



# Technical Guideline: *Bitumen Stabilised Materials*

*A Guideline for the Design and Construction of  
Bitumen Emulsion and Foamed Bitumen  
Stabilised Materials*



**TG 2**  
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## PREFACE

The first TG2 was published in 2002 and covered the design and construction of foamed bitumen treated materials. Since 2002, significant research in bitumen emulsion and foamed bitumen treatment has been done, which needed to be included in the TG2 guideline, hence this update. This guideline supercedes the TG2 published in 2002 and covers the design and construction of Bitumen Stabilised Materials (BSMs) and includes both materials treated with bitumen emulsion (BSM-emulsion) and foamed bitumen (BSM-foam).

The inclusion of BSM-emulsion materials into TG2 has been done because the design and construction of BSM-emulsion and BSM-foam are identical in many respects. Where there are differences between the materials, the inappropriate techniques are often applied by incorrectly adopting the technology for the other material. For this reason, this guideline highlights the similarities and differences, which should prevent the inappropriate application of either technology.

This guideline covers the uses of BSMs, their classification for design purposes, the mix and structural design and construction aspects.



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## SCOPE

This guideline document covers the classification, design and construction of Bitumen Stabilised Materials (BSMs), and includes both bitumen emulsion (BSM-emulsion) and foamed bitumen treated materials (BSM-foam).

BSMs are described, and guidelines for their appropriate use are given. Applications for which BSMs are not appropriate are also discussed. The approaches to classification, mix and structural design and construction are discussed.

The classification of BSMs includes three material classes:

- » **BSM1:** This material has a high shear strength, and is typically used as a base layer for design traffic applications of more than 6 million equivalent standard axles (MESA). For this class of material, the source material is typically a well graded crushed stone or reclaimed asphalt.
- » **BSM2:** This material has a moderately high shear strength, and would typically used as a base layer for design traffic applications of less than 6 MESA. For this class of material, the source material is typically a graded natural gravel or reclaimed asphalt.
- » **BSM3:** This material is typically a soil-gravel and/or sand, stabilised with higher bitumen contents. As a base layer, the material is only suitable for design traffic applications of less than 1 MESA.

A consistent and rational system for classifying the materials is presented. This system is new and is applicable to granular and cemented materials as well as BSMs. Full details of the method for all materials are given in Appendix A.

The mix design of BSMs involves three levels of testing, which depend on the design traffic level. ITS testing in dry and soaked states is used for Level 1 and 2. For Level 3 (design traffic exceeding 6 MESA), triaxial testing is recommended. A simple triaxial test has been developed to facilitate such testing in standard laboratories. A method for testing the moisture sensitivity of BSMs in the triaxial test has also been developed, which utilises the MIST equipment for saturating the triaxial specimens. This is described in Chapter 4.

The structural design of BSMs utilises the Pavement Number (PN) design method. This method is based on observed performance of field pavements and is based on an "intelligent" structural number. The PN method is recommended for design traffic between 1 and 30 MESA and for Category A and B roads. Because the PN method is also new, and is applicable for all road building materials, the complete details of the method are given in Appendix C. For design traffic less than 1 MESA, a catalogue of typical designs is given.

The construction of BSMs includes in situ recycling with recyclers, conventional construction equipment, and in plant treatment. Quality control for construction is also included, and Appendix D contains details on construction controls for BSM treatment using recyclers.

While this guideline is the culmination of many years of research and development, it may be necessary to update details in the laboratory test methods and in the material classification system and Pavement Number method. Any such updates will be posted on [www.asphaltacademy.co.za/bitstab](http://www.asphaltacademy.co.za/bitstab).



## GLOSSARY OF TERMS

°C	degrees Celcius
$T_{1/2}$	half-life
%	percent
AASHTO	American Association of State Highway and Transportation Officials
Active filler	Fillers that chemically alter the mix properties. This includes fillers such as lime, cement, fly ash, etc, but excludes natural fillers such as rock flour.
BSM(s)	Bitumen Stabilised Material(s)
BSM-emulsion	Bitumen emulsion treated material
BSM-foam	Foamed bitumen treated material
CBR	California Bearing Ratio
COLTO	Committee of Land and Transport Officials
CS	Crushed stone
DE-G1 to DE-G10	Design equivalent G1 to G10 material classes
DEMAC	Design equivalent material class
ELTS	Effective long term stiffness. This is a relative indicator of the average long term in situ stiffness of a pavement layer.
EMC	Equilibrium moisture content
ER	Expansion Ratio
$E_{\tan}$	Tangent modulus, stiffness from monotonic triaxial test
EWC	bitumen emulsion water content including water used for dilution as percentage of dry aggregate fluff point moisture content at which the "maximum bulk volume of loose mineral aggregate is obtained
FMC	field moisture content of aggregate
G1 to G10	Granular materials classes, see TRH4 for definitions
GS	Gravel soil
HMA	Hot mix asphalt
ICL	Initial consumption of lime
ITS <sub>dry</sub>	Indirect Tensile Strength test, 100 mm diameter specimens cured for 72 hours at 40 °C.
ITS <sub>equil</sub>	Indirect Tensile Strength test, specimens cured according to curing procedure.
ITS <sub>soaked</sub>	Indirect Tensile Strength test, specimens cured according to curing procedure and then soaked for 24 hours at 25 °C.
ITS <sub>wet</sub>	Indirect Tensile Strength test, 100 mm diameter specimens cured then soaked for 24 hours at 25 °C.
Lime	Lime refers to hydrated road lime
Mastic	The mastic is the mix of fines and bitumen.
maximum stiffness	The maximum stiffness a material can achieve depends on the material quality.
MESA	million equivalent standard axles, 80 kN axles
MIST	Moisture Induced Sensitivity Test used to induce moisture into triaxial specimens.
mm	millimeters
Mod. AASHTO	Modified AASHTO compaction
Modular Ratio	Ratio of a layer's stiffness relative to the stiffness of the layer below.
MPa	megaPascals
N	Weinert's N-value
NG	Natural gravel
OFC	optimum fluids content
OMC <sub>Mod-U</sub>	optimum moisture content using Mod. AASHTO compaction on untreated material
OMC <sub>Mod-BSM</sub>	optimum moisture content using Mod. AASHTO compaction on treated material
OMC <sub>Vib-BSM</sub>	optimum moisture content using vibratory hammer compaction on treated material
PI	Plasticity Index
PN	Pavement number
PTR	Pneumatic Tyred Roller
RA	Reclaimed asphalt
RBC	residual bitumen content as percentage of dry aggregate
SSSC	Silt, silty sand, clay
TSR	Tensile Strength Retained. Ratio of ITSwet and ITSdry.
UCS	Unconfined Compression Test



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CHAPTER 1: Introduction – What are BSMs?

# 1 INTRODUCTION

Road pavements constructed with bitumen stabilised materials (BSMs) using either bitumen emulsion or foamed bitumen are environmentally sustainable and cost effective; and, when good construction techniques are used, these pavements perform very well. BSMs are suited to both construction of new pavements and to pavement rehabilitation using in situ recyclers and/or conventional construction equipment. BSMs are also ideally suited to labour intensive construction. Worldwide, the state of road pavements is deteriorating, and the demand for rehabilitating road pavements far exceeds the demand for new roads. This situation has seen the adoption of in place recycling as the preferred procedure for addressing the rehabilitation backlog by reusing material in the existing pavement. Bitumen stabilisation enhances the properties of these recycled materials, providing service lives that equates to or exceeds those achievable had virgin aggregates been used, all at a lower cost.


This guideline covers the approach to classification, design, construction and risk assessment of pavements using BSMs. To differentiate between bitumen emulsion and foamed bitumen treated materials, the terms BSM-emulsion and BSM-foam are used. Where there are differences in the approach to BSM-emulsion and BSM-foam, these are clearly highlighted in the text by separating the text into columns, where BSM-emulsion aspects are in the left column and the BSM-foam aspects in the right column

## 1.1. WHAT ARE BITUMEN STABILISED MATERIALS?

BSMs are pavement materials that are treated with either bitumen emulsion or foamed bitumen. The materials treated are normally granular materials, previously cement treated materials or reclaimed asphalt (RA) layers. Where an existing pavement is recycled, old seals or asphalt surfacing is usually mixed with the underlying layer and treated to form a new base or subbase layer.

The quantities of residual bitumen emulsion or foamed bitumen added do not typically exceed 3% by mass of dry aggregate. In many situations, active filler in the form of cement or hydrated lime is also added to the mix. The cement content should not exceed 1%, and should also not exceed the percentage of the bitumen stabiliser, (ie. the ratio of bitumen percentage to cement percentage should always be greater than 1). If this ratio is less than one, then the material should be considered a cement treated material and the guidelines in TRH13 should be followed.

The addition of bitumen emulsion or foamed bitumen to produce a BSM results in an increase in material strength and a reduction in moisture susceptibility as a result of the manner in which the bitumen is dispersed amongst the finer aggregate particles.



**Cement Contents**

The cement content of BSMs should be  $\leq 1\%$ , and the cement content should not exceed the bitumen content.

<b><i>BSM-emulsion</i></b>	<b><i>BSM-foam</i></b>
<p>With BSM-emulsion the bitumen emulsion disperses preferentially amongst the finer particles, but not exclusively. There is some “painting” of the larger particles by the bitumen emulsion. This is illustrated schematically in Figure 1.1.</p> <p>With bitumen emulsions, there is a chemical bond between the bitumen and the aggregate promoted by the emulsifier.</p>	<p>Foamed bitumen distributes exclusively to the finer particles, producing “spot welds” of a mastic of bitumen droplets and fines. This is illustrated schematically in Figure 1.1.</p>

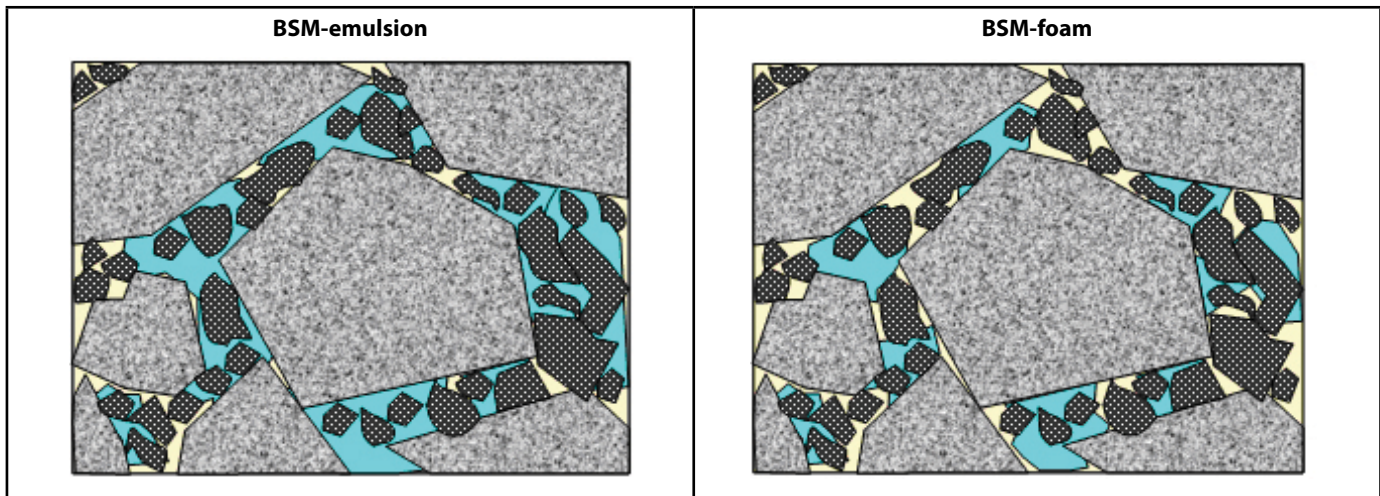


Figure 1.1 Aggregate and Binder Bond

Such “non-continuous” binding of the individual aggregate particles makes BSMs different from all other pavement materials. The dispersed bitumen changes the shear properties of the material by significantly increasing the cohesion value whilst effecting little change to the internal angle of friction. A compacted layer of BSM will have a void content similar to that of a granular layer, not an asphalt. BSMs are therefore granular in nature and are treated as such during construction. The many benefits that accrue from using BSMs are discussed in Chapter 2.

The behaviour of BSMs, relative to other pavement materials is illustrated in Figure 1.2.

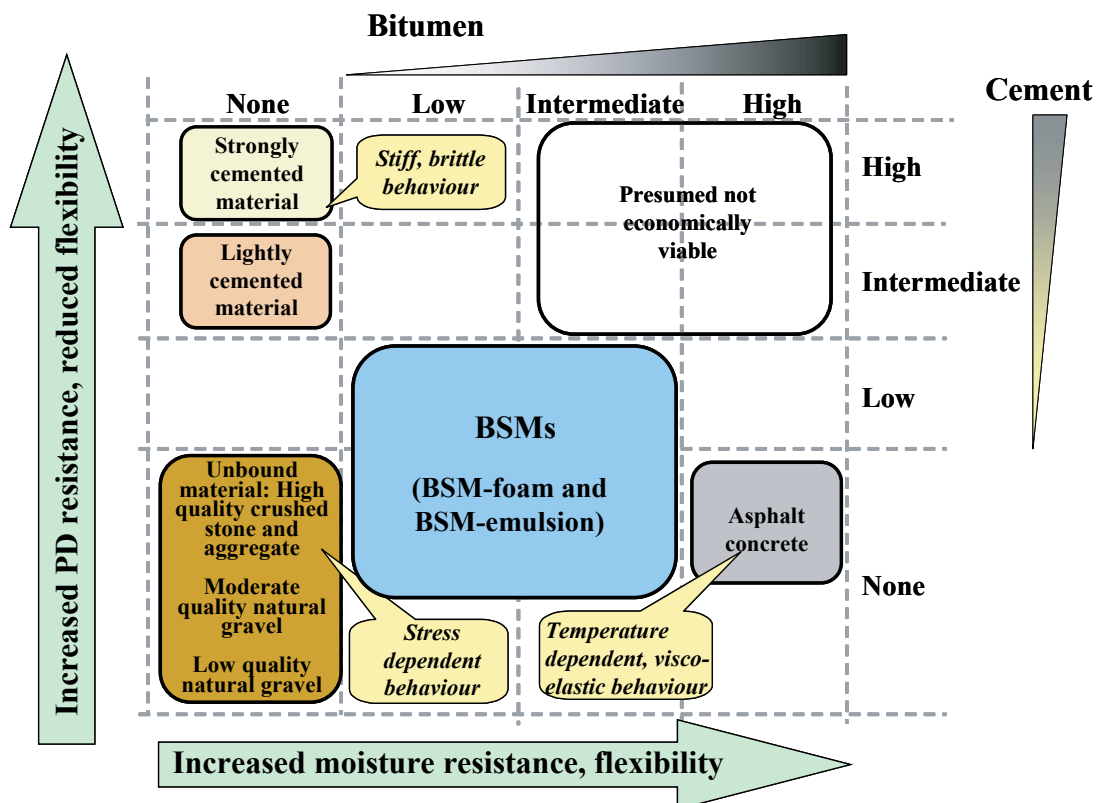


Figure 1.2 Conceptual Behaviour of Pavement Materials



## CHAPTER 1: Introduction – Layout and Purpose of Guideline

Contrary to some misconceptions, the addition of foamed bitumen or bitumen emulsion does not change the nature of the material so that it becomes cold-mix asphalt. BSMs remain granular in nature and must be processed as such during construction. For this reason, terminology such as “foamed asphalt” is not recommended for BSM-foam, as it perpetuates the misinterpretation.

In this guideline, the terms stabilise and treat are used interchangeably. The differentiation between stabilisation and modification used previously is no longer used because the focus is on the behaviour of the final product, rather than the quantity of the constituents which make up the product.

### 1.2. PURPOSE OF GUIDELINE

This guideline is an update to the following manuals:

- » GEMS – The Design and Use of Granular Emulsion Mixes, Manual 14 (SABITA, 1993).
- » ETB – The Design and Use of Emulsion-treated Bases, Manual 21 (SABITA, 1999).
- » Interim Technical Guideline: The Design and Use of Foamed Bitumen Treated Materials, Technical Guideline 2 (Asphalt Academy, 2002).

Because of the many similarities between BSM-emulsion and BSM-foam, it is appropriate to publish one guideline document on bitumen stabilisation that incorporates both materials. The advantage of the combined guideline is that the similarities and differences between BSM-emulsion and BSM-foam are highlighted. This will aid in preventing the incorrect application of the technologies.

Significant research into the behaviour and performance of BSMs has occurred in the last five years. Much of this work has focussed on mix design, classifying materials for design, and structural design. Observations of in-service pavements were also made, which has contributed to the knowledge base of BSM pavements. All this research has been incorporated into this guideline.

The purpose of this guideline is to provide a complete reference for the project selection, treatment selection, material classification, mix design, structural design, construction and risk assessment of projects utilising BSMs. This guideline should however be used in conjunction with other established guidelines, such as:

- » **TRH4:** Structural Design of Flexible Pavements for Interurban and Rural Roads, Draft 1996.
- » **TRH12:** Flexible pavement rehabilitation investigation and design, Draft 1997.
- » **TRH14:** Guidelines for road construction materials, 1985.
- » **TRH21:** Hot-mix asphalt recycling, Draft, 2008.
- » Job Creation, Skills Development and Empowerment in Road Construction, Rehabilitation and Maintenance, GDPTRW, 2008.
- » **Wirtgen Cold Recycling Manual:** 2nd Edition, November 2004

### 1.3. LAYOUT OF GUIDELINE

This guideline contains six chapters, a bibliography and four appendices:

- » Chapter 2 describes **bitumen stabilisation**, where BSMs are **used** and the **approach to design**.
- » Chapter 3 presents the **material classification method**, with particular focus on BSMs.
- » Chapter 4 deals with the **mix design** process for BSMs.
- » Chapter 5 discusses the **structural design** of BSMs and provides the details necessary to perform the Pavement Number structural design method for BSMs.
- » Chapter 6 deals with the **construction** of pavement layers using BSMs.
- » A comprehensive **bibliography** is given. No references are cited in the text of the guideline.
- » Appendix A gives the background and complete details of the **material classification system**.
- » Appendix B gives a list of all **laboratory tests and methods** referred to in the guideline and provides the reference for the test method. Where the methods cannot be found in standard test manual references, the methods can be downloaded from [www.asphaltacademy.co.za/bitstab](http://www.asphaltacademy.co.za/bitstab).
- » Appendix C gives the background details of the **Pavement Number** structural design method.
- » Appendix D contains **Construction Controls** for Bitumen Treatment.

**BSM Behaviour**  
**i** The addition of bitumen emulsion or foamed bitumen **does not transform the material to an asphalt** like material. The **material remains granular** in nature, albeit with improved behavioural characteristics.



## 2 BITUMEN STABILISATION, USAGE AND DESIGN APPROACH

This chapter covers much of the background information for the subsequent chapters. A description of bitumen emulsion and foamed bitumen is presented and the behaviour of BSMs are discussed. The selection of materials and projects suitable for bitumen stabilisation is reviewed along with the benefits of using BSMs and where they are most appropriately used. Finally, the philosophy underlying the design approach for mix and structural design is presented and discussed.

### 2.1. WHAT IS BITUMEN EMULSION AND FOAMED BITUMEN?

Both bitumen emulsion and foamed bitumen are methods of reducing the viscosity of bitumen, allowing it to be mixed with cold moist material. They are, however, produced using completely different methods.

#### Bitumen Emulsion

Bitumen emulsion is comprised of bitumen emulsified in water. The bitumen is dispersed in the water in the form of an oil-in-water type bitumen emulsion. The bitumen is held in suspension by an emulsifying agent. The emulsifying agent determines the charge of the bitumen emulsion. Cationic bitumen emulsions have a positive charge and anionic bitumen emulsion have a negative charge. The manufacture of a typical bitumen emulsion is illustrated in Figure 2.1. Bitumen emulsion is manufactured in a plant and has a shelf life of several months, provided the manufacturer's storage guidelines are strictly followed.

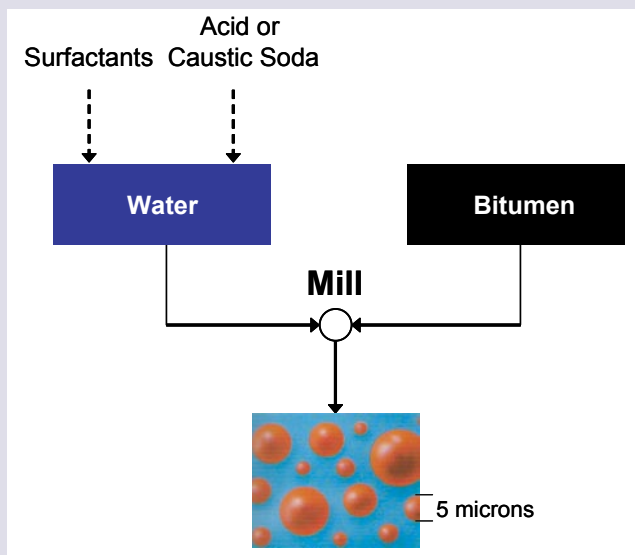


Figure 2.1 Manufacture of Bitumen Emulsion

#### Foamed Bitumen

Foamed bitumen is produced by injecting water into hot bitumen, resulting in spontaneous foaming. The physical properties of the bitumen are temporarily altered when the injected water, on contact with the hot bitumen, is turned into vapour, which is trapped in thousands of tiny bitumen bubbles. This process is shown in Figure 2.2. The foam dissipates in less than a minute. The foaming process occurs in an expansion chamber. The expansion chamber developed by Mobil in the 1960's is still the most commonly used system for producing foamed bitumen. Expansion chambers are relatively small thick-walled steel tubes, approximately 50 mm in depth and diameter, into which bitumen and water (plus air on some systems) are injected at high pressure.

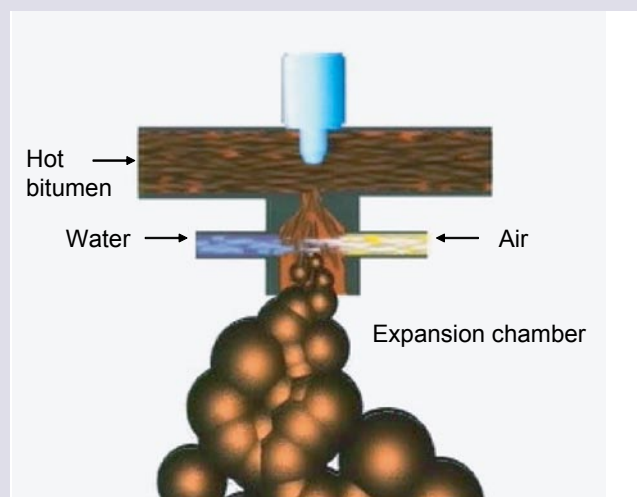


Figure 2.2 Foamed Bitumen Production in Expansion Chamber



CHAPTER 2: Bitumen Stabilisation, Usage and Design Approach – Behaviour of BSMs

<p>When mixed with aggregate, the charge on the individual bitumen droplets causes them to be attracted to the aggregate particles, focusing on the smaller fractions due to their surface area and charge concentration features. The moisture and type of aggregate in the mix plays an important role in dispersing the bitumen emulsion and preventing a premature “break” (separation of the bitumen from the water) during mixing.</p> <p>Once mixed, the bitumen emulsion needs to break to allow the bitumen to act as a binder. Since the bitumen emulsion acts as a lubricant, the break should occur only after the material has been fully compacted. The treated material will have a “speckled” appearance due to the concentration of bitumen on the finer particles. Bitumen emulsions are discussed in more detail in Section 4.2.2.</p>	<p>To produce a BSM-foam, the bitumen is foamed on site and incorporated into the aggregate while still in its foamed state. The greater the volume of the foam, the better the distribution of the bitumen in the aggregate.</p> <p>During the mixing process, the bitumen bubbles burst, producing tiny bitumen particles, that disperse throughout the aggregate by adhering to the finer particles (fine sand and smaller) to form a mastic. The moisture in the mix prior to the addition of the foamed bitumen plays an important role in dispersing the bitumen during mixing. On compaction, the bitumen particles in the mastic are physically pressed against the larger aggregate particles resulting in localised non-continuous bonds (“spot welding”). Foamed bitumen production is discussed in more detail in Section 4.2.2.</p>
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2.2. BEHAVIOUR OF BITUMEN STABILISED MATERIALS

The behaviour of BSMs is similar to that of unbound granular materials, but with a significantly improved cohesive strength and reduced moisture sensitivity. BSMs, unlike hot-mix asphalt, are not black in appearance and do not have a sticky feel. With BSMs, the larger aggregate particles are not coated with bitumen. The bitumen disperses only amongst the finest particles, resulting in a bitumen-rich mortar between the coarse particles. There is a slight darkening in the colour of the material after treatment. Typically, small amounts of active filler (cement or hydrated lime) are added to the mix in conjunction with the bitumen emulsion or foamed bitumen. In addition to improving the retained strength under saturated conditions, such active filler assists in dispersing the bitumen.

<p><b>BSM-emulsion</b></p> <p>When bitumen emulsion is added to a material, the charged bitumen droplets are attracted to the smaller aggregate particles with the opposite charge.</p> <p>Active filler assists the extraction of the water phase from a bitumen emulsion, causing breaking.</p>	<p><b>BSM-foam</b></p> <p>The tiny bitumen particles that are produced when the foamed bitumen bubbles burst have only enough energy to warm the smaller aggregate particles sufficiently to permit adhesion.</p> <p>Active filler acts as a catalyst in dispersing the bitumen particles.</p>
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No distinction is made in these guidelines between the behaviour of BSM-foam and BSM-emulsion. This assumption is based on numerous observations of in-service pavements. The main features and assumed behaviour of BSMs are:

- » BSMs exhibit a significant **increase in cohesion** in comparison to the parent material. The **friction angle** of the treated material is typically similar to the untreated material.
- » BSMs **acquire flexural strength** as a result of the combined effect of the visco-elastic properties of the dispersed bitumen droplets. Since the individual bitumen droplets are not linked and the coarser aggregate particles remain uncoated, BSMs retain the granular characteristics of the parent material. It is therefore stress dependant and is not prone to cracking when subjected to tensile stresses.
- » BSMs **perform well when cohesive strength is optimised** through proper mix design (to determine the optimal bitumen and active filler contents), whilst retaining enough flexibility so that friction resistance is still activated under load.
- » Since the bitumen is dispersed only amongst the finer aggregate particles, the fines are encapsulated and immobilised. This improves the **moisture sensitivity and durability** of the treated materials. Provided sufficient bitumen is applied, the tendency for the BSM to pump under loading in saturated conditions is also significantly reduced because the fines are bound.

**i BSM Behaviour**

The behaviour of BSMs is **similar** to that of **unbound granular** materials, but with **improved cohesive strength** and **reduced moisture sensitivity**.



## CHAPTER 2: Bitumen Stabilisation, Usage and Design Approach – Behaviour of BSMs

» Similar to unbound granular materials, the **stiffness** of bitumen stabilised materials is dependent on:

- The inherent **stiffness of the parent material**.
- The **density** of the material in the layer.
- The **quantities of binder and active filler** added, and their dispersion throughout the mixed material.
- The **local climate**, particularly ambient temperature and rainfall.
- The **stiffness** of the support.

However, the high cohesive strength allows the material to sustain a **higher stiffness** under load than the unbound parent material.

» The primary **mode of failure** of BSMs is permanent deformation.

» The behaviour and stiffness of BSMs varies significantly depending on the **quantities of bitumen and active filler** used. In particular, when excessive cement is used, the materials behave more like cement treated materials and the benefit of adding bitumen is questionable. For this reason, cement contents that exceed 1% are not recommended, and the ratio of added bitumen to added active filler should always exceed one.

For optimal BSM performance, it is important that the mix design is balanced and the pavement is well designed. For optimal mix designs, the reader is referred to Chapter 4 and for optimal pavement design the reader is referred to Chapter 5. However, it is important to understand that there are two ways in which optimal shear strength of a BSM can be compromised, both resulting from the inclusion of too much active filler:

- » **Excessive amounts of active filler** will transform the material from a flexible to a brittle state. In this state, the cohesive strength will dominate but will significantly reduce once fracture occurs. This is likely to be associated with deformation and cracking, and will result in a material consisting of large fractured clumps, with a low frictional resistance.
- » **Poorly graded or non-durable source materials** (soft weathered natural gravel or material with excessive fines) will compromise the frictional resistance of the material. Inexperienced designers may be tempted to compensate for such a situation through the addition of higher amounts of cement. Such fine grained, brittle materials will be highly susceptible to crushing and fatigue failure.

BSMs are clearly very different to asphalt and cement treated materials in terms of behaviour and performance. In particular, they should not be confused with cold asphalt mixes manufactured with cut-back bitumen.

### 2.3. BENEFITS OF BITUMEN STABILISATION

The primary benefits of using BSMs are:

- » The **increase in strength** associated with bitumen treatment allows a BSM to replace alternative high-quality materials in the upper pavement. For example, a G2 quality material treated with either bitumen emulsion or foamed bitumen can be used in place of an asphalt base provided it meets the layer requirements, thereby offering significant cost savings.
- » **Improved durability and moisture sensitivity** due to the finer particles being encapsulated in bitumen and thereby immobilised.
- » **Lower quality aggregates** can often be successfully used.

<b>BSM-emulsion</b>	<b>BSM-foam</b>
» These mixes may be used for materials with a <b>low fines content</b> .	» These mixes may be <b>produced in bulk and stockpiled</b> close to the point of application, to be placed and compacted at a later stage. This provides flexibility in mix manufacturing.

- » The typical **failure mode** of a BSM (permanent deformation) implies that the pavement will require far less effort to rehabilitate when the terminal condition is reached compared with a material that fails due to full-depth cracking.
- » BSMs are **not temperature sensitive**, unlike hot mix asphalt. This is because the bitumen is not continuous throughout the mix.

In addition, on pavement rehabilitation projects where the material in the existing pavement is recycled in situ with bitumen, the following benefits accrue:

- » The process has significant **advantages in terms of environmental considerations** with conservation of natural aggregates and a reduction in transport, material wastage, noise, exhaust, dust emissions and traffic disruptions. Where a layer of BSM can be substituted for an asphalt base, significant energy savings accrue through reduced heating and haulage requirements.



## CHAPTER 2: Bitumen Stabilisation, Usage and Design Approach – Benefits of BSMs

- » Unlike a hot mixed asphalt, BSMs are **not overly sensitive** materials. Small variations in both the amount of bitumen added and untreated material properties will not significantly change the strength achieved through treatment. This allows the inevitable variability in the recycled material to be tolerated.

<b>BSM-emulsion</b>	<b>BSM-foam</b>
<ul style="list-style-type: none"> <li>» Layers of BSM-emulsion may be subjected to <b>traffic within a few hours</b> (after the bitumen emulsion in the upper portion of the layer breaks).</li> </ul>	<ul style="list-style-type: none"> <li>» BSM-foam mixes can be successfully used for treating in situ material with a <b>relatively high moisture content</b>.</li> <li>» After compaction, layers of BSM-foam have <b>sufficient strength</b> to be trafficked immediately with little detrimental effect.</li> </ul>

- » **Traffic disruption and time delays are minimised** by working in half widths and opening to traffic soon after completion. The construction and maintenance of detours is therefore avoided.
- » Pavements showing a **wide range of distress types** can be effectively rehabilitated.
- » The process **eliminates most of the heavy construction traffic** that damages newly-constructed layers and adjacent access and service roads.

Provided they are used under the correct circumstances, the use of BSMs normally result in significant cost and time savings on a project. However, the overriding consideration in the selection of projects for bitumen treatment is the estimate of the cost-benefit ratio. A full economic evaluation should be carried out, taking into account the investment cost, the maintenance costs, the road user costs and the cost of rehabilitation at the end of the service life. The environmental benefits in terms of energy savings and preservation of natural resources are often difficult to quantify, but should also be considered in an appropriate life-cycle analysis.

### 2.4. LIMITATIONS OF BITUMEN STABILISATION

The following concerns need to be addressed when considering the use of a BSM on a project:

- » **Economics.** Bitumen treatment adds significant cost to a project due to the price of penetration grade bitumen or bitumen emulsion and active filler (if used), as well as related transport costs. Where sources of alternative construction materials are close by (e.g. quarries), the cost of treating with bitumen compared to other pavement solutions may preclude this option, especially for lower category roads with a structural capacity of less than 3 MESA.
- » **Design expertise.** BSMs behave differently from all other pavement materials and are not always well understood. One of the driving forces behind this guideline is to provide design engineers with the tools needed to consider a BSM as an option in a pavement structure.
- » **Construction expertise.** Bitumen treatment may be compared with other construction operations that require attention to detail (e.g. asphalt manufacture and paving). Operators and supervisors need specialist training on both the equipment and the use of such equipment. Much of the required expertise comes with time since many control checks are visual.

#### **i** Benefits of Recycling with BSMs

- » **Environmentally friendly** process
- » Can be **trafficked soon after compaction**
- » **Traffic disruption minimised**
- » Does not require **heavy construction traffic**



CHAPTER 2: Bitumen Stabilisation, Usage and Design Approach – Limitations of BSMs

<b>BSM-emulsion</b>	<b>BSM-foam</b>
<ul style="list-style-type: none"> <li>» <b>Moisture content of in situ material.</b> On recycling projects, the total fluid content of the mixed material can pose a problem when treating with bitumen emulsion. Where the moisture content of the in situ material is relatively high, adding bitumen emulsion can increase the total fluids content to beyond the zero-voids limit when compaction energy is applied. When such a condition is encountered, the material cannot be properly compacted.</li> <li>» <b>Bitumen emulsion stability.</b> The bitumen emulsion selected for use on a project must be sufficiently stable to tolerate the pump and spraybar operating pressure of the application system. Once mixed with the material, however, a quick set is required to allow the material to gain strength. To ensure that the bitumen emulsion breaks within a reasonable time period, the formulation is critical for thick layers of BSM-emulsion (&gt; 150 mm).</li> <li>» <b>Bitumen emulsion formulation.</b> The use of poorly formulated bitumen emulsion has caused problems on some projects. Premature breaking (flash set) of an unstable bitumen emulsion prevents mixing and clogs the milling chamber on a recycler. Where the bitumen emulsion is too stable or incompatible with the material, it may take many months (or even years) to break.</li> </ul>	<ul style="list-style-type: none"> <li>» <b>Percentage fines.</b> Foamed bitumen requires sufficient fine particles to be present in the material to facilitate the dispersion of the bitumen. Where the material is deficient in fines, a poor mix (characterised by many bitumen-rich lumps “stringers”) will result. For this reason, the minimum requirement normally specified is 5% (by mass) passing the 0.075 mm sieve.</li> <li>» <b>Foaming equipment.</b> Premature failures have been experienced on some projects due to the use of poorly engineered systems incapable of producing a uniform and consistent supply of foamed bitumen.</li> <li>» <b>Incompatibility of water and hot bitumen.</b> Foamed bitumen requires specialist equipment that has been properly engineered. The two liquids (water and hot bitumen) used to create the foam are not compatible: water does not exist in its liquid state above 100 °C and the grade of bitumen normally used for foamed bitumen treatment does not flow at such a low temperature. Unless the system is designed with positive measures to address this incompatibility, system blockages are inevitable. The foamed bitumen system must therefore be properly designed and engineered to avoid blockages.</li> </ul>

- » On recycling projects, other limitations relating to **variability of the in situ materials** are often encountered. However, such limitations pertain to all recycling projects and are not specific to bitumen treatment. The key to solving such variability problems lies with the design engineer and the attention to detail during the design investigation and construction phases.

## 2.5. MATERIALS SUITABLE FOR BITUMEN TREATMENT

The materials to be treated must be suitable for treatment with bitumen emulsion or foamed bitumen. The various types of material that can be used successfully for BSMs vary from G1 to G6 quality from cuttings and borrowpits (normally in the G4 to G6 range) or quarries (normally in the G1 to G3 range). In addition, material reclaimed from an existing road pavement, generally ranging from G2 to G6 quality, can also be treated with foamed bitumen or bitumen emulsion, either in situ or in plant.

Examples of material that are usually treated with bitumen are:

- » **Crushed stone** of all rock types (G1 to G3).
- » Previously untreated (G4 to G6) **natural gravels** such as andesite, basalt, chert, diabase, dolerite, dolomite, granite, limestone, norite, quartz, sandstone gravels and pedogenic materials such as laterite/ferricrete.

**i Suitable Materials**

Materials ranging from **G1 to G6** quality are suitable for BSMs.

<b>BSM-emulsion</b>	<b>BSM-foam</b>
Calcrete gravels can be successfully treated with bitumen emulsion.	Experience has shown that calcrete gravels should not be treated using foamed bitumen.



## CHAPTER 2: Bitumen Stabilisation, Usage and Design Approach – Suitable Materials

- » **Reclaimed asphalt (RA)** material (mostly blended with a crushed stone layer or a gravel layer beneath).
- » Reclaimed pavement layers comprised of **previously stabilised** crushed stone and/or gravel.
- » **Marginal materials**, such as sands of G7 quality. These materials could be considered when the practitioners have experience with such materials.

For new construction or when importing new materials, the material selection criteria are dictated by the specification requirements to be met for constructing the BSM layer and the proposed material must be tested by an accredited roads laboratory for compliance.

### 2.6. WHERE TO USE BSMS?

As described above, bitumen treatment improves the shear strength of a material and significantly reduces moisture susceptibility. These benefits are however, costly and BSMS are therefore best suited to upper pavement layers where stresses from applied loads are highest and moisture ingress due to surfacing defects are most likely to occur.

BSMs have mainly been used on pavement rehabilitation projects where the existing pavement structure is sound (balanced) and distress is confined to the upper layers. This scenario is common where the surfacing layer has aged and cracked, allowing water to enter the pavement and cause moisture-activated distress in the underlying granular materials. Such pavements are ideal for in situ recycling and the bitumen is added to restore (and often improve) the structural integrity before a thin surfacing layer is applied (asphalt or chip seal, depending on the traffic demands). Thus, most BSM projects carried out over the last two decades have been concerned with pavement rehabilitation and upgrading (strengthening and/or widening) where the in situ material is recycled. Due mainly to escalating costs, a recent trend is to use good quality material (RA and/or virgin graded crushed stone) treated with bitumen in specialised plant as a substitute for asphalt base.

Some of the more important factors to be considered when using BSMS are discussed below.

#### 2.6.1. CONSTRUCTION METHOD

Bitumen stabilisation projects can be constructed in several ways and the choice of which way is best suited to a particular application is influenced by several factors, of which the major ones are:

- » **Size of the project.** The rehabilitation of a major highway will demand a different approach from that used to rehabilitate a lightly trafficked residential street (refer to TRH12)
- » **The type of work to be undertaken.** Rehabilitation by recycling material from the existing pavement will be approached differently from a project where a new lane is added to an existing carriageway using virgin aggregates.
- » **Geographic and environmental considerations.** The overall approach to projects located in mountainous regions with high seasonal rainfall, sub-zero temperatures, steep gradients and low geometric standards is different from a project located in the middle of a flat, arid region.
- » **Locality.**

<b>BSM-emulsion</b>	<b>BSM-foam</b>
Bitumen emulsion is not always available in the vicinity. In addition, it can be difficult and expensive to transport the large amounts of water required to a remote site.	It may be difficult and expensive to transport hot bitumen to a remote site.

- » **Other factors.** Some project specifications demand that a certain construction method must be used (e.g. labour-intensive).

