not exact.
  - Weathering is a function of climatic conditions and material properties, which are both variable.
  - Durability phenomena that influence performance, e.g., oxidation of binders and carbonation of stabilizers, change with climate and time, and are co-dependent on many other factors, e.g., voids in an HMA mix.
- **Traffic:**
  - Axle loads and wheel loads are not constant and are dynamically applied.
  - Tyre pressure, contact stresses at the surface, and contact area are all variable, so the stresses experienced by the road materials are not constant.
  - Traffic speeds, which influence the response of some materials, are variable.
  - Models to take account of different traffic loads, e.g., damage factor calculations and equivalent standard axle loads, are over-simplified.
- **Construction:**
  - Layer thicknesses in the pavement structure must meet specification requirements, but are nevertheless variable.
  - Compaction of layers must meet specification requirements, but the achieved density is still variable.
  - Laboratory simulations of material behaviour cannot exactly simulate construction behaviour, thus introducing systematic error.

It is important to take account of variability in a pavement during the design. A design that uses average results for all of the input variables has 50% reliability when the design life is reached. In addition, it is important to reduce variability wherever possible, which can be achieved through improved quality management during the material investigation phase, construction and testing. This limits the occurrence of failures under in-service conditions.

At this point, it is opportune to introduce the concept of reliability. Reliability is a measure of precision, e.g., high reliability of results implies high precision, and low random error, which is part of variability. Reliability does not imply accuracy, however. Accuracy is the validity of the results, i.e., how closely do they resemble reality? For example, high accuracy implies high validity and low systematic error, which is part of variability. In pavement design, reliability is used to assess the confidence of a design. In important roads, high design reliability is required, typically 90 to 95%. This ensures the likelihood of premature failure is reduced. See also Chapter 10: 3.1.

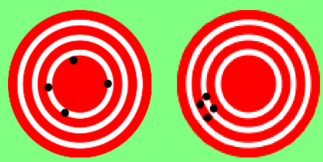
Construction variability has a dominant effect on the ability of road infrastructure to successfully fulfil its purpose. For example:

- A 15% reduction in constructed **layer thickness** can result in 50% reduction in pavement life.
- An increase of 2% increase in **apparent density** achieved, through improved compaction, can almost double the structural capacity of a granular layer.

Sound construction practices and reduced variability are the most cost-effective measures to ensure road infrastructure is fit for purpose. In addition, extra investment in compaction technology provides the best return on investment in road construction activities.

Precision vs Accuracy

Accuracy is the degree of closeness of measurements to the actual value. **Precision** is the reproducibility or repeatability of the measurements.



High accuracy, low precision | Low accuracy, high precision

10. LIFE CYCLE STRATEGY

Functional requirements are defined for a road over a period known as the analysis period. This usually extends over 20 to 30 years and sometimes longer. Structural considerations define the life of a road in terms of its structural bearing capacity, which is shorter than the analysis period. In short, the structural capacity is normally defined as the number of equivalent single axle loads of a specified mass (E80s) that the pavement can support before it reaches a defined terminal condition. The period in which this takes place is termed the structural design period. Refer to Chapter 10: 3.2 for more details.

It is important, therefore, not just to design and build a road, but to have a strategy as to how to retain the structural bearing capacity with time, i.e., a life cycle strategy that includes maintenance. The deterioration of the riding quality and skid resistance with time defines when maintenance is required. Two approaches to the maintenance strategy are possible. In both of these examples, the same rate of deterioration of the pavement is assumed. It should be noted that this deterioration is exponential and NOT linear.

- **Less maintenance and rehabilitation interventions**, but more severe measures are required, as illustrated in Figure 35.
- **More maintenance interventions**, requiring less severe measures, as illustrated in Figure 36.