Treating a material with bitumen emulsion or foamed bitumen can be achieved in-plant by feeding the material components through a mixing plant or in situ on the road using recycling techniques. Where the material in an existing pavement is suitable for recycling, in-plant treatment could invariably be more expensive than in situ in terms of the BSM cost per cubic metre, primarily due to double handling and transport costs. Logistically, where virgin materials are to be bitumen treated, the cost difference between in-plant and in situ treatment will determine the appropriate technique. Each construction method therefore has its place in the construction industry and the method adopted on a specific project is influenced by several factors, the most important being:



## CHAPTER 2: Bitumen Stabilisation, Usage and Design Approach – Where to Use BSMs

- » **Type of construction.** In-plant mixing is normally considered for new roads, upgrading projects that require additional structural layers and for labour-intensive construction.
- » **Rehabilitation and upgrading projects.** Where materials recycled from the upper layers of an existing pavement are to be treated with bitumen, the variability and/or condition of the in situ material will normally dictate whether a process of selection and/or pre-treatment is warranted (for example, sizing thick asphalt material). Such technical issues may preclude in situ treatment.
- » **Traffic accommodation.** Restrictions on the accommodation of traffic may influence the preferred construction method to be adopted on a particular project.

Until the mid-1990s, in situ treatment was undertaken using conventional construction equipment (motor graders, disc ploughs and rotavators). Although purpose-built recycling machines have generally replaced such conventional equipment, the conventional equipment remains an option on smaller projects where the cost of establishing a large recycler may not always be justified.

<b>BSM-emulsion</b>	<b>BSM-foam</b>
A choice between these two in situ options is only available to BSM-emulsion treatment.	BSM-foam cannot be applied using conventional equipment and its application is limited to the use of specialised foaming equipment mounted on a recycling machine.

The end specification requirements of the BSM layer must however be the same irrespective of which construction method is adopted. The quality limitations of using conventional equipment versus an in situ recycler must be considered when selecting the construction method.

### 2.6.1.1 In Situ versus In-plant Treatment

In situ treatment saw a phenomenal increase in popularity during the 1990s due to the advent of modern powerful recycling machines that allow pavements to be rehabilitated at a lower cost than conventional reconstruction. In addition, these machines introduced the capability of constructing thick monolithic treated layers, thereby increasing their structural contribution and allowing engineers to design more cost-effective pavements.

As a consequence of the deteriorating state of road pavements worldwide, coupled with the huge financial investment therein, the need for the rehabilitation of existing pavements far exceeds the demand for new roads. This situation has driven the adoption of in situ recycling as a preferred procedure for addressing the enormous backlog of rehabilitation required.

In-plant mixing is an option that should always be considered, particularly where new layers of BSMs are to be constructed from virgin materials and/or a blend of virgin and recycled materials from a stockpile. The main benefits that accrue from in-plant mixing compared to in situ treatment are:

- » **Control of input materials.** In situ recycling allows little control of the material being mixed. With in-plant recycling, the required end-product can be obtained by blending several different aggregates in a purpose-built plant. Input materials can be stockpiled and tested prior to mixing and the input proportions determined and changed as required.
- » **Quality of mixing.** Various changes can be made to the mixer (e.g. adjusting the angle of individual paddles in a pugmill type mixer) to increase the retention time in the mixer, thereby improving the quality of the mixed material.
- » **Stockpiling capabilities**





**CHAPTER 2: Bitumen Stabilisation, Usage and Design Approach – Where to Use BSMs**

<p><b>BSM-emulsion</b></p> <p>It is not recommended to stockpile BSM-emulsion. This is because the bitumen emulsion tends to leach from the aggregate. The aggregates should rather be pre-blended and held in stockpile for mixing with the bitumen emulsion.</p> <p>In exceptional circumstances BSM-emulsion may be stockpiled if the following conditions are met:</p> <ul style="list-style-type: none"> <li>» The <b>cement content is 1% or less</b> (as recommended for BSM mixes.</li> <li>» The bitumen emulsion content is more than 2%.</li> <li>» The <b>stockpile is covered</b> with an impervious blanket to prevent water ingress and water loss.</li> <li>» The mix is stockpiled for a <b>maximum of 2 days</b>.</li> <li>» The ambient temperate <b>does not exceed 30 °C</b>.</li> </ul>	<p><b>BSM-foam</b></p> <p>BSM-foam may be placed in stockpile and used when required, thereby removing the inter-dependency of the mixing process and the construction of the new layer. Stockpile life (the time that the mixed material can remain in stockpile without losing any of its properties) is primarily a function of moisture content and the amount of active filler added to the mix.</p> <p>BSM-foam may be kept in stockpile for several days provided the following conditions are met:</p> <ul style="list-style-type: none"> <li>» The material in the stockpile must <b>remain uncompacted</b>. The height of the stockpile is limited to the maximum reach of the conveyor or loader used to place the material in the stockpile. Vehicles must not be allowed to drive on the mixed material to end-tip.</li> <li>» Since the individual bitumen droplets in a BSM-foam mix lose their adhesion ability when the material dries out, the moisture content of the material in the stockpile must be <b>maintained at approximately the optimum moisture content (OMC)</b>. This can be achieved by “sheeting” the entire stockpile with an impervious blanket. Such a sheet <i>also</i> protects against oxidation of the bitumen near the surface of the stockpile. If no impervious blanket can be provided, stockpiles of BSM-foam can be kept wet by frequently spraying the surface with water or spraying a fog spray of bitumen emulsion over the entire stockpile.</li> </ul>
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**2.6.2. CLIMATIC CONSIDERATIONS**

The following climatic considerations are important when working with BSMs:

<p><b>BSM-emulsion</b></p> <p>BSM-emulsions should only be constructed at temperatures exceeding 5 °C. At low temperatures, the bitumen emulsion may break prematurely resulting in a poor mix. In addition, the lower the temperature, the slower the rate of evaporation of the excess moisture in the material.</p> <p>The moisture content of the pre-treated material needs careful consideration when working in wet climates. When the bitumen emulsion is added to a material that already has a high moisture content, the resulting fluid content may be too high for compaction.</p>	<p><b>BSM-foam</b></p> <p>Temperature affects the foaming process. If the temperature of the aggregate is too low, the foamed bitumen will not be properly dispersed in the mix. Extra care should therefore be taken when using foamed bitumen in cold temperatures, particularly when the temperature of the material prior to mixing is between 10 and 15 °C. Foaming should not occur at aggregate temperatures below 10 °C.</p>
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**2.6.3. GENERAL PROJECT SELECTION CRITERIA FOR IN SITU TREATMENT**

To date, most BSM projects have been constructed in situ. For many years conventional equipment has been used for in situ treatment. However, by the end of 2008, more than 50 recycling machines capable of constructing BSMs were operating in the southern African region. In contrast, few in-plant mixing units were available for the production of BSM-emulsion and even fewer capable of producing BSM-foam. Clearly the market is geared for in situ treatment.



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Although this focus on in situ treatment can change, recycling is likely to remain the preferred construction method for the foreseeable future and is therefore the centre of attention for these guidelines. The following sections summarise the main factors that need consideration when assessing the potential for using in situ treatment on a pavement rehabilitation project.

### 2.6.3.1 Type and Quality of Existing Pavement and Materials

The quality of the untreated material largely dictates the performance of the treated material. The following situations that impact on the quality of the final mix should be noted:

- » **Roads with shallow structures** resulting in poor structural capacities can seldom be adequately rehabilitated using only in situ recycling. Where the subgrade CBR is less than 3%, the use of in situ recycling is not recommended unless the subgrade is first improved with deep, high energy compaction or adequate cover with sufficient strength is provided. The subgrade material should not be mixed with material from the structural layers.
- » If the depth of the pavement structure is adequate and **structural problems are confined to the base layer**, then recycling is a good option and can produce a high-quality base. The recycling process does not disturb the material in a sound pavement layer beneath the recycling horizon.
- » Pavements with **waterbound macadam bases should not be recycled** because the coarse grading of such material is unlikely to be suitable for BSMs.
- » Pavements with **severe crocodile cracking** in the asphalt can present problems. If the cracked segments are close to or smaller than the distance between the cutting teeth on the recycler, the particles may pass through the recycling process without being broken down. The grading so obtained may be unsuitable and may require pre-treatment by pre-milling (as discussed in Chapter 6).
- » The **thicknesses and variability** of the layers available for recycling play a significant role in determining the suitability of the project. Where two or more layers are to be recycled, the relative thicknesses and material properties need to be identified and the extent of the variability quantified as part of the field investigations.
- » In some cases, **additional material** needs to be added to that being recycled to:
  - **Increase the total pavement thickness.**
  - **Reduce variability** of the recycled material.
  - **Modify the properties** (especially the grading) of the recycled material.
  - Provide the recycler with a **working platform** that conforms to the final shape requirements.Such material addition is normally imported, spread as a layer on the existing road surface and precompacted.
- » A problem often encountered with in situ recycling is **excessive moisture** or variations in the moisture content of the material recovered from the existing road. This needs to be evaluated prior to recycling to determine how best it can be addressed.

### 2.6.3.2 Geometry of Existing Road and Services

In situ recycling is particularly useful on rehabilitation projects where the existing road geometry must be retained. Kerbing, concrete drains and access ramps in the urban environment are typical cases where changes in road level should be avoided.

The quality of the material that is recycled from a pavement with layers constructed to different cambers will vary laterally across the width. This situation needs to be recognised and allowances made during the design process.

Roads with large numbers of buried services and those with steel manhole covers require careful planning and preliminary work before recycling can be undertaken. Careful attention must be paid to the possible presence of steel manhole covers that have been buried by asphalt as these can damage the recycler's cutting equipment.

## 2.7. DESIGN APPROACH

The approach to designing BSMs, in terms of both mix and structural design, are presented in this section.

### 2.7.1. DESIGN SEQUENCE

The typical design sequence followed in a BSM project is illustrated in Figure 2.3. The process begins with an investigation into the design traffic, the available materials, the pavement structure (for recycling projects) and the climate. Once these parameters are known, the



### Construction Temperatures

**BSM-emulsion** should only be constructed at **ambient temperatures > 5 °C.**

**BSM-foam** should only be constructed at **ambient temperatures > 10 °C.**



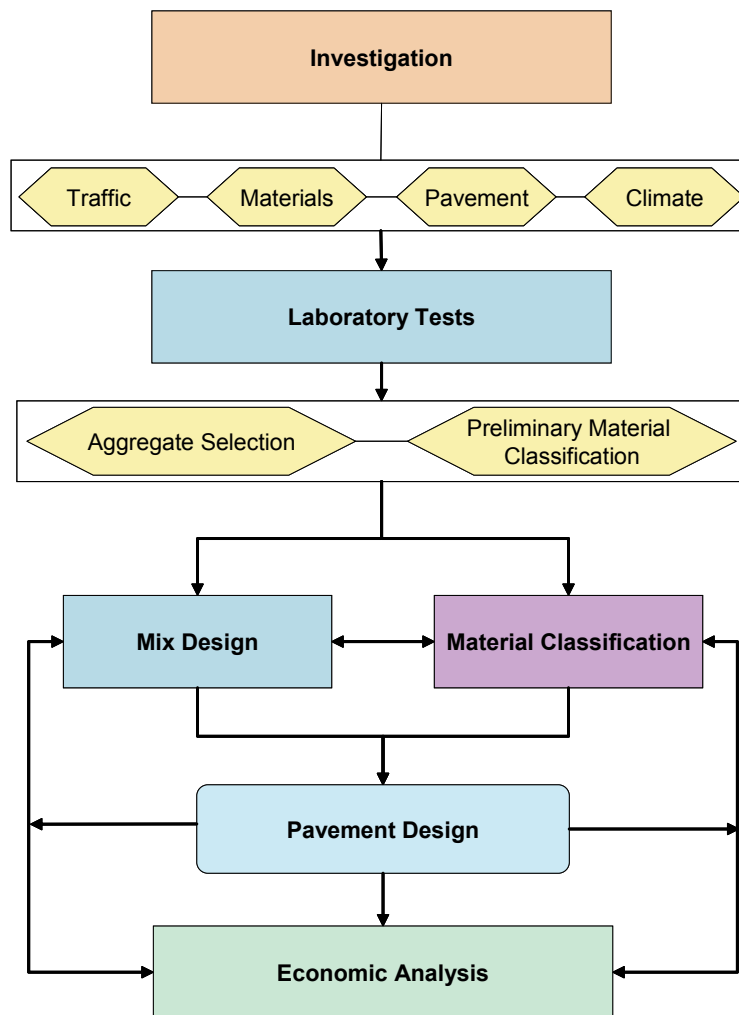
### Buried Utilities

Roads with large numbers of **buried services** and those with **steel manhole covers** require careful planning before recycling can be undertaken.



**CHAPTER 2: Bitumen Stabilisation, Usage and Design Approach – Design Approach**

laboratory investigation into the materials begins. The untreated aggregate is first investigated, and is classified to determine the design equivalent material class. During this investigation, a preliminary pavement design is necessary for recycling projects as the depth of recycling and resulting layer thickness directly influence the materials used for the laboratory investigation. Following laboratory testing, the mix design is done, followed by the final material classification. The structural design follows. Should the economic analysis show the design to be inappropriate, the mix design will be redone or refined.



**Figure 2.3 Design Sequence**

**2.7.2. MATERIAL CLASSIFICATION APPROACH**

One of the primary objectives of this guideline is to link the mix and structural design of BSMs with the performance of these materials, through their classification. The objective of the material classification method is to provide a reliable, rational and consistent indication of the appropriate material class, using all the available data. The method attempts to move away from the yes/no type classification, where one test can result in a material being classified in a much lower class than what its behaviour suggests. The method classifies the certainty of a material belonging to a material class. The material classes are termed design equivalent material class (DEMOC). A DEMOC denotes a material that exhibits shear strength, stiffness and flexibility properties similar to newly constructed materials of the same class. A method for classifying BSMs is given in Chapter 3 and Appendix A.

**2.7.3. MIX DESIGN APPROACH**

The primary objective of the mix design process is to create a BSM that is fit for purpose, whether using bitumen emulsion or foamed bitumen. The considerations that need to be accounted for in the mix design include:



## CHAPTER 2: Bitumen Stabilisation, Usage and Design Approach – Classification of BSMs

- » Understanding the **primary mode of failure** by which the performance of a material may be defined, is it durability, permanent deformation, or some other mechanism?
- » Identifying the most **appropriate laboratory tests** to simulate the key performance criteria and failure mechanisms.
- » Identifying **key mix properties** and intrinsic **material properties** that can influence performance. For example, gradation of aggregate, hardness of aggregate and bitumen content.
- » Taking account of **variability**, considering that many BSMs are prepared from recycled and reused materials with significantly variable properties, such as percentage of RA and degree of weathering.
- » Taking account of the **environmental factors** that influence the conditioning of the material and thus its performance, e.g. climate (especially temperature and moisture), pavement type and permeability. These factors influence the curing rate and equilibrium moisture conditions, and need to be considered for short, medium and long term effects.
- » Effective **simulation of field compaction** procedures in the laboratory for the preparation of specimens for evaluation. This is especially important given that current roller technology has taken the optimisation of field densities to new levels.

The outcome from the mix design process largely depends on:

- » The **design traffic** that needs to be accommodated.
- » The **quality of available material**.
- » **Cost considerations** and budget constraints.

In terms of the selection of an appropriate mix composition, the optimum bitumen content is not necessarily selected to provide the peak material strength, but rather to satisfy minimum requirements with regard to mix properties, for example, strength, stiffness and durability including resistance to moisture. Consideration of predominantly strength criteria leads to the design of brittle, inflexible mixes that are susceptible to cracking. Durability considerations, on the other hand, lead to adjudication of minimum bitumen contents to satisfy moisture resistance requirements, which automatically satisfy the flexibility needs. Mix composition selection criteria that consider the design traffic and the quality of the untreated aggregate are provided as part of the material classification system (Chapter 3).

### 2.7.4. STRUCTURAL DESIGN APPROACH

The purpose of structural pavement design is to make an unbiased, rational estimate of the structural capacity of layered pavement systems. Such estimates allow the unbiased comparison of alternative designs during the structural and economic analyses. If the structural capacity of a specific design is under- or overestimated in relation to the structural capacity of alternative designs, that particular design will be unfairly penalised or promoted during the economic analysis. A structural design method that assesses the structural capacity of different pavement types according to the same set of rules is provided in this guideline.

A pavement design method has been developed for BSMs, but is in fact applicable to most pavement materials used in southern Africa. The method, called the Pavement Number (PN), is an empirical method based on accepted pavement design rules and uses a pavement index approach. The method was developed with data from well-established catalogues of design, long-term pavement performance data and Heavy Vehicle Simulator test sections. Data from over twenty pavement sections were used. The use of these field data, and the coarseness of the data, precluded the development of mechanistic-empirical design models.

The structural design of BSMs is discussed further in Chapter 5. The approach to structural design in this guideline is complementary to TRH4 and TRH12. In conjunction with those guidelines, the designer should ensure that all relevant aspects of pavement design are investigated.

## 2.8. CLASSIFICATION OF BSMS

BSMs are classified into three classes, depending on the quality of the parent material and the design traffic. The three classes are:

- » **BSM1:** This material has a high shear strength, and is typically used as a base layer for design traffic of more than 6 MESA. For this class of material, the source material is typically a well graded crushed stone or reclaimed asphalt (RA).
- » **BSM2:** This material has moderately high shear strength, and is typically used as a base layer for design traffic applications of less than 6 MESA. For this class of material, the source material would typically be a graded natural gravel or RA.
- » **BSM3:** This material typically consists of soil-gravel and/or sand, stabilised with higher bitumen contents. As a base layer, the material is only suitable for design traffic applications of less than 1 MESA.



## 3 MATERIAL CLASSIFICATION

The material classification system provides a critical link between the mix and structural design, and construction quality control checks. The determination of material classes for each pavement layer is a critical aspect of the structural design process, since this process effectively determines the structural design inputs. In this chapter, a method for classifying materials is presented. The object of the method is to provide a reliable, rational and consistent indication of the appropriate material class. The system can be used for all materials common in southern Africa and in all pavement design contexts. However, the method is particularly appropriate for rehabilitation, specifically recycling, as the quality of the existing material is not typically engineered, but must be well characterised.

The sections below describe the method in more detail and provide all relevant details for classification of BSMs. The material classification system has not yet been formally published in a guideline, and is therefore described in full in Appendix A for BSMs, granular and cemented materials.

### 3.1. CONCEPT

Many material classification methods are specification type approaches that rely on pass or fail type criteria. For these types of approaches, if any one test fails the criteria for the material class then the material cannot be classified in that class. For example, if the ITS value is below the specification for a BSM1 material, then the material cannot be classified as a BSM1 even if all other available test results do meet the BSM1 criteria.

The concept underlying the material classification system is to use all available material information to give a consistent, rational and objective assessment of a material class. The system gives a holistic assessment, which works best when a comprehensive range of test indicators are used. This approach is more rational, albeit less exact and can handle vagueness in the data. Rather than giving a yes or no answer, the method indicates the conformance to a material class in less restrictive terms. The approach associates a certainty that the material can be considered as a particular material class, and uses Fuzzy Logic and Certainty Theory to provide this type of assessment.

The result of the material classification process is a Design Equivalent Material Class (DEMAC). A DEMAC denotes a material that exhibits shear strength, stiffness, durability and flexibility properties similar to a newly constructed material of the same class. The DEMAC implies that the material may not meet exact specifications for a particular material class, but in terms of expected behaviour the material is similar.

### 3.2. MATERIAL CLASSIFICATION SYSTEM

The material classification system for BSMs assigns a material to one of four material classes, and determines the certainty that the material can be represented by that DEMAC. The following material classes (as defined in Section 2.8) are used:

- » BSM1
- » BSM2
- » BSM3
- » Unsuitable for treatment with bitumen emulsion or foamed bitumen.

The DEMAC does not differentiate between BSM-emulsion and BSM-foam.

The method works by determining, for each test result available, the certainty that the material falls into each of the four material classes. This is done by using the 10th percentile, median and 90th percentile of all the results from the specific test, as illustrated in Figure 3.1 for the DCP penetration and ITS. The blue lines represent the 10th and 90th percentiles and the red dot the median. The certainty that a material belongs to a particular DEMAC is dependant on how much of the data falls into that class. The specific details of the calculation are given in Appendix A. Using Figure 3.1 as an example, the DCP suggests that the material is either a design equivalent BSM2 (DE-BSM2) or design equivalent BSM3 (DE-BSM3), and the ITS suggests a DE-BSM1, DE-BSM2 or DE-BSM3.

#### *i* Design Equivalent Material Class (DEMAC)

A **DEMAC** denotes a material that exhibits shear strength, stiffness and flexibility properties similar to newly constructed material of the same class.

#### *i* Software

Software to determine a DEMAC, and a template for data preparation are available on [www.asphaltacademy.co.za/bitstab](http://www.asphaltacademy.co.za/bitstab)



Test or Indicator	Material Class			
	BSM1	BSM2	BSM3	Unsuitable
DCP Penetration (mm/blow)	< 3.7	3.7 to 9.1	9.1 to 19.0	< 19.0
ITS (kPa)	> 100	75 to 100	50 to 75	< 50

Figure 3.1 Interpretation of Test and Indicator Results

Because most pavement materials tests provide only a partial indication of the material behaviour, each test is assigned a certainty factor. This certainty factor (CF) represents the subjective confidence in the ability of a test to serve as an accurate indicator for material strength and stiffness in the pavement layer. The value of CF ranges from 0 to 1, with a value of 1 indicating absolute confidence in a test or indicator (highly unlikely).

Using the spread of data for each test, and the certainty factor, the cumulative certainty that a material falls into one of the four material classes is calculated. The more tests utilized, the higher the cumulative certainty. The details of this calculation are given in Appendix A. The method can be done using a spreadsheet. However, to make it easier to utilise, software to perform the material classification and a template for data preparation are available on [www.asphaltacademy.co.za/bitstab](http://www.asphaltacademy.co.za/bitstab).

### 3.3. TESTS AND INTERPRETATION OF RESULTS FOR BSMS

The tests that are used for the material classification, interpretation of the test results and certainty factors for BSMS are provided in this section. The values shown for the tests included in this guideline were the values used at the time of publication of the guideline. Although these values were well validated, it may be necessary from time to time to make changes to improve the system. If changes are made, the modified values will be reflected on [www.asphaltacademy.co.za/bitstab](http://www.asphaltacademy.co.za/bitstab). It is recommended that before commencing the material classification process, the website is checked for any changes in values or tests.

The classification for BSMS is intended to assess the suitability of the material for BSM treatment. It therefore assesses the material based on many of the same tests and indicators used for granular materials, representing the material before treatment, and then evaluates the BSM mix using tests from the mix design process. Although some of the limits in the tests are different for BSM-emulsion and BSM-foam, in the final classification no distinction is made between the two materials.

The indicators and tests for the classification of BSMS are detailed in Table 3.1 and the relevance of the test or indicator is explained. The interpretation of the test results and actual limits used for each test are provided in Table 3.2. The interpretation of grading requires the determination of a rating, which is detailed in Table 3.3 and Figure 3.2. Figure 3.2 is a repeat of Figure 4.2 in Chapter 4.

**i** **Test and Indicator Limits**

[www.asphaltacademy.co.za/bitstab](http://www.asphaltacademy.co.za/bitstab) Contains the most **up to date limits** and **certainty factors** for the selected tests and indicators.



### CHAPTER 3: Material Classification – Tests and Interpretation

**Table 3.1 Indicators and Tests for Classification of Bitumen Stabilised Materials**

Test or Indicator	Relevance for Material Classification	Interpret. or Rating
Soaked CBR (untreated)	When soaked, tests mainly the frictional strength component of shear strength.	Table3.2
Percent passing 0.075 mm sieve (Fines) (untreated)	Impacts on the density that can be achieved, bitumen content and on the bearing strength of the material. As such, relates mainly to frictional component of shear strength.	Table3.2
Relative Density (untreated)	Relates to the density of packing of particles, and hence to the potential to develop frictional resistance.	Table3.2
DCP Penetration (untreated)	Indicator for overall shear strength. Sensitive to density, moisture content, particle strength, grading and plasticity.	Table3.2
FWD Backcalculated Stiffness (untreated)	Provides a direct but relative indication of the stiffness under dynamic loading. Likely to be highly correlated to shear strength at small strains for most materials.	Table3.2
Plasticity Index (untreated)	Determines the influence of water on shear strength. For a fixed maximum aggregate size, shear strength is greatly reduced with an increase in PI.	Table3.2
Relative Moisture Content (untreated)	The relative moisture content is the measured moisture content, relative to the optimum moisture content for the material.	Table3.2
Grading Assessment Rating (untreated)	Rating quantifies the conformance of the material grading to applicable specifications. Good conformance to grading indicates increased frictional resistance.	Table3.3 Figure 3.2
Grading Modulus (untreated)	Quantifies the relative amount of fines in the material. As such, it influences the ability of the material to develop interlock between coarse particles.	Table3.2
Cohesion, Friction angle and Tangent Modulus (treated)	The shear parameters and material stiffness from triaxial testing provide critical performance properties related to resistance to permanent deformation.	Table3.2
ITS (treated)	Provides a reference to the historic performance of mixes ( $ITS_{dry}$ and $ITS_{equil}$ ) and a measure of moisture resistance ( $ITS_{wet}$ ).	Table3.2
UCS (treated)	Provides a measure of the compressive strength of mixes, and a reference to the historic performance of mixes.	Table3.2
Retained Cohesion (MIST) (treated)	The change in cohesion after moisture conditioning from triaxial testing provides a measure of moisture resistance.	Table3.2



Table 3.2 Interpretation of Indicators and Tests for Classification of Bitumen Stabilised Materials

Test or Indicator	Material <sup>1</sup>	Design Equivalent Material Class			Not suitable for treatment	CF
		BSM1	BSM2	BSM3		
Soaked CBR (%)	CS (98%)	> 80	25 to 80	10 to 25	< 10	0.4
	NG (95%)		> 25	10 to 25	< 10	
P0.075 (%) (Bitumen emulsion)	CS	4 to 15			> 15	0.35
	NG		5 to 25	25 to 40	> 40	
	GS		5 to 20	15 to 30	> 30	
	SSSC			0 to 20	> 20	
P0.075 (%) (Foamed bitumen)	CS	2 to 15			> 15	0.1
	NG		11 to 25	23 to 40	> 40	
	GS		0 to 20	13 to 30	> 30	
	SSSC			0 to 20	> 20	
Relative density	All	> 0.98	0.95 to 0.98	0.93 to 0.95	< 0.93	0.1
DCP Pen (mm/blow)	All	< 3.7	3.7 to 9.1	9.1 to 19.0	> 19.0	0.1
FWD Backcalculated Stiffness (MPa)	All	> 300	150 to 300	70 to 150	< 70	0.1
Plasticity Index	CS	< 10	> 10			0.25
	NG	< 6	6 to 12	> 12		
	GS		> 11	11 to 15	< 15	
	SSSC			< 15	> 14	
Relative moisture (%)	CS	< 90	> 90			0.1
	NG	< 70	70 to 100	< 80		
	GS		> 100	80 to 100	< 100	
	SSSC			> 100	> 100	
Grading modulus	NG	2.0 to 3.0	1.2 to 2.7	0.15 to 1.2	0.15	0.2
	GS		1.2 to 2.5	0.75 to 2.7	< 0.75	
Cohesion (kPa)	All	> 250	100 to 250	50 to 100	< 50	0.45
Friction Angle (°)	All	> 40	30 to 40	< 30		0.4
Tangent Modulus (MPa)	All	> 150	50 to 150	< 50		0.1
ITS (kPa)	Dry, 100 mm <sup>2</sup>	> 225	175 to 225	125 to 175	< 125	0.1
	Equilib, 150 mm	> 175	135 to 175	95 to 135	< 95	0.2
ITS (wet) kPa)	100 mm	> 100	75 to 100	50 to 75	< 50	0.1
UCS (kPa)	All	1 200 to 3 500	700 to 1 200	450 to 700	< 450	0.1
Retained cohesion after MIST (%)	All	> 75	60 to 75	50 to 60	< 50	0.45
Rating	All	0.5 to 1.5	1.5 to 2.5	2.5 to 3.5	3.5 to 4.5	N/A

**Notes:**

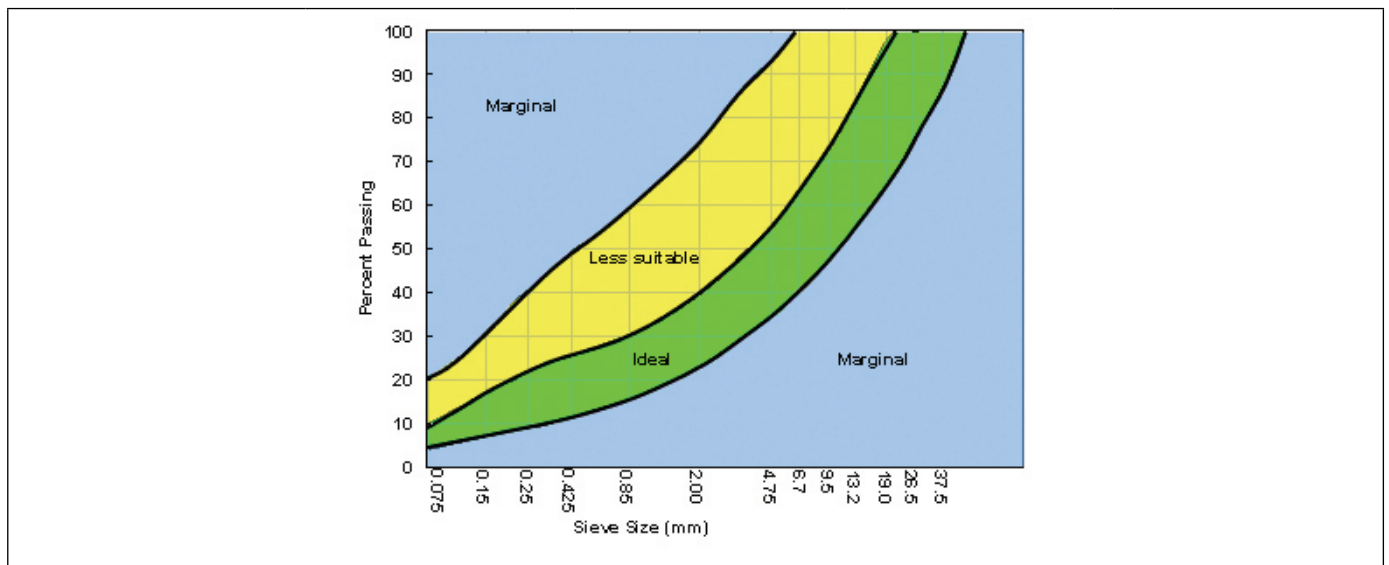
1. CS = crushed stone, NG = natural gravel, GS = gravel soil, SSSC = sand, silty sand, silt, clay; 98%, 95%, 93%, 90% are Mod. AASHTO densities.
2. Diameter of specimen.



CHAPTER 3: Material Classification – Tests and Interpretation

Table 3.3 Interpretation of Grading Rating for BSMs

Test or Indicator	Material <sup>1</sup>	Rating				CF
		1	2	3	4	
Grading (see Figure 3.2)	CS	Ideal	Less suitable		Marginal	0.4
	NG		Ideal	Less suitable	Marginal	
	GS		Ideal	Less suitable	Marginal	



Sieve Size (mm)	Percent Passing			
	BSM-Emulsion		BSM-Foam	
	Ideal	Less suitable	Ideal	Less suitable
50	100		100	
37.5	87 – 100		87 – 100	
26.5	77 – 100	100	77 – 100	100
19.5	66 – 99	99 – 100	66 – 99	99 – 100
13.2	67 – 87	87 – 100	67 – 87	87 – 100
9.6	49 – 74	74 – 100	49 – 74	74 – 100
6.7	40 – 62	62 – 100	40 – 62	62 – 100
4.75	35 – 56	56 – 95	35 – 56	56 – 95
2.36	25 – 42	42 – 78	25 – 42	42 – 78
1.18	18 – 33	33 – 65	18 – 33	33 – 65
0.6	12 – 27	27 – 54	14 – 28	28 – 54
0.425	10 – 24	24 – 50	12 – 26	26 – 50
0.3	8 – 21	21 – 43	10 – 24	24 – 43
0.15	3 – 16	16 – 30	7 – 17	17 – 30
0.075	2 – 9	9 – 20	4 – 10	10 – 20

The differences between the grading zones of BSM-emulsion and BSM-foam are small enough that the differences cannot be discerned on the figure.

Figure 3.2 Interpretation of Grading to Quantify Relative Conformance to Grading (BSM)



### 3.4. CONFIDENCE ASSOCIATED WITH ASSESSMENT

The confidence in the certainty associated with the material classes depends on the number of tests or indicators used and the certainty factors associated with these tests and indicators. The strength of confidence in the assessment is thus quantified by the certainty of the assessment, and this is an indirect indicator of the reliability of any design based on this assessment. Table 3.4 provides some guidelines to assess the confidence associated with the material classification.

**Table 3.4 Relative Confidence of Materials Classification**

Cumulative Certainty	Confidence in Classification
< 0.3	<b>Very low confidence.</b> It is strongly recommended that more data be gathered to enable a more confident assessment to be made.
0.3 to 0.5	<b>Low confidence.</b> Suitable only for situations where the existing pavement condition and age is such that structural rehabilitation will not be considered, or is very unlikely.
0.5 to 0.7	<b>Medium.</b> Suitable or situations where the existing pavement condition and age is such that structural rehabilitation is unlikely, or for which the condition and/or other factors predetermines the treatment type.
> 0.7	<b>High.</b> This is the minimum recommended certainty for situations where structural rehabilitation is likely, and for which the rehabilitation design will rely completely on the quality and state of existing pavement layers.



## CHAPTER 4: Mix Design – Requirements

# 4 MIX DESIGN

The mix design of Bitumen Stabilised Materials (BSMs) is particularly challenging due to the number and types of ingredients that comprise these materials. Each component material, including aggregate, water, bitumen and active filler, with its own variability, availability and cost, needs to be blended and processed to formulate a composite product for a specific purpose or application. To produce construction materials with the necessary quality and consistency to fulfil their intended function, sound procedures need to be followed that assist in identifying optimal formulation, blending and production. This process is the mix design procedure.

The BSM mix design procedure requires optimisation not only in terms of volumetric and compaction characteristics, but also requires the consideration of engineering properties and durability. It is thus essential that the material samples used during the mix design be representative of the materials in the layer or layers that will be treated with bitumen. At the same time, economic considerations remain paramount in the determination of mix designs. The bitumen contributes significantly to the cost of BSMs, underlying the need for effective optimisation of bitumen content.

This chapter deals with the mix design procedure of BSMs, and includes all the details necessary for performing and evaluating a mix design.

All test methods referred to in this guideline are explicitly referenced in Appendix B. Where test methods cannot be found in standard manuals, such as THM1, the methods have been compiled and are on [www.asphaltacademy.co.za/bitstab](http://www.asphaltacademy.co.za/bitstab) from where they can be downloaded. It is advisable to always check the website to ensure the most up to date test method is used.

## 4.1. MIX DESIGN REQUIREMENTS

The complex behaviour of BSMs allows the materials engineer to design a product best suited to the particular design conditions. By changing the mix proportions of the aggregate, bitumen and active filler it is possible to create a mix with behaviour that will approach the behaviour of granular materials, cemented materials or hot-mix asphalt.

There are two fundamental failure mechanisms that need to be designed for in the mix design, namely:

- » **Permanent Deformation.** This is accumulated shear deformation with loading and is dependent on the material's shear properties and densification achieved. Resistance to permanent deformation (rutting) is enhanced by:
  - Improved **aggregate angularity, shape, hardness and roughness.**
  - Increased **maximum particle size.**
  - Improved **compaction.**
  - Reduced **moisture content** (curing).
  - Addition of a **limited amount of bitumen**, usually less than 3.5% because higher bitumen contents encourage rutting.
  - Addition of **active filler**, usually limited to a maximum of 1% because higher active filler contents create brittleness which encourages shrinkage and traffic associated cracking.
- » **Moisture Susceptibility.** The presence of water in BSMs, as well as the partially coated nature of the aggregate makes moisture susceptibility an important consideration in evaluation of material performance. Moisture susceptibility is the damage caused by exposure of a BSM to high moisture contents and pore-pressures, caused by traffic. This results in loss of adhesion between the bitumen and the aggregate. Moisture resistance is enhanced by:

### *i* Mix Design Process

The mix design process aims to optimise the mix for permanent deformation, moisture susceptibility and durability.BSMs.

### *i* Laboratory Test Methods

All the laboratory test methods referred to in this guideline are either available in standard manuals or are available for download on [www.asphaltacademy.co.za/bitstab](http://www.asphaltacademy.co.za/bitstab).

### *i* Mix Design

The procedure optimises the materials used, and determines the bitumen content to maximise the performance, with due consideration of the cost.

### *i* Mix Constituents

Aggregate properties dominate rut resistance.

Bitumen content influences durability.



- Increased **bitumen content**, bearing in mind the cost implications and potential for permanent deformation.
- Addition of **active filler**, usually limited to 1% by mass of dry aggregate.
- Improved **compaction**.
- Smooth continuous **grading**.

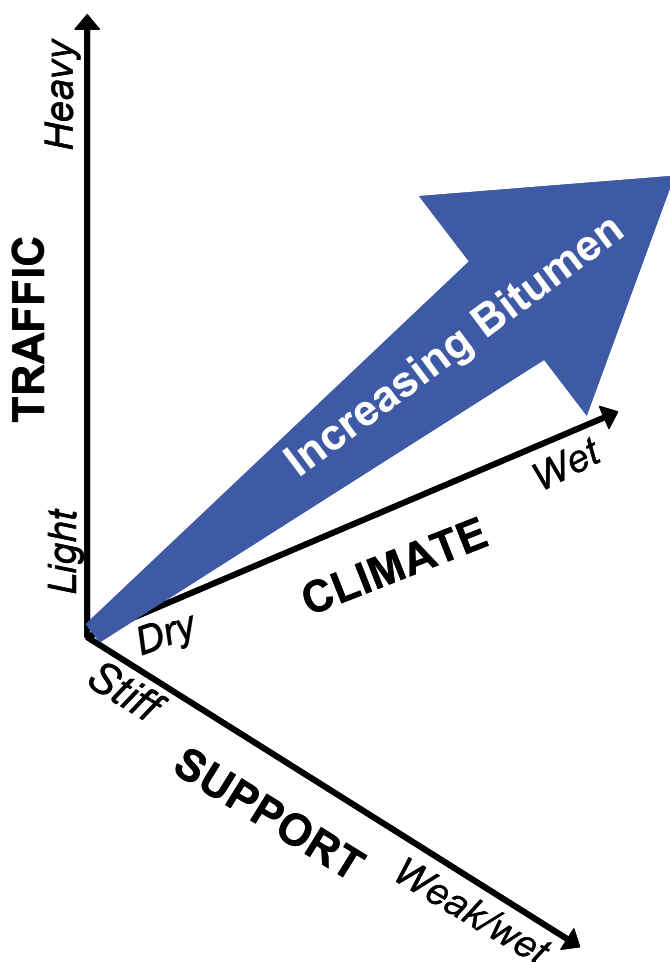
#### 4.1.1. MIX TYPE SELECTION

The type of BSM mix that is selected for a particular design is largely governed by:

- » The **design traffic** that has to be accommodated.
- » The quality of the **aggregate** that is available.
- » **Economic considerations**.

The three main factors that influence the bitumen and active filler selection during mix design, are:

- » **Traffic**, both volumes and vehicle loads.
- » **Climate**, particularly the moisture considerations.
- » **Supporting layers**, whether weak or stiff.



As shown in Figure 4.1, a very important factor influencing bitumen content selection is moisture sensitivity and its influence on durability. Increasing the bitumen content reduces the material's moisture susceptibility, and increases flexibility allowing the pavement to carry more traffic on weaker support.

Where mixes have more than 1% cement, the addition of bitumen seldom provides additional benefits. It is therefore recommended that mixes containing more than 1% cement are considered cement treated materials, and the guideline (TRH13) for their use should be followed. Therefore, this guideline is applicable to BSMs containing a maximum of 1% cement.

Hydrated lime is often used as an active filler (discussed in Section 4.2.3), especially where the untreated material is plastic. In such cases, the hydrated lime content may exceed 1% if dictated by the lime demand (Initial consumption of lime, ICL).

It is recommended that the bitumen content exceeds the active filler content, to ensure the benefits of bitumen treatment are achieved.

Figure 4.1 Factors Influencing Bitumen and Active Filler Content Selection



## CHAPTER 4: Mix Design – Requirements

### 4.1.2. OUTLINE OF MIX DESIGN PROCEDURE

Considering the number of variables that need to be addressed in the mix design and the amount of material required to investigate these variables, the mix design procedure involves several steps and one or more series of tests (levels), depending on the magnitude of design traffic. The mix design procedure always starts by testing the material to be treated (preliminary tests) to determine whether it is suitable for treating with bitumen and, if not, the type of pre-treatment or blending required to make it suitable. Following this, the actual mix design procedure commences with an initial series of tests (Level 1 Mix Design) that provides an indication of the application rate of bitumen and active filler (if necessary) required to achieve an indicated class of BSM. Thereafter, depending on the design traffic, additional tests are undertaken to refine the application rate of bitumen and gain confidence in the performance potential of the treated material (material classification). These are the Level 2 and Level 3 Mix Designs. In summary, the mix design procedure consists of:

- » **Preliminary tests:** These include standard laboratory tests to determine the grading curve, moisture, density relationships and Atterberg limits. Where the results indicate that some form of pre-treatment is required, additional tests must be undertaken after such pre-treatment to ensure that the desired result was achieved.
- » **Level 1 Mix Design:** Level 1 starts with the preparation of samples that will be used to manufacture the specimens required for all levels of mix design testing. 100 mm diameter specimens (Marshall briquettes) are compacted and cured for Indirect Tensile Strength (ITS) testing. Test results are used to:
  - Identify the preferred **bitumen stabilising agent**.
  - Determine the optimum **bitumen content**.
  - Identify the need for **filler**, and, where required, the type and content of filler.

Level 1 mix design is sufficient for lightly trafficked pavements, which will carry less than 3 MESA.

- » **Level 2 Mix Design:** This level uses 150 mm diameter by 127 mm high specimens (Proctor specimens) manufactured using vibratory compaction, cured at the equilibrium moisture content and tested for Indirect Tensile Strength to:
  - **Optimise** the required **bitumen** content.

This level is recommended for roads carrying 3 to 6 MESA.

- » **Level 3 Mix Design:** This level uses triaxial testing on 150 mm diameter by 300 mm high specimens for a higher level of confidence. This step is recommended for design traffic exceeding 6 MESA.

The details of the mix design procedure for each level are given in Section 4.5.

## 4.2. MIX CONSTITUENTS

### 4.2.1. AGGREGATE

Bitumen treatment, using either bitumen emulsion or foamed bitumen, is suitable for treatment of a wide range of mineral aggregates, ranging from sands, through weathered gravels to crushed stone. Aggregates of sound and marginal quality, from both virgin and recycled sources have been successfully utilised in the process. It is important, however, to establish the boundaries of aggregate acceptability, as well as to identify the optimal aggregate composition for bitumen treatment, recognising differences between BSM-emulsion and BSM-foam.

The aggregate properties required for successful treatment with bitumen include durability characteristics of the natural (untreated) aggregate, as well as plasticity, grading, spatial composition and weathering characteristics.

The recommendations of TRH4 and TRH14 for granular materials are generally applicable to granular materials to be treated with bitumen.



### Cement Contents

The **cement content** of BSMs should be  $\leq 1\%$ , and the cement content should not exceed the bitumen content.



#### 4.2.1.1 Aggregate Source

##### i. Virgin Aggregate


Mineral aggregates selected for BSMs should generally meet the quality requirements of G1 to G6 materials (TRH14), depending on the levels of traffic. Poorer quality gravels, for example G7 and lower, are seldom used and, where they are, generally only used for low levels of traffic, BSM3. Specific limits for tests and indicators for the material class of aggregates for BSM are given in Table 3.1 in Section 3.3.

- » **Soaked CBR.**
- » **Percentage passing the 0.075 mm sieve (fines).** Higher filler contents create higher bitumen demands, due to the increased surface area of particles. The fines content of BSMs is considered to be very important, and is discussed in Section 4.2.1.3.
- » **Plasticity Index.** Plasticity is mainly attributed to the fine fraction of the aggregate. Materials with a high PI can be treated with lime or other active fillers before treatment with bitumen.

<b>BSM-emulsion</b>	<b>BSM-foam</b>
The PI of materials to be treated with bitumen emulsion should be less than 7.	The PI of materials to be treated with foamed bitumen should be less than 10.

- » **Grading.** The grading of the material being treated requires careful consideration. Sieve analyses carried out on representative samples, taken from the layers in the case of an existing road or from the material source for a new road, will indicate deficiencies in the fines or filler content. Cohesive materials should be treated with care as wet-grading tests may indicate a high percentage of material passing the 0.075 mm sieve, whilst the loose filler available during full-scale mixing may be less. This occurs when the cohesive filler binds itself together, rendering this fraction unavailable for the bitumen emulsion or foamed bitumen to react with. A comparison of the washed and unwashed grading test carried out in the laboratory can be used to indicate the likelihood of cohesion preventing the filler from being released. The unwashed grading provides an indication of the available filler.

A deficiency in filler content can be addressed by adding additional fines or by adding active filler.



### Plasticity Index

The **PI** of a material to be treated with bitumen emulsion should be **7 or less**.

The **PI** of a material to be treated with foamed bitumen should be **10 or less**.

If the PI exceeds these limits, the material should be **pre-treated with lime** to reduce the PI.

##### ii. Recycled Granular Layers

In the case of recycled materials, the quality and composition of the aggregates can be highly variable and will depend upon:

- » The structure of the **existing pavement** (materials and their thickness).
- » Construction **variability** (material quality and thickness).
- » **Depth of recycling.**
- » **Age** of the pavement (particularly for previously treated materials and materials prone to weathering).
- » Degree of **patching and repair** on the existing pavement.
- » Thickness and nature of old surfacing **seals**.

The pulverized aggregate after recycling and immediately prior to treatment should be well-graded, complying with the criteria in Figure 4.2 (and Figure 3.2 in Chapter 3). In some cases this may necessitate the incorporation of a portion of the underlying layer into the composite recycled layer. It is however preferable to rather incorporate supplementary fines by pre-spreading at the surface before mixing. The addition of virgin material can be considered to rectify non-compliant gradings, as can the addition of milled old chip seals. Caution should be taken when including the underlying layer where the layer includes cohesive, plastic material. In such cases pre-treatment with lime should be considered.

The maximum stone size and amount of coarse aggregate is important with regard to the mix compaction and abrasion of the milling equipment. The maximum stone size should be limited to 75 mm in recycled layers. The layer thickness should be at least three times the largest stone size. In addition, the mass of stone larger than 50 mm should not exceed 20% to minimize abrasion on the recycler.



## CHAPTER 4: Mix Design – Mix Constituents

### iii. Reclaimed Asphalt (RA)

Recycling projects sometimes require the reuse of high percentages of RA, 75% to 100% before blending with additional materials. In such cases, the influence of the aggregate (RA) composition needs to be carefully considered in the mix design, especially where traffic levels exceed 6 MESA. In particular, the following aspects need attention:

- » **Climatic region.** If the BSM is intended for application in a warm climate, the shear properties identified through triaxial tests, should be determined at representative temperatures.
- » **Axle loads.** If the BSM is intended for use in an area where overload control is not well regulated, higher stress ratios will result in accelerated deformation. This needs to be considered when analysing the shear properties.
- » **RA Composition.** If the above two factors are applicable, then the composition of the RA needs to be modified (blending with 15% to 25% crusher dust). This will provide an angular sand skeleton that will improve the shear resistance of the mix.

The use of 100% RA in BSMs has been successfully applied in regions of moderate climate and well regulated axle loading.

#### 4.2.1.2 Sampling

Sampling of materials for BSM mix designs is very important, particularly for recycling. Refer to TMH1 for sampling guidelines. Cognisance needs to be taken of numerous factors, including:

- » The **depth of recycling** and proportions of the in situ layers blended to form a representative composite layer.
- » The **variability of material type** over the length and depth of the existing pavement, so that adjustments can be made to the mix design where necessary. Where variability is encountered, the individual layers should be sieved into the respective fractions and recombined in the required ratios. In this way a consistent blend can be achieved and the influence of variations in grading on the mix properties can be investigated.
- » The crushing and blending of **existing asphalt** into the composite mix, where such asphalt is to be incorporated in the recycled layer. On-site milling is the most suitable method for achieving representative samples.
- » For virgin aggregates, a **bulk sample** with a representative grading must be obtained from the applicable source.

The inclusion of existing seals in the recycled material is useful for enhancing the grading modulus of the recycled layer. Milling and blending the existing seal together with the recycled layer usually improves the layer's structural capacity provided that the maximum particle size is limited (large chunks of bound material, greater than 50 mm, should be removed). Methods of preventing oversize materials are covered in Chapter 6.

#### 4.2.1.3 Grading

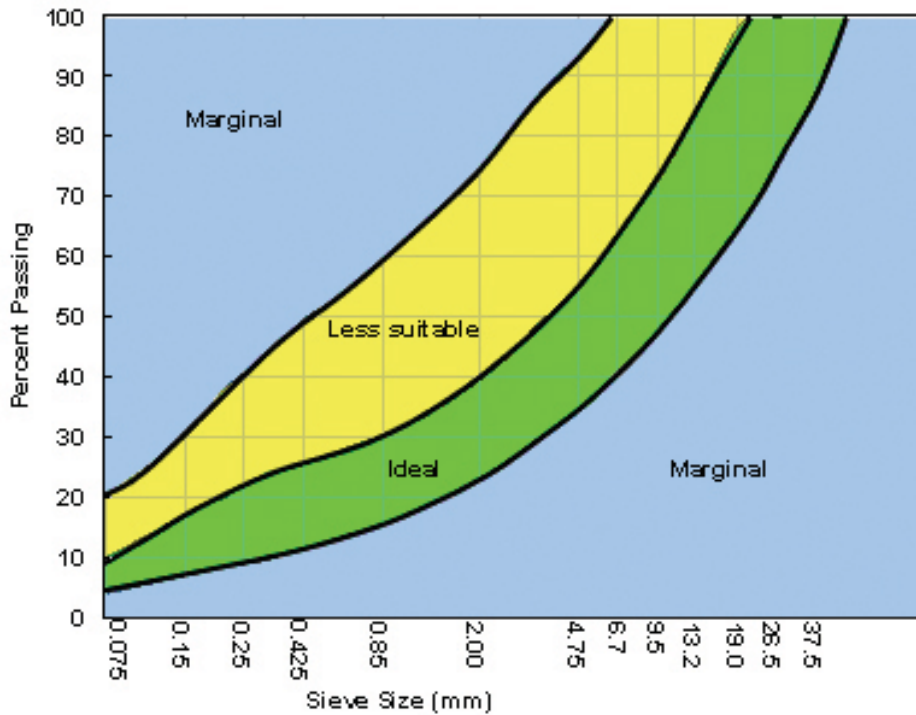
The nature of dispersion of the bitumen in BSMs is different for BSM-foam and BSM-emulsion. It is understandable, therefore, that the aggregate grading requirements differ for the two types of treatments. The purpose of fines (material passing the 0.075 mm sieve) in the aggregate used for BSMs is dependent on the type of bitumen being used. In particular, the grading requirements in terms of the target filler content differ for BSM-foam and BSM-emulsion.

<b>BSM-emulsion</b>	<b>BSM-foam</b>
<p>Bitumen emulsion coats the larger aggregate particles to a greater extent than foamed bitumen.</p> <p>A minimum filler content of 2% is sufficient.</p>	<p>The dispersed bitumen droplets in BSM-foam only partially coat the larger aggregate. The mastic (filler, bitumen and water) "spot welds" the coarser aggregate fractions together in BSM-foam.</p> <p>Approximately 5% filler is required to produce a treated material that performs well. Where lower bitumen contents are used, this value can be reduced to 4%.</p>

The general grading requirements for BSMs are indicated in terms of zones of most suitable aggregate composition in Figure 4.2. This figure is a repeat of Table 3.3 and is included here for completeness. The less suitable zone is only utilised where alternatives are severely limited. Where necessary, aggregates can be blended with missing fractions to improve their grading. Coarse-graded materials require less bitumen than finer graded materials.

**i Binder Contents**

**Coarse graded materials** typically require **less bitumen** than fine graded gravels.



Sieve Size (mm)	Percent Passing			
	BSM-Emulsion		BSM-Foam	
	Ideal	Less suitable	Ideal	Less suitable
50	100		100	
37.5	87 – 100		87 – 100	
26.5	77 – 100	100	77 – 100	100
19.5	66 – 99	99 – 100	66 – 99	99 – 100
13.2	67 – 87	87 – 100	67 – 87	87 – 100
9.6	49 – 74	74 – 100	49 – 74	74 – 100
6.7	40 – 62	62 – 100	40 – 62	62 – 100
4.75	35 – 56	56 – 95	35 – 56	56 – 95
2.36	25 – 42	42 – 78	25 – 42	42 – 78
1.18	18 – 33	33 – 65	18 – 33	33 – 65
0.6	12 – 27	27 – 54	14 – 28	28 – 54
0.425	10 – 24	24 – 50	12 – 26	26 – 50
0.3	8 – 21	21 – 43	10 – 24	24 – 43
0.15	3 – 16	16 – 30	7 – 17	17 – 30
0.075	2 – 9	9 – 20	4 – 10	10 – 20

The differences between the grading zones of BSM-emulsion and BSM-foam are small enough that the differences cannot be discerned on the figure.

Figure 4.2 Guidelines for Suitability of Grading for Treatment



**CHAPTER 4: Mix Design – Mix Constituents**

Within the envelopes provided in Figure 4.2 above, a refined target grading should be targeted that provides the lowest Voids in the Mineral Aggregate (VMA). Minimising the VMA produces the most desirable mix properties.

<p><b>BSM-emulsion</b></p> <p>The minimization of the VMA is important for BSM-emulsion, but not as essential as for BSM-foam.</p>	<p><b>BSM-foam</b></p> <p>For BSM-foam, the minimization of the VMA is particularly important in the fraction of mineral aggregate smaller than 2.36 mm, as this is where the bitumen droplets disperse within the mix. Where necessary, two materials should be blended to create a dense gradation.</p>
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A unique relationship for achieving the minimum VMA, is shown in Equation 4.1, where a value of n = 0.45 should be used.

$$P = \left[ \frac{d}{D} \right]^n \quad \dots (4.1)$$

- Where
- d = selected sieve size (mm)
  - P = percentage by mass passing a sieve of size d (mm)
  - D = maximum aggregate size (mm)
  - n = variable dependent on aggregate packing characteristics

Sieve analysis of the aggregate is carried out with washing of the fines. The aggregate sampled is divided into three fractions at the 19 mm and 4.75 mm sieves. The fraction greater than 19 mm should be removed from the mix design. The proportions of the material fractions that are now divided at the 4.75 mm sieve should be recorded as this information is required when the maximum dry density is determined. Three sieve sizes should be added to the typical sieves used for grading analyses of soil, namely 0.15 mm, 0.30 mm and 1.18 mm. This assists in achieving the gradation with minimum VMA more accurately. Equation 4.1 can be used to calculate the target grading for the additional sieves.

**4.2.1.4 Durability**

One of the most important aspects of the untreated aggregate is durability. Durability does not just apply to the resistance to moisture of a BSM or the resistance to ageing of the bitumen. It also applies to the durability of the untreated aggregate before treatment. To determine the durability of the untreated aggregate, the Durability Mill Index (DMI) is recommended. This test identifies the potential durability of aggregates in terms of breakdown and generation of excessive plastic and non-plastic fines. The test has the most potential for simulating the likely breakdown of the materials in service, and is applicable for all material types. Although the acceptable limits for these tests were initially applicable to granular materials only, these limits have been adapted for pre-treated (natural) materials for use in selection of component aggregates during mix design. The DMI limits are shown in Table 4.1.

**Table 4.1 Durability Mill Index, Limit for Rocks and Soils**

Aggregate Type	Rock and Soil Group	DMI Limit
Granites, gneiss, granite	Acid Crystalline	< 420
Hornfels, quartzite	High silica	
Dolomite, limestone,	Carbonate	
Ironstone, magnesite, magnetite	Metalliferous	
Calcrete, ferricrete, silcrete	Pedogenic materials	< 480
Sandstone, siltstone, conglomerate	Sandstone	< 125
Greywacke, tillite	Diamictite	
Mudrock, phillites, shale	Mudrock	
Basalt, Dolerite, Gabbro	Basic crystalline	< 100



#### 4.2.1.5 Aggregate Temperature

<p><b>BSM-emulsion</b></p> <p>Typically, aggregates with temperatures of 10 °C or higher can be treated with bitumen emulsion without compromising the bitumen distribution and particle coating.</p> <div style="background-color: #4CAF50; color: white; padding: 10px; margin: 10px 0;"> <p style="text-align: center; font-weight: bold; font-size: 1.2em;">Aggregate Temperature</p> <p>Aggregates with temperatures <b>lower than 10 °C</b> should not be treated with bitumen. Aggregate temperatures in the laboratory should match the expected field temperatures.</p> </div>	<p><b>BSM-foam</b></p> <p>Aggregate temperature for BSM-foam production has a significant influence on the degree of coating and the properties of the mix. Higher aggregate temperatures increase the size of the aggregate particle that can be coated. Temperature measurements of the aggregate are therefore essential before laboratory or field production commences.</p> <p>Laboratory mixes should be produced at temperatures that reflect the expected field temperatures, taking account of daily and seasonal effects. Field mixes on the other hand, should not be attempted with aggregate temperatures less than 10 °C. Where the aggregate temperature ranges between 10 to 15 °C, mixes should only be produced with superior quality foamed bitumen, s superior foaming characteristics (especially the half-life). Where the expected aggregate temperatures range between 10 to 15 °C the quality of the mix should be checked in the laboratory at the anticipated mixing temperature before commencing construction.</p>
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#### 4.2.2. BITUMEN SELECTION

Penetration grade bitumen is used to produce both the foamed bitumen and bitumen emulsion that is then used to manufacture BSMs. The types of bitumens and specific bitumen requirements are outlined below.

<p><b>Bitumen Emulsion</b></p> <p>» <b>Bitumen emulsion category.</b> Base bitumens with penetration values between 80 and 100 are generally selected for bitumen emulsion production, although softer and harder bitumens have been successfully used. The selection of the correct grade or category of bitumen emulsion for the application is essential, as outlined in Table 4.2.</p>	<p><b>Foamed Bitumen</b></p> <p>BSM-foam only requires low percentages of bitumen (typically 1.7% to 2.5%) and can utilise softer grades of bitumen without compromising the stability of the mix.</p> <p>Bitumens with penetration values between 80 and 100 are generally selected for BSM-foam, although softer and harder bitumen have been successfully used in the past and may be used when available. For practical reasons, harder bitumen is generally avoided due to poor quality foam, leading to poorer dispersion of the bitumen in the mix.</p>
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## CHAPTER 4: Mix Design – Mix Constituents

- » In South Africa, **slow set stable grade anionic bitumen emulsions** are almost exclusively used for BSMs as they typically work well with dense graded aggregates or with aggregates with high fines contents. These bitumen emulsions have long workability times to ensure good dispersion and are formulated for mix stability. The motivating forces in southern Africa for using this type of bitumen emulsion are economics and climate. In the rest of the world, cationic bitumen emulsions are extensively used. The test methods for bitumen emulsions are referenced in Appendix B.
- » **Breaking rate.** There have been many developments in bitumen emulsion technology recently to improve stability of the bitumen emulsion without prolonging the break time. These bitumen emulsions are typically slower setting than the standard products, and should be used on projects where the treated layer can be allowed to cure for a period before opening to traffic. During the mix design phase, and on site before full-scale application begins, the breaking rate should be tested with representative samples of aggregate, active filler and water, at realistic temperatures.
- » **Compatibility of bitumen emulsion and aggregate.** The selection of the bitumen emulsion type for treatment is influenced by the type of aggregate to be treated. The guidelines outlined in Table 4.3 indicate that certain aggregates are not suitable for treatment with anionic bitumen emulsions. The aggregates listed in this table have silica contents above 65% and alkali contents below 35%, i.e. these are acidic rocks. In such cases a cationic bitumen emulsion should be used.

Manufacturers normally recommend that undiluted bitumen emulsion is heated to between 50 and 60 °C to prevent premature breaking of the bitumen emulsion while pumping in the construction equipment.

The penetration value alone does not qualify bitumen for use in a foamed bitumen mix. The foaming properties or foamability of each bitumen type needs to be tested. Two characteristics form the basis of bitumen's suitability for use, namely the Expansion Ratio (ER) and Half-life ( $\tau_{1/2}$ ):

- » The **expansion ratio** is a measure of the viscosity of the foam and will determine how well the bitumen will disperse in the mix. It is calculated as the ratio of the maximum volume of foam relative to the original volume of bitumen.
- » The **half-life** is a measure of the stability of the foam and provides an indication of the rate of collapse of the foam during mixing. It is calculated as the time taken in seconds for the foam to collapse to half of its maximum volume.

Appendix B references the measurement of the expansion ratio and half-life. Minimum limits for ER and  $\tau_{1/2}$  are given in Table 4.4.

One of the dominant factors influencing the foam properties is the water that is injected into the expansion chamber (or reactor in some plants) to create the foam as illustrated in Figure 4.3. A higher application rate of foamant water creates greater expansion (higher ER) but leads to more rapid subsidence or decay, i.e. a shorter half-life ( $\tau_{1/2}$ ). The foamant water application rate and bitumen temperature are the most important factors influencing foam quality. A higher bitumen temperature usually creates better foam. A sensitivity analysis in the laboratory is recommended to identify a target bitumen temperature for foaming. As with HMA production, temperature limits should be implemented to prevent damage to the bitumen at the plant.

The variability of the foam characteristics measured in a laboratory and in the field, both in terms of repeatability and reproducibility, are significant. At least three tests are recommended for each set of conditions, to attain an acceptable level of statistical reliability. In addition, potential variability in the bitumen composition from the same source necessitates checking the foamability of each tanker.



### Diluting Bitumen Emulsion

When diluting a bitumen emulsion, it is important to **add the emulsion to the water**, and not the water to the emulsion. This will prevent the emulsion from breaking.



### Foaming Characteristics

The **expansion ratio (ER)** is the maximum volume of foam relative to the original volume.

The **half-life ( $\tau_{1/2}$ )** is the time the foam takes to collapse to half of its maximum volume.



**Table 4.2 Categories of Bitumen Emulsion for Treatment**

Bitumen Emulsion Type	Anionic	Cationic
Emulsifier type	Fatty acid or resin acid	Amine
Bitumen emulsion charge	Negative	Positive
pH	High (alkali)	Low (acid)
Grades	Stable mix (slow set): recycling and treatment	

**Table 4.3 Compatibility of Bitumen Emulsion Type with Aggregate Type**

Aggregate Type	Compatible With	
	Anionic Bitumen Emulsion	Cationic Bitumen Emulsion
Dolerite	✓	✓
Quartzite	✗	✓
Hornfels / Greywacke	✓	✓
Dolomite	✓	✓
Granite	✗	✓
Andesite	✓	✓
Tillite	Variable	✓
Basalt	✓	✓
Sandstone	✗	✓
Rhyolite	✗	✓
Marble/Norite	✓	✓
Syenite	✗	✓
Amphibolite	✓	✓
Felsite	✗	✓



CHAPTER 4: Mix Design – Mix Constituents

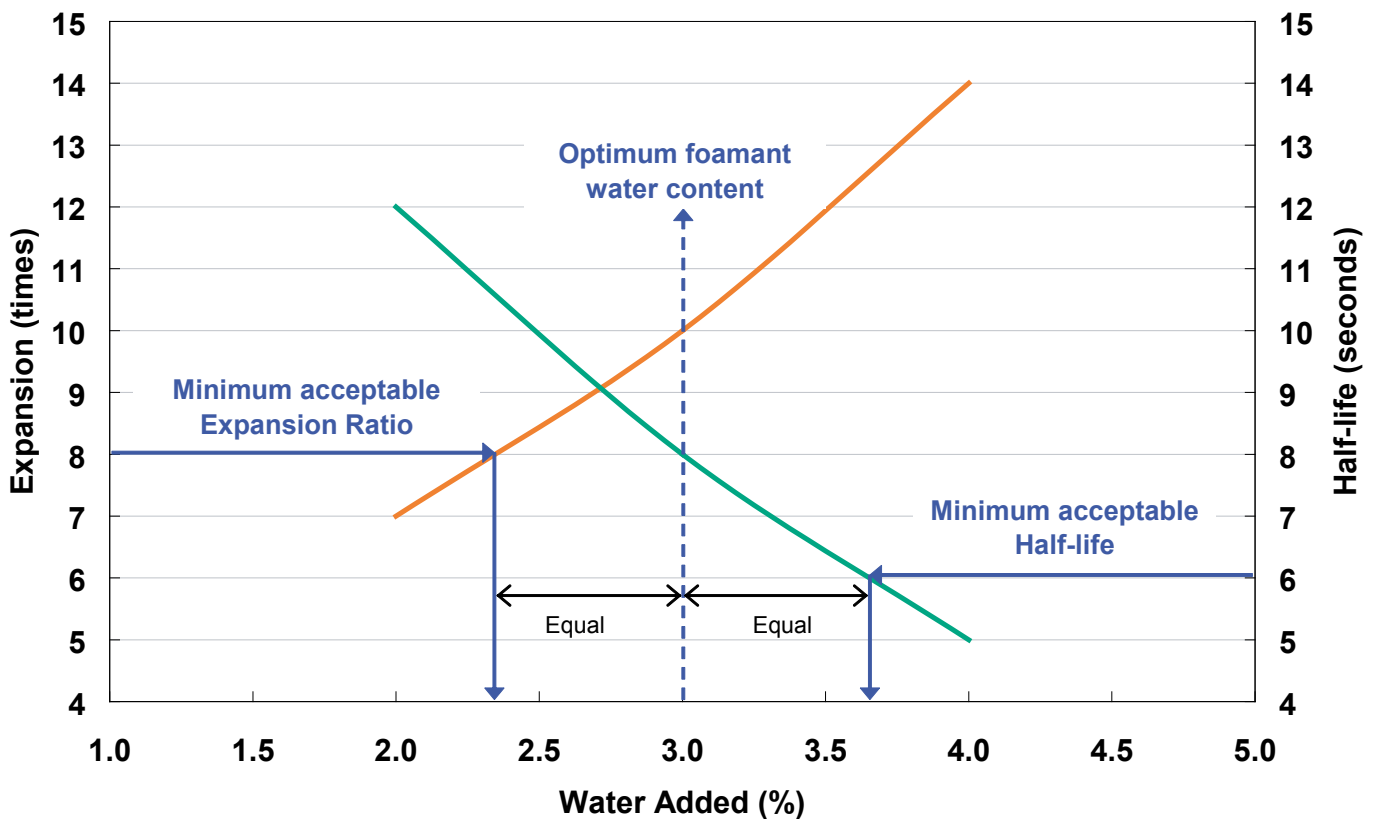


Figure 4.3 Determination of Optimum Foamant Water Content

Table 4.4 Foam Characteristic Limits (minimum values)

Aggregate Temperature	10 °C to 25 °C	Greater than 25 °C
Expansion Ratio, ER (times)	10	8
Half-life, $\tau_{1/2}$ (secs)	6	6

4.2.3. FILLER (NATURAL AND ACTIVE)

The types of filler used with BSMs are: cement (various types, but not rapid hardening cements), lime, rock flour, fly ash and slagment. For the purpose of this guideline, the term active filler is used to define fillers that chemically alter the mix properties. This includes fillers such as lime, cement and fly ash but excludes natural fillers such as rock flour. In this guideline, lime always refers to hydrated lime.

The purpose of incorporating active filler in BSM is to:

- » **Improve adhesion** of the bitumen to the aggregate.
- » **Improve dispersion** of the bitumen in the mix.
- » **Modify the plasticity** of the natural materials (reduce PI).
- » **Increase the stiffness** of the mix and rate of strength gain.
- » **Accelerate curing** of the compacted mix.

**i Active filler**

The term active filler is used to define fillers that **chemically alter** the mix properties. This includes fillers such as lime, cement and fly ash but excludes natural fillers such as rock flour.



<p><b>BSM-emulsion</b></p> <ul style="list-style-type: none"> <li>» Control the <b>breaking time</b> of BSM-emulsion.</li> <li>» Improve the <b>workability</b> of BSM-emulsion (in some cases).</li> </ul>	<p><b>BSM-foam</b></p> <ul style="list-style-type: none"> <li>» To assist in <b>dispersing the bitumen</b> droplets.</li> </ul>
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The purpose of adding natural filler is primarily to supplement the fines needed for bitumen dispersion.

Various types of active filler can be used, both separately or in combination. The filler type selected for application will depend on availability, cost and efficacy with the actual component materials. Research has shown that it is almost impossible to predict which active filler will prove to be the most effective without experimentation during mix design. Testing cured and soaked 100 mm diameter specimens for Indirect Tensile Strength ( $ITS_{wet}$ ) and the retained cohesion from a triaxial test are useful tests to guide active filler selection.


When cement is used, the application rate must be limited to a maximum of 1% by mass of dry aggregate. When using hydrated lime, the application rate may be increased to 1.5% or more where the lime is required to modify plasticity. However, it should be noted that the increase in mix stiffness is compromised significantly by a loss in flexibility of the material. Above these application rates, the benefit of the bitumen is hardly realized.

Where active fillers are applied, the time delay between mixing the active filler with the material and application of the foamed bitumen or bitumen emulsion should be reduced to a minimum (in the laboratory and the field). The active filler reaction begins immediately upon contact with moist material, promoting adhesion between the fine particles. The longer the delay between premixing with active filler and applying the bitumen, the lower the percentage of filler available for dispersion of the bitumen in the BSM mix.

Where materials with unacceptably high PI values are encountered, they can be treated with hydrated lime to modify the plasticity, thereby rendering them acceptable for treatment with foamed bitumen or bitumen emulsion. Pre-treating with lime must allow for sufficient time for modification to take place before bitumen treatment. Depending on the material type, 4 hours or more may be necessary for effective lime modification.


#### 4.2.4. WATER QUALITY

The quality of the water used to create the foamed bitumen and bitumen emulsion is important to ensure a mix of reliable quality. The standard COLTO requirements should be followed in this regard.



**Cement Content**

When **cement** is used as the active filler in BSMs, the cement content should be limited to **1% or less**.



**Pre-treating with Lime**

When pre-treating with lime, allow **at least 4 hours** before treating with bitumen.



CHAPTER 4: Mix Design – Specimen Preparation

<b>BSM-emulsion</b>	<b>BSM-foam</b>
<p>The pH levels of the water must be checked, as must the compatibility of the bitumen emulsion and the water. These checks are done by performing a dilution test.</p> <p>» <b>Dilution “can” test</b></p> <p>The bitumen emulsion is diluted to specification, in a clean container such as a can. The water is added to the bitumen emulsion (not bitumen emulsion to water to prevent premature breaking). The “can” is then heated to about 60 °C, and left to stand for 20 to 30 minutes. The diluted bitumen emulsion is then passed through a fine sieve (0.600 mm) to determine if any premature breaking has taken place.</p> <p>Note that the dilution water for cationic bitumen emulsion must not be alkaline; dam water can be rather alkaline especially in limestone areas. For a cationic bitumen emulsion, the addition of hydrochloric acid to the water will reduce this tendency. For anionic bitumen emulsion, lime or caustic soda is added to the dilution water if necessary.</p>	<p>Although acceptable foam may be achieved using water containing impurities, such practice should be avoided. Impurities often lead to scales forming on the walls of the feed pipes and these eventually dislodge and block the water injection jets, preventing the bitumen from foaming</p>

4.3. SPECIMEN PREPARATION

4.3.1. FLUID CONSIDERATIONS

The role of moisture in the mineral aggregate is similar for BSM-emulsion and BSM-foam in many respects, but there are some differences. The entire fluid content in the mix, moisture and bitumen, needs to be considered. The role of moisture in the two types of BSM is explained in Table 4.5.

Table 4.5 Role of Fluids in BSMs

Component	BSM-emulsion	BSM-foam
Bitumen	Contributes to fluids for compaction	Negligible contribution to fluids for compaction
Moisture in aggregate	Reduces absorption of bitumen emulsion water into aggregate	Separates and suspends fines making them available to bitumen during mixing
	Prevents premature breaking	Acts as carrier for bitumen droplets during mixing
	Extends curing time and reduces early strength	Reduces early strength
	Provides workability of BSM at ambient temperatures	
	Reduces friction angle and lubricates for compaction	
	Provides shelf-life for the mix	



#### **BSM-emulsion**

Changes in moisture content occur in two distinct phases, namely:

- » **Breaking** is the separation of the bitumen from the water phase through flocculation and the coalescence of the bitumen droplets to produce films of bitumen on the aggregate. The rate at which the bitumen globules separate from the water phase is referred to as the breaking or setting/ settling time.

The breaking process with anionic bitumen emulsions is a mechanical process (evaporation), whereas cationic bitumen emulsions produce a chemical break. For dense mixtures, more time is needed to allow for mixing and placement and slower breaking times are required. As the bitumen emulsion breaks, the colour changes from dirty brown to black. Although this can be observed with the naked eye, it is recommended that a magnifying glass is used.

- » **Curing** is the displacement of water and resultant increase in stiffness and tensile strength of the bitumen. This is important as a mix needs to acquire sufficient stiffness and cohesion between particles before carrying traffic.

Some of the factors which influence the whole **setting process**, i.e. breaking and curing of bitumen emulsions, include:

- » **Rate of absorption** of water by the aggregate. Rough-textured and porous aggregates reduce the breaking and setting time by absorbing water contained in the bitumen emulsion.
- » **Moisture content** of the mix prior to mixing influences breaking time.
- » **Moisture content** of the mix after compaction influences curing rate.
- » **Grading** of the aggregate and voids content of the mix.
- » **Type, grade and quantity** of the bitumen emulsion.
- » **Mechanical forces** caused by compaction and traffic.
- » **Mineral composition of the aggregate.** The rate of cure may be affected by possible physicochemical interactions between the bitumen emulsion and the surface of the aggregate.
- » **Intensity of electrical charge** on the aggregate in relation to that of the bitumen emulsion.
- » **Active filler** percentage, the amount of cement or lime.
- » **Temperature** of aggregate and air. The higher temperature, the quicker the bitumen emulsion breaks and cures.

#### **BSM-foam**

Changes in moisture content occur as a result of curing. The rate of change of the moisture content of BSMs is variable for in situ mixing.

- » **Curing** is the gradual reduction in moisture due to evaporation, resulting in an increase in stiffness and tensile strength of the bitumen. This is important as a mix needs to acquire sufficient stiffness and cohesion between particles before carrying traffic.

The moisture content of the aggregate to be used in the BSM requires optimisation at the different stages of preparing the mix, and these optimum values do not coincide. Different optimum values require consideration, as discussed in the following sections.



## CHAPTER 4: Mix Design – Specimen Preparation

### 4.3.1.1 Mixing Moisture

The moisture content that will provide the best BSM mix is termed the optimum mixing moisture content (OMMC). This is the moisture in the aggregate plus, for BSM-emulsions, any additional moisture in the bitumen emulsion. OMMC varies with gradation of the aggregate and, in particular, the size of the fraction smaller than 0.075 mm.

### *i* Fluids Available in Mix

The water in the **BSM-emulsion** is considered part of the total fluid contents, whereas for **BSM-foam** the foamant water is not part of the total fluid content.

<b>BSM-emulsion</b>	<b>BSM-foam</b>
<p>BSM-emulsion A minimum of 1 to 2% moisture is required in the aggregate prior to adding the bitumen emulsion.</p> <p>The water and bitumen in the bitumen emulsion act as lubricants for BSM-emulsion mixes. The optimum moisture content (OMC) using modified AASHTO compaction should be used for the total mixing fluid content. This is explained in Equation 4.2 below:</p> $OFC = OMC_{MOD-U} = FMC + EWC + RBC \quad \dots (4.2)$ <p>Where                      OFC = optimum fluids content (%)                      OMC<sub>MOD-U</sub> = optimum moisture content using Mod. AASHTO compaction on untreated material (%)                      FMC = field moisture content of aggregate (%)                      EWC = bitumen emulsion water content including water used for dilution as percentage of dry aggregate (%)                      RBC = residual bitumen content as percentage of dry aggregate (%)</p>	<p>65 to 85% of the optimum moisture content (OMC) using modified AASHTO compaction should be used for the mixing moisture content when adding foamed bitumen. The fluff point moisture content at which the maximum bulk volume of loose mineral aggregate is obtained, is the minimum value for the mixing moisture content.</p>

### 4.3.1.2 Compaction Moisture

<b>BSM-emulsion</b>	<b>BSM-foam</b>
<p>Compaction of BSM-emulsion can be carried out at the optimum fluids content (OFC) as outlined in Section 4.3.1.1. Alternatively, a sensitivity analysis should be carried out using vibratory hammer compaction, to determine a representative compaction moisture content.</p>	<p>To achieve the required level of compaction, the optimum compaction moisture content (OCMC) needs to be determined in the laboratory using vibratory hammer compaction.</p>

A procedure for carrying out vibratory hammer compaction is referenced in Appendix B, and uses a Bosch® vibratory hammer. In all cases, 150 mm diameter specimens are compacted to obtain the most representative volumetric results.

Modern rollers used for compaction of thick pavement layers impart very high energy. This type of compaction reduces the effective optimum fluids content required in the field, relative to that determined in the laboratory. For this reason it is possible to compact at up to 1.5% lower fluid contents in the field than the optimum used in the laboratory.

## 4.3.2. MATERIAL PREPARATION

Several options are available for producing BSMs in the laboratory, including the type of mixer, type of compaction as well as several other variables. Standardisation of the apparatus and procedures is required to ensure that representative mixes are produced and relevant results are obtained that can be compared with the guideline limits. This section includes a summary of the sample preparation and



mixing.

The generalised procedure for material preparation is provided below. The full details and test methods are referenced in Appendix B and are available in TMH1 or for download on [www.asphaltacademy.co.za/bitstab](http://www.asphaltacademy.co.za/bitstab).

- Step 1:** Determine the grading curve of the aggregate and the OMC of the natural (untreated) material using the Modified AASHTO compaction method.
- Step 2:** Determine the Atterberg Limits of the material. Where necessary, pre-treat or blend the material to address any deficiencies.
- Step 3:** Determine the moisture and density relationship using Mod. AASHTO compaction for the untreated material to obtain  $OMC_{U-Mod}$ \*
- Step 4:** Determine the moisture and density relationship using Mod. AASHTO compaction for the treated BSM material to obtain  $OMC_{Mod-BSM}$ \*
- Step 5:** Determine the moisture and density relationship vibratory for hammer compaction for the treated material to obtain  $OMC_{Vib-BSM}$ \*

### 4.3.3. MIXING

Prepare the BSM-emulsion or BSM-foam mixes, preferably using a laboratory pugmill mixer.

### *i* Mixer Types for BSM-foam

**Vertical agitators**, i.e. blender type mixers must not be used for BSM-foam as they produce significantly inferior mixes.

A **pugmill** type mixer is recommended for producing BSM-foam mixes that are representative of field mixes.

Different mixers can produce up to **25% difference in strength**.