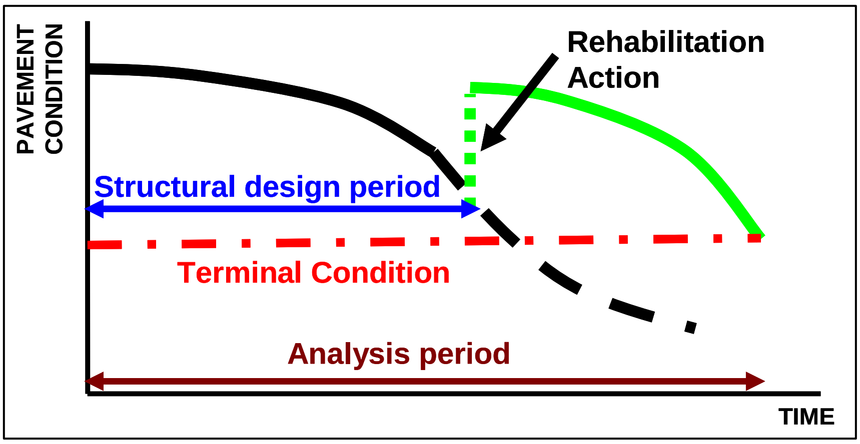


Figure 35. Pavement Deterioration with a Heavy Rehabilitation Strategy

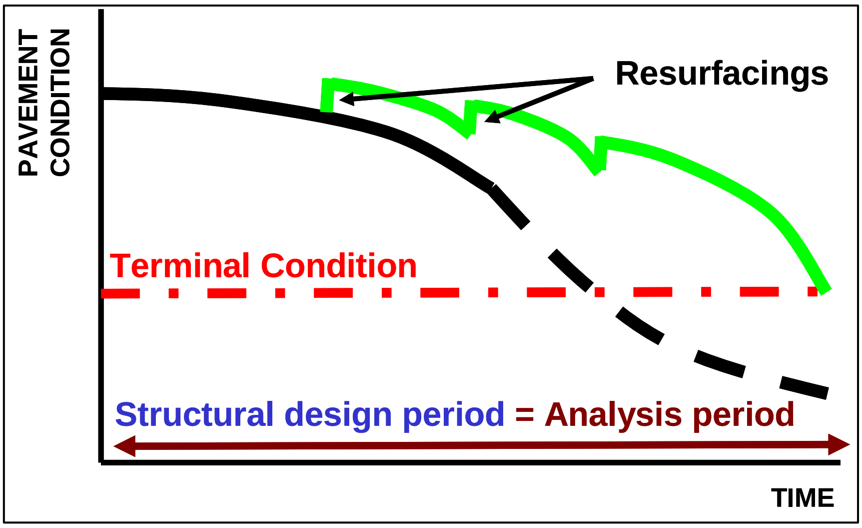


Figure 36. Pavement Deterioration with a Frequent Maintenance Strategy

If the trigger mechanism for maintenance is set at a higher pavement condition (or riding quality), then more frequent and less severe actions are required, as shown in Figure 36. Because the deterioration of roads is nonlinear, it is typically most effective to do routine and preventative maintenance frequently, rather than waiting until the condition is severe enough to warrant expensive rehabilitation actions. The old saying: *"A stitch in time saves nine"* is highly applicable to road maintenance. This is illustrated in Figure 37.

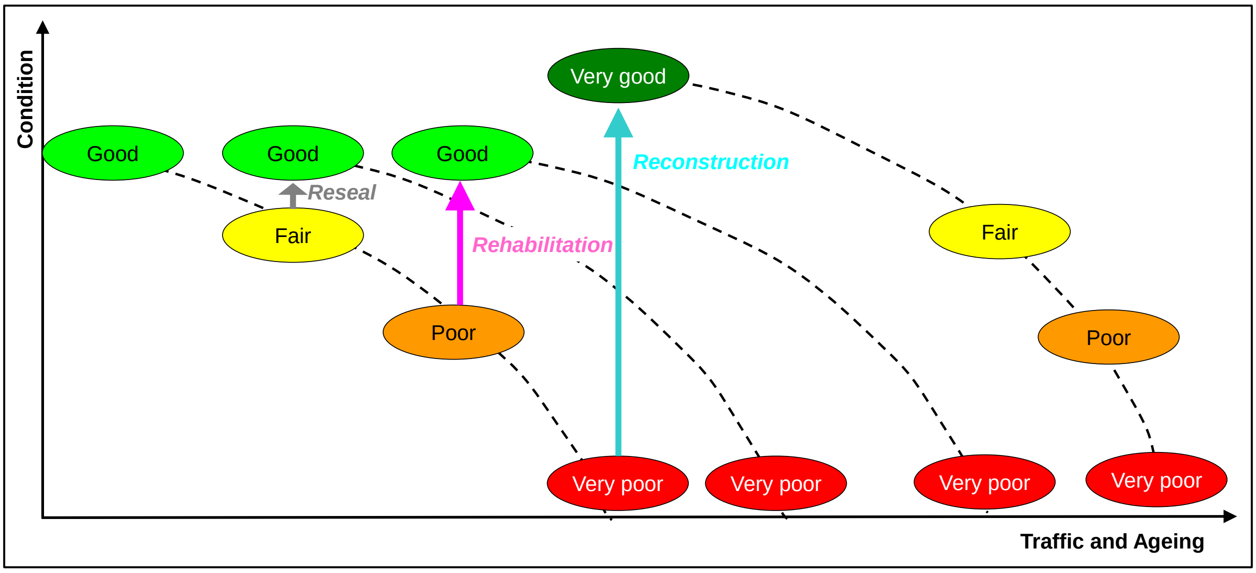


Figure 37. Impact of Timeous Maintenance on Life Cycle Costs

The terminal condition is defined as the degree and extent of distress or serviceability for a given class of road at which point it cannot fulfil its purpose and requires immediate repair or rehabilitation, both in terms of road user and asset value considerations.

The degree and extent of distress manifestation selected as terminal conditions are dependent on the category of pavements. For example, 10 mm rutting over 30% of the road length for Category A pavements (a freeway with 95% reliability in the design) is applicable. In many cases, terminal conditions are only defined in terms of minimum serviceability levels, which represent the measured roughness resulting from a combination of a variety of distress manifestations. These distress mechanisms are not directly used in pavement designs and are only empirically considered. See more on serviceability levels and distress measurements in Chapter 6: 7.

An economic analysis called Life Cycle Costing is required to determine which of the different strategies are more cost-effective. The Present Worth of Cost (PWOC) is one of the methods of economic analysis that can be used. See TRH4 and TRH12 for more on economic analyses.

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TRH Revisions

Many of the TRH guideline documents are in the process of being updated. See the SANRAL website, www.nra.co.za for the latest versions.