<b>BSM-emulsion</b>	<b>BSM-foam</b>
<p>Blender-type laboratory mixers and flat-pan mixers with a rotary mixing motion are suited to mix preparation for BSM-emulsion. Care should be taken to ensure that bitumen does not remain on the mixing drum or paddles, as this will influence the final bitumen content.</p>	<p>The mixing process for BSM-foam is a dynamic one as the foamed bitumen begins to collapse rapidly once contact is made with the cold aggregate. Different mixers can produce discrepancies of up to 25% in material strength properties. It is imperative, therefore, to utilise a laboratory foaming plant and mixer that emulates the site mixing.</p> <p>The rotary mixing motion of the blenders used in the laboratory are neither ideal for restricting particle segregation nor for simulating site mixing. The methods used on site provide sufficient volume in the mixing chamber and energy of agitation to ensure that the mineral aggregate is airborne when it makes contact with the foam. Blender type laboratory mixers do not emulate this, and subsequently the quality of laboratory mixes is usually inferior to site mixes. For this reason, a pug-mill type mixer must be used in the laboratory. A mixing time of 20 to 30 seconds is generally used in the laboratory, which is longer than in situ mixing but simulates the differences in the energy of the laboratory mixer and field plant.</p>

### 4.3.4. COMPACTION

Special attention needs to be paid to compaction, as it improves particle contacts and reduces voids. The density achieved is critical to the ultimate performance of the mix.



CHAPTER 4: Mix Design – Specimen Preparation

<p><b>BSM-emulsion</b></p> <p>The inclusion of bitumen emulsion typically improves compactibility of the mix.</p>	<p><b>BSM-foam</b></p> <p>Compaction promotes adhesion of the bitumen mastic to the stone.</p>
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A laboratory compaction technique that not only achieves the density expected in the field, but also emulates the particle orientation after rolling, is achieved using vibratory hammer compaction. The vibratory hammer compaction procedure is referenced in Appendix B. Vibratory hammer compaction is preferred to Modified AASHTO compaction because problems are experienced with delamination within the specimen with Modified AASHTO compaction. For Level 1 mix designs where 100 mm diameter specimens are used, and where the necessary vibratory hammer equipment is not available, Marshall compaction may be used.

It must be noted that the moisture and density relationship, and the resulting OMC are dependant on the compaction method used. The OMC used is typically that of the untreated material.

In terms of specifying compaction, absolute density using the Bulk Relative Density method as outlined in TMH1 can be used for BSMs produced with G1 to G4 quality materials. For poorer quality materials, lower than G4, the vibratory hammer technique is preferred.

The laboratory compaction method for BSMs should follow the vibratory hammer compaction procedure (available on [www.asphaltacademy.co.za/bitstab](http://www.asphaltacademy.co.za/bitstab)), at a moisture content of 80% of  $OMC_{U-Mod}$ . This facilitates the compaction of 300 mm high by 150 mm diameter specimens for triaxial testing. Compaction should be carried out at  $25 \pm 2$  °C.

Split moulds should generally be used for compaction of 150 mm diameter specimens. This is particularly important for the production of triaxial specimens.

**i** **Compaction Equipment**

Use **Vibratory** compaction for both BSM-emulsion and BSM-foam.

A new method of laboratory vibratory compaction has been developed using a **Bosch hammer**.

4.3.5. CURING

Curing of BSMs is the process where the mixed and compacted layer discharges water through evaporation, particle charge repulsion and pore-pressure induced flow paths.

<p><b>BSM-emulsion</b></p> <p>Chemistry plays a significant role in the curing of BSM-emulsions. Water is an intrinsic component of bitumen emulsions. Breaking of the bitumen emulsion needs to take place before curing via migration and evaporation.</p> <p>BSM-emulsion usually requires longer curing times than BSM-foam because of the higher moisture contents.</p>	<p><b>BSM-foam</b></p> <p>Curing takes place as a result of migration of water during compaction and continues with evaporation of the water.</p>
--	---

The reduction in moisture content leads to an increase in the tensile and compressive strength, as well as stiffness of the mix. It is imperative that this process is realistically simulated in the laboratory for mixes to be assessed for their expected field performance.

The rate of moisture loss from newly constructed BSM layers plays a significant role in determining the performance of the layer. It is in the early period of repeated loading that the majority of the permanent deformation takes place in BSM layers. Where a new BSM layer is to be trafficked immediately after finishing, it is important to minimise the moisture content during construction. The lower the degree of saturation of the BSM, the greater the resistance to permanent

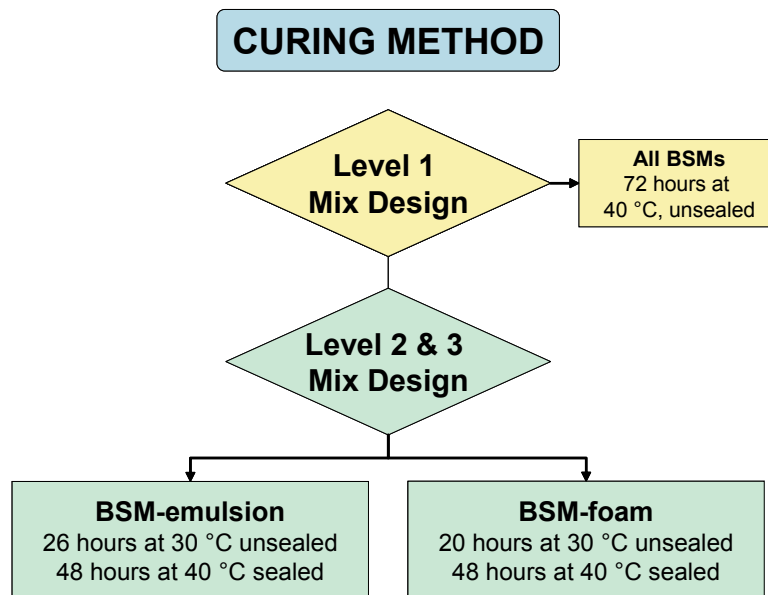
**i** **Accelerated Curing**

The accelerated laboratory curing method is aimed at representing the **long-term equilibrium moisture content**.



deformation. The temperature of the layer in the field and the loss of moisture with time are the two factors to consider with curing, and hence, stiffness and strength gain. Although a BSM should have sufficient stiffness and strength to withstand moderate levels of early traffic, the layer will continue to gain strength over several years in the field.

The recommended curing procedure differs for the specimen size and bitumen types, BSM-emulsion and BSM-foam. Although the use of active filler has an impact on curing, its inclusion in a BSM does not justify extensions in the curing time as cementation is not one of the desired properties of these materials. The two curing protocols are illustrated in Figure 4.4.



**Figure 4.4** Mix Factors Considered for Selection of Curing Protocol

For Level 1 mix designs, the 100 mm diameter specimens are cured until they reach a constant (dry) mass, typically with moisture contents of less than 0.5%. Testing follows 72 hours of curing at 40 °C without sealing the specimens to determine the  $ITS_{dry}$  value. Half the specimens are then soaked for 24 hours before testing to determine the  $ITS_{wet}$  value. This procedure is aimed at evaluating the moisture susceptibility of the BSM.

The curing procedure for 150 mm diameter specimens used in Level 2 and Level 3 mix designs typically produces moisture contents of 43 to 50% of OMC, which represents the long-term equilibrium moisture content of the material in the field. To achieve this, different curing periods are required for BSM-emulsion and BSM-foam. Unsealed specimens are initially placed in a draft oven at 30 °C to allow the moisture content to reduce. Thereafter, they are individually sealed in loose-fitting plastic bags (at least twice the volume of the specimen) and cured for a further 48 hours at 40 °C. The wet plastic bags must be replaced with dry bags every twenty four hours.

Before the specimens are tested, they should be allowed to cool down to the required test temperature whilst sealed in a new dry plastic bag to prevent any further moisture loss.

## 4.4. MECHANICAL TESTS

The ITS and triaxial tests are used in the various mix design levels, and are discussed in the following sub-sections.

### 4.4.1. INDIRECT TENSILE STRENGTH (ITS)

The ITS test is used as an indirect measure of the tensile strength and flexibility of the BSM to reflect the flexural characteristics of the material. Although this test does not produce highly repeatable results, it is the most economical method for investigating the effectiveness of the bitumen. In addition, a background of historical data is available.



## CHAPTER 4: Mix Design – Mechanical Tests

The 100 mm diameter specimens are used in Level 1 to indicate the optimum bitumen content, the need for an active filler and, if active filler is required, at what content. The 150 mm specimens are used to refine the optimum bitumen content and provide additional confidence for the material classification system.

The 100 mm diameter and 63 mm high specimens are cured for 72 hours at 40 °C (Section 4.3.5) to reach a constant mass.  $ITS_{dry}$  values are determined from these specimens. The results obtained after soaking these specimens for 24 hours at 25 °C are termed  $ITS_{wet}$ . The ratio of  $ITS_{wet}$  and  $ITS_{dry}$  expressed as a percentage, is the Tensile Strength Retained (TSR).

The 150 mm diameter and 127 mm high specimens are cured according to the procedure in Section 4.3.5 to simulate the field moisture conditions. The ITS results from specimens tested after this curing are termed  $ITS_{equil}$ . After soaking for 24 hours at 25 °C, the results from these tests are termed  $ITS_{soaked}$ .

The limits for interpreting the various ITS tests, and the purpose of the tests are provide in Table 4.6.

**Table 4.6 Interpretation of ITS tests**

Test	Specimen diameter	BSM1	BSM2	BSM3	Purpose
$ITS_{dry}$	100 mm	> 225	175 to 225	125 to 175	Indicates optimum bitumen content.
$ITS_{wet}$	100 mm	> 100	75 to 100	50 to 75	Indicates need for active filler.
TSR	100 mm	N/A			Indicates problem material where $TSR < 50$ and $ITS_{dry} > 400$ kPa.
$ITS_{equil}$	150 mm	> 175	135 to 175	95 to 135	Optimise bitumen content.
$ITS_{soaked}$	150 mm	> 150	100 to 150	60 to 100	Check value on $ITS_{wet}$ .

The TSR is useful to identify problem materials. If the TSR is less than 50%, it is recommended that active filler be used. Where a material has a TSR less than 50%, and the  $ITS_{dry}$  exceeds 400 kPa, the material is likely to contain clays and the bitumen is ineffective. In this situation, the material probably requires pretreatment.

### 4.4.2. TRIAXIAL TEST

A Simple Triaxial Test (STT) has been developed to facilitate triaxial testing in standard laboratories. The STT apparatus is only applicable to monotonic triaxial testing to obtain cohesion and friction angle values. However, the monotonic stiffness of the material, tangent modulus ( $E_{tan}$ ), provides an indication of resilient response of the material and to track trends in stiffness of different mix compositions. The tangent modulus is however, not a direct measure of the resilient modulus. Advanced triaxial setups may also be used for testing. The cohesion, friction angle and tangent modulus are used in the classification of BSMs (Section 3.3). The procedures for triaxial testing and calculation of the results are referenced in Appendix B. The limits used to interpret the data for the three material classes are shown in Table 4.7.

#### 4.4.2.1 Moisture Induced Sensitivity Test (MIST)

Triaxial testing also provides a means to a more reliable measure of the moisture susceptibility of BSMs. BSMs with superior moisture resistance are able to retain a greater percentage of the cohesion that is generated from the bitumen treatment. Triaxial specimens are conditioned with moisture exposure using the Moisture Induced Sensitivity Test (MIST) apparatus, as referenced in Appendix B. The MIST device applies cyclic moisture ingress at realistic pore pressures. The cohesion values are compared for specimens with and without moisture exposure, to provide the retained cohesion parameter for the particular BSM. The reference for the retained cohesion calculations is provided in Appendix B. These values, which provide a measure of the relative loss in cohesion of the BSM, assist in the classification of the mix. The values are shown in Table 4.7.

**i** **MIST**

The MIST test procedure and limits may need revision as the test is widely adopted. Check [www.asphaltacademy.co.za/bitstab](http://www.asphaltacademy.co.za/bitstab) for the **latest test procedure and limits**.



The MIST test is new and is introduced because it gives the most realistic simulation of pore pressures generated in BSMs that have been exposed to water under traffic. And, therefore it gives the best assessment of mix durability. Because the test is new, it may be necessary to revise the test method, or the limits associated with the tests. Check the [www.asphaltacademy.co.za/bitstab](http://www.asphaltacademy.co.za/bitstab) to obtain the latest values.

**Table 4.7 Interpretation of Triaxial Tests**

Test or Indicator	BSM1	BSM2	BSM3
Cohesion (kPa)	> 250	100 to 250	50 to 100
Friction Angle (°)	> 40	30 to 40	< 30
Retained cohesion (MIST)	> 75	60 to 75	50 to 60

## 4.5. MIX DESIGN PROCEDURE

The complete mix design procedure is explained by means of the flow chart in Figure 4.5. Each level is discussed in the following sections.

### 4.5.1. LEVEL 1 MIX DESIGN

Level 1 Mix Design utilises Indirect Tensile Strength (ITS) tests on 100 mm diameter specimens to:

- » Indicate the optimum bitumen content using  $ITS_{dry}$  and  $ITS_{wet}$  and TSR.
- » Select the active filler type and content using  $ITS_{wet}$  and TSR.

The specimens are cured according to Section 4.3.5. The optimum binder content is determined by ensuring the  $ITS_{wet}$  is sufficiently high. The limits in Table 4.6 should be used.

### 4.5.2. LEVEL 2 MIX DESIGN

Level 2 Mix Design utilises the Indirect Tensile Strength (ITS) tests on 150 mm diameter specimens. Specimens are cured according to Section 4.3.5. The ITS allows the binder content to be determined with increased confidence. The procedure uses the following tests:

- » Tensile strength at equilibrium moisture conditions (using  $ITS_{equil}$ ).
- » Tensile strength after moisture exposure (using  $ITS_{soaked}$ ).

Values of  $ITS_{equil}$  and  $ITS_{soaked}$  used for BSM classification are included in Table 4.6.

### 4.5.3. LEVEL 3 MIX DESIGN

Level 3 mix design utilizes triaxial testing to assess the shear strength of the BSM and the moisture resistance via the MIST apparatus.

Values of cohesion, friction angle, and retained cohesion for mix assessment are given in Table 4.7.

If a Level 3 mix design is performed, it is not necessary to also do a Level 2 mix design.

**i Level 1 Mix Design**

- » All traffic levels
- »  $ITS_{dry}$ ,  $ITS_{wet}$  and TSR
  - For bitumen type and content optimisation
  - Active filler and amount selection
  - Material classification for traffic < 3 MESA

**i Level 2 Mix Design**

- » > 3 MESA traffic levels
- »  $ITS_{equil}$  and  $ITS_{soaked}$ 
  - Bitumen content finalisation

**i Level 3 Mix Design**

- » > 6 MESA traffic levels
- » Triaxial (with MIST)
  - Shear properties
  - Moisture resistance



CHAPTER 4: Mix Design – Procedure

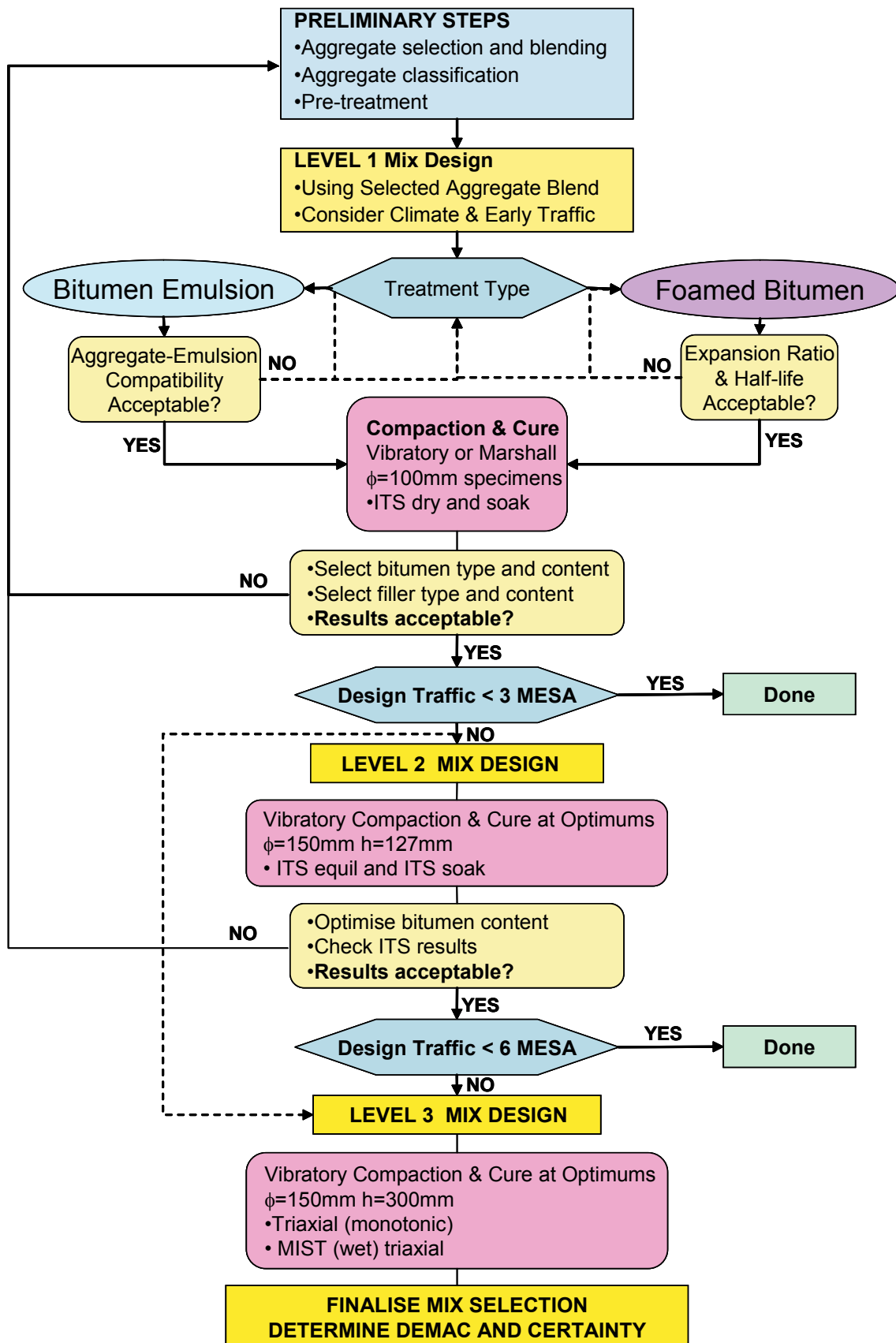


Figure 4.5 Mix Design Flow Chart for BSM Mixes



## 5. STRUCTURAL DESIGN

The basic principle of pavement design is to provide structural layers to protect the pavement subgrade against the stresses imposed by traffic. The combined system, consisting of the structural layers and the subgrade, should then function as a unit in a balanced system to achieve the desired design structural capacity. In essence, pavement balance requires that there should be a gradual decrease in strength from the top to the bottom pavement layers and that the strength of the structural pavement layers should not greatly exceed that of the subgrade. The exception to this is the use of inverted pavement structures in South Africa, although the structural layers typically have more strength than the subgrade. The structural design of pavements with BSM layers should follow these general principles and cognisance should be paid to general pavement design and rehabilitation guidelines, such as TRH4 and TRH12.

This chapter presents the structural design methods recommended for BSMs. For pavements carrying between 1 and 30 MESA and Category A (95% reliability) and Category B (90% reliability), the Pavement Number Method is recommended. This is discussed in Section 5.1. For pavements which have design traffic less than 1 MESA and are Category B, C (80% reliability) or D (50% reliability), the catalogue of designs is recommended. The catalogue is presented in Section 5.2. This chapter also discusses Appropriate Surfacing (Section 5.3) and Economic Analyses and Maintenance Requirements (Section 5.4).

The structural design of BSMs does not differentiate between BSM-emulsion and BSM-foam.

### 5.1. PAVEMENT NUMBER STRUCTURAL DESIGN METHOD

The structural design of pavements incorporating BSMs uses a knowledge based approach, termed the Pavement Number (PN). The PN method is applicable to Category A and B roads where the design traffic is between 1 and 30 MESA.

The PN is based on the Structural Number concept, which was used in the original AASHTO methods. However, some of the shortcomings of the Structural Number have been overcome in the PN method. The complete description of the PN method is given in Appendix C. The PN method was chosen for several reasons:

- » Data from in-service pavements were used to develop the method. The type and detail of the data suggests the use of a relatively simple method and precludes the use of a Mechanistic-Empirical design method.
- » The method gives a good fit to the available field data.
- » The method is robust, and cannot easily be manipulated to produce inappropriate designs.

The method is applicable to all pavement materials commonly used in southern Africa. This method relies on basic rules-of-thumb, which reflect well-established principles of pavement behaviour and performance, and which will ensure an appropriate pavement design solution in most situations. The concepts in the rules-of-thumb are quantified into specific rules with constants or functions associated with each rule. The rules-of-thumb are briefly described in the following sections.

The constants shown for the PN method included in this guideline and the Appendix were the values used at the time of publication of the guideline. Although these values are well validated it may be necessary from time to time to make changes to improve the system. If changes are made, the modified values will be reflected on [www.asphaltacademy.co.za/bitstab](http://www.asphaltacademy.co.za/bitstab). It is therefore recommended that before commencing a Pavement Number calculation, the website is checked for any changes in values or tests. The PN method is designed to be used in conjunction with the material classification system described in Chapter 3.

#### 5.1.1. APPLICABILITY OF PAVEMENT NUMBER METHOD

Before the Pavement Number method is used, the designer must check that the following situations do not apply:

- » **Design traffic greater than 30 MESA.** The method was calibrated using a knowledge base which was limited to pavements that had accommodated less than 30 MESA. Thus, in such a design situation, the design should be checked using more in-depth analysis.

**i** BSM-emulsion ≡  
BSM-foam

The structural design of BSMs  
**does not differentiate** between  
BSM-emulsion and BSM-foam.

**i** PN Method

Complete details of the PN  
method are given in **Appendix C**.

The most recent values for the  
method, and software to perform  
a calculation are available on  
[www.asphaltacademy.co.za/  
bitstab](http://www.asphaltacademy.co.za/bitstab)



## CHAPTER 5: Structural Design – Pavement Number

- » **Presence of thin, weak lenses.** If thin, weak lenses of material exist below the surfacing, or between stabilised layers, then zones of high slip and shear will develop, and the PN calculations will not apply. In such instances, the structural capacity assessment of the PN method is not appropriate, and special treatment of the affected weak lens must be undertaken. The PN design method cannot be applied to situations where such lenses still exist within the pavement structure, especially where such lenses are located within the upper 400 mm of the pavement structure.
- » **Subgrade CBR less than 3%.** The knowledge base on which the PN method was calibrated did not include any pavements that had a subgrade CBR less than 3%. The PN method should therefore not be used in cases where the subgrade CBR is less than 3% at a depth 600 mm below the surface.

### 5.1.2. RULES OF THUMB / DEPARTURE POINTS

This section presents a discussion of the basic rules-of-thumb underlying the method for calculating the PN. These rules reflect well-established principles of pavement behaviour and performance. The following rules-of-thumb, with particular reference to BSMs were adopted:

- » Rules Relating to the **Pavement System in General:**
  - The structural capacity of a pavement is a function of the combined **long term load spreading** potential of the pavement layers and the **relative quality of the subgrade** on which the pavement is constructed.
  - The **relative quality and stiffness of the subgrade** is the departure point for design, as the subgrade is a key determinant in the overall pavement deflection, and in the relative degree of bending and shear that will take place in overlying pavement layers.
  - For pavements with thin surfacings, the **base layer is the most critical component**, and failure in this layer effectively constitutes pavement failure. Experience can guide the relative confidence in different material types to serve as base layers under heavy traffic.
- » Rules Relating to **Specific Pavement Layers:**
  - The **load spreading potential** of an individual layer is a product of its thickness and its effective long term stiffness under loading.
  - The **Effective Long Term Stiffness (ELTS)** of a layer depends on the material type and class and on its placement in the pavement system.
  - Fine-grained subgrade materials act in a **stress-softening manner**. For these materials, the ELTS is determined mainly by the material quality and by the climatic region. Owing to the stress softening behaviour, subgrade materials will generally soften with decreased cover thickness.
  - Coarse-grained, unbound layers act in a **stress-stiffening manner**. For these materials, the ELTS is determined mainly by the material quality and the relative stiffness of the supporting layer. The ELTS of these materials will increase with increasing support stiffness, by means of the **modular ratio** limit, up to a **maximum stiffness** which is determined mainly by the material quality.
  - BSMs are assumed to act in a similar way to coarse granular materials but with a higher cohesive strength. The cohesive strength is subject to breakdown during loading and thus some softening over time can occur. The rate of softening is mainly determined by the stiffness of the support, which determines the degree of shear in the layer. However, owing to the higher cohesive strength in bituminous stabilised materials, these layers are less sensitive to the support stiffness than unbound granular materials and can therefore **sustain higher modular ratio limits**. If the cement content of a BSM mix exceeds 1% then the material is assumed to behave as a cemented material.

The above-noted rules-of-thumb introduce several concepts such as the ELTS, modular ratio limit, maximum stiffness and stress-stiffening behaviour. These terms are briefly described in the following section.

#### 5.1.2.1 The Effective Long Term Stiffness (ELTS)

The ELTS is a model parameter which serves as a relative indicator of the average long term in situ stiffness of a pavement layer. As such, the ELTS averages out the effects of decreasing stiffness owing to traffic related deterioration, as well as seasonal variations in stiffness. Thus the ELTS does not represent the stiffness of a material at any specific time.

The ELTS is also not a stiffness value that can be determined by means of a laboratory or field

**i** **Behaviour of BSMs**  
BSMs can **sustain higher modular ratio limits** than granular material because of the improved **cohesive strength**.

**i** **ELTS**  
This is a relative indicator of the **average long term in situ stiffness**, and does not represent the stiffness at any specific time.



test. It is a model parameter, which is calibrated for use in the PN design method and it may therefore differ from stiffness values typically associated with material classes.

### 5.1.2.2 Modelling of Subgrade Materials

Characterization of the support is critical to the pavement design of all pavements, including pavements with BSM layers. For new construction, the TRH4 procedure for delineation of the in situ subgrade and for importing selected subgrade material, if necessary when the structural strength of the in situ subgrade is insufficient, applies to the PN method. For rehabilitation projects, the guidelines in TRH12 for evaluating and designing for changing support conditions should be followed in conjunction with the PN method.

The first step in the calculation of the PN-value is the determination of the subgrade material class. To do this, specific guidelines are provided in Appendix C.

Once the subgrade class has been determined, the ELTS for the subgrade is calculated. This involves the following steps:

1. Assignment of a basic long term stiffness based on the materials class.
2. Adjustment of the basic long term stiffness for different climatic regions (wet, dry or moderate).
3. Adjustment of the stiffness determined to take account of depth of subgrade cover.

The adjustment of the subgrade stiffness to take account of the depth of cover gives an indication of the stress-softening tendencies of fine grained materials under load. The details on the relationship between the cover depth and the adjustment to the subgrade stiffness are given in Appendix C.

### 5.1.2.3 The Modular Ratio Limit and Maximum Stiffness

The modular ratio is defined as the ratio of a layer's stiffness relative to the stiffness of the layer below it. Thus, if the stiffness of a base layer is 300 MPa, and the stiffness of the support below it is 200 MPa, then the modular ratio of the base layer would be 1.5.

The modular ratio accounts for the stress-sensitive stiffness of granular and, albeit to a lesser extent, BSM materials. The stress-sensitivity causes the stiffness of the material to decrease when the material is placed over a weaker (less stiff) support. This decrease in stiffness occurs where the support layer is soft, causing a tendency for the overlying layers to bend into the support, thereby increasing the likelihood of developing higher shear and tensile forces in the overlying layers. This effect limits the stiffness that can be obtained in a stress-sensitive layer placed over a weaker support. By placing a limit on the modular ratio that can be sustained for a specific material, it is ensured that the stiffness value assumed for that layer is realistic, given the material quality and stiffness of the support. In essence, the concept of a limiting modular ratio for materials ensures that stress-sensitive stiffness behaviour is implicitly taken into account.

The modular ratio that a material can sustain varies over the life of a pavement and in the PN method it pertains to the overall long term stiffness that a material can maintain.

### 5.1.2.4 Maximum Stiffness

Under the action of loading, there is a maximum stiffness that materials can achieve. As with the modular ratio, the maximum stiffness depends on the quality of the material. Less dense and angular materials will not develop very high stiffnesses under loading, regardless of the stiffness of the support.

In the PN model, the modular ratio limit and the maximum allowed stiffness are used extensively to determine realistic ELTS values. These parameters are used in the following way:

1. The **stiffness of the supporting layer** is first determined. Thus the PN calculation process starts from the subgrade and proceeds upward toward the surfacing.
2. The **modular ratio limit and maximum allowed stiffness** for each layer are determined based on the material type and class.

**i Subgrade ELTS**

**Depends on:**

- » Material class
- » Climate
- » Depth of cover

**i Modular Ratio**

This is ratio of a **layer's stiffness** relative to the stiffness of the layer below.



## CHAPTER 5: Structural Design – Pavement Number

3. The **ELTS** for a layer is determined as the minimum of the support stiffness multiplied with the modular ratio limit and the maximum allowed layer stiffness.

The ELTS values for BSMs are higher than that of granular materials because they can sustain a higher stiffness. In the case of base layers, the ELTS is further adjusted by means of a base confidence factor.

### 5.1.2.5 The Base Confidence Factor

The type of material in the base layer is an important determinant of the performance of the pavement because the base is the main load bearing element in the pavement system and failure of the base effectively constitutes pavement failure. Experience has shown that there is a limit on the types of base materials that can be considered for any given traffic situation. In particular, suitable design options are significantly limited as the design traffic increases.

In the PN method, the appropriateness of the base material is controlled by the Base Confidence Factor (BCF) which is used to adjust the ELTS for the layer.

**i** **BCF**  
To prevent the use of **inappropriate bases**, a Base Confidence Factor is assigned, which depends on the type of materials.

### 5.1.3. PAVEMENT NUMBER CALCULATION

Appendix C contains the full details of the PN calculation along with a worked example. The main steps are summarized below. In a pavement design situation, the steps described are applied for each uniform design section. For rehabilitation design situations, it is thus presumed that the designer will have detailed information on the existing pavement layer properties for each uniform section.

- Step 1:** Check to ensure that the design method is applicable for the design situation.
- Step 2:** Determine the layer thicknesses, and available material properties for each layer. Determine the design equivalent material class (DEMAC) using the guidelines in Chapter 3 and Appendix A. To prevent the use of unrealistic layer thicknesses, maximum and minimum limits are given. BSM layers can only have a thickness between 100 mm and 350 mm. Values outside these limits have not been validated.
- Step 3:** Combine layers with similar properties to obtain a five layer pavement system, including the subgrade (i.e. four layers plus the subgrade). Check that the layer thicknesses do not exceed the maximum for design purposes.
- Step 4:** Determine the basic stiffness of the subgrade by means of the given values (Appendix C). Adjust the stiffness for the climatic region and depth of subgrade cover.
- Step 5:** For each layer above the subgrade, determine the modular ratio limit and maximum allowed stiffness.
- Step 6:** Use the modular ratio limit and maximum allowed stiffness to determine the ELTS for each layer by working up from the subgrade.
- Step 7:** For the base layer, determine the Base Confidence Factor (BCF).
- Step 8:** For each layer, calculate the layer contribution using the ELTS, layer thickness and BCF (for base layers).
- Step 9:** Add the layer contributions for each layer to get the PN.

**i** **PN Inputs**  
The ELTS, modular ratio, layer thickness limits and BCF are specific for the PN method **should not be changed by the user.**

The values used for the ELTS, modular ratio, layer thickness limits and BCF are specific to the PN method and should not be adjusted by the designer. The relevant values for BSMs are shown in Table 5.1. BSM3 values are not given as BSM3 materials are applicable to design traffic less than 1 MESA and in these situations the design catalogue should be used.



**Table 5.1 Modular Ratio Limit and Maximum Allowed Stiffness for Pavement Layers**

Design Equivalent Material Class	BSM1	BSM2
<b>General Material Description</b>	High strength bitumen stabilised material, normally using crushed stone or reclaimed asphalt (RA) source material	Medium strength bitumen stabilised material, normally using natural gravel or RA source material
<b>Modular Ratio Limit</b>	3.0	2.0
<b>Maximum Allowed Stiffness (MPa)</b>	600	450
<b>Base Confidence Factor</b>	1.0	0.7
<b>Thickness limit</b>	100 mm to 350 mm	

## 5.2. CATALOGUE OF DESIGNS FOR LOWER TRAFFICKED ROADS

The PN Design Method is only valid for Category A and B roads that carry more than 1 MESA. For design situations that will carry less than 1 MESA, the catalogue in Figure 5.1 should be used. The catalogue is only applicable to Category B, C and D roads.

The catalogue is applicable to new construction, however, it may also be used as a guideline for rehabilitation. For rehabilitation purposes, the existing pavement situation should be matched to the nearest catalogue design, ensuring that the existing materials are not weaker than the catalogue design.

The material classes shown in the catalogue should be obtained from the material classification system described in Chapter 3. The S symbol in the catalogue represents a double seal.



CHAPTER 5: Structural Design – Catalogue

	Pavement Class and Design Bearing Capacity		Foundation (CBR)	
Road Category	ES0.3 ≤ 300 000	ES1 300 000 to 1 000 000		
B (95% Reliability)		S 125 BSM2	> 15	
		S 125 BSM2 150 G6	7 to 15	
		S 125 BSM2 150 G5 150 G7 150 G9 40 AC 300 BSM2	3 to 7	
C (80 % Reliability)	S 100 BSM3 125 G6	S 125 BSM3 150 BSM3	> 15	
	S 125 BSM3 125 G6 125 G7	S 300 BSM3	40 AC 200 BSM3	7 to 15
	S 100 BSM3 125 G6 125 G7 125 G9	40 AC 200 BSM3	S 150 BSM3 150 G5 150 G7 150 G9	40 AC 200 BSM3
D (50% Reliability)	S 100 BSM3	S 100 BSM3	> 15	
	S 100 BSM3 125 G6	S 250 BSM3	30 AC 150 BSM3	7 to 15
	S 125 BSM3 125 G6	S 300 BSM3	30 AC 175 BSM3	3 to 7

Figure 5.1 Catalogue of Designs for BSM Pavements Carrying up to 1 MESA



### 5.3. APPROPRIATE SURFACINGS

The selection of a surfacing type to overlay a BSM base should be based on sound structural design and economic considerations as well as the functional requirements of the road. Based on observations from in-service pavements, roads carrying in excess of 1 MESA had HMA surfacings, often in combination with a single seal. Based on these observations, recommendations for the minimum surfacing thickness are shown in Figure 5.2. For traffic less than 1 MESA, a surfacing seal should be adequate. For traffic between 1 and 15 MESA, the formula shown in Figure 5.2 should be used, with the thickness rounded to the nearest 5 mm. For traffic exceeding 15 MESA, an HMA thickness of at least 50 mm is recommended.

#### Surfacings

Pavements carrying  
**> 1 MESA** should have an  
**HMA surfacing.**

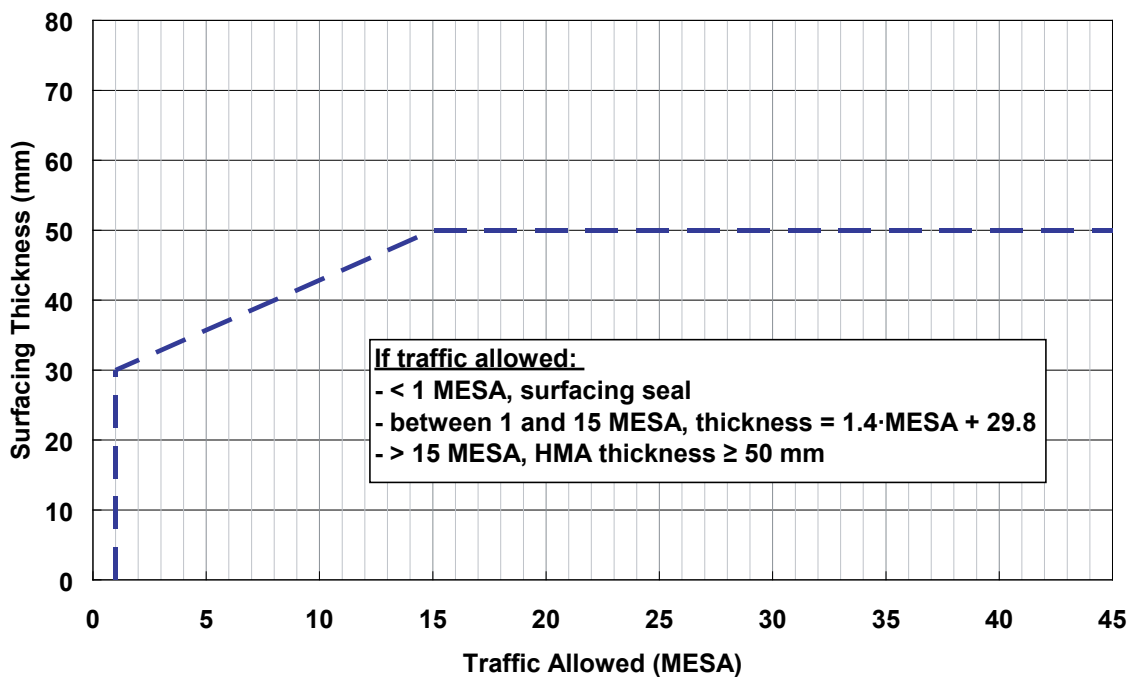


Figure 5.2 Minimum Surfacing Thickness for BSM Pavements

### 5.4. ECONOMIC ANALYSES AND MAINTENANCE REQUIREMENTS

The purpose of structural pavement design is to identify pavements with the same structural capacity that meet the traffic demand. The present worth of the construction and life-cycle cost of the alternative designs are then compared to select the most cost effective design. The alternatives should be compared in terms of total project cost. The reader is referred to TRH4 (Table 24) and to Table 5.2 below for an indication of the estimated typical future maintenance requirements for life cycle cost analysis. The estimates in Table 5.2 assume a 20 year structural design life.



CHAPTER 5: Structural Design – Economic Analysis

Table 5.2 Typical Future Maintenance Measures for BSM Base Pavements

Measures to improve the surfacing condition		Structural maintenance	
Original surfacing		Moderate distress	Severe distress
Surface treatment	Asphalt		
S1 (9 years) <sup>1</sup> S1 (14 years) S1 (19 years)	S1 (12 years) S1 (17 years) <sup>2</sup>	30 to 40 mm AG, AC <sup>3</sup>	> 100 mm BTB <sup>4</sup> BSM Overlay <sup>5</sup>

Notes:

1. S1 (5 years) represents a single surface treatment after five years.
2. For low trafficked roads this seal may be replaced with a 50 mm overlay to increase the structural capacity.
3. AG and AC are asphalt surfacings.
4. BTB is bitumen treated base.
5. BSM overlay should be plant mixed.

The discount present worth of cost approach described in TRH4 is recommended for the project level analysis of pavements containing BSM layers. The cost comparison should not attempt to justify the economic benefits of a labour-intensively constructed pavement by comparison with that of a machine-constructed pavement. The decision to use labour-intensive construction should be taken at a policy level, not at the project level.



## 6. CONSTRUCTION

This chapter provides guidelines for constructing pavement layers using BSMs. An explanation of the general construction approach to BSMs is provided, followed by specific construction requirements for working with BSMs regardless of whether foamed bitumen or bitumen emulsion is used as the stabilising agent. Aspects specific to either BSM-emulsion or BSM-foam are clearly highlighted.

From a construction perspective, once bitumen emulsion or foamed bitumen has been mixed into a material, the resulting BSM behaves in a similar way to an untreated material. The various construction operations required to place the material, cut levels, compact to achieve the required level of density and finish off the new layer are practically the same as those that would be used had the material not been treated. The performance properties of the layer of treated material are, however, different from those of the untreated material. The behavioural characteristics that influence the workability of the material before it is finally compacted and finished off are similar to that of untreated materials. Contrary to some misconceptions, the addition of foamed bitumen or bitumen emulsion to a granular material will not create a cold-mix asphalt look-alike. The treated material will remain granular in nature and must be processed in the same way as the untreated material would be processed for layer construction.

The primary factor influencing the approach to construction is the type of project that is being undertaken. Figure 6.1 illustrates the options available for BSMs.

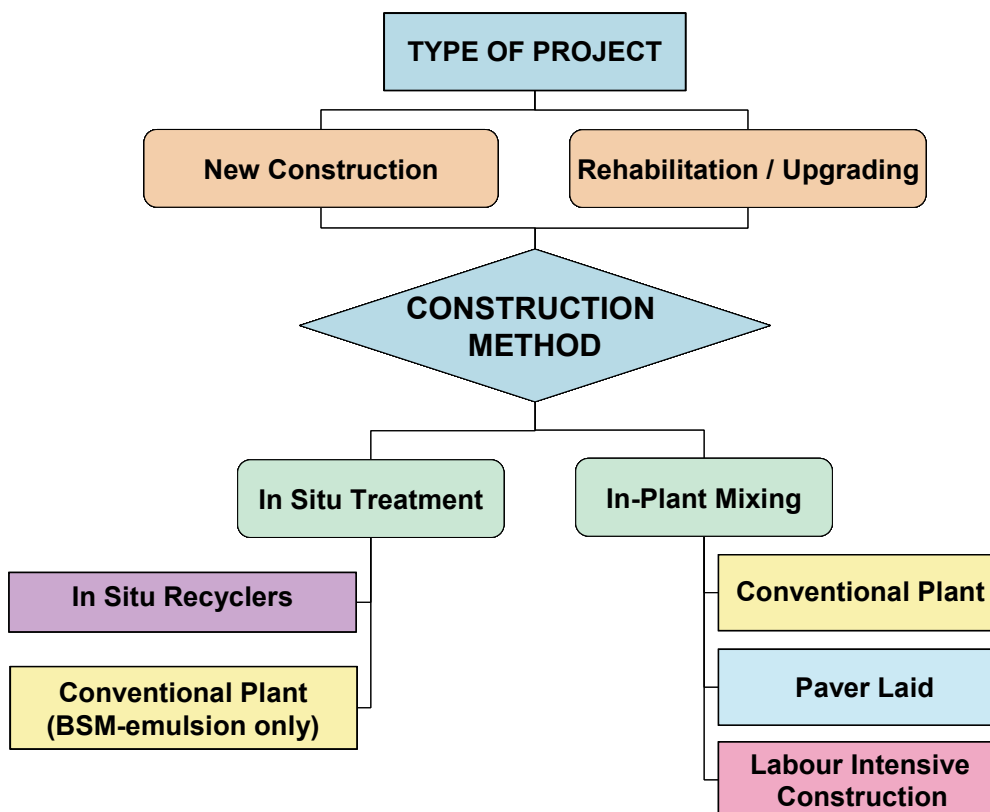


Figure 6.1 BSM Construction Options

The type of project and the specific requirements for constructing a new layer using a BSM falls into two primary categories, new construction or pavement rehabilitation/upgrading. The method selected for treating the material with bitumen, in situ or in-plant will then determine the options available for processing the material to construct the layer. In situ treatment requires a different construction approach to material that is treated in-plant and these are explained in two separate sections. In situ treatment is covered in Section 6.1 to 6.3 and in-plant treatment in Section 6.4. These sections cover the complete construction procedure, including material preparation, mixing, placing, achieving the required levels, compaction and finishing. This is followed by sections that are common to all BSM construction projects, which includes curing the finished layer, trafficking, surfacing, constructing trial sections and, finally, quality control requirements. Details for controlling the product (both process and acceptance controls) are included in Appendix D.



## CHAPTER 6: Construction – In situ Treatment Using Recyclers

### 6.1. IN SITU TREATMENT (GENERAL)

Although purpose-built recycling machines have generally replaced conventional construction equipment (graders, ploughs, rotavators, etc.) for in situ treatment, conventional equipment remains an option for BSM-emulsion on projects where the cost of establishing a large recycler may not be justified. Construction with recyclers and conventional equipment is discussed in Sections 6.2 and 6.3, respectively.



**Conventional Equipment**

**BSM-foam** is not suitable for construction with conventional equipment.

<b>BSM-emulsion</b>	<b>BSM-foam</b>
Only BSM-emulsion can be constructed using either of the two in situ options. The use of conventional equipment needs careful process control to ensure proper mixing.	Foamed bitumen cannot be constructed using conventional construction equipment. This is because of the specialised equipment required to foam the bitumen and because of the short time required to mix the foam into the material.

#### 6.1.1. DILUTING BITUMEN EMULSION WITH WATER

Until the advent of recyclers, bitumen emulsion was always diluted prior to mixing. This practise is still required when using conventional equipment.

The need to dilute the bitumen emulsion when using recyclers is dependant on two factors:

- » The **application rate of the bitumen emulsion**. Bitumen emulsion must always be diluted where the application rate of bitumen emulsion (as opposed to residual bitumen) is less than 2%. This is to ensure sufficient spraybar pressure and adequate fluid for effective mixing.
- » The **number of spraybars on the recycler**. When the application rate is sufficiently high, bitumen emulsion and water can be applied separately provided the recycler is fitted with two spraybars. In this case, the water must be applied prior to the bitumen emulsion, which typically requires the water spraybar to be mounted below the bitumen emulsion spraybar. When undiluted bitumen emulsion is used, the bitumen emulsion must be preheated to 60 °C. Where the recycler has only one spraybar, bitumen emulsion must always be applied in the diluted form. However, it is highly recommended that only recyclers fitted with two integrated computer-controlled spraybars are used for BSM-emulsion. This allows good control of moisture content adjustment during mixing.



**Number of spraybars**

It is highly recommended that recyclers are fitted with **two spraybars**.

After the material has been treated with bitumen emulsion, should additional fluid need to be added, it is good practice to use a diluted bitumen emulsion (“dirty water”) as opposed to water on its own.

### 6.2. IN SITU TREATMENT USING RECYCLERS

This section describes the operations when using a recycler to treat material from the existing road with bitumen. This is applicable to both new construction and rehabilitation. In addition to the recycling operation that incorporates the mixing process, this section includes placing and compacting the treated material, as well as finishing off the treated layer. The intention here is not to replicate the generalities of recycling but rather to highlight those issues that are important when constructing a new BSM layer using a recycler.

In situ treatment using conventional construction equipment is covered separately in Section 6.3.

#### 6.2.1. FACTORS REQUIRING CONSIDERATION (PLANNING THE WORK)

The daily production of a recycling train can be high. Additionally there are demands to open the completed work to traffic at the end of each day’s work. Meticulous planning and diligent execution is required to ensure that the output potential is realised without



**Recycling Projects**

**Meticulous planning and diligent execution** is required for recycling projects using recyclers.



## CHAPTER 6: Construction – In situ Treatment Using Recyclers

compromising quality and at the same time ensuring that the BSM product stands up to early traffic loading. The factors that need to be considered when planning recycling projects are described in the following sections.

### 6.2.1.1 Equipment Selection

The recycling machine, bulk supply tankers and large primary roller are items of plant that are not generally used for road construction. In addition, equipment used for spreading the low application rates of active filler normally specified with BSM needs careful consideration. Sufficient equipment must be available to ensure that a good quality BSM can be produced within the allowed working period. The following requirements for the recycler, bulk tankers, spreaders for active filler and compactors are recommended:

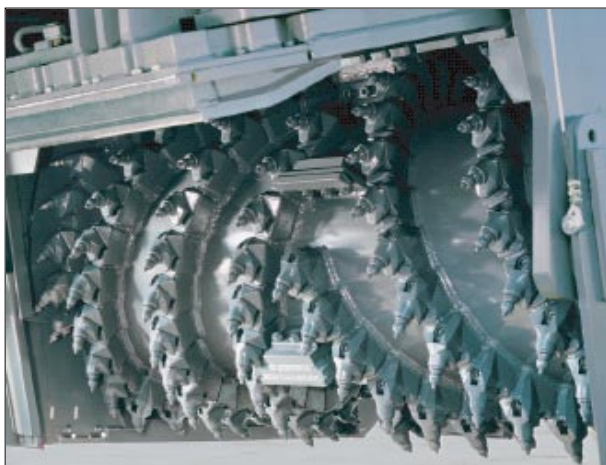
#### i. Recycler

The recycler works in tandem with other construction plant, such as water and bitumen tankers. Several types of recycling machines are available, ranging from simple stabilisers to purpose-built tyre-mounted recyclers with computer controlled application systems. Although the decision as to which machine is best suited to a specific project is primarily influenced by the size and type of project, it is a critical decision since the outcome of the project will be dictated by the ability of the machine to do the job. The recycler used for treatment of the material with bitumen should meet the following minimum requirements:

- » **Sufficient horsepower to cut/mill** into the pavement to the required depth and simultaneously push the recycling “train”.
- » Sufficient **volume in the milling chamber** to accommodate and mix the material generated by the milling or pulverising to the required depth.
- » Two independent micro-processor controlled application systems with **separate spray bars**; one for the bitumen and the other for applying water to increase the moisture content of the recycled material.
- » A positive **control system** for maintaining the set-up of the recycler (depth of cut and relative inclination).

Track-mounted recyclers are milling machines that have been adapted to simultaneously recycle and treat the material. Their capabilities are different from tyre-mounted recyclers, primarily due to:

- » The **smaller diameter of the milling drum** and the **mounting of the cutting tools** on the drum results in a lower peripheral speed of the tools on a track-mounted recycler compared to those on a tyre-mounted recycler. The mounting of the cutting tools of milling machines and recyclers are illustrated in Figure 6.2.



**Milling Machine (Track Mounted Recyclers)**



**Recycler (Tyre Mounted)**

**Figure 6.2 Mounting of Cutting Tools on Milling Machines and Recyclers**

- » The differences in the cutting tools have a direct influence on the grading of the recycled material and on the quality of the mix.
- » The cutting tool pattern on a milling drum windrows the material to the centre where it exits through a door at the rear of the milling chamber. On a recycler, the cutting tool pattern limits material movement to a maximum 200 mm horizontally.
- » Large milling machines have the milling chamber and drum attached to the chassis whereas most recyclers have the milling chamber attached to the chassis with the drum on a swing arm that moves away from the chassis as it is lowered into the pavement. The capacity of the milling chamber on milling machines is therefore constant, and the depth of cut is limited to the amount of material that can be accommodated. This in turn is dictated by the amount of bulking that occurs when the material is pulverised.



**CHAPTER 6: Construction – In situ Treatment Using Recyclers**

The BSM produced by a track-mounted recycler will therefore be different from that produced by a tyre-mounted recycler in terms of grading and mix quality. Experience has shown that better quality BSMs are produced by tyre-mounted recyclers on thick layers.

The number of recyclers deployed on a project obviously has a significant impact on production potential. More than one pass is normally required to cover the width to be treated in one shift (for a road half-width or traffic lane), therefore productive time will be wasted when only a single recycler is used, which has to reverse to make a second pass. Such wasted time can be eliminated by deploying two recyclers working in echelon (one immediately behind the other, but offset), thereby covering the full recycling width as dictated by the geometry of the cross-section. The efficiency of such an operation is further increased by the improved efficiency of the grader cutting final levels.

**ii. Bitumen Application System**

The micro-processor controlled pumping system mounted on the recycler must be designed to monitor and adjust the application rate of the bitumen in accordance with the volume of material being recovered as the recycler advances. The bitumen is sprayed into the milling chamber and is mixed with the recycled material. The bitumen emulsion and bitumen used to foam must meet the requirements in Section 6.2.2.

<b><i>BSM-emulsion</i></b>	<b><i>BSM-foam</i></b>
<p>The pump incorporated into the bitumen emulsion system on the recycler, together with the injection nozzles fitted on the spraybar need to be “bitumen emulsion friendly” to prevent premature breaking. Gear-type pumps and ultra-high pressure nozzles will cause the bitumen emulsion to break instantly (so-called flash break). Once the bitumen emulsion has broken, mixing is impossible and the milling chamber on the recycler will clog up to such an extent that it can take several hours to clear.</p>	<p>The foamed bitumen application system is one of the most important determinants of the quality of the final mix. Poor or inconsistent foaming will produce a mix with many stringers and, in the worst extreme, blobs of sticky, shiny bitumen will be produced if the bitumen is not foaming. These are indicators of poor foaming characteristics and inadequate bitumen dispersion. Such a mix will not meet performance expectations.</p> <p>Before accepting any foamed bitumen system on a project, it should be checked to ensure that it has a proven track record of successful applications. Homemade and other systems, such as those that create foam by squirting water at a spray of hot bitumen (so-called “external foaming systems”) should not be used. Such systems produce inconsistent foam, which results in a poor mix.</p> <p>The system must have the capability of demonstrating that it is free from blockages, both prior to work commencing and at any stage during the operation.</p> <p>In addition, the system must be equipped with a “test nozzle” that operates under the same temperature and pressure conditions as the spraybar. Such a test nozzle must have the capability of producing a representative sample of foamed bitumen at any stage of the operation.</p>

**iii. Bulk Tankers**

Bitumen, bitumen emulsion and water tankers coupled to the recycler should be sized in accordance with the scope of the work and geometry of the road. In general, single-chassis tanker units (maximum capacity of 15 000 litres) are preferred on small projects and/or where the road alignment has low geometric standards. Large semi-trailer bulk tankers are usually used on large projects through flat terrain.



CHAPTER 6: Construction – In situ Treatment Using Recyclers

All tankers should be inspected for leaks prior to coupling into the recycling train. A bitumen or water leak causes little harm while the train is moving but can give rise to wet soft spots when the train is stationary (e.g. when changing cutting tools) and the drip falls on loose recycled material for a prolonged period.

iv. **Compaction Equipment**

The type of material and thickness of layer being compacted will dictate the type and number of rollers required on a project. Three rollers are usually used to compact the recycled material. The “primary” roller with a static mass commensurate with the thickness of the layer (normally fitted with a padfoot drum) is first deployed immediately behind the recycler to apply high-amplitude vibrating compactive effort that penetrates through to the bottom of the treated layer. After final levels have been cut, a smooth drum roller with a static mass of about 10 tons applying low-amplitude vibrating effort is used to finally compact the upper portion of the constructed layer. A pneumatic-tyred roller (PTR) is then used for finishing the layer.

The primary roller is critical to achieve density in the lower half of the BSM layer. Figure 6.3 is a basic guide for selecting the static mass and type of roller for different combinations of layer thickness and grading characteristics of the material being compacted.

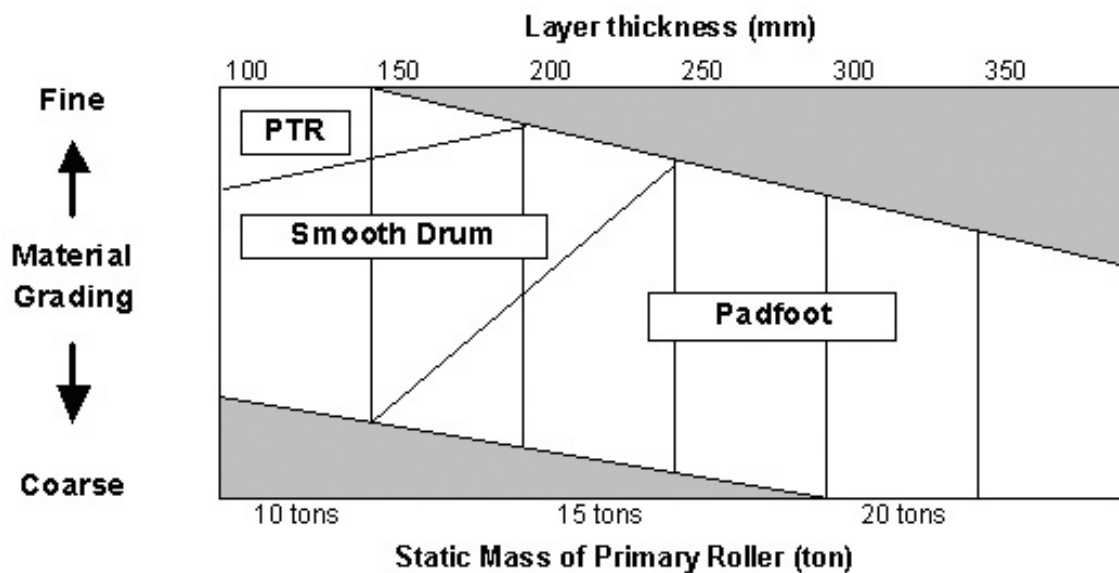


Figure 6.3 Primary Roller Selection Guide

Vibrating padfoot rollers tend to leave pockmarks (indentations) in the surface of the layer which cannot be eliminated when a thin surface treatment is applied. However, such pockmarks in a completed layer are actually an indication of either insufficient compaction or poor construction practices, or both. With good compaction practices, the following should be achieved:

- » As **more roller passes are applied**, the increased compactive effort results in a greater density being achieved in the lower regions of the BSM layer. As this density increases, so does the resistance to penetration by the individual pads on the roller, with the result that the padfoot imprints will rise higher and higher within the body of the layer as the roller “walks out” of the material. These scenarios are illustrated in Figure 6.4.



## CHAPTER 6: Construction – In situ Treatment Using Recyclers



**Deep imprints of padfoot roller (Initial stage of compaction)**



**Padfoot roller “walking out” of compacted material leaving “pockmarks”**

**Figure 6.4 Padfoot Roller Imprints on Material Being Compacted**

- » **Elimination of such pockmarks** requires the judicious addition of water or diluted bitumen emulsion sprayed from a water tanker (Section 6.3.4), blading with the grader whilst cutting the final levels and secondary compaction with a smooth drum vibrating roller. It must, however, be recognised that this operation requires experience to avoid surface laminations or biscuit layers forming, especially when working with fine graded materials.

### 6.2.1.2 Traffic Accommodation

Provisions always need to be made for the safe accommodation of public traffic. Recycling work is usually done in half-widths, or by closing off only a portion of the existing road. Correct signage, delineators and traffic control measures all need to be in place before any work can start.

### 6.2.1.3 Survey Control

Most pavement rehabilitation projects call for the existing road to be recycled in place, thereby retaining existing surface levels and shape. This also minimises the need for extensive survey and design input. The survey is best carried out by staking the existing road and transferring relevant surface elevations to a series of level-control posts placed at regular intervals outside both shoulder edges. Standard survey controls are recommended for new construction.

### 6.2.1.4 Material Preparation


#### i. Recycled Material

Recycling machines pulverise the existing pavement layer(s) to the required depth, breaking down the upper portion of a layered pavement structure to a produce material that is essentially granular in nature. The milling drum on a recycler is designed to break down previously bound material, such as asphalt and cement treated bases.

Due to the upward rotating direction of the milling drum, the reclaimed material is lifted and tends to “fall apart” into a graded material, rather than being crushed into smaller particles. Very little aggregate crushing occurs. The degree of pulverisation actually achieved depends on the strength and condition of the in situ material. Lightly cemented material generally produces an aggregate grading resembling that used in the original construction. The fines content should, however, be checked.

The grading of reclaimed asphalt (RA) is more difficult to control since it is influenced by several variables, including:

- » **The degree of oxidation of the bitumen in the RA.** For example, recently applied asphalt patches containing fresh bitumen will break down differently from the aged asphalt.
- » **The total thickness of asphalt.** Thin layers tend to produce more “chunks” than thick layers.



**Pockmarks from Vibrating Rollers**

Pockmarks from vibrating padfoot rollers are generally an indication of **insufficient compaction** and / or **poor construction practices**.




## CHAPTER 6: Construction – In situ Treatment Using Recyclers

- » **The original asphalt mix**, particularly the quality and grading of the aggregate.
- » **The extent and geometry of any crocodile cracking** in the upper asphalt layers.
- » **The condition of the bond** between various asphalt overlays in the existing pavement.
- » **The peripheral speed of the cutting tools on the milling drum, machine advance speed and the position of the “breaker bar”** mounted at the front of the milling chamber.
- » **The temperature of the asphalt** during the recycling process.

One of the main reasons for conducting a Trial Section (described in Section 6.7) is to determine how the material in the existing pavement will break down when recycled. Such Trial Sections should therefore be carefully selected to be truly representative of the pavement that will be recycled.

### ii. Pre-Milling

Any pre-milling of asphalt must be undertaken using a milling machine, not a recycler. The removal of some of the asphalt material is sometimes required to ensure that the post-recycling levels will match with existing elevation constraints (e.g. kerbs, intersection tie-ins, etc.). In addition partial-depth pre-milling without removing the RA may be necessary to break down asphalt layers that are severely distressed, such as pavements with advanced crocodile cracking. The purpose of pre-milling such asphalt layers is to eliminate oversized particles such as asphalt chunks. To achieve the required material breakdown, the depth of pre-milling must be less than the thickness of asphalt.



**Pre-milling Asphalt**


Pre-milling of asphalt must be undertaken using a **milling machine** not a recycler.

### iii. Pre-Pulverising

Pre-pulverising an existing pavement prior to recycling and treating with bitumen is normally only considered when the following conditions are present in the existing pavement:

- » **Surface irregularities** are significant relative to the depth of recycling or the surface is so badly out of shape that the recycler will be unable to achieve a consistent depth of cut.
- » The **recycling depth** includes pavement layers that require more power than the recycler can deliver to break down the material whilst simultaneously achieving sufficient and constant advance speed. Sufficient advance speed is important as this dictates the flow rate for bitumen which, in turn, determines the operating pressures. Such tough milling conditions are usually associated with thick layers of aged asphalt and strongly cemented layers.
- » When material needs to be **cross-blended** across the pavement to achieve uniformity. This situation is normally encountered where the road was previously widened using different materials from those used in the original pavement, and is discussed below.
- » For materials exhibiting plasticity, consideration may need to be given to **chemical modification**, typically using hydrated lime. (See Section 4.2.3)

Where pre-pulverising is deemed necessary, the depth of cut during the initial pulverising pass must be carefully controlled to ensure that a thin layer (normally 50 mm) of the existing layer remains to be recycled with the second stabilising pass. In addition, a water cart should be coupled to the recycler and water added whilst pre-pulverising so that the loosened material can be compacted and levels cut to provide the recycler with the correct surface shape for the second stabilising pass. The density requirement for compaction of the pre-pulverised material is normally 93% of the modified AASHTO density.



**Density of pre-pulverised material**

The density requirement for compaction of the pre-pulverised material is normally **93% of modified AASHTO**.

### iv. Material Import

For the reasons explained in Section 2.6.3.1, some projects require virgin material to be imported and spread on the existing road surface prior to recycling. Such material is normally hauled to site and dumped prior to adding water, mixing and placing by grader to the required surface shape. The material is then compacted to 93% of the modified AASHTO density.

Where the existing road is so badly out of shape that the thickness of the imported layer will vary excessively, the existing pavement should be pulverised and shaped (as described above) prior to importing and placing the new material.



## CHAPTER 6: Construction – In situ Treatment Using Recyclers

The material import and preparation is normally undertaken immediately ahead of recycling. When working in half-widths, such additional material can often result in a vertical step on the centre-line. Where this presents a safety hazard, both half-widths should be recycled during the same work shift.

### v. Material Cross-Blending

Some pavement layers include material type or quality differences across the width of the road, often resulting from pavement widening operations. It is not uncommon to encounter graded crushed stone in the base layer of the carriageway and a natural gravel material in the shoulder base layer.


Recyclers do not cross-blend materials (maximum lateral movement of material particles is 200 mm). Blending two materials to achieve uniformity across the carriageway and shoulder requires one of the following two options:

- » **Pre-pulverise the shoulder base layer only**, blade the resulting material on top of the adjacent traffic lane of the carriageway, spread as a uniform layer and pre-compact. The depth of recycling and treatment on the carriageway is then increased to include this added material with the underlying in situ material, thereby obtaining a homogenous blend. Once blended, the material is spread and processed across the full width of the carriageway and shoulder.
- » **Pre-pulverise the entire half width**, cross-blend the loosened material with a grader, spread, shape and pre-compact before making another pass with the recycler to add the bitumen.

#### 6.2.1.5 Spreading Active Filler

Any active filler requirements are usually met by accurately spreading the filler on the road surface immediately prior to commencing work with the recycler. Such spreading is normally confined to one cut width at a time rather than spreading over the entire half-width of road.

The application rate for cement or lime normally applied with BSMs is always low (1% by mass). Such low application rates are difficult to achieve with sufficient accuracy when using the bulk spreaders that are normally employed for cement stabilisation where higher percentages are specified. As stated above, recyclers do not “cross or forward blend” material, the maximum particle movement in the horizontal plane is 200 mm. The accurate spreading and distribution of active filler ahead of the recycler is therefore very important. Where bulk spreaders cannot achieve the degree of accuracy required, they should not be used.



### Cement Contents

The **cement content** of BSMs should be  $\leq 1\%$ , and the cement content should not exceed the bitumen content.

Alternative application methods such as hand-spreading with rubber squeegees immediately ahead of the recycling train, purpose-built spreaders or slurry injection using specialised equipment can be incorporated into the recycling train. When using slurry injection, the particle size of cement may vary and such variation should be noted as it may affect the accuracy of application. To minimise variations, the use of consistent sources and standard routines for spreading are recommended.

#### 6.2.1.6 Working on Steep Gradients

In addition to recycling the material, the recycler is the “locomotive” for pushing (or pulling) two bulk tankers, one containing hot bitumen or bitumen emulsion, the other water. Where slurry injection is used for applying the active filler, the water tanker is replaced with a heavy specialised slurry mixing unit.

The most commonly used recyclers are tyre-mounted with each wheel being driven by a hydraulic motor. The two rear wheels always run on loose recycled material. Traction between the front tyres and road surface can be lost on steeper gradients when working uphill, particularly where the material was pre-pulverised. This leads to several problems, the most critical being an over-application of bitumen and water due to slippage of the front wheels where the speed of advance is measured and relayed to the computer controlling the supply pumps. Steep gradients should therefore be recycled by working downhill with due consideration given to maintaining sufficient supplies in the respective tankers.

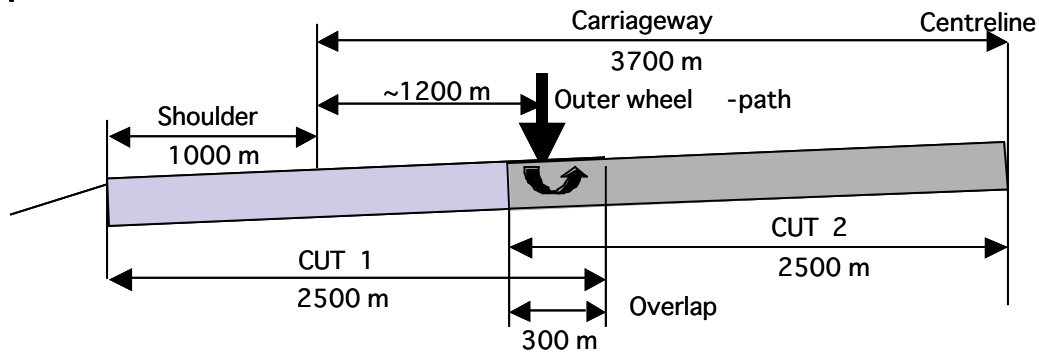
#### 6.2.1.7 Cut Plan, Overlaps and Longitudinal Joints

Due to the demand for early trafficking coupled with the configuration of the spraybars commonly in use, an important consideration when treating with bitumen is the location of the outer wheel-path relative to the longitudinal joint between adjacent cuts. Such an



CHAPTER 6: Construction – In situ Treatment Using Recyclers

overlap invariably falls in the outer wheel-path when recycling single carriageway roads in half-widths where the overall surfaced width is between 7 and 10 metres. Figure 6.5 gives an example for a 9.4 metre wide pavement.



**Figure 6.5 Typical Recycling Cut Plan Showing the Overlap Relative to the Outer Wheel Path**

Over-application of the bitumen and water, or diluted bitumen emulsion, in the overlap must be avoided to prevent the overlap material from being too wet. To prevent over application of the bitumen, the standard practice when dealing with overlaps is to reduce the width of application by selectively closing off nozzles at the affected end of the spray bars. Unless the width of overlap is significant (e.g. approaching half the cut width), nozzles should only be closed on one of the cuts. Normally the first cut is made to include the outer wheel path with full-width application (i.e. all nozzles open). The width of application is then reduced on the second cut by selectively closing off those nozzles coinciding with the overlap. Failure to ensure that the outer wheel-path receives the required treatment can result in an under-application of bitumen and premature failure.

This situation, illustrated in Figure 6.6, occurred where the overlap between two passes coincided with the outer wheel path. Incorrect nozzle closure caused insufficient bitumen to be applied across the overlap and traffic has caused excessive ravelling along the outer wheel-path. The lack of ravelling on the inner wheel path indicates that the correct application of bitumen was achieved.



**Figure 6.6 Bitumen Starvation along Longitudinal Joint**



## CHAPTER 6: Construction – In situ Treatment Using Recyclers

However, to ensure continuity across the width of the road, adjacent cuts must always overlap by at least 150 mm. This means that the second cut must extend at least 150 mm into the material already recycled and treated during the first cut.

<b>BSM-emulsion</b>	<b>BSM-foam</b>
Extreme care must be exercised when adding bitumen emulsion to an in situ material that has a relatively high moisture content. An over-application on the overlap will result in soft spots in the material along the full length of the longitudinal joint.	As a general rule when working with foamed bitumen, it is preferable to aim for a small (approximately 10%) over-application on the overlap rather than an under-application.

It is therefore recommended that a cut plan should always be compiled and the detailed spraybar configuration showing each nozzle location is superimposed on the diagram to illustrate the effect of closing individual nozzles.

### 6.2.1.8 Logistics

The logistical requirements for feeding a recycling operation with bitumen, active filler and water must receive due attention. An average daily production rate of 5 000 m<sup>2</sup> (about 1.4 km of 3.7 m wide lane) can be expected from a modern recycler, regardless of the depth of cut. Assuming a cut depth of 250 mm, an average density of 2 100 kg/m<sup>3</sup> and application rates of 2.2% residual bitumen and 1.0% active filler (by mass) translates to the following approximate daily consumption of materials:

<b>BSM-emulsion</b>	<b>BSM-foam</b>
» 96 tons of 60% bitumen emulsion	» 58 tons of bitumen for foaming
» 25 tons of active filler (500 x 50 kg pockets of cement or 1 000 x 25 kg bags of hydrated lime). This lime quantity is in addition to any pre-treatment requirements.	

These are significant daily quantities. Where the site is distant from the source of supply, temporary storage facilities need to be made available to ensure a consistent supply, thereby reducing the potential for delays caused by material shortages.

## 6.2.2. EXECUTING THE WORK

Mixing with bitumen emulsion or foamed bitumen, combined with primary compaction, shaping, cutting final levels, secondary compaction and finishing should achieve the following objectives:

- » **Thorough mixing of the material with the bitumen.** The resultant mix must be homogeneous with the same appearance throughout, with minimal bitumen “blobs” being visible.
- » **Achieve the density requirements** in the lower two-thirds of the layer with primary compaction.
- » **Achieve a layer that meets the tolerances** for thickness, surface levels and shape that is free from segregation of coarse or fine material.
- » **Achieve full compaction** and a **uniform surface texture** with secondary compaction and finishing.

To achieve these objectives, there are two distinct processes involved when recycling existing pavement layers. The first is the recycling and mixing process. This is usually accomplished in a single pass with a recycler. The second process is the work required behind the recycler, which includes compacting the BSM, cutting levels and finishing off the constructed layer.

### 6.2.2.1 Occupational Health and Safety

Standard occupational health and safety procedures must be followed when working with BSMs, such as described in the following SABITA manuals:

- » **Manual 8:** Guidelines for the safe and responsible handling of bituminous products
- » **DVD 410:** BitSafe – The safe handling of bitumen
- » **DVD 420:** BitSafe – Working with bitumen burns
- » **DVD 430:** BitSafe – Working safely with bitumen



<p><b>BSM-emulsion</b></p> <p>Standard OHS procedures must be followed.</p>	<p><b>BSM-foam</b></p> <p>Bitumen at temperatures in excess of 160 °C can be dangerous. The equipment selected for the production of foamed bitumen must be designed to prevent potential accidents.</p>
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**6.2.2.2 Mixing and Placing**

Mixing is accomplished by assembling a “train” consisting of the recycler and one or two tankers. A typical recycling train for treating with bitumen is shown in Figure 6.7.



**Figure 6.7 Typical Recycling Train for Bitumen Treatment**

To reduce the potential for blockage, the length of the feed pipe between the tanker and recycler should be minimised by locating the bitumen tanker immediately ahead of the recycler. In addition, to promote unrestricted suction flow to the bitumen pump on the recycler, the internal diameter of this feed pipe should not be less than 100 mm.

The water tanker can either be coupled ahead of the bitumen tanker and pushed (implying that the bitumen tanker must be fitted with a front push-block) or be pulled behind. Either location requires a long flexible pipe to feed the water to the inlet coupling located at the front of the recycler. All feed pipes operate under suction and must therefore be capable of withstanding negative pressure, i.e. not the “lay-flat” type of hose. Fitting a valve at both ends of the water feed pipe will prevent large volumes of water from escaping when changing water tankers. To prevent soft spots (described in Section 6.2.1), all feed pipes must be free of leaks.

The essential requirements for a successful recycling operation are included in Appendix D.



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### 6.2.2.3 Bitumen Stabilising Agent Considerations

<b>Bitumen Emulsion</b>	<b>Foamed Bitumen</b>
<p>Recycling with bitumen emulsion is often described as being easier than foamed bitumen. This is because a tanker containing the bitumen emulsion is brought to site, connected to the recycler and used without the inconvenience of heating and having to conduct a long list of checks. These claims are largely true if the following concerns are addressed:</p> <ul style="list-style-type: none"> <li>» <b>Haulage and storage tankers.</b> Bitumen emulsion is manufactured under a specialised factory environment that is normally located in an urban centre that may be some distance from the site. It is therefore normally brought to site in bulk tankers and either used immediately by connecting the tanker to the recycler or pumped into a stationary tank for temporary storage. All haulage units and storage tanks must be dedicated to the sole use of one type of bitumen emulsion. If previously used for a different type of bitumen emulsion (or other bituminous product) the tank must first be thoroughly cleaned before being used.</li> <li>» <b>Use of correct bitumen emulsion.</b> Extreme care must be exercised to ensure that the correct bitumen emulsion is brought to site. Each tanker must have a delivery note issued at the point of loading on which is stated the details of the product and the loading conditions. Samples of each tanker load should be retained for future testing, if and when required.</li> <li>» <b>Storage and usage conditions.</b> Recommendations from the manufacturer concerning storage and usage conditions and limitations must be meticulously followed to prevent product deterioration or premature breaking.</li> <li>» <b>Heating requirements.</b> When undiluted bitumen emulsion is used, to reduce viscosity and facilitate pumping, bitumen emulsion is normally applied through the recycler at 60 °C. This means that the bitumen emulsion often needs to be heated on site. Such heating must be undertaken under strict control, following the manufacturer’s guidelines. As a minimum, the bitumen emulsion needs to be circulated in the tank whilst being heated. Failure to follow these guidelines will inevitably result in a premature break.</li> </ul>	<p>Foamed bitumen is “manufactured” from hot bitumen on the recycling machine immediately before it is injected into the milling chamber. Understanding the process requires an appreciation of the equipment deployed and the operating systems on the equipment.</p> <p>Foamed bitumen is produced in a series of expansion chambers positioned equidistant on a spraybars fitted to the milling chamber. Provided no anti-foaming agents are present, all but the hardest bitumens can be foamed and the foaming characteristics (expansion ratio and half-life) are specific to a particular bitumen. These foaming characteristics are influenced by several factors, all of which can be regulated to varying extents on site. Although these factors were explained in Chapter 3 (Mix Design), they are summarised below with particular emphasis on the practical site considerations:</p> <ul style="list-style-type: none"> <li>» <b>The temperature of the bitumen.</b> In general, the higher the temperature, the better the foaming characteristics due to the reduction in viscosity of the bitumen. However, bitumen should never be heated above 195 °C. In addition to hardening the bitumen, such high temperatures can cause damage to the more sensitive components in the bitumen reticulation system on the recycler (e.g. flow meter sensors).</li> <li>» <b>The quality of the water.</b> Relatively pure water should be used for foaming since impurities can block the water jets, preventing the bitumen from foaming.</li> <li>» <b>The temperature of the water used for foaming.</b> Warm water, as will typically be experienced on site requires less energy than cold water, as in an air-conditioned laboratory, to effect the change in state from liquid to vapour.</li> <li>» <b>The operating pressure in both the bitumen and water supply systems.</b> Operating pressure is a function of flow and these two systems must be interlinked and micro-processor controlled by the speed of advance of the recycler. The higher the pressure, the more uniform the foam due to better “atomising” of both liquids as they enter the expansion chamber through their respective jets. Conversely, the lower the pressure, the less uniform the foam.</li> </ul>



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- » **Water used for dilution.** Diluting the bitumen emulsion with water is often carried out on site. Care must be exercised to use relatively pure water because impurities in the water can cause the bitumen emulsion to break.
- » **Addition of water during mixing.** Diluting bitumen emulsion is necessary where the recycler is fitted with only one pumping or spraybar system and dilution is required to obtain the required fluid content in the treated material. When two spraybars are used, water is applied through one spraybar and bitumen emulsion the other. As discussed in Section 6.2.2.4, the moisture content of in situ pavement material is never dry, nor is it consistent. Experience has shown that adding water separately from the bitumen emulsion allows improved control in achieving the required fluid content in the treated material. Where the material being recycled is dry (normally only encountered where virgin material has been imported) an initial pre-treatment with the recycler adding only water will achieve the correct moisture regime to accept the bitumen emulsion added by making a second pass with the recycler.

- » **The amount of water injected into the bitumen to create the foam.** The “optimal” amount of water addition is determined initially in the laboratory. However, site conditions differ from those in the laboratory and water addition often requires adjusting to achieve the best foam on the recycler.

In practice, the foam produced in the expansion chambers on the recycler’s spraybar are always an improvement on those produced in the laboratory. The main reason for this is the higher operating pressure on a recycler (5 to 10 bars), compared to laboratory units that normally function at approximately 3 bars. In addition, the temperature of the water used for foaming on site is usually significantly warmer than tap water in an air conditioned laboratory. As a result, it is often possible to achieve a workable foam at bitumen temperatures less than the minimum determined in the laboratory. It is therefore important to always check the foaming characteristics on site.

The recycler must be fitted with a functioning pressure gauge to allow the operator to maintain a minimum operating pressure above 5 bars. Where cutting conditions become so tough that sufficient advance speed cannot be achieved to maintain such a pressure, pre-pulverising is required. Where the application rate of foamed bitumen is low (< 2%) and the depth of recycling is low (less than 200 mm), the bitumen jets in the expansion chambers may need to be exchanged for ones with smaller diameters in order to maintain sufficient pressure at normal operating speeds. Under no circumstances should the speed of advance be increased above 12 m per minute in order to increase the bitumen pressure as this will negatively affect the quality of the BSM-foam.

The foaming characteristics of each load of bitumen must be checked using the test nozzle (described in Section 6.2.1.1). Initial checks are normally made while using the test nozzle to bleed air from the system. Once an adequate foam is observed, the tanker can be accepted and work commence. Definitive measurements of the expansion ratio and half-life should only be made after the system has been in operation for a few minutes (typically 2 minutes) and a consistent operating temperature and pressure have been reached.

### **i** Foaming Characteristics

The **expansion ratio** and **half-life** must be regularly checked on site. The recycler must be fitted with a **test nozzle** for such checks.

### 6.2.2.4 Moisture Considerations

The moisture content of the mixed material is one of the most important variables directly influencing the end-product. The effectiveness of bitumen dispersion, the compactive effort required to achieve density, and the potential for surface cracking are all significantly influenced by not only the actual moisture content itself, but also by the uniformity of the moisture content throughout the recycled material.

Varying moisture conditions in the pavement layers must be expected. Material beneath a bituminous surface will always be moist and the “equilibrium moisture content” (EMC) relative

### **i** Moisture Contents

Great care must be taken with the moisture content of the mix as it effects:

- » **Bitumen dispersion**
- » **Compaction achieved**
- » **Curing time**



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to the OMC of the material is predictable. Hence, the EMC can be expected to be reasonably consistent where the material is similar. However, variations must be anticipated when the following conditions are encountered:

- » **Cracks in the surfacing** allow water to penetrate into the underlying pavement layers, resulting in higher moisture in the vicinity of the crack.
- » **Where the road has unsurfaced shoulders**, an increase in moisture content at the high side of super elevated curves should be expected.
- » **The pavement materials at the bottom of sag vertical curves** is often more moist than elsewhere in the pavement.

Pavements with natural or crushed stone bases that have many deep asphalt patches may be prone to saturation when recycled. Mixing RA (from patches and pavement layers) with a granular base material will produce a blend that has a lower OMC value than the original base material. However, this is normally only encountered where the EMC in the base approximates the OMC, a condition most likely to be encountered during wet seasons and where the surfacing is severely cracked.

Where the in situ moisture content of the material to be recycled is above the OMC, the material must first be dried back before it can be treated. This is normally achieved by pre-pulverising on a warm day and leaving the loose material open to dry. When the moisture content has reduced sufficiently, the pulverised material must be shaped and pre-compacted before being treated.

<p><b>BSM-emulsion</b></p> <p>Standard South African practice when treating with bitumen emulsion is to target a fluid content of 90% of OMC for mixing.</p>	<p><b>BSM-foam</b></p> <p>Mixing is ideal when the moisture content of the material is at the “fluff point” (approximately 70% to 80% of OMC).</p>
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**6.2.2.5 Compaction, Cutting Levels and Finishing**

Compacting thick layers of BSM is similar to compacting thick layers of granular material. Using the correct compaction equipment is critical (number and types of rollers, drum configuration, static mass, vibration capabilities), as is their correct operation (travel speed, rolling pattern and number of passes) and the sequence of rolling, e.g. padfoot first.

The correct rolling sequence is normally determined during the construction of a Trial Section, as described below in Section 6.7. The material exiting the recycler is in a “fluffed-up” loose state. As shown in Figure 6.8, the rear wheels on the recycler run on this loose material and compact it. The heavier the recycler, the more compaction occurs. Measurements have shown that the difference in density between the material in the wheel paths and that between the wheel paths is some 10% of the modified AASHTO density.

It is imperative that the material between the wheel paths is compacted to at least the same density as the material in the wheel paths before allowing the grader to start levelling. Failure to follow this simple requirement will result in a permanent density differential between the material in the wheel paths and that between the wheel paths. This is because the drum width of standard rollers is 2.14 m which is always greater than the width of uncompacted material between the wheel paths. If this loose material is cut to the same elevation as the compacted material in the wheel paths, subsequent compaction will always bridge-out across the wheel paths. The material in the wheel paths will therefore be at a higher level of density relative to the material between the wheel paths.



**Figure 6.8 Material Compacted by the Rear Wheels of the Recycler**



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Initial rolling should always be carried out using a single-drum vibrating roller with a static mass that is commensurate with the thickness of the layer being compacted. The vibration mode must be set on high amplitude to achieve maximum penetration of compactive effort. The rolling pattern should first concentrate on the middle section between the rear wheel paths of the recycler, then across the full cut width to achieve uniform density. Whilst compacting, the travel speed of the roller should never exceed 3 km/h (50 m/min).

Applying low amplitude vibration or using a roller with insufficient static mass will not impart sufficient compactive energy to penetrate through to the lower horizon of the layer. Only the material in the upper horizon of the layer will densify, thereby forming a bridge of compacted material over relatively loose material. In time this loose material will densify under repeated traffic loads and the resulting settlement will be regarded as a “premature failure” (wide-radius ruts in the wheel paths).

When the recycler works at 10m/min, the primary roller can make 5 (uni-directional) passes at 3 km/h for the compaction operation to keep pace with the recycler. Where the primary roller needs to make more than 5 passes to achieve the density requirements, compaction will fall behind the recycling operation and consideration should be given to using two primary rollers, one working immediately behind the other. In such cases, the second roller should be identical to the first. If the rollers fall behind the recycler, the recycler must be stopped to allow the rollers to catch up.

Assuming that work is being undertaken in half-widths, once the entire half-width of the road has been recycled and treated, and the initial compaction is complete, a grader is used to cut the final level. Recycled material always bulks, particularly where the original pavement included asphalt layers (due to the increase in voids). A windrow of surplus material is therefore always available after cutting final levels to assist in achieving a tightly-knit surface finish.

Since there is always a delay between recycling, compacting and starting work with the grader, the material at the surface of the layer will dry out. This drying out is exacerbated when using a padfoot roller for primary compaction. To prevent laminations forming, the surface must be given a thorough wetting before the grader moves any material.

<p><b><i>BSM-emulsion</i></b></p> <p>Before breaking, bitumen emulsion can be washed out of the material (leached) if water is used as a wetting agent. It is important therefore to use a water tanker containing 10% to 15% diluted bitumen emulsion for increasing the moisture content of the material. This should be sprayed across the full recycled width after the initial compaction and immediately ahead of the grader. The bitumen emulsion must be evenly distributed on the surface ahead of the grader doing the blading.</p>	<p><b><i>BSM-foam</i></b></p> <p>Since the bitumen droplets adhere to the fine particles, they are not susceptible to leaching. Water can therefore be used for adjusting the moisture content of the material.</p>
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A single smooth-drum vibrating roller with a static mass in the order of 10 tons is used behind the grader to compact the upper horizon of the layer. This roller works only in low-amplitude vibration mode. When complete, the surface is subjected to a mild “slushing” using a PTR to achieve a tightly-knit surface finish.

<p><b><i>BSM-emulsion</i></b></p> <p>Slushing is undertaken using only a 10% to 15% diluted bitumen emulsion.</p>	<p><b><i>BSM-foam</i></b></p> <p>Straight water is used, similar to finishing off a layer of graded crushed stone material (e.g. G2 material).</p>
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The “mild slushing” process should not be confused with the “full-depth slushing” process associated with G1 crushed stone bases. The “mild slushing” is merely aimed at improving the condition and quality of the top of the BSM base layer and knitting together the surface.



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### i. Target Density for Recycled Layers

Since the typical mode of failure for a layer of BSM is primarily permanent deformation, the density that is achieved during construction is critical to ensure that the required structural capacity of the layer is reached. Increasing density improves the shear properties of the material making it less susceptible to deformation. Hence, the highest density achievable should always be targeted.

Density requirements are usually specified in terms of a percentage of some reference density. Normally the maximum dry density (MDD) of the material is used as the reference density and this MDD value is determined in a soils laboratory by carrying out a standard moisture-density relationship test on the material. For base layers, at least 100% of the MDD is the norm for BSM1 and BSM2, and at least 98% for BSM3.

The challenge in achieving a specified density on a recycling project is twofold:

- » **Variations in the recycled material change the reference density.** A 5% reduction in the MDD value (e.g. from 2 100 kg/m<sup>3</sup> to 2 000 kg/m<sup>3</sup>) is not unusual, especially where the existing road has been extensively patched. Using an incorrect MDD value will therefore over- or understate the density achieved, the latter being classified as a failure with the consequence that the layer could be rejected. To overcome this problem, a representative MDD value has to be determined by carrying out a moisture-density relationship test on a sample collected from every location where the field density is measured. This is an onerous requirement as it significantly increases the amount of laboratory work required on the project.
- » The level of density that can be achieved in a new BSM layer is a function of the **underlying support conditions** (the anvil effect). Since materials recycled in situ are compacted on top of existing pavement layers, it is difficult to hold the contractor responsible for not achieving a specific level of density, provided the appropriate equipment is utilised and appropriate compaction techniques are followed.

It is normal practise to determine the rolling sequence and number of rollers required to achieve the target density from the trial section.

To circumvent these challenges, it is becoming increasingly popular to specify “refusal density” as the target, again provided the appropriate equipment is utilised and appropriate compaction techniques are followed. Refusal density in this context is the maximum density that can be achieved on a material under the prevailing field conditions and takes cognisance of both material characteristics and the underlying support conditions.

Recent developments in compaction technology (so called “intelligent compaction” systems) offer the opportunity to monitor density development and determine when the maximum has been achieved. These systems incorporate a “compactometer” fitted to the vibrating drum to measure “rebound acceleration” which is a measure of the response of the material to an impulse (vibration) which, in turn, reflects the density of the material. Coupling these measurements with data from a device that records the precise location of the roller (a GPS-based system working with reference satellites) allows multiple measurements taken at the same location to be compared. Using a colour-coded display mounted in the cab, the roller operator can continuously monitor density development at every location. When successive passes of the roller show no further increase in density, the “refusal density” has been achieved and the roller can move forward to compact the next section of work.

An additional benefit of employing such a system is the compaction record that is obtained at the end of the day’s work. Such data provides the following detailed information that covers the entire area where the roller worked:

- » **Number of roller passes** made (coverage) at any location.
- » The **maximum compactometer reading** achieved (an indication of the density achieved).
- » Whether or not **refusal density** was actually achieved.

This information can then be analysed to provide details at any specific location on the site or the relevant compaction statistics for a selected area. In this manner, regions of poor support can be identified (low compactometer values) and investigated. A limited number of density tests will also allow the compactometer readings to be calibrated in terms of actual material density, but only as an indicator since material variability will persist, making any relationship with an assumed MDD value meaningless.

### **i** Benefits of achieving density

Increasing density improves the shear properties, making it less **susceptible to deformation.**



### Obtaining Density

To achieve the desired density, it is essential that the **correct rollers, roller sequence** and **moisture contents** are used.



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It must, however, be understood that these systems are not a panacea and rely on correct roller selection and operation to be effective. Furthermore, it is vital that the moisture content of the material being compacted is in the required range relative to the OMC of the material.

### 6.3. IN SITU TREATMENT USING CONVENTIONAL EQUIPMENT (BSM-EMULSION ONLY)

This section describes the operations involved when using conventional construction equipment to mix and treat material.

<b>BSM-emulsion</b>	<b>BSM-foam</b>
In situ treatment with conventional equipment can only be used for BSM-emulsion treatment.	This method of construction cannot be used with foamed bitumen because mixing takes place over an extended period of time, far longer than the half-life of foamed bitumen.

This section focuses on the preparation and mixing activities which constitutes the main differences in construction between using recyclers and conventional equipment to reuse existing pavement material for BSM-emulsion treatment. Although recyclers have generally replaced conventional equipment for in situ treatment, the use of conventional equipment remains an option and is still commonly used on projects where the depth of treatment is 200 mm or less.

#### 6.3.1. EQUIPMENT SELECTION

Sufficient watering, mixing and compaction plant in good working order must be available to ensure that the specified quantities of water, active filler and bitumen emulsion can be mixed in and the required degree of compaction obtained within the working period (8 to 10 hours) allowed by the process.

Various items of plant can be provided to cater for different methods of material preparation, processing and subsequent compaction depending on the project needs. These are described in the following sections.

##### 6.3.1.1 Self-Propelled Heavy Duty Motor Grader

A heavy duty motor grader is an essential item of plant for BSM-emulsion treatment, irrespective of the combination of any of the other plant items used. This grader is required to pre-shape the material prior to being treated, for processing the material and, thereafter, to cut the layer to final levels. Processing by grader includes mixing the material prior to treatment and mixing in the active filler and bitumen emulsion.

Depending on the volume of material being mixed and the quantity to be treated in a single shift, more than one grader may be required.

##### 6.3.1.2 Milling Machine

A milling machine may be more cost effective than a grader to break up a thick asphalt layer and/or a strongly cemented material to produce a material suitable for bitumen emulsion treatment. A milling machine is generally more cost effective when a previously treated layer has failed, but remains bound between the failed areas, with cube crushing strengths well in excess of 5 MPa, or when an asphalt layer is severely cracked and the large chunks need to be pulverised. When in situ material is to be augmented with imported material, a milling machine can also be effectively used to blend the two materials after the additional material has been levelled out on top of the in situ material and pre-shaped with a grader.

Alternatively, layers that have developed a high in situ strength can be broken down using a 'woodpecker-type' breaker fitted to an excavator. The resulting chunks of pavement material can then be transported to a single-stage crusher to be crushed and transported back to the road for further processing.

##### 6.3.1.3 Diluted Bitumen Emulsion Tankers

Self-propelled water tankers, with a 15 000 litre capacity, are essential plant items for the successful construction of a BSM-emulsion layer. In addition to supplying the bitumen emulsion for mixing, water tankers are required to ensure proper finishing of the treated layer of



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material after the initial mixing and processing stage has been completed. Sufficient water tankers must be provided to ensure that the processing of the material is a continuous procedure with no stopping to wait for a tanker.

The water tankers involved with bitumen emulsion treatment should only ever transport bitumen emulsion in various stages of dilution as the need dictates. At no stage in the process of material being treated with bitumen emulsion is neat water to be added to the material on its own. To increase the moisture content of the material, moisture can only be added in the form of a diluted bitumen emulsion, as described in Section 6.3.2.

All water tankers used for bitumen emulsion treatment must be equipped with a circulating pump system to circulate the diluted bitumen emulsion after standing for an extended period and for circulating during the dilution process. Water tankers must not be fitted with a conventional spraybar but with valves (such as a clam-lock valve) which will not easily clog. The application of the diluted bitumen emulsion is a cold process and there is always the possibility of the bitumen emulsion breaking and causing blockages. Tankers must be properly flushed should they need to stand empty for extended periods (e.g. overnight).


### 6.3.1.4 Static Storage Tanks

Static tanks should be provided to store sufficient bitumen emulsion for the needs of the project. Normally such tanks will have a capacity of between 60 000 and 120 000 litres. Static tanks must be fitted with a circulating pump system which will enable the stored bitumen emulsion to be properly circulated from time to time in the static tank, especially if no bitumen emulsion has been drawn or added for a period of 2 to 3 consecutive days.

### 6.3.2. BITUMEN EMULSION

At no time whatsoever should a standard bitumen emulsion with 60% residual bitumen content be applied to the layer of material being processed with conventional construction equipment. Such bitumen emulsion added without dilution with water will be inclined to break too quickly, particularly on a hot day, thereby preventing the bitumen emulsion from being thoroughly mixed throughout the depth of the layer of material. Coating of all the granular particles within the layer will not take place when the bitumen emulsion breaks too early and a poorly treated layer will result which will in turn lead to the early failure of the layer. The coating of particles with bitumen emulsion ensures the successful construction of the BSM layer. As a consequence, the in situ moisture content of the untreated layer must never be so high that it cannot accommodate a bitumen emulsion that has been diluted to a residual bitumen content of between 30% and 40%.

A 60% anionic stable grade bitumen emulsion is normally diluted by the addition of clean water to at least a 40% bitumen emulsion (40% residual bitumen to 60% water) and preferably to a 20% residual bitumen content for treatment of granular materials. On rare occasions where the moisture content of the in situ material is high, it is necessary to dilute the bitumen emulsion to a residual bitumen content of 50%, but this should be the exception and not the rule. The dilution of the bitumen emulsion is detailed in Table 6.1. When additional water is added to the bitumen emulsion, the product should be circulated.



### Addition of Bitumen Emulsion

Bitumen emulsion added without dilution with water will be inclined to **break too quickly**, particularly on a hot day, thereby preventing the bitumen emulsion from being thoroughly mixed.

Once bitumen emulsion has been added, any additional water required must only be added as a **very diluted (“dirty water”) bitumen emulsion**.

**Table 6.1 Dilution of Bitumen Emulsion**

Percentage residual bitumen content in the diluted bitumen emulsion (%)	Litres of water to be added to 10 litres of standard bitumen emulsion (60% residual bitumen content)
50	2
40	5
30	10
20	20
10	50



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### 6.3.3. MIXING

Blade-mixing by grader is undertaken by using the blade to move the material from side to side. This mixing process is often supplemented with the use of ploughs and/or rotavators. Where the width of the treatment restricts the horizontal movement of the material, extra use should also be made of the grader rippers with specially designed “shoes” welded onto the rippers. Such shoes are in the shape of a horizontal “V”, with the sharp end of the V pointing in the direction of travel of the grader. The rippers with their V-shaped shoes are lowered to the treated depth and the “fast forward” gear of the grader is used to plough through the layer. In this manner, the material is pushed aside, ensuring that proper mixing is achieved, even when working in confined widths.

Where the layer to be treated was previously stabilised, the rippers of the grader can be used to break up the layer if the in situ strength is low enough to permit such an operation.

Standard bitumen emulsion must first be diluted with the compaction water to a residual bitumen content of 30% to 40% and applied in several applications onto the material after the active filler has been mixed into the material. Water tankers are used to apply the bitumen emulsion and the grader(s) must travel directly behind the water tanker, immediately covering the freshly sprayed bitumen emulsion with material, thereby preventing the bitumen emulsion from breaking. The volume of bitumen emulsion applied is determined by the residual bitumen content required, expressed as a percentage by mass of the finally treated layer. Should weather conditions be particularly hot or dry, then the bitumen emulsion must be diluted to a bitumen content that is less than 30% with proportionately more water having to be added to the bitumen emulsion.

Care should be taken to ensure that the diluted bitumen emulsion is applied in such a way that no rivulets are formed and that the bitumen emulsion does not run off the layer before it has been mixed in.

During mixing, attention must be paid to the fluid content of the mix. The fluid content is the total quantity of fluid in the mix, including hygroscopic moisture, the bitumen still in suspension in the bitumen emulsion and the water in the bitumen emulsion. If 80 litres of bitumen emulsion diluted to a residual bitumen content of 30% is introduced into the BSM per cubic metre, then 24 litres of residual bitumen forms part of the fluid content while in suspension as part of the bitumen emulsion. However, as it breaks and comes out of suspension, the fluid content reduces by about 1.1% (assuming the material density to be 2 100 kg/m<sup>3</sup>). The actual moisture content of the material is then 1.1% less than the fluid content.

The fluid content should not be so high as to result in deformation of the surface under final compaction. The optimum fluid content determined in the laboratory may be amended, based on on-site observations, to make allowance for the type of compaction equipment being used.

When working with porous material, no dry material should be present at the time of mixing in the diluted bitumen emulsion, since the water absorption of the aggregate may lead to the premature breaking of the bitumen emulsion.

Where the existing asphalt surfacing is being recycled with the underlying gravel layer using conventional construction equipment, the asphalt layer must first be milled off and left in a windrow on top of the granular base that is to be recycled. Once the asphalt layer has been milled off in this manner then the base layer can be milled or ripped and broken down. Once the milled asphalt layer and the existing gravel base material have been thoroughly blended, then the active filler must be mixed in immediately ahead of the introduction of the bitumen emulsion on the same day.

### 6.3.4. COMPACTION, CUTTING LEVELS AND FINISHING

The procedures described under Section 6.2.2.5 for in situ treatment using recyclers are essentially the same as those to be followed when working with conventional equipment.

It must be noted that when processing BSMs, the material behaves similar to an ordinary granular material. Once mixed, the BSM should then be processed in the same way as the untreated material. The operations involved for placing, compacting, cutting levels and the finishing required to achieve a new pavement layer are the same, with or without the addition of a bitumen emulsion. The only differences are:

- » **Neat water should not be applied** to the material once diluted bitumen emulsion has been added.
- » 10% of the bitumen emulsion should be held back for **enrichment of the upper 5 mm** to 10 mm of the layer during the finishing (slushing) process.



## CHAPTER 6: Construction – In-plant Treatment

### 6.4. IN-PLANT TREATMENT

In-plant mixing is normally used on projects where:

- » **A consistent quality BSM** is required, usually using graded crushed stone blended with processed RA material for asphalt base replacement either from recycled materials or new materials. This is achieved by stockpiling the input materials prior to blending and mixing. Such pre-stockpiling allows the materials to be tested prior to mixing to ensure that they meet the standards required.
- » **All input aggregates are available at one location.** Mixing at source reduces the transport demand and eliminates double-handling.
- » After treatment, the mixed BSM product needs to be **stockpiled for later use.** This is an important requirement on some projects, such as those using labour intensive methods for layer construction.
- » The BSM needs to be **placed by paver** in order to meet stringent shape and level tolerances on the completed layer. This situation arises where the BSM is used as the main structural base with a thin surfacing.

Controlling the quality of the input materials increases the degree of confidence that the mixed product will meet performance expectations. In addition, the application rate of bitumen stabilising agent and active filler can be minimised with confidence by undertaking a series of mix designs on a material that is relatively consistent. The guidelines in Chapter 4 for Mix Design should be followed.

Stockpiling BSMs are normally undertaken only when mixing in-plant. Requirements for stockpiling BSMs are discussed in Section 2.6.1.1. Sections 6.4.1, 6.4.2 and 6.4.3 describe general requirements for in-plant treatment.

#### 6.4.1. IN-PLANT MIXING

The plant used to produce BSMs must be capable of:

- » **Accurately blending predetermined proportions** of different input materials whilst simultaneously adding the correct amount of bitumen stabilising agent, water and active filler.
- » **Consistently producing a homogenous product.** This is normally achieved using a high-energy pugmill type mixer that allows continuous mixing.

<b>BSM-emulsion</b>	<b>BSM-foam</b>
<p>Relatively unsophisticated mixers can be used for producing a satisfactory BSM-emulsion product. On smaller projects, a concrete mixer is often used with volume batching. Provided the constituent materials are correctly proportioned in the mixer and the retention time in the mixer is sufficient, an acceptable product will normally be obtained.</p>	<p>Since foamed bitumen has to be produced on site, the mixing plant needs to be more sophisticated than those suitable for BSM-emulsion. The system used for producing foamed bitumen must meet <i>all</i> the requirements described in Section 6.2.1.1. To achieve these requirements, the mixer needs to be micro-processor controlled. A load sensor located on the material feed conveyor normally provides the primary input for regulating the pumps for bitumen and water (both for foaming and increasing the moisture content, if necessary) as well as a continuously weighed auger feeding the active filler. In addition, the system must be capable of automatically maintaining bitumen operating pressures above 5 bars when material throughput reduces. The recommended operating pressure is between 5 and 10 bars. Figure 6.9 illustrates a mixing plant for foamed bitumen.</p>

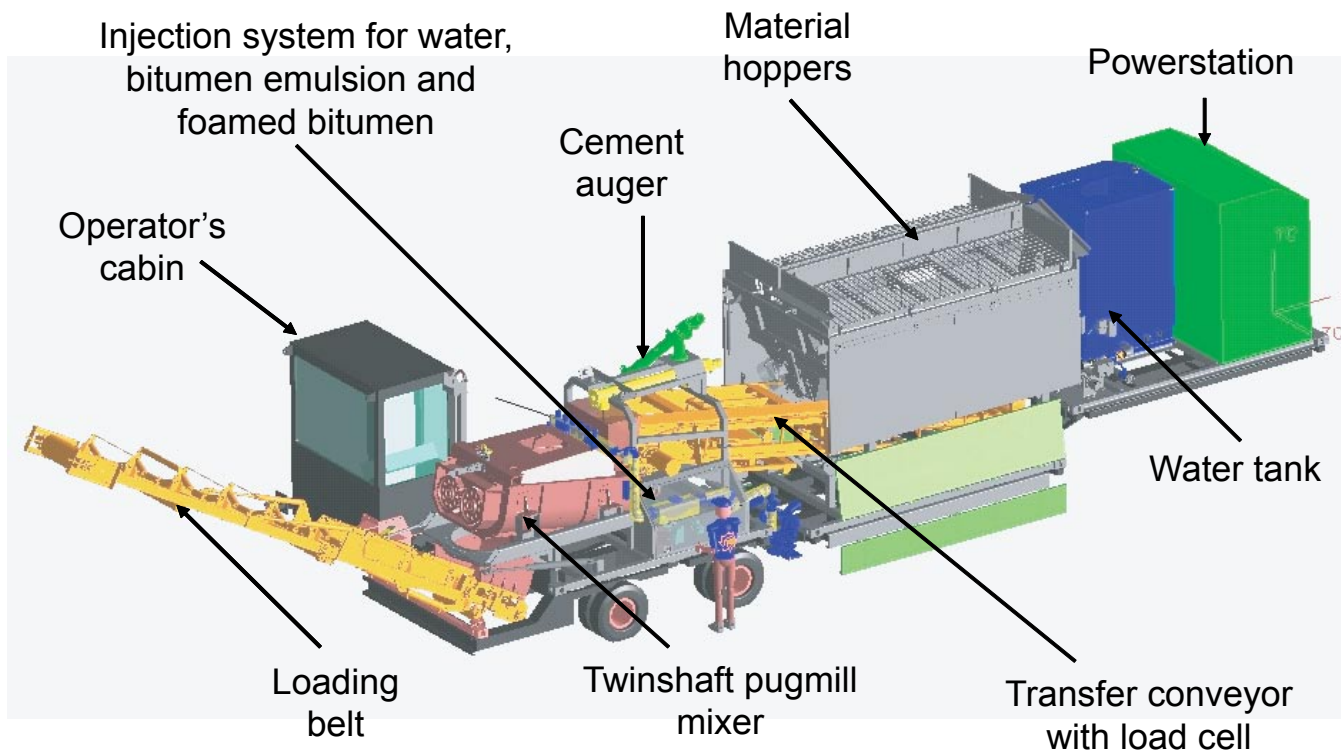


Figure 6.9 Mixing Plant for BSM-foam

Since materials lying in stockpiles are more susceptible to changing weather conditions than in situ material protected within a pavement, in-plant mixing requires additional care to monitor the condition of the material, particularly in terms of:

- » **Temperature of the material at the time of mixing.** The limitations prescribed in Section 2.6.2 must be strictly followed. However, it must be recognised that the wind chill phenomenon often plays a significant role in reducing the temperature of moist material that is exposed to the elements. When working in windy conditions with an ambient temperature approaching the lower limit, it is advisable to check the temperature of the material as it enters the mixer.
- » **The moisture content of the material being mixed.** As explained in Section 6.2.2.4, material that is too wet (over OMC) or too dry (< 50% of OMC) will not produce a satisfactory product. When working during periods of unstable or wet weather, covering the stockpiles of input material will assist in maintaining a constant moisture content.

The mixed material is normally trucked directly to site and used immediately to construct a new pavement layer. Alternatively, the treated material can be stored in a stockpile at a strategic location for later use. In addition to the stockpiling requirements described in Sections 2.6.1.1, the normal precautions concerning material placed in stockpiles must be addressed. These precautions include the avoidance of contamination by preparing a work platform beneath the stockpile and preventing material segregation.

#### 6.4.2. TRANSPORTING BSM

Material segregation is a primary concern, especially where the material is relatively coarse. Where such segregation cannot be adequately controlled when loading trucks directly from the delivery conveyor on the plant, the material should be transferred to a temporary stockpile. Normal loading procedures should then be followed when extracting material from such a temporary stockpile. (Note that the temporary stockpile must contain sufficient material to allow such loading procedures to be followed.)

Where BSMs are transported over long distances, moisture loss can be minimised by covering the treated material with an impervious heavy duty sheet (tarpaulin).



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6.4.3. LAYER CONSTRUCTION USING A PAVER / FINISHER

The type of paver and screed, the condition of the equipment and the expertise of those operating the equipment are critical factors that dictate the quality of product achievable when paving a layer of BSM. Unlike asphalt, a BSM is not a cohesive material. Paver set up and operating procedures are therefore different.

Construction joints are zones of potential weakness in a pavement structure and should therefore be kept to the barest minimum. Consequently, longitudinal joints between successive paver runs (or pulls) should be limited and should never coincide with the location of trafficked wheel paths. For this reason, large pavers are usually used to construct layers of BSM over the full- or half-width of the road.

**i Paving Thickness**  
It is advisable to pave BSMs in **one layer**.

The thickness of a layer that can be successfully paved is dictated by material coarseness and restricted by compaction requirements. The more coarse the material, the more prone it is to segregation and, the thicker the layer paved, the more difficult it is to compact without rolling the surface out of shape. As discussed in Section 6.4.3.3, these limitations may be overcome by paving two thinner layers to achieve the required layer thickness.

<p><b>BSM-emulsion</b></p> <p>Paving BSM-emulsion is restricted to a single layer.</p>	<p><b>BSM-foam</b></p> <p>Stringent controls are required to ensure that an integral bond is established between the two layers. Paving two thinner layers is not recommended and should only be undertaken as a last resort when paving a BSM-foam.</p>
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6.4.3.1 Paver and Screed

The thickness of the layer being constructed and the paving width dictate the volume of BSM that the paver has to handle. A 150 mm thick layer paved over a 5 m half-width requires 0.75 m<sup>3</sup> (about 1.6 tons) of compacted BSM per running linear metre. To achieve a consistent mat, a heavy-duty tracked paver would normally be used to handle such a volume of material and simultaneously push the delivery truck.

Provided the paver is capable of managing the amount of material, it is the screed attached to the paver that determines the quality of the paved mat which, in turn, will largely dictate the quality of the final product. A thick layer of relatively low-cohesion material requires a screed that is sufficiently light to “float” on the spread material whilst simultaneously imparting sufficient pre-compaction energy to achieve a uniform level of density across the paved width. Utilising the correct screed is therefore critical. Screeds with hydraulically-adjustable width capabilities are generally too heavy and, because they comprise three components, are difficult to set up to eliminate steps forming across the paved width. To get such screeds to float normally requires the deployment of a “screed assist” function which, in turn, requires a high level of expertise in paving BSM. Single unit screeds with bolt-on extension boxes to obtain the required paving width are therefore preferred. To mould the material and minimise lateral movement, both ends of the screed should be fitted with 45° bevelled end plates.

In addition to placing the material to the required line and level, the screed must uniformly pre-compact the material to the highest achievable level of density. The higher the density obtained by the screed, the less rolling required to achieve the target density and the lower the risk of rolling the mat out of shape. Screeds are normally equipped with tamper bars and vibrators to effect compaction. “High Compaction Screeds” offered by some manufacturers are fitted with features which introduce additional compaction energy. Where possible, such a screed should be employed when paving a BSM.

6.4.3.2 Compaction Equipment

Unlike in situ treated BSMs where layer thicknesses in excess of 200 mm are the norm, layers of BSM placed by paver seldom exceed 150 mm in thickness. Such a layer thickness can be compacted using a vibrating roller with a static mass of between 10 ton and 12 tons. Tandem smooth-drum vibrating rollers are normally used on paved material since the material encountered behind the paving screen is denser than the loose material that is typical behind in situ recyclers. In addition, tandem rollers do not disturb the surface of the mat as do the rear wheels of single drum rollers.




Once compacted, the paved layer is finished off in the same manner as an in situ treated layer using a pneumatic tyred roller.

### 6.4.3.3 Limitations of Paving a Thick Layer

It is always preferable to construct a pavement layer as a single monolithic unit. Separating the layer into two thinner sub-layers introduces a horizontal construction joint that can become a weak horizon (delamination plane) when the pavement deflects under load.

Although it is possible to pave a thick (> 200 mm) layer of BSM, the consequence is invariably a loss of shape when using rollers to apply the high amplitude vibrating energy required to densify such a thick layer. Since the amount of compactive energy exerted by the screed is constant, increasing the thickness of material being paved will reduce the density that can be achieved by the screed. Although reducing the forward speed of the paver will increase the amount of compaction energy on each unit area, such energy is not the high amplitude type required to penetrate to the bottom of the layer and may introduce a bridging problem (see Section 6.2.2.5).

Paving the layer as two thinner layers is not recommended. In theory, it should be possible to achieve an integral bond between the two but the realities of a construction site make it all but impossible to guarantee that such a bond is achieved over the full length and width of the road.



**Layer thickness for paved layers**

Layers of BSM placed by paver **seldom exceed 150 mm.**

Paving in **two layers is not recommended.**

<p><b>BSM-emulsion</b></p> <p>Paving in two layers cannot be done with BSM-emulsion since constant watering will wash the bitumen emulsion out of the material in the upper horizon of the lower layer. Substituting a dilute bitumen emulsion for water is not a solution since such practice may result in a film of bitumen forming at the surface which will only exacerbate the risk of delamination.</p>	<p><b>BSM-foam</b></p> <p>Should a situation arise where two layers must be constructed on top of one another, only BSM-foam can be considered because bonding between the two layers is possible if the surface of the first layer is kept continuously wet until the second layer is paved.</p> <p>Paving BSM-foam in two thinner layers has been successfully achieved using the following method:</p> <ul style="list-style-type: none"> <li>» <b>Determine the thickness of each of the two layers</b>, keeping in mind that the thickness of each layer must be more than 3 times the maximum particle size (i.e. where the maximum particle is 37.5 mm, the layer thickness must be greater than 113 mm). Always try and pave a thicker first layer with the second layer kept as thin as is practical, but never less than 100 mm. For example, where a 250 mm thick layer is required and the maximum particle size is 25 mm, the first layer should be paved 150 mm thick and the second layer 100 mm.</li> <li>» <b>Pave the lower layer on the first half-width for a maximum distance of 200 m.</b> Compact using only a smooth drum roller operating in high amplitude vibration. A PTR must not be used. Prevent the surface from drying out by frequent watering sprayed sideways from a water tanker travelling on the adjacent half-width.</li> <li>» <b>Reverse the paver over the completed first layer and immediately pave the second lift</b> to achieve the required layer thickness. Compact with low amplitude vibration and finish off with a PTR.</li> </ul>
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	<p>In addition to keeping the surface of the first paved layer constantly wet, the immediate surrounds must be kept dust free. This requires the surface of the adjacent half-width to be kept moist whilst paving the first half-width. It also implies that no work should be undertaken when there is a risk of wind-blown dust contaminating the wetted surface of the first layer. As discussed below, the paved edge that coincides with the centre-line joint requires constant protection. Trucks must not be allowed to run over this edge when delivering BSM-foam to the paver for the second layer. Special entry / exit ramps need to be constructed (and removed afterwards) to facilitate such material import.</p>
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Paving two layers to achieve one thick layer is time consuming and requires constant attention to detail by the construction team. There is always a risk that the two layers will not bond properly and premature failures may arise due to delamination and shearing. When faced with having to construct a thick layer of BSM, serious consideration should be given to placing by grader as a single layer (as described in Section 6.4.4) rather than paving.

### 6.4.3.4 Construction Requirements

The following aspects are critical when placing BSMs by paver.

#### i. Paver Set Up

Setting up the paver and screed are fundamental requirements on any paving job. However, setting up the paver to work with BSMs requires an understanding of material behaviour, especially how the particular BSM will flow and bulk. These material characteristics are determined primarily by the grading and angularity of the aggregate in the mix, as well as the moisture content. These characteristics influence what adjustments need to be made to the screed so that it achieves the consistent “float” that is imperative to obtain a smooth mat. Where the screed is not set up properly, it will tend to sink into the mat and create undulations.

Trial sections for paved BSMs should be constructed off site where the consequences of varying the screed settings will not affect the permanent work. This is discussed in Section 6.7 below.

#### ii. Paving the Layer

The same basic procedures followed when paving hot mixed asphalt are applicable to paving a BSM:

- » **Continuity of paving.** Sufficient trucks should be provided to ensure a continuous supply of material to the paver. Irregularities (bumps) in the mat are normally created by the screed settling in to the paved material when the paver stops. The biggest steps in the mat, however, are caused by delivery trucks reversing into the paver, forcing the screed backwards into the paved material. Trucks should always stop immediately ahead of the paver, allowing the paver to advance and gently engage.
- » **In rolling terrain,** the paver should always advance uphill pushing the delivery truck. Such practice facilitates material feed from the truck to the augers feeding the screed and maintains pressure on the screed. Paving downhill runs the risk of material starvation as the paver tends to pull away from the material under the screed.

Similar to paving a G2 type crushed stone material, material segregation is always a concern when paving a BSM, especially where the material is relatively coarse. Segregation can be minimised by:

- » **Maintaining the moisture content of the material above 50% of OMC.** Material that has been allowed to dry out (normally due to standing for prolonged periods un-sheeted in the truck) will segregate far more than moist material. Such material can be sent back to the plant and retreated.

### **i** Segregation

To avoid segregation while paving:

- » The moisture should be **> 50 % of OMC.**
- » The material in the **wings of the receiving hopper** must be discarded.



<b>BSM-emulsion</b>	<b>BSM-foam</b>
Re-treat with diluted bitumen emulsion.	Re-treat with water.

- » **Sacrificing the material in the wings of the paver’s receiving hopper.** The receiving hopper should be filled with material from the first truck load of the day and never tilted. This material must be discarded at the end of the working shift.

The surface of the layer on which the new layer of BSM will be paved must be clean and free of all loose material and foreign matter. Immediately prior to paving, the surface must be thoroughly moistened by spraying with water. Any ponding water must be removed by brooming before the BSM is paved. Additional watering is required if the surface dries out.

Paving is normally undertaken in half-widths. A good joint on the centre-line is best achieved by constructing both halves during the same working shift. This means that the initial half-width is first paved over the full length of road to be paved, compacted and finished off, often with a fog spray and light application of crusher dust to facilitate early trafficking.

### iii. Construction Joints

Longitudinal joints are inevitable since few roads are paved full width in one operation. As described in Section 6.4.3, these joints are zones of potential weakness and therefore need to fall outside the trafficked wheel paths. On a typical rural road with two lanes, the longitudinal joint will normally be located on the centre-line. Longitudinal joints generally receive the following treatment when a BSM is paved:

- » Once the first half-width is paved, the outer 500 mm of material closest to the centre-line receives only one pass with the roller, leaving it in a relatively uncompacted state, as can be seen in Figure 6.10. All public traffic and construction vehicles must be prevented from running over the step of material thus formed on the centre-line.
- » Immediately before paving the second half-width, the exposed edge on the centre-line together with the partially compacted strip is thoroughly moistened. This is normally undertaken by a separate team equipped with hand sprayers walking ahead of the paver.

<b>BSM-emulsion</b>	<b>BSM-foam</b>
Diluted bitumen emulsion is applied where BSM-emulsion is paved.	Water is applied where BSM-foam is paved.

- » Prior to paving the second half-width, the bevelled end plate is removed from the centre-line end of the screed. This allows the screed to butt up against the exposed step of the first half-width, as illustrated in Figure 6.10.



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Figure 6.10 Longitudinal Joint Treatment

- » The partially compacted strip of material remaining on the first half-width then receives the full compaction and finishing treatment together with the second half-width.

Lateral joints occur at every location where paving stops and a ramp is constructed to accommodate the traffic. The following day, or when paving restarts, the material in the ramp is removed and the paved BSM material cut back to achieve a 45° slope. The material lying on the slope is then thoroughly moistened before paving can continue.

<p><b>BSM-emulsion</b></p> <p>As with longitudinal joints, diluted bitumen emulsion is applied where BSM-emulsion is paved.</p>	<p><b>BSM-foam</b></p> <p>As with longitudinal joints, water is applied where BSM-foam is paved.</p>
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**iv. Compacting the Paved BSM**

The primary concern when using heavy vibrating rollers that are required to compact a paved layer of BSM is loss of shape. The rolling pattern established whilst constructing a Trial Section (see Section 6.7) must be strictly followed, especially when making the initial pass that creates the outside edge restraint.

As described in Section 6.4.3.2, tandem smooth drum rollers are always used to compact the BSM behind the paver. Equipped with two vibrating drums, these rollers normally achieve the required density with relatively few passes. However, operators need training to prevent over-rolling and shape loss since the technique required to compact a BSM is very different from compacting hot mixed asphalt. Once the required density has been achieved, the layer is finished off using a PTR. The procedure is the same as described in Section 6.2.2.5 for in situ treated layers of BSM.

**6.4.4. LAYER CONSTRUCTION USING CONVENTIONAL CONSTRUCTION EQUIPMENT**

Conventional equipment is normally used in preference to paving where in-plant mixed material is used to construct thick layers of BSM. However, there are two limitations:



- » Thick layers demand more material than can be managed when working in half-widths. For this reason, placing a BSM with conventional equipment is normally **only applicable to new construction** where the **full road width** is available.
- » Working with graders always results in **moisture loss** since the material has to be spread out over a relatively large area for extended periods of time. This moisture loss needs to be replaced by adding water.

<b>BSM-emulsion</b>	<b>BSM-foam</b>
The demand for additional moisture makes this method inappropriate for BSM-emulsion.	The demand for additional moisture limits the application of this method to BSM-foam.

Essentially, the procedure followed is the same as that described in Section 6.3 for placing in situ treated material with the following differences:

- » The **surface of the layer** on which the new layer of BSM is to be constructed must be cleaned and thoroughly moistened before the treated material is imported and tipped out.
- » To **limit moisture loss**, the grader should start placing as soon as material has been imported over a sufficient length of the road required for this method of work (normally 100 m). The addition of water or diluted bitumen emulsion and the in situ mixing necessary to achieve a uniform moisture content is always required to compensate for the inevitable loss of moisture due to evaporation.

The procedure followed for finishing off the new layer is the same as described in Section 6.2.2.5 for in situ treated layers.

#### 6.4.5. LAYER CONSTRUCTION USING LABOUR INTENSIVE METHODS

BSMs are becoming popular on road upgrading projects using labour intensive construction. Most of the labour is used for spreading and placing the BSM prior to compacting with relatively light vibrating rollers. This normally limits the layer thickness to 125 mm.

The process starts by preparing the surface on which the new layer is to be constructed. A grader and heavy vibrating roller is often used for this work since the longevity of the pavement is largely determined by the competence of the underlying support. Alternatively, where the support is competent, the existing road surface can be trimmed by hand and swept clean.

Once a firm surface has been achieved, side forms are erected to contain the imported BSM. Since these side forms will dictate the line and level of the new BSM layer, they need to be made out of heavy duty material with a truly straight top edge. Thin steel shutters that are commonly used for structural work are often employed. Such side forms are positioned with the top edge at the correct elevation by placing or excavating material beneath the bottom edge. Side forms need to be firmly anchored in place using a series of suitable steel stakes.

**i Labour Intensive Construction**

BSMs are appropriate for labour intensive construction, but the **thickness of the layers is normally limited to 125 mm.**

<b>BSM-emulsion</b>	<b>BSM-foam</b>
Mixing the BSM-emulsion is usually undertaken on site using a concrete mixer. Input materials are volume batched and the mixed product taken straight to the road in wheelbarrows. Two mixers are often used to increase the production rate and maintain a consistent flow of treated material.	Due primarily to its ability to be held in stockpile for extended periods, BSM-foam is ideal for constructing a new pavement layer using labour. Stockpiles should be kept covered until the material is required and then thoroughly wetted before extracting the material. The mixing plant for this type of work is normally located at a central venue and the material trucked to site, stockpiled and covered for later use.

The BSM is imported by wheelbarrow and tipped between the side forms. This material is then raked into place and struck off flush with the top of the side forms. It is important that a reasonably uniform density is achieved in the material that is loosely spread between the side forms. Material lying in the mound created by tipping from a barrow will be partially compacted by the tipping action, whereas



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material spread by hand will be completely loose. Care must therefore be taken to rake all the material away from the location where it was tipped. Failure to follow this simple requirement will inevitably result in a poor surface shape after the material has been compacted.

As soon as the material has been spread and struck off, the surface is thoroughly moistened (using water with BSM-foam and diluted bitumen emulsion with BSM-emulsion) before the roller starts work. The surface must be kept moist during the entire compaction process. Pedestrian rollers that are commonly used for trench backfilling are normally employed. To assist the operator achieving the same compactive effort over the entire area, stakes are often positioned across the road at the same interval as the width of the drum to act as a guide. The same number of roller passes is then undertaken on each strip, with the drum overlapping the previous strip by 50%.

The strip of material immediately against the side forms normally receives an additional two passes with the roller with care being taken not to disturb the shutter. Once a section has been compacted, the side forms can be removed and a small plate compactor employed to compact the exposed edge.

Finishing is usually achieved by deploying a second pedestrian roller together with additional moisture to achieve a mild slush.

Although labour intensive construction may be deemed to be beneficial for socio-political reasons, the physical limitations of the process must dictate where it is used. Layer thicknesses in excess of 125 mm cannot be properly compacted using the type of equipment used in this process. This is deemed to be a major limiting factor. Moisture loss due to the slow rate of progress is also a limiting factor. Other limitations include the production rate achievable, the space required for working with side forms and the conflict of labour and traffic where construction in half-widths is contemplated. For these reasons, this method of construction is normally restricted to projects concerned with upgrading low-volume roads.

### 6.5. CURING AND TRAFFICKING

One of the main benefits of using BSMs on rehabilitation projects is the ability of these materials to withstand traffic loading soon after the layer has been completed. This feature eliminates the need for extensive traffic diversions or detours. Rehabilitation work is normally undertaken by recycling the road in half-widths with unidirectional traffic being accommodated by means of stop/go controls on the adjacent half. Outside construction hours the full road width is open to traffic.

<b>BSM-emulsion</b>	<b>BSM-foam</b>
After compaction, the increase in density is not sufficient to ensure resistance to traffic damage. An increase in cohesion is required for resistance to traffic damage, which is dictated by the time required for the bitumen emulsion to break. This normally takes a few hours at the surface where evaporation forces the break, but can take several days for the bitumen emulsion deeper in the layer.	On compaction, the instant increase in cohesion makes layers of BSM-foam resistant to traffic damage. However, they remain “tender” until the moisture content reduces.

The resistance to traffic damage can be monitored by parking a heavily loaded vehicle on the new layer. After a relatively short period (< 1 hour), the wheels will settle into the material, leaving localised indentations that can be as deep as 10 mm. As the material dries back, this propensity to deform reduces until, after a day or two of warm weather, it ceases altogether. This phenomenon needs to be taken into account when planning road closures. Stop/go controls should be positioned such that the daily traffic is only allowed to stand where the layer of BSM was completed at least 24 hours previously.

Allowing traffic to travel on BSM layers has the benefit of showing up construction defects. As was illustrated in Figure 6.6, sections with an under-application of bitumen will tend to ravel excessively under the action of traffic, drawing attention to any area that requires

### **i** Spreading the mix

A reasonably uniform density must be achieved in the material that is loosely spread between the side forms. This requires raking of areas that are partially compacted by the wheel barrow and tipping action.



### Stop/go Controls

Stop/go controls should be positioned such that the daily traffic is only allowed to stand where the layer of BSM was completed at least 24 hours previously.



remedial measures to be taken before the final surfacing is applied. The surface must be kept clean to prevent abrasion and ravelling. It is recommended that fog spray is applied.

## 6.6. SURFACING

The dispersed nature of the bitumen is responsible for increasing the cohesion that gives BSMs sufficient early strength to withstand traffic loads without a surfacing. Since the particles at the surface are only held in place by such spot welds along their lower faces, dynamic forces imparted by heavy tyre loads will tend to loosen and remove the coarser particles at the surface, causing roughness. Whilst some remarkable successes have been achieved in protecting the surface from such damage by using a dilute bitumen emulsion in the slushing process and/or the application of a light fog spray, it is recommended that the surfacing must be applied between 2 and 4 weeks after compaction to provide protection against both water ingress and excessive traffic abrasion. The surfacing must not be placed before the moisture content in the upper 100 mm of the layer has reduced to below 50% of OMC, which usually takes 2 weeks.

Asphalt surfacings (30 mm thick) have proved to be exceptionally durable on BSM layers and there are no reports of delamination. Chip seals, however, need to be carefully designed to prevent bleeding. The bleeding is invariably the result of the stone punching into the BSM layer. BSMs are relatively soft and Ball Penetration measurements in excess of 3 mm can be expected, even where the treated material consists of G2 quality graded crushed stone. High summer temperatures will exacerbate this “softness”, especially where the seal is fresh, thereby increasing the potential for individual stones or chips to punch into the base when heavy loads are applied. Some strengthening of the surface is required to prevent stone punching.

## 6.7. CONSTRUCTING TRIAL SECTIONS

A Trial Section should always be undertaken at the start of a new project (or when warranted by changes on site) to determine the correct settings on the equipment and subsequent treatment of the material. Prior to commencing the Trial Section, the contractor must prepare a detailed proposal indicating how the various operations to produce the BSM layer will be conducted.

**i** **Trial Sections**  
Trial sections should always be undertaken because they provide **valuable information** for construction.

### 6.7.1. TRIAL SECTIONS FOR IN SITU TREATMENT

As a minimum, the following details should be included in the Trial Section proposal:

- » A **schedule listing the plant and equipment** that will be used for the work. This schedule must include all items that the contractor intends using for the permanent works.
- » A **sketch detailing the number of passes required by the recycler** to cover the width to be recycled together with all overlap details.
- » **Assumptions made regarding the maximum dry density** that govern the application rates for the bitumen stabilising agent and active filler, based on the initial laboratory tests.
- » **Roller details** (static mass and drum type), the anticipated number of passes to be made by each roller, the rolling pattern and method to be employed in determining when sufficient compactive effort has been applied.
- » **Sampling frequency and tests** to be conducted.
- » Trial Sections must always be located so as to be **truly representative of the recycling work**, and, where possible, representative of the **pavement support** in the determination of the so-called target density.

While the Trial Section is being executed, the following details need to be monitored:

- » **Grading of the recycled material.** The forward speed of the recycler, the rate of rotation of the milling drum and positioning of the breaker-bar should be varied to determine which combination produces the best result in terms of pulverisation and smoothness of the resulting grading curve.
- » **Moisture addition.** Determination of the optimum mixing moisture content (the “fluff point”) and the amount of water that needs to be added through the dedicated water spraybar to achieve the required moisture content.
- » **Mixing quality.** Experience has shown that advance recycler speeds in excess of 10 metres per minute are detrimental to mixing quality. In addition, the pressure exerted on the rear door of the milling chamber can be varied, thereby changing the degree of “choking” (the amount of material retained in the milling chamber). As well as improving the quality of the mix, these settings affect the grading of the product, particularly of the coarser fraction.
- » **Bulking.** Bulking of the material occurs because of the increase in voids after recycling. Bulking of the recycled material must be measured or determined along with the consequential effects on level control. Where bulking results in changed final levels, the excess material should be removed.



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- » **Compaction requirements.** Adequacy of the roller for achieving density and the number of passes required can be determined by monitoring the rate of densification. If the primary roller is not equipped with a compactometer device, a nuclear gauge can be used to determine the density of the layer and the change in density with each pass.
- » **Detailed records.** A record of the precise sequence of events and the relevant timings should be taken for future scheduling purposes.

Invaluable information is obtained from Trial Sections. They should always be properly planned and monitored. The area of the recycling should be limited to one tanker-load of the bitumen stabilising agent. A full working day should be set aside to conduct the necessary surveys and tests without production pressures.

### **i** Representative Trial Sections

Trial sections should be representative of the **recycling work** and the **pavement support**.

### 6.7.2. TRIAL SECTIONS FOR IN-PLANT TREATMENT

Where the BSM is paver laid, the site selected for constructing the Trial Section should be a side road away from the permanent work. Paver set up is a process of trial and error, invariably resulting in the initial work being out of shape with many undulations. Trial Sections for paving applications are seldom finite in length. The objective is to fine-tune the paver and screed until the correct settings for the particular BSM have been established. The length of section paved is therefore dependent on how long it takes to find the settings that work.

## 6.8. QUALITY CONTROL ASPECTS

Quality controls are required to ensure that the end product will meet the performance expectations embodied in the design. Two aspects of quality need to be monitored:

- » The **quality of the BSM** used to construct the pavement layer, and
- » The **quality of the pavement layer** that was constructed.

For any quality control programme to be effective, the specific quality requirements for each project need to be clear and unambiguous. Project Specifications must therefore include details of the particular characteristics of both the material and the layer to be controlled. Specific quality requirements must be stated as well as the method to be followed in determining whether or not such requirements have been achieved. In addition, the consequences of not achieving the specified quality requirements must be stated (e.g. rejection, partial payment, etc.)

The quality of a BSM is a function of the parent material, the added stabilising agent (and any active filler) as well as the effectiveness of the mixing process. Quality controls need to be applied during the mixing process to ensure that the mixed product is capable of meeting the performance expectations embodied in the design. Additional controls are required to ensure that the BSM is placed, compacted, shaped and finished off in such a manner that the required end-product is obtained. Acceptance controls are then applied to the finished layer to determine whether such end-product requirements have indeed been met.

Sections 6.8.1, 6.8.2 and 6.8.3 consider quality controls specific to the production of a BSM layer.

### 6.8.1. QUALITY OF THE BSM

#### 6.8.1.1 Material to be Treated

Regardless of whether bitumen emulsion or foamed bitumen is applied, the material to be treated must be similar to that envisaged by the designer. Where the material is mixed in-plant, a testing programme should always be put in place to check the quality of the material stockpiled prior to mixing.

The quality of material recovered from an existing pavement through in situ recycling cannot be controlled other than its physical condition (degree of pulverisation and moisture content). This implies that the onus rests with the designer to determine whether or not the material in an existing pavement is suitable for recycling as a BSM. Imposing material quality controls on an in situ recycling operation is therefore unrealistic, other than the degree of pulverisation of previously bound material (asphalt and/or cemented material). In specifying such requirements, however, the designer needs to be familiar with the capabilities of modern recyclers; in particular they are not mobile crushers. Maximum particle size should therefore be specified; not a grading envelope.



### 6.8.1.2 Stabilising Agent and Active Filler

Most stabilising agents and active fillers used to manufacture a BSM are generic products that conform to specific industry standards. It is therefore relatively simple to specify and control the quality of a specific additive:

<p><b>BSM-emulsion</b></p> <ul style="list-style-type: none"> <li>» <b>Anionic</b> bitumen emulsion, SANS 309</li> <li>» <b>Cationic</b> bitumen emulsion, SANS 548</li> </ul>	<p><b>BSM-foam</b></p> <ul style="list-style-type: none"> <li>» <b>Penetration grade</b> bitumen, SANS 307 .</li> </ul>
<ul style="list-style-type: none"> <li>» <b>Active filler:</b> Ordinary portland cement, SABS 471 Hydrated road lime, SABS 824</li> </ul>	

Where penetration-grade bitumen or bitumen emulsion is not supplied in accordance with industry standards, they need to be tested prior to being used in the permanent works to ensure that they will achieve the performance requirements.

<p><b>BSM-emulsion</b></p> <ul style="list-style-type: none"> <li>» <b>Breaking characteristics.</b> In addition to the charge (anionic or cationic), the breaking characteristics of the bitumen emulsion need to be checked. Samples of the bitumen emulsion are normally sent to a specialised laboratory for such tests.</li> <li>» <b>pH of water.</b> Where a bitumen emulsion is diluted on site prior to mixing, the pH of the water to be used in the dilution process needs to be checked and, where necessary, adjusted to the particular bitumen emulsion charge by adding acid or alkali.</li> <li>» <b>Dilution test.</b> After dilution, the potential for premature breaking must then be checked using the “Dilution can test” (Section 4.2.4). The actual dilution of deliveries must be checked.</li> </ul>	<p><b>BSM-foam</b></p> <ul style="list-style-type: none"> <li>» <b>Penetration.</b> If the results fall outside the specified range then consideration may be given to using a cut back (diesel oil is normally used, not kerosene).</li> <li>» <b>Foaming characteristics.</b> As long as acceptable foam is obtained, which is determined by the expansion ratio and half-life, the penetration of the bitumen is not that important.</li> </ul>
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In cases where the active fillers are not supplied in accordance with industry standards, their effectiveness should be tested (by repeating the mix design in the field laboratory) prior to being used in the permanent works. In the absence of a field laboratory equipped for bitumen treatment mix design testing, the grading and moisture content of the active filler may be used as indicators of effectiveness (more than 95% of the active filler should be smaller than 0.075 mm and the moisture content must be less than 5% by mass). If these basic requirements are met, a test section should be constructed and the mixed material tested to determine the effectiveness of the active filler.

### 6.8.1.3 Process Controls for the Mixing Operation

Regardless of whether mixing is undertaken in situ or in plant, the basic process controls to be followed when mixing a BSM are similar. Where there are differences between the addition of bitumen emulsion or foamed bitumen, these are highlighted in the following sections.

Appendix D includes a series of checklists and report sheets (together with examples) that are normally used on site when working with BSMs. These include:

- » **Appendix D1:** Essential Requirements for a successful recycling operation using recyclers
- » **Appendix D2:** Prestart check lists
- » **Appendix D3:** Daily reports for in situ recycling

**i** **Process Controls**

Appendix D includes a series of **checklists and report sheets** (together with **examples**) that are normally used on site.



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- » **Appendix D4:** Determining the strength of field samples
- » **Appendix D5:** Determining the strength of core specimens

The primary determinants of mix quality that need careful monitoring are discussed in the following sections.

### i. Temperatures

The temperature of the material being mixed has a significant influence on the quality of mix. In general, the colder the material, the poorer the mix quality and, conversely, the warmer the material, the better the mix quality. Bitumen treatment should therefore only be undertaken when the temperature of the material is above the minimum stated in the Project Specifications.


<b>BSM-emulsion</b>	<b>BSM-foam</b>
<ul style="list-style-type: none"> <li>» The <b>temperature of the pretreated material</b> should exceed 5 °C.</li> <li>» Manufacturers of bitumen emulsion normally recommend that their product is applied through a spraybar at 60 °C when undiluted bitumen emulsion is used. The primary reason for adopting such a temperature is the <b>reduction in viscosity</b> that facilitates pumping at reduced pressure, thereby reducing the risk of the bitumen emulsion suffering a premature break.</li> </ul>	<ul style="list-style-type: none"> <li>» The <b>temperature of the pretreated material</b> must be 10 °C or more, preferably 15 °C.</li> <li>» The <b>bitumen temperature</b> must be above 160 °C to provide sufficient heat energy for the water to change state and create the foam. The normal bitumen temperature for foaming is 175 °C. Although bitumen does foam at lower temperatures, the quality of such foam is inferior to that achieved when the bitumen is at higher temperature.</li> </ul> <p>Bitumen should never be heated above 195 °C.</p>

### ii. Mixing Moisture Content

At the time of mixing, the moisture content of the material must be properly controlled. As explained in Section 6.2.2, the moisture content of in situ pavement materials is likely to vary. It is therefore essential that the moisture content of the treated material is continually assessed (especially when recycling in situ) and the amount of water being added to the mix is adjusted immediately a change is detected. The moisture content of the treated material is easier to control when mixing in plant, provided the stockpiles of input materials are protected from the environment (rain). Once established, the required water or diluted bitumen emulsion addition will usually remain relatively constant.

### iii. Amount of Bitumen Added

It is important to recognise that variations in the parent material make it practically impossible to precisely determine the quantity of bitumen added. Unlike a manufactured product such as hot-mixed asphalt, the grading of a recycled material tends to vary considerably and the inclusion or exclusion of a single 25 mm stone particle makes a significant difference when attempting to determine the amount of bitumen that was added, expressed as a percentage of the mass of the sample. Inclusion of bitumen concentrations in the sample (stringers in the case of foamed bitumen) also makes an appreciable difference. This situation is exacerbated by the presence of old bitumen in the recycled material, especially where the existing road was extensively patched with various bituminous materials, for example, asphalt, cold mix and chip seal.



### Bitumen Consumption

The consumption of bitumen emulsion and foamed **bitumen must be carefully** monitored. It is not possible to determine the bitumen content after construction using extractions.

Bitumen extractions are therefore meaningless and effective control can only be exercised by monitoring the consumption of bitumen (bitumen emulsion or foamed bitumen) to ensure that the required application rate is achieved. Such control necessitates that every tanker load of bitumen is supplied with an assized weighbridge certificate and that the area covered by each tanker-load is accurately monitored. When a recycler is fitted with a flow meter, the bitumen used should be recorded after each run and reconciled with the bulk usage.

The alternative to measuring bitumen consumption by using a dip-stick to measure the contents of a tanker is usually considered to be impractical where bulk tankers are used. Dip-sticks are used routinely with distributors for chip seal surfacing, but are seldom used with



bulk tankers that are coupled into the recycling train. Furthermore, gauging the contents of a tank by dipping requires a reasonably level or consistent surface which cannot be guaranteed on most rehabilitation projects.

#### iv. Amount of Active Filler Applied

The relatively low application rate of active filler used in producing a BSM and the encapsulation of the individual particles of active filler in bitumen make it practically impossible to apply the standard control tests used when stabilising with cement or lime. Consumption controls are therefore used to check that the required amount of active filler is applied and that the spread is uniform.

For in situ treatment, active filler is normally supplied in bags and spread by hand. To achieve the required application rate, a grid pattern is marked on the existing road surface with each grid block representing the area to be covered by the contents of one bag. Bags are then placed in each grid block, opened and the powder carefully spread by squeegee. Process controls for this operation include checking the dimensions of the grid markings, ensuring that one bag is placed in each block and that a uniform spread is achieved within each block. Alternatively, on larger projects, active filler is often supplied in bulk tankers and applied using a spreader attached to the rear of the tanker. The canvas patch test is usually used to check the spread rate coupled with an overall consumption check to ensure that the mass supplied (weighbridge ticket) is applied to the area that was spread.

Where the material is recycled in situ, spreading should always be restricted to one cut at a time, with the filler being spread on the road surface immediately ahead of the recycler. Constant attention is then required to ensure that the filler is not moved to the side by the front door on the recycler's mixing chamber. Traffic must never be allowed to travel over the spread filler.

The application rate of active filler is usually computer controlled when mixing in plant. However, the consumption rate should be checked regularly to ensure that the plant is correctly calibrated.

### 6.8.2. QUALITY OF THE LAYER OF BSM

Layers constructed from BSMs must meet specific geometric requirements (layer width and thickness), material condition (density and uniformity) and surface finish (shape and level). The method employed for placing the material, levelling, compacting and finishing off will dictate the quality of the final product and whether the specified requirements are achieved.

Layers constructed from in situ mixed material involve construction methods that are very different from those used to construct a layer from material that is mixed off site. Different process controls are therefore employed to ensure the required end product is achieved. These are covered separately in the following sections.

#### 6.8.2.1 Layers Constructed from In Situ Treated Material Using Recyclers

Process controls for layers constructed by in situ recycling are focused on achieving the correct depth of cut that will provide the required layer thickness, continuity across joints and adopting the correct sequence of operations for compacting the material, cutting levels and finishing off.

As described in Section 6.2.2.1, the depth of cut is best controlled using a T-bar to probe to the bottom horizon of the recycled material. A tape is usually attached to the T-bar to measure the depth relative to a stringline stretched between the same level references (poles) that will be used to cut final levels. Such measurements should be taken at least once every 100 m of cut.

Recyclers invariably need to make more than one cut to cover the required width of treatment, thereby introducing a longitudinal joint between adjacent cuts that always requires an overlap. The width of overlap is dictated by the guideline and indicator (chain dangling from an arm attached to the front of the recycler). These must be checked before starting each cut. In addition, the actual overlap achieved must be physically checked at least once every 200 m by measurements taken in front and behind the recycler.

#### Active Filler Application

Active filler is usually **spread by hand**. The placement of the bags and the spreading of the filler must be **carefully controlled**.



#### Traffic on Active Filler

Traffic must **never be allowed** to travel over the spread filler.



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As described in Section 6.2.2.5, the sequence of compacting and level cutting behind the recycler is critical. These operations need to be constantly monitored to ensure that primary compaction is complete before levels are cut.

### 6.8.2.2 Layers Constructed In Situ Treated with Conventional Plant (BSM-emulsion)

Once the material has been mixed, constructing a layer of BSM-emulsion is similar to constructing any pavement layer using conventional plant. However, additional controls are essential to ensure that the specified layer thickness (depth of processing) is achieved. The depth of pre-ripping of the material in the existing pavement must be carefully monitored, as must the bottom horizon cut by the mouldboard of the grader. These are best controlled by dipping from a stringline stretched between the same level references (poles) that will be used to cut final levels.

### 6.8.2.3 In Plant Treatment

BSMs treated in plant are invariably used to construct a new layer. Before placing the material, the surface of the underlying layer must be cleaned and thoroughly moistened. Visual controls are required to ensure that the surface remains in such a clean and moist state until covered by the BSM.

The moisture content of the BSM requires careful monitoring throughout the placing and compacting process. Additional moisture in the form of water or a very diluted bitumen emulsion (“dirty water”) is sprayed on the surface of the partially completed layer as and when required, based on an assessment made by the supervisor.

#### i. Paver Laid

As discussed in Section 6.4.3.3, constant monitoring is required to prevent segregation, particularly whilst the material is in transit and when it is transferred from the supply truck to the paving screed.

After the paver has been properly set up so that the screed achieves a consistent “float” on the material, the process is controlled mainly by observing the operation to ensure that the correct line is followed, speed is restricted to the rate of material delivery, material flow to the screed is constant and that the tampers / vibrators / pulse bars are functioning. Measurements need to be taken at both ends of the screed (normally once every 50 m) to ensure that the required pre-compacted thickness is achieved.

When paving against a previously formed joint, the face of the joint must be thoroughly moistened and kept moist until covered (visual observations).

Rollers used to compact the paved mat also need to be closely monitored to ensure that the correct rolling pattern and sequence is followed, sufficient passes are made and that the energy applied does not roll the mat out of shape.

#### ii. Placed by Grader

Where an in-plant treated BSM is dumped on the road and placed by grader, the same procedures and controls used to construct a layer from G2 material are followed.

#### iii. Placed by Labour Intensive Methods

Controls are necessary to ensure that the density of the spread material is reasonably consistent prior to any compactive effort being applied. Visual observations are used to ensure that all material is moved from where it was dumped. The “heel penetration test” carried out on the surface of the spread layer can also be useful as an indicator of variations in density.

### 6.8.3. ACCEPTANCE CONTROLS FOR PAVEMENT LAYERS CONSTRUCTED WITH BSMS

The Project Specifications for each project need to detail the relevant tolerances and quality control tests that will be conducted on the completed works. These will normally include the minimum acceptance criteria and relevant tolerances relating to:

- » **Thickness of the Completed BSM Layer.** This is one of the most critical parameters influencing the performance of the overall pavement structure. Small changes in layer thickness significantly influence structural capacity. Hence, layer thickness must be carefully monitored on site.




**Conventional Equipment**

BSM-foam cannot be constructed using conventional equipment.



On in situ recycling projects it is important to appreciate that the thickness of the completed layer is not necessarily the same as the depth of recycling. A grader is always used to shape the material behind the recycler, always after initial deep compaction has been applied, and to cut the final levels. Level control pegs should always be established on site and checked against existing surface levels prior to recycling.

A minimum thickness is normally specified. For example, where the structural design requires a 200 mm thick layer, the minimum requirement measured at any one position should not be less than 200 mm.



### Thickness Tolerances

The tolerances allowed should ensure that the thickness at any point is **not less than the design thickness**.

- » **Application Rates for the Bitumen Stabilising Agent and Active Filler.** A tolerance of  $\pm 0.3\%$  is normally specified for the application of the bitumen stabilising agent. When 2.5% residual bitumen is specified, application rates of between 2.2 and 2.8%, measured on actual consumption, will meet the required limits.

The tolerance for application rate of active filler, also based on actual consumption, is normally specified as  $\pm 0.1\%$ . Thus, if the specified application rate is 0.7%, application rates of between 0.6 and 0.8% will meet the requirements. Emphasis must be placed on process controls to ensure that the active filler is uniformly spread on the road surface.

- » **Mix Quality.** The quality of mix is evaluated by testing the strength of the material. Due to the lack of sophistication found in most field laboratories, the strength of field samples is normally evaluated from simple ITS tests carried out on 100 mm diameter specimens.

Bulk samples (approximately 50 kg) of the BSM are usually taken from the road, prior to being compacted, and retained in a sealed bag. Two such samples are normally taken for each day's work. These samples are then transported to the field laboratory and used immediately to manufacture specimens. Appendix D4 describes the procedure to be followed in manufacturing and curing the specimens and for determining relevant ITS values. Minimum ITS values (dry and soaked) that must be achieved for the different classes of materials (BSM1, BSM2 or BSM3) are given in Chapters 4 and 5.

Care needs to be exercised when manufacturing 100 mm diameter test specimens, especially where the material is coarse and non-plastic. Each specimen should be inspected after extruding from the mould. Those exhibiting evidence of particle segregation or poor composition should be discarded and replaced by manufacturing additional specimens. There should always be sufficient material available since each 100 mm diameter specimen has a mass of approximately 1 kg.

In the final analysis, if there is any doubt about the quality of the as-built product, 150 mm diameter cores can be extracted from the completed layer and subjected to a testing programme to estimate the potential performance of the material in the recycled layer. Since a "young" BSM is relatively tender and significantly less dense than hot mix asphalt, coring must be undertaken with gentle pressure applied to the core barrel and minimal water addition. Likewise, the recovered specimen will be tender and needs to be handled with care, especially whilst being transported from site to the laboratory. Once in the laboratory, core specimens must be inspected for damage prior to conditioning, curing and testing (as described in Appendix D5). Damaged specimens must be discarded since any test carried out on such a specimen will not be a true reflection of the material in the field. To ensure 100% core recovery, coring should be delayed until the material has gained sufficient strength.

<p><b>BSM-emulsion</b></p> <p>100% Core recovery is normally achieved after four weeks.</p>	<p><b>BSM-foam</b></p> <p>100% Core recovery is normally achieved after two weeks.</p>
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- » **Compaction Requirements.** The minimum dry density requirement is usually specified, similar to the provisions contained in the Standard Specifications (COLTO, 1998) for pavement layers constructed from treated materials. The actual level of density specified (as a percentage of the MDD or BRD) will depend on the support characteristics of the underlying pavement. Densities between 97



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and 100% of the modified AASHTO density are normally specified where the pavement support consists of natural granular material, depending on the in situ stiffness, and up to 102% where a cement treated layer exists in the subbase.

Where layers thicker than 175 mm are recycled, it is normal to specify that a minimum percentage (typically 10%) of all density tests are carried out on two separate horizons in the layer. Thus, where the layer thickness is 200 mm, one density test is conducted on the upper 100 mm thick horizon and a second test on the underlying lower 100 mm horizon. The average of the two measurements must meet the minimum specified density for acceptance.

- » **Levels, Width, Cross-Section and Surface Regularity.** The construction tolerances specified in clause 3405 of the Standard COLTO Specifications are usually applicable to the completed layer. Measurements should always be taken immediately after completing the layer, before opening to traffic.



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# APPENDIX A: MATERIAL CLASSIFICATION SYSTEM

## A.1. INTRODUCTION

The derivation of the material classes for each pavement layer is a critical aspect of the design process, since this process effectively constitutes the determination of structural design inputs. When appropriately done, the classification process also provides a link between the mix design and structural design processes. In this Appendix, the recommended method for classifying materials is presented. The object of the method is to provide a reliable, rational and consistent indication of the appropriate material class. The method is based on the use of all available information, and uses fuzzy logic and certainty theory to assess the certainty that materials belong to a particular class.

The sections below describe the method in more detail and provide all relevant details for the implementation of the method. Although the method was specifically developed for use in the structural design method for pavements that incorporate BSMs, the approach can be used in any pavement design context with all common material types, and is especially relevant for rehabilitation design.

## A.2. CONCEPT

During a routine pavement rehabilitation investigation, an engineer is typically faced with a wide array of test parameters and condition indicators. These parameters can be quantitative or qualitative, subjectively or objectively determined, and the sample sizes for different indicator types may vary significantly. For example, for a specific pavement layer within a uniform design section, an engineer may typically be faced with the following set of information:

- » Seven Dynamic Cone Penetrometer (DCP) tests.
- » Fifty Falling Weight Deflectometer (FWD) deflections.
- » Two sets of material descriptions and samples from test pits, together with standard materials test results, including Plasticity Index (PI), grading, California Bearing Ratio (CBR), moisture content and density.
- » One subjective visual assessment with a description of observed distresses.
- » Fifty semi-subjectively determined backcalculated stiffnesses from FWD tests.
- » A general description of the material type from historical records.
- » A general description of the history and past performance of the pavement.

From such a set of information, the engineer has to derive the key assumptions needed for the rehabilitation design. The synthesis of the information to arrive at design assumptions is one of the most important and difficult parts of the rehabilitation design process. Apart from basic analytical skill, it also requires considerable experience and knowledge of the main drivers of material behaviour. When incorrectly done, inconsistent conclusions can be drawn and the design assumptions will not be consistently supported by available evidence.

The concept behind the material classification method is therefore to guide engineers in the interpretation of available pavement condition data, and to synthesize available information so that key design assumptions can be derived in a consistent and rational manner. The objective of the materials classification method is therefore to provide a method for the consistent assessment of pavement materials using routine tests and indicators.

Many material classification methods are specification type approaches that rely on pass or fail type criteria. For these type of approaches, if any one test fails the criteria for the material class then the material cannot be classified as that class. For example, if the CBR value is below the specification for a G6 material, then the material cannot be classified as a G6 even if all other available test results do meet the G6 criteria.

The approach described in this Appendix is a more rational, albeit less exact method, which can handle vagueness in the data. Rather than giving a yes or no answer, the method indicates the conformance to a material class in less restrictive terms. The approach assesses the certainty that the material can be considered as the particular material class, and uses Fuzzy Logic to provide this type of assessment. The evaluation of pavement materials as part of rehabilitation investigations poses several unique challenges. These challenges are related to the realities of pavement investigations and pavement design, which includes the following aspects:



## APPENDIX A: Material Classification System

- » **Many Sources of Uncertainty:** Pavement engineering deals with large quantities (i.e. long distances) of natural and thus highly variable materials, which are subject to highly variable loads.
- » **Risk is Poorly Defined:** The risk associated with pavement failure is poorly defined. For example, what is the consequence of 5% more crocodile cracking over a twelve year period, and is it cost-effective to spend an extra R10 million now to prevent it? Several assumptions are needed to answer this question, and many of these – although they can be estimated – are beyond control (e.g. rainfall, overloading, future budgets, etc). Because of this situation, subjective assessment using experience plays a considerable role in pavement design.
- » **Small Sample Sizes:** Reliance on small samples is part of the reality of pavement investigations. It is not unusual for a rehabilitation design over 20 km of road, over varying terrain and geological areas to be based on ten or less trial pits.
- » **All Tests are Indicators:** In pavement design situations, the assessment of materials always aims to assess stability and (for some materials) flexibility. It does so either directly (as in a stability test) or indirectly (as in a grading assessment, which will impact on stability). Because the actual load situation varies, no pavement material test is able to completely quantify long term stability or flexibility. Even a highly sophisticated test, like the repeated load triaxial test, must be performed at a fixed moisture content and stress state which will never correspond completely to the real pavement situation that it aims to assess. Thus all tests provide only a relative indication of the two key properties to be assessed, and some tests do so very poorly.
- » **Interpretation is Vague:** In pavement rehabilitation investigations, an engineer needs to decide what information is available, and what can be done with it. A yes or no interpretation is not always appropriate, and a relative interpretation is needed. This complicates the interpretation of data considerably, especially when conflicting information is involved. It also introduces more subjectivity into the process.

The material classification system deals with these realities. Specifically, the approach incorporates the following elements:

- » Clear and rational formulation of the objective.
- » Ability to handle vagueness and uncertainty of interpretation.
- » Ability to work with small sample sizes.

### A.2.1. Assumed Material Behaviour

To provide a sound basis for the materials classification method, a model of pavement material behaviour was adopted. The assumed model is shown in Figure A.1, and represents the material as a conglomerate of course particles, fine particles, bitumen and air voids. This material model is the well-known Mohr-Coulomb model, which generally applies to composite materials consisting of a combination of loose aggregate and bitumen. This model applies to almost all pavement engineering materials except clay and silt and manufactured materials such as geotextiles, with the important distinction that the composition of the mastic differs significantly for different materials.

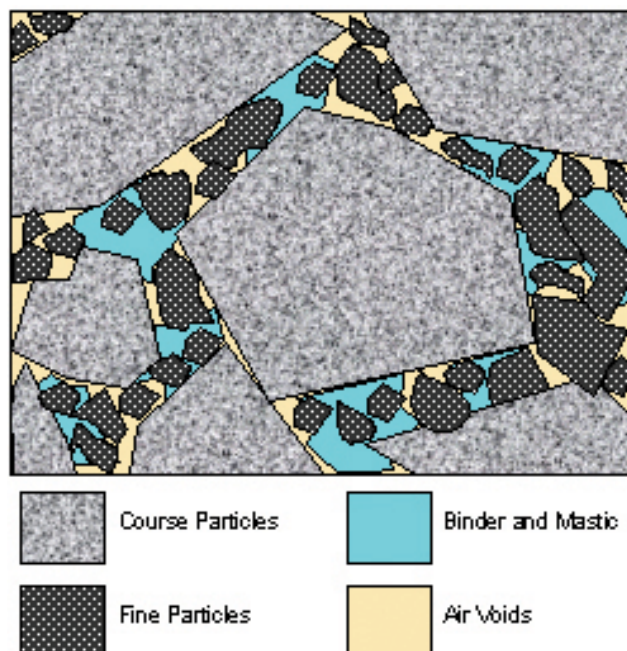


Figure A.1 Mohr-Coulomb Material Model



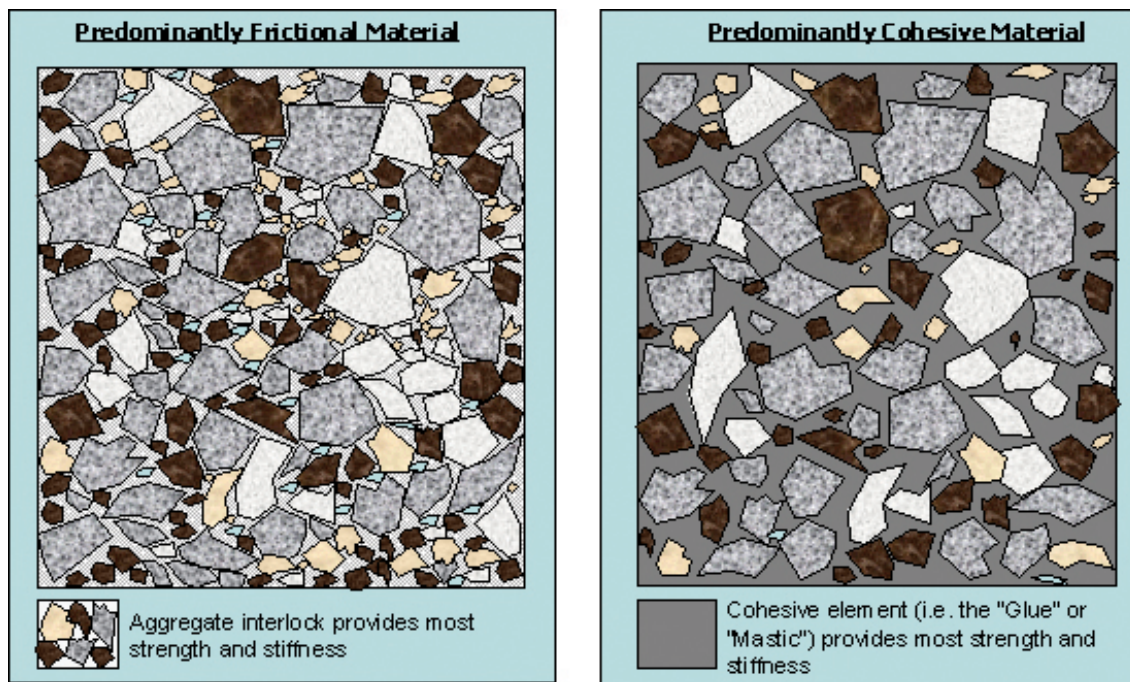
## APPENDIX A: Material Classification System

The material model shown in Figure A.1 can be used to explain the components that determine the strength and stiffness of the material. There are two components that determine the material's shear strength:

- » The cohesive strength, which is determined mainly by the mastic (consisting of the mixed bitumen and fine material), and
- » The strength provided by inter-particle friction, and mobilized when compressive stresses force the fine and coarse particles together.

The cohesive and frictional strength components determine not only the shear strength or stability, but also the stiffness and tensile strength. When the material is in compression, the stiffness and shear strength is primarily determined by a combination of the cohesive and frictional elements. When the material works in tension, particles are not pushed together and the stiffness and tensile strength are determined mainly by the cohesive element (i.e. the mastic). Stability and flexibility provide an indication of the resistance to the two main sources of pavement deterioration: deformation (either due to volume change or shear) and cracking (due to fatigue in tension).

The materials that are most resistant to shear and tensile failure are those in which there is a good balance between the strength provided by the cohesive and frictional elements. However, some materials tend to be dominated either by the frictional or cohesive element, as illustrated in Figure A.2.



**Figure A.2 Material Composition, Showing Dominance of Friction and Cohesion**

The relative role that the frictional or cohesive component plays in determining the strength and stiffness depends almost entirely on the state of the mastic. In the case of asphalt, for example, the mastic consists of the bitumen and filler combination. At high temperatures, the visco-elastic bitumen softens. When the material is loaded in this condition, load is transferred directly to the coarse aggregate matrix, and shear strength is almost completely from the frictional component. A similar effect is observed in crushed stone and natural gravels, where excess water destroys the suction forces that bind the fine particles together in a mastic, thereby significantly reducing the cohesive strength or stiffness component.

A clear understanding of the role of cohesion and friction in determining the strength and stiffness of pavement materials is important, as most test indicators provide an assessment of one or both of these elements. Thus some tests, like the Plasticity Index (PI), relate only to the cohesive element, while others, like a grading analysis, relate to the shear strength element. A fundamental understanding of what is measured by a specific test can provide the key to a rational and useful interpretation of the test's results.

The above definition and discussion of the Mohr-Coulomb model, and the cohesive and frictional components that drive this model, are used in Section A.4 to classify the various materials tests, and to guide their interpretation.



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### A.2.2. Design Equivalent Material Class

The material classes for granular and cement stabilised materials adopted for this material classification method are aligned with TRH14 (1985). The TRH14 classification system is regarded as being highly suitable for new construction and rehabilitation design, as the behaviour and performance patterns of each material class is known with some certainty. However, with the material classification method, the obtained materials class is regarded as the design equivalent materials class (DEMAC) and will not necessarily meet the specifications for that material class as given in TRH14. However, since materials to which design equivalent classes are assigned have been in service for some time, the raw material would conform to (or exceed) the specifications for the class, as stated in TRH14, in almost all instances. The material classes for BSMs are defined in Chapter 2 of the Guideline and Section A.4.2 of this Appendix.

When a design equivalent material class (DEMAC) is assigned to a material, it implies that the material exhibits in situ shear strength, stiffness and flexibility properties similar to those of a newly constructed material of the same class. For example, a layer in an existing pavement structure classified as a G2 design equivalent would indicate that the material is considered to be equivalent to a G2 for design purposes, based on the available test evidence. For brevity, a DEMAC will be denoted DE-G2, for example.

The materials classification system described in the next section provides a consistent method to evaluate and document the necessary evidence to support the material classification.

## A.3. MATERIAL CLASSIFICATION SYSTEM

### A.3.1. Theory of Holistic Approach

The material classification system provides a framework for the rational synthesis of several different test indicators. The outcome of the assessment becomes more reliable as more test indicators are added to the assessment. This is because each test typically explains only a small part of the cohesive or frictional elements of material behaviour. More complex tests, like triaxial tests, may evaluate these two elements together, but will do so only for a specific moisture or bitumen content. The use of other indicators will still be needed to determine how the material will behave if the moisture state or bitumen content changes. Since each test provides only a partial explanation of the material's behaviour, the reliability of the assessment can be greatly increased by increasing the sample size, and by adding more indicators (i.e. test types) to the assessment. The system is therefore a holistic assessment, which works best when a comprehensive range of test indicators are used.

The theory underlying the method is based on Fuzzy Logic and Certainty Theory. The development of the method is described in detail by Jooste *et al* (2007) and the validation of the method is described by Long (2009). A summary of the theoretical process to classify a material is as follows:

1. If H is the hypothesis to be tested, then the certainty that the hypothesis is true is designated as C(H), which has a value of 1.0 if H is known to be true, 0.0 if H is unknown and -1.0 if H is known to be false. In the context of the present study, H could for example be the hypothesis that the base layer is a DE-G1.
2. The value of C(H) is determined by applying rules which are based on experience or domain knowledge. Each rule has a certainty factor (CF) associated with it, to reflect the level of certainty in the available evidence, or in the knowledge on which the rule is based. A typical rule may be:

*If [PI < 4] then [Material is a DE-G1] With Certainty CF*

3. The certainty factor of a rule, CF, is modified to reflect the level of certainty in the evidence. This gives the modified certainty factor CF', calculated simply as:

$$CF' = CF \times C(E) \tag{A.1}$$

Where C(E) is a number between 0 and 1, indicating that the evidence in support of the hypothesis is either completely absent (C(E) = 0.0) or known to be present with absolute certainty (C(E) = 1.0).



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4. To get  $C(H|E)$ , which is the updated certainty that the hypothesis  $H$  is true, given the evidence  $E$ , the following composite function is applied:

$$\text{If } C(H) \geq 0 \text{ and } CF' \geq 0 \text{ then: } C(H|E) = C(H) + [CF' \times (1 - C(H))] \quad (\text{A.2})$$

$$\text{If } C(H) \leq 0 \text{ and } CF' \leq 0 \text{ then: } C(H|E) = C(H) + [CF' \times (1 + C(H))] \quad (\text{A.3})$$

If  $C(H)$  and  $CF'$  have opposite signs, then:

$$C(H|E) = \frac{C(H) + CF'}{1 - \min(|C(H)|, |CF'|)} \quad (\text{A.4})$$

In the application of the above methodology for material classification, the certainty factor  $CF$  associated with a specific test is assigned based on domain knowledge and experience. If the test is known to be a good overall indicator of cohesion, frictional resistance or both, then  $CF$  will tend to be higher.  $CF$  can also be adjusted based on the sample size and range of sampled values. For small sample sizes,  $CF$  can be lowered to reflect decreased confidence in the available evidence.

The steps and equations outlined above provide a general method for consistently evaluating the certainty that a hypothesis is true, given uncertain and vague rules and evidence. A generalized and simplified example of the method's application for materials classification is outlined below:

1. We want to test the hypothesis  $H$  that the material for which we have information is a graded natural gravel (DE-G4). To do this, we formulate the following rules:
  - If [Material is Natural Gravel] and  $[PI < 4]$  then [Material is a DE-G4] with  $CF = 0.4$*
  - If [Grading conforms to G4 Envelope] then [Material is a DE-G4] with  $CF = 0.3$*
2. We now obtain samples and measure the  $PI$  and grading. The certainty factors can be adjusted based on the sample size.
3. We start with the first available evidence ( $PI$  test). At this stage  $C(H) = 0$ . Since  $CF = 0.4$  for the first rule concerning  $PI$ , we use Equation 4.1 and 4.2 to calculate the updated certainty for the hypothesis that the material is a DE-G4 ( $C(H|E)$ ).
4. The updated certainty  $C(H|E)$  becomes the new starting certainty  $C(H)$  for the second rule which interprets the grading. We again apply Equation 4.2 to calculate the new value for  $C(H|E)$ .

This process can be applied for each material class to obtain a relative indication of how much the available test data point to each class. The following sections give more details on the process, and a worked example is included in Section A.5.

### A.3.2. Step by Step Material Classification

The Certainty Theory approach involves an assessment of how well the available evidence suits a given hypothesis. In the present context, the evidence would be available test data, and the hypothesis to evaluate would be that the material conforms to a specific material class. The method involves the following steps:

- Step 1:** For each of the available material tests, determine and report the 90<sup>th</sup> percentile, median and 10<sup>th</sup> percentile values from the available observations. For those tests for which a rating system is provided, use the ratings at each observation to determine the required statistics. Where there is only one observation available, simply report the observation as the median value.
- Step 2:** Determine the certainty factor associated with each of the available tests (i.e.  $CF$  as defined in Section A.4). This certainty reflects the confidence that we have in each test to provide an accurate indication of the in situ shear strength and stiffness of the material. Details related to this step are provided in Section A.3.3.
- Step 3:** Adjust the relative certainty determined in Step 2 to take account of sample size. This adjustment decreases the confidence for smaller sample sizes. Details related to this step are provided in Section A.3.4.
- Step 4:** Select a likely material class (e.g. DE-G4) for the layer in question.
- Step 5:** For each of the available tests, determine the expected range of values for each DEMAC for the selected material from Table A.3 (Granular), Table A.8 (BSM) or Table A.11 (Cemented). For example, if the material in question is a DE-G4, and the test is the soaked CBR at 98% Mod. AASHTO density, we will use Table A.3 to obtain the expected range of CBR values for a G4 (i.e. 80 to 99%). For tests that involve a rating system, as defined in Section A.4, the rating values corresponding to different material classes are shown in Table A.3 (Granular), Table A.8 (BSM) and Table A.11 (Cemented). Some tests or indicators have expected ranges for the material classes for different material types, compaction levels or specimen diameter. For example, in Table A.3, the Plasticity Index has different values for crushed stone, natural gravel, gravel



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sand and silt, silty sand, sand and clay. In these cases, only one material type, density level or specimen diameter may be selected per test or indicator.

- Step 6:** For each test, determine how much the 10<sup>th</sup> percentile to 90<sup>th</sup> percentile range overlaps with the expected range of values for the material. This provides the relative certainty that the test data points to the material class in question (i.e. factor C(E) as defined in Section A.3.1). Details of how to perform this calculation are provided in Section A.3.5.
- Step 7:** For each test, use the certainty factor CF from steps 2 and 3 and the certainty of evidence C(E) from Step 6, to update the certainty that the material tested conforms to the class selected in Step 4. This calculation then provides the relative certainty that the material belongs to the selected DEMAC, given the available evidence (i.e. C(H|E) as defined in Section A.3.1). Details on these calculations are provided in Section A.3.6.
- Step 8:** Repeat Steps 4 to 7 for each likely material class. For example, if we are performing a classification for an unbound granular base, we may evaluate the certainty associated with classes DE-G1 to DE-G5.
- Step 9:** Select the material with the highest certainty given the available evidence. This material class is assigned to the layer in question. Properly document the evidence and calculations.

### A.3.3. Certainty Factors for Different Tests and Indicators

Because most pavement materials tests provide only a partial indication of the shear strength and stiffness of a material, a certainty factor is assigned to each test indicator. This certainty factor represents the factor CF as defined in Section A.3.1. In essence, CF represents the subjective confidence in the ability of a test to serve as an accurate indicator for material strength and stiffness. The value of CF can range from 0 to 1, with a value of 1 indicating absolute confidence in a test or indicator (a highly unlikely assignment).

Suggested certainty factors for the tests and indicators used in the classification system are provided in Table A.3 (granular materials), Table A.8 (BSMs) and Table A.11 (cemented materials). The ratings shown in these tables are based on a subjective assessment of the completeness and appropriateness of each test or indicator. Engineers can adjust these values to take account of experience or specific project situations, but the assumed values should be reported to clients. If the assumed values deviate substantially from those suggested in the tables, the assumed values must be motivated in the assessment report.

### A.3.4. Adjustment for Sample Size

Small sample sizes, i.e. one or two observations are not uncommon in pavement condition assessments. However, this affects the certainty with which a material class is assessed. To take account of this, the Certainty Factor (CF) associated with each test is adjusted to take account of the sample size. Table A.1 shows the recommended adjustment factors based on sample size. These factors are applied by multiplying the factor from Table A.1 with the CF factor for the test from Table A.3 (Granular), Table A.8 (BSM) and Table A.11 (Cemented).

**Table A.1 Recommended Adjustment of CF based on Sample Size**

Sample Size (number of observations)	Adjustment Factor
1	0.2
2	0.3
3	0.6
4 to 6	0.7
6 or greater	1.0

### A.3.5. Assessing the Relative Certainty of Evidence

The material classification method assesses the certainty that a material can be classified as a particular material class. This assessment is vague and uncertain because of the incompleteness of most tests and because a sampling estimate is used. The incompleteness is taken into account with the Certainty Factor (Section A.3.3), but the variation in the tests results needs to be considered.

The method for achieving this is illustrated in Figure A.3. The figure shows the CBR limits associated with material classes DE-G5, DE-G6 and DE-G7. Also shown is a triangle which is determined as follows: left bottom corner is the 10<sup>th</sup> percentile value, top corner is the median value and right bottom corner is the 90<sup>th</sup> percentile value.



The triangle represents the available evidence in a relative manner. The height of the triangle is given a fixed value of 1.0. The total area of the triangle and the portion of the triangle that falls within the DE-G6 class are calculated. The relative area that overlaps with the DE-G6 class gives us a relative indication of how strongly the CBR evidence points to a DE-G6 class. In the context of the certainty theory methodology, we assume that the relative area that overlaps with the material class in question, gives us the factor  $C(E)$  as defined in Section A.3.1.

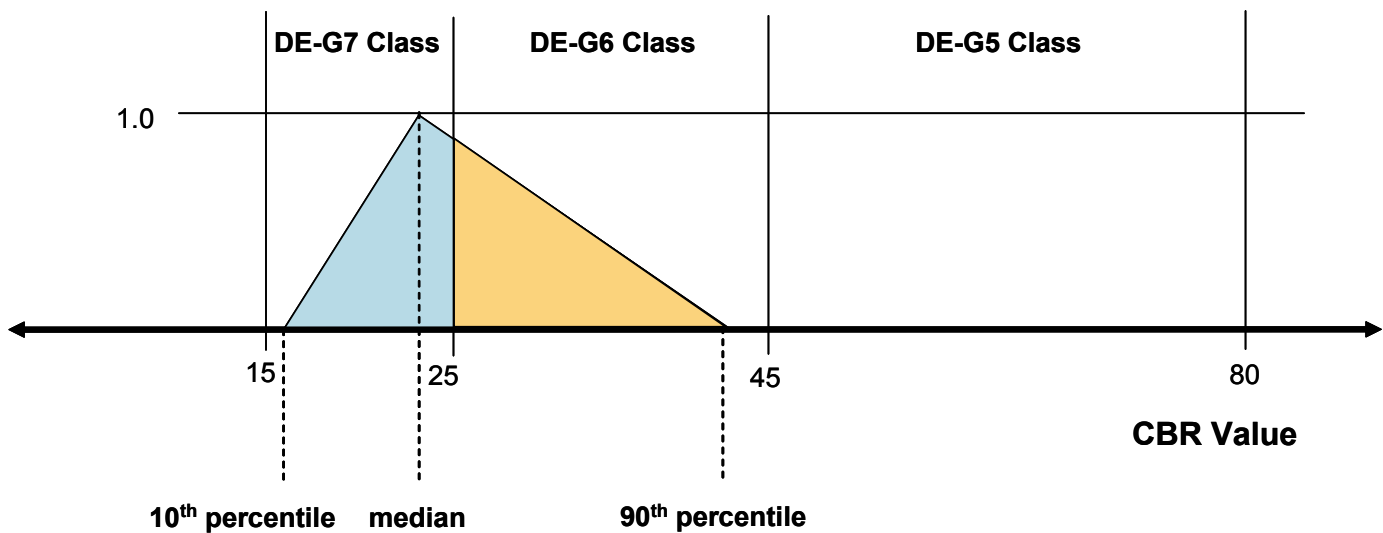


Figure A.3 Determining Relative Conformance of Evidence to Material Class Limits

### A.3.6. Updating Material Classification for Available Evidence

The objective of the assessment is to determine the certainty associated with the hypothesis that a material conforms to a selected DEMAC. For example, if the material selected for evaluation is a DE-G6, and we want to obtain the relative certainty that the material is indeed a DE-G6. As defined in Section A.3.1, the certainty for this hypothesis is  $C(H)$ , which is initially zero, but which will increase when we consider tests for which the results conform partly to the range expected for a DE-G6 material.

The certainty factors for the different tests, combined with the adjustment for sample size, provide the certainty factor  $CF$  associated with each test (Section A.3.3). The comparison of the test results with the expected limits for the DEMAC in question (as shown in Figure A.3 and discussed in Section A.3.5) provides us with the certainty that evidence is present,  $C(E)$ . These are all the factors needed to calculate an updated certainty for the hypothesis that the material tested conforms to the selected DEMAC, i.e.  $C(H|E)$  as defined by Equations A.1 to A.4 (Section A.3.1).

Usually, the calculation of  $C(H|E)$  mostly involves repeated application of Equation A.2. Initially,  $C(H)$  is zero. Then,  $CF'$  is calculated using Equation A.1, and then  $C(H|E)$  using Equation A.2. Then, the next test type is evaluated, which has a new  $CF$  and  $C(E)$  associated with it. The  $CF'$  is then recalculated. For the new test type, the certainty  $C(H)$  is set equal to  $C(H|E)$  determined from the previous test type. The  $C(H)$  and  $CF'$  in Equation A.1 are used to calculate the new  $C(H|E)$ . This process is repeated for each test type to obtain an overall certainty that the material conforms to the selected DEMAC.

Once the overall certainty that the material conforms to the selected DEMAC is assessed, the next likely class is selected and the process repeated using the same set of information. In some instances, this evaluation may require that the conformance to five or more classes be evaluated. Although this seems cumbersome, the calculations are simple and the process can easily be automated using a spreadsheet macro or a computer program.

A software program to do the material classification is available on [www.asphaltacademy.co.za/bitstab](http://www.asphaltacademy.co.za/bitstab). The software runs on the website and it is not necessary to download the software to a local computer. A Microsoft Excel template for preparing and uploading the data can be downloaded from the website.




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**A.4. TESTS AND INTERPRETATION OF RESULTS**

This section details the tests that are used for the material classification, the interpretation of the test results and the certainty factors. Three materials are covered: untreated granular materials, bitumen stabilised materials and cement stabilised materials.

The material classification method is relatively new, and although it has been well validated, especially for granular and cemented materials (Long, 2009), it is possible that further refinements may be necessary. If such refinements are made, the most up to date limits and certainty factors will be posted on [www.asphaltacademy.co.za/bitstab](http://www.asphaltacademy.co.za/bitstab). It is therefore recommended that before commencing the material classification process, the website is checked for any changes in values or tests.



**Test and Indicator Limits**

[www.asphaltacademy.co.za/bitstab](http://www.asphaltacademy.co.za/bitstab) has the most **up to date** limits and certainty factors for the selected tests and indicators.

**A.4.1. Granular Materials**

The classification of granular materials is aligned with TRH14 (1985). The indicators and tests for the classification of unbound granular materials are detailed in Table A.2, and the relevance of the test or indicator is explained. The interpretation of the test results are given in Table A.3. The values shown have been validated and provide consistent, reasonable results (Long, 2009). The interpretation of consistency, visible moisture, grading and historical performance requires the determination of a rating. Details on the ratings are given in Table A.4, with additional information in Table A.5 (historical performance), Table A.6 (consistency) and Figure A.4 (grading).

**Table A.2 Indicators and Tests for Classification of Unbound Granular Materials**

Test or Indicator	Relevance for Material Classification	Interpretat. or Rating	Comments
Soaked CBR	When soaked, tests mainly the frictional strength component of shear strength.	Table A.3	Test relevance and interpretation is based on TRH14 specifications.
Percent passing 0.075 mm Sieve (Fines)	Impacts on the density that can be achieved, and on the bearing strength of the material. As such, relates mainly to frictional component of shear strength.	Table A.3	Ideal range is 6 to 10%. At less than 4% fines, density is difficult to achieve. Shear strength reduces when fines exceed roughly 13% (Hefer and Scullion, 2002; Gray, 1962).
Relative Density	Relates to the density of packing of particles, and hence to the potential to develop frictional resistance.	Table A.3	Test relevance and interpretation is based on TRH14 specifications.
DCP Penetration	Indicator for overall shear strength. Sensitive to density, moisture content, particle strength, grading and plasticity.	Table A.3	Test relevance and interpretation is based on experience and ranges published Kleyn (1984).
FWD Backcalculated Stiffness	Provides a direct but relative indication of the stiffness under dynamic loading for most materials. Likely to be highly correlated to shear strength at small strains.	Table A.3	Test relevance and interpretation ranges based on experience in southern Africa.
Consistency Rating	Provides a rough indication of material density and stiffness.	Table A.4	Rating based on material consistency evaluation from test pits.
Plasticity Index	Determines the influence of water on shear strength. For a fixed maximum aggregate size, shear strength is greatly reduced with an increase in PI.	Table A.3	Based on TRH14. Test relevance and main effects related to shear strength are reported in Hefer and Scullion (2002); and in Gray (1962).



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Test or Indicator	Relevance for Material Classification	Interpretat. or Rating	Comments
Visible and Measured Moisture Content	The relative moisture content is the measured moisture content, relative to the optimum moisture content for the material. It provides an indication of the degree of saturation and the relative cohesive strength.	Table A.3 and Table A.4	Rating and limits are based on experience, and on specifications reported by Hefer and Scullion (2002). These include the specifications of New South Wales (1997), and Queensland (1999).
Grading Assessment Rating	Rating quantifies the conformance of the material grading to applicable specifications. Good conformance to grading indicates increased frictional resistance.	Table A.4 and Figure A.4	Rating requires that the relative conformance to the appropriate grading be quantified. This value is then used to obtain an overall rating for grading based on material type.
Grading Modulus	Quantifies the relative amount of fines in the material. As such, it influences the ability of the material to develop interlock between coarse particles.	Table A.3	Based on TRH14 and on COLTO (1998) specifications.
Historical Performance	The historical performance for the base and subgrade can be isolated with some confidence using past traffic and observed condition.	Table A.5	Based on experience and existing guidelines (e.g. TRH12, 1998).



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Table A.3 Interpretation of Indicators and Tests for Classification of Unbound Granular Materials

Test or Indicator	Material	Design Equivalent Material Class										CF
		DE-G1	DE-G2	DE-G3	DE-G4	DE-G5	DE-G6	DE-G7	DE-G8	DE-G9	DE-G10	
Soaked CBR (%)	CS (98%)	> 100		80 to 99		45 to 79	25 to 44	15 to 24	10 to 14	7 to 9	< 7	0.4
	NG (95%)					> 45	25 to 44	15 to 24	10 to 14	7 to 9	< 7	
	NG/GS (93%)						> 25	15 to 24	10 to 14	7 to 9	< 7	
	SSSC (90%)							> 15	10 to 14	7 to 9	< 7	
P <sub>0.075</sub> (%)	CS	4 to 12										0.3
	NG				5 to 15	13 to 20	15 to 25	25 to 30	30 to 40	40 to 50	> 50	
	GS					5 to 15	13 to 20	15 to 25	25 to 30	30 to 40	> 40	
	SSSC						0 to 10	10 to 15	15 to 20	20 to 30	> 30	
Relative density	All	> 1.02	1.00 to 1.02	0.98 to 1.0	0.95 to 0.98	0.93 to 0.95					< 0.93	0.3
DCP Pen (mm/blow)	All	< 1.40	1.40 to 1.79	1.80 to 1.99	2.00 to 3.69	3.70 to 5.69	5.7 to 9.09	9.1 to 13.99	14 to 18.99	19.0 to 25.0	> 25	0.4
FWD Backcalc. Stiffness (MPa)	All	> 600	500 to 600	400 to 499	300 to 399	200 to 299	150 to 199	100 to 149	70 to 99	50 to 69	0 to 49	0.3
	CS	< 4	4 to 5	5 to 7	7 to 10	> 10						0.4
	NG			< 5	5 to 6	6 to 10	10 to 12	> 12				
	GS						< 11	11 to 12	12 to 15	> 15		
SSSC							< 12	12 to 14	14 to 20	> 20		
Relative moisture (%)	CS	< 60	60 to 65	65 to 80	80 to 90	90 to 100	> 100					0.3
	NG			< 65	65 to 70	70 to 80	80 to 100	> 100				
	GS						< 80	80 to 90	90 to 100	> 100		
	SSSC							< 90	90 to 100	100 to 120	> 120	
Grading modulus	NG				2.0 to 2.6	1.5 to 2.6	1.2 to 2.7	< 1.2				0.2
	GS						1.2 to 2.5	0.75 to 2.7	0.75 to 2.7	0.75 to 2.7	< 0.75	
Rating	All	0.5 to 1.5	1.5 to 2.5	2.5 to 3.5	3.5 to 4.5	4.5 to 5.5	5.5 to 6.5	6.5 to 7.5	7.5 to 8.5	8.5 to 9.5	9.5 to 10.5	N/A

Abbreviations: CS = crushed stone, NG = natural gravel, GS = gravel soil, SSSC = sand, silty sand, silt, clay; 98%, 95%, 93%, 90% are Mod. AASHTO densities.

Table A.4 Rating of Indicators and Tests for Classification of Unbound Granular Materials

Test or Indicator	Material	Rating										CF						
		1	2	3	4	5	6	7	8	9	10							
Consistency (see Table A.6)	CS	Very dense	Dense	Medium dense	Loose	Very loose												
	NG			Very dense	Dense	Medium dense	Loose	Very loose										
	NG/GS					Very dense	Dense	Medium dense	Very loose								0.2	
	SSSC							Very stiff	Stiff	Firm	Soft	Very soft						
Visible moisture	CS	Dry	Slightly moist	Moist	Very moist	Wet												
	NG		Dry	Slightly moist	Moist	Very moist	Wet											
	GS					Dry		Slightly moist	Moist	Very moist	Wet						0.2	
	SSSC									Dry		Slightly moist	Moist	Very moist	Wet			
Grading (see Figure A.4)	CS	1	2	3	4													
	NG				1	2	3	4										0.4
	GS									1	2	3	4					

Abbreviations: CS = crushed stone, NG = natural gravel, GS = gravel soil, SSSC = sand, silty sand, silt, clay





APPENDIX A: Material Classification System

Table A.5 Rating of Historical Performance

Layer	Condition Description	Traffic Accommodated to Date (MESA)				
		< 0.5	0.5 to 1	1 to 3	3 to 10	> 10
Base <sup>1</sup>	No visible rutting, deformation, pumping or potholes, surfacing mostly intact. Minor patching only.	Difficult to assess		2	1	1
	Less than 8 mm narrow rutting in wheelpath, minor pumping and traffic-related cracking. Minor patching.	Difficult to assess	4	3	2	1
	8 to 12 mm narrow rutting in wheelpath, some deformation, shoving and/or pumping. Frequent patching noted.	7	5	4	3	Difficult to assess
	More than 12 mm narrow rutting in wheelpath, severe and frequent shoving, pumping and/or deformation. Frequent patching.	9	7	5	Difficult to assess	
Subbase <sup>2</sup>	No wide, subgrade relative rutting visible.	Difficult to assess		7	6	5
	Suspect some subgrade deformation occurred, as shown by wide, subgrade related rutting (<10 mm depth), and slight undulation and/or subgrade related failures.	Difficult to assess		8	7	6
	Strong evidence of subgrade related rutting (>10 mm depth) and/or definite signs of subgrade related failures.	10	9	8	Difficult to assess	

Notes:

1. Assessment is only valid if there are no surfacing related problems (e.g. stripping, brittleness, rutting) which may have caused a rapid deterioration in the base layer. Also, assessment is not valid if overlay or surface seal was recently placed.
2. Assessment is only valid if an overlay or surface seal was no recently placed.

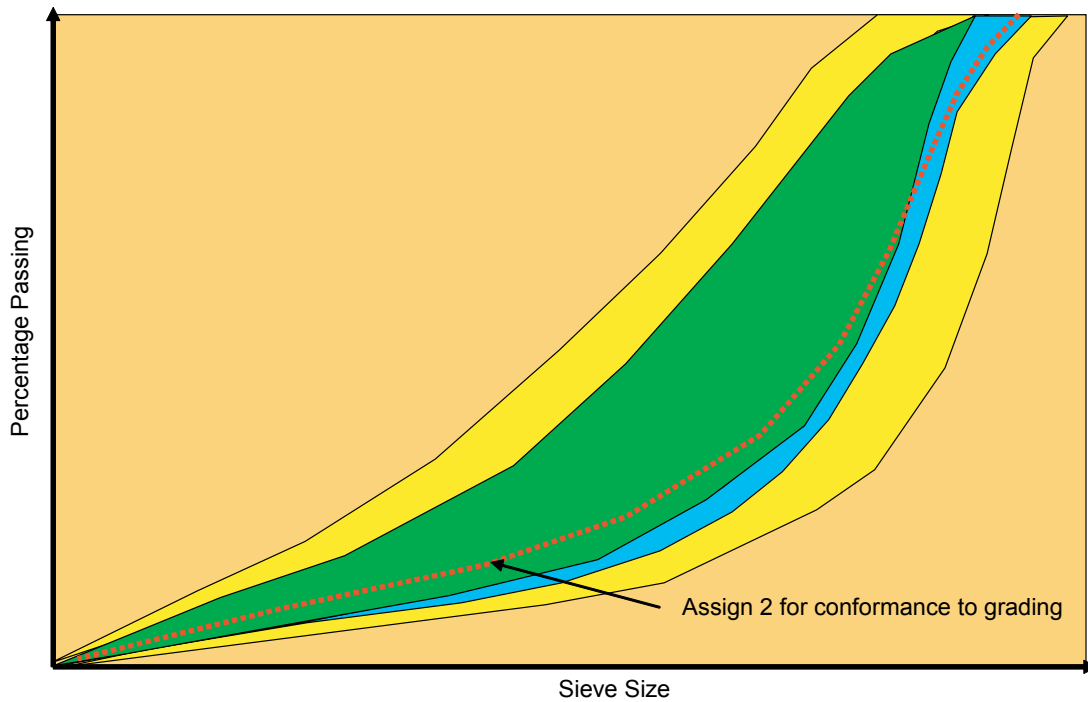


Table A.6 Guidelines for Consistency

Material Type	Consistency	Description of Layer Condition
Coarse granular materials	Very Loose	Very easily excavated with spade. Crumbles very easily when scraped with geological pick.
	Loose	Small resistance to penetration by sharp end of geological pick.
	Medium Dense	Considerable resistance to penetration by sharp end of geological pick.
	Dense	Very high resistance to penetration of sharp end; and requires blows of geological pick for excavation.
	Very Dense	Very high resistance to repeated blows of geological pick; and requires power tools for excavation.
Cohesive soils	Very Soft	Geological pick head can easily be pushed in to the shaft of handle; easily moulded by fingers.
	Soft	Easily penetrated by thumb; sharp end of geological pick can be pushed in 30 to 40 mm; moulded with some pressure.
	Firm	Indented by thumb with effort; sharp end of geological pick can be pushed in up to 10 mm; very difficult to mould with fingers; can just be penetrated with an ordinary hand spade.
	Stiff	Penetrated by thumb nail; slight indentation produced by pushing geological pick point into soil; cannot be moulded by fingers; requires hand pick for excavation.
	Very Stiff	Indented by thumb nail with difficulty; slight indentation produced by blow of geological pick point; requires power tools for excavation.



APPENDIX A: Material Classification System



- 1** Inside Grading Envelope
- 2** Just coarse of envelope, but follows envelope closely (well-graded)
- 3** Fine of envelope, or significantly coarse of envelope
- 4** Significant deviation from specified envelope

Figure A.4 Interpretation of Grading to Quantify Relative Conformance to Grading (Granular)

A.4.2. Bitumen Stabilised Materials

The classification for BSMs is intended to assess the suitability of the material for treatment with bitumen emulsion or foamed bitumen and to determine the DEMAC. It therefore assesses the material based on many of the same tests and indicators as used for granular materials, and then in addition evaluates the BSM mix using test results from the mix design process. Although some of the limits in the tests are different for BSM-emulsion and BSM-foam, in the final classification no distinction is made between the two materials.

The following three material classes are used for BSMs:

- » **BSM1:** This material has high shear strength, and is typically used as a base layer for design traffic applications of more than 6 million equivalent standard axles (MESA). For this class of material, the source material is typically a well graded crushed stone or reclaimed asphalt (RA).
- » **BSM2:** This material has moderately high shear strength, and is typically used as a base layer for design traffic applications of less than 6 MESA. For this class of material, the source material is typically a graded natural gravel or RA.
- » **BSM3:** This material is typically a soil-gravel and/or sand, stabilised with higher bitumen contents. As a base layer, the material would only be suitable for design traffic applications of less than 1 MESA.

A fourth option is also shown for many of the tests or indicators, which indicates that the material is not suitable for treatment. In these cases, the material should be classified as a granular material (Section A.4.1).

The indicators and tests for the classification of BSMs are detailed in Table A.7, and the relevance of the test or indicator is explained. The interpretation of the test results are given in Table A.8. The values shown have been validated and provide consistent, reasonable results (Long, 2009). The interpretation of grading requires the determination of a rating, which is detailed in Table A.9 and Figure A.5 (which is a repeat of Figure 3.2 and Figure 4.2.)



APPENDIX A: Material Classification System

Table A.7 Indicators and Tests for Classification of Bitumen Stabilised Materials

Test or Indicator	Relevance for Material Classification	Interpret. or Rating	Comments
Soaked CBR (untreated)	When soaked, tests mainly the frictional strength component of shear strength.	Table A.8	Test relevance and interpretation is based on TRH14 specifications.
Percent passing 0.075 mm Sieve (Fines) (Untreated)	Impacts on the density that can be achieved, and on the bearing strength of the material. As such, relates mainly to frictional component of shear strength.	Table A.8	Ideal range is 6 to 10%. At less than 4% fines, density is difficult to achieve. Shear strength reduces when fines exceed roughly 13% (Hefer and Scullion, 2002; Gray, 1962). Fines are also required to distribute bitumen emulsion and foamed bitumen.
Relative Density (Untreated)	Relates to the density of packing of particles, and hence to the potential to develop frictional resistance.	Table A.8	Test relevance and interpretation is based on TRH14 specifications.
DCP Penetration (Untreated)	Indicator for overall shear strength. Sensitive to density, moisture content, particle strength, grading and plasticity	Table A.8	Test relevance and interpretation is based on experience and ranges published Kley (1984).
FWD Back-calculated Stiffness (Untreated)	Provides a direct but relative indication of the stiffness under dynamic loading. Likely to be highly correlated to shear strength at small strains for most materials.	Table A.8	Test relevance and interpretation ranges based on experience in southern Africa.
Plasticity Index (Untreated)	Determines the influence of water on shear strength. For a fixed maximum aggregate size, shear strength is greatly reduced with an increase in PI.	Table A.8	Based on TRH14. Test relevance and main effects related to shear strength are reported in Hefer and Scullion (2002); and in Gray (1962).
Measured Moisture Content (Untreated)	The relative moisture content is the measured moisture content, relative to the optimum moisture content for the material.	Table A.8	Rating and limits are based on experience, and on specifications reported by Hefer and Scullion (2002). These include the specifications of New South Wales (1997) and Queensland (1999).
Grading Assessment Rating (Untreated)	Rating quantifies the conformance of the material grading to applicable specifications. Good conformance to grading indicates increased frictional resistance.	Table A.9 and Figure A.5	Rating requires that the relative conformance to the appropriate grading be quantified. This value is then used to obtain an overall rating for grading based on material type.
Grading Modulus (Untreated)	Quantifies the relative amount of fines in the material. As such, it influences the ability of the material to develop interlock between coarse particles.	Table A.8	Based on TRH14 and on COLTO (1998) specifications.
Cohesion, Friction Angle and Tangent Modulus (Treated)	The shear parameters and material stiffness from triaxial testing provide critical performance properties related to resistance to permanent deformation.	Table A.8	Test relevance and interpretation based on global mix designs and research in Jenkins <i>et al</i> (2008).
ITS (Treated)	Provides a reference to the historic performance of mixes ( $ITS_{dry}$ ) and a measure of moisture resistance ( $ITS_{wet}$ ).	Table A.8	Test relevance and interpretation ranges based on experience in southern Africa.
UCS (Treated)	Provides a measure of the compressive strength of mixes, and a reference to the historic performance of mixes	Table A.8	Test relevance and interpretation ranges based on experience in southern Africa.
Retained Cohesion (MIST) (Treated)	The change in cohesion after moisture conditioning from triaxial testing provides a measure of moisture resistance.	Table A.8	Test is new, selected because gives most realistic simulation of pore pressures in BSMs trafficked in wet conditions. Test relevance and interpretation base on research testing of limited South African materials. Based on Jenkins <i>et al</i> (2008).



## APPENDIX A: Material Classification System

**Table A.8 Interpretation of Indicators and Tests for Classification of Bitumen Stabilised Materials**

Test or Indicator	Material <sup>1</sup>	Design Equivalent Material Class			Not suitable for treatment	CF
		DE-BSM1	DE-BSM2	DE-BSM3		
Soaked CBR (%)	CS (98%)	> 80	25 to 80	10 to 25	< 10	0.4
	NG (95%)		> 25	10 to 25	< 10	
P0.075 (%) (Bitumen emulsion)	CS	4 to 15			> 15	0.35
	NG		5 to 25	25 to 40	> 40	
	GS		5 to 20	15 to 30	> 30	
	SSSC			0 to 20	> 20	
P0.075 (%) (Foamed bitumen)	CS	2 to 15			> 15	0.35
	NG		11 to 25	23 to 40	> 40	
	GS		0 to 20	13 to 30	> 30	
	SSSC			0 to 20	> 20	
Relative density	All	> 0.98	0.95 to 0.98	0.93 to 0.95	< 0.93	0.1
DCP Pen (mm/blow)	All	< 3.7	3.7 to 9.1	9.1 to 19.0	< 19.0	0.1
FWD Backcalculated Stiffness (MPa)	All	> 300	150 to 300	70 to 150	< 70	0.1
Plasticity Index	CS	< 10	> 10			0.25
	NG	< 6	6 to 12	> 12		
	GS		> 11	11 to 15	< 15	
	SSSC			< 15	> 14	
Relative moisture (%)	CS	< 90	> 90			0.1
	NG	< 70	70 to 100	< 80		
	GS		> 100	80 to 100	< 100	
	SSSC			> 100	> 100	
Grading modulus	NG	2.0 to 3.0	1.2 to 2.7	0.15 to 1.2	< 0.15	0.2
	GS		1.2 to 2.5	0.75 to 2.7	< 0.75	
Cohesion (kPa)	All	> 250	100 to 250	50 to 100	< 50	0.45
Friction Angle (°)	All	> 40	30 to 40	< 30		0.4
Tangent Modulus (MPa)	All	> 150	50 to 150	< 50		0.1
ITS <sub>dry / equil</sub> (kPa)	100 mm <sup>2</sup>	> 225	175 to 225	125 to 175	< 125	0.1
	150 mm	> 175	135 to 175	95 to 135	< 95	0.15
ITS <sub>wet</sub> (kPa)	100 mm	> 100	75 to 100	50 to 75	< 50	0.1
UCS (kPa)	All	1 200 to 3 500	700 to 1 200	450 to 700	< 450	0.1
Retained Cohesion (%)	All	> 75	60 to 75	50 to 60	< 50	0.45
Rating	All	0.5 to 1.5	1.5 to 2.5	2.5 to 3.5	3.5 to 4.5	N/A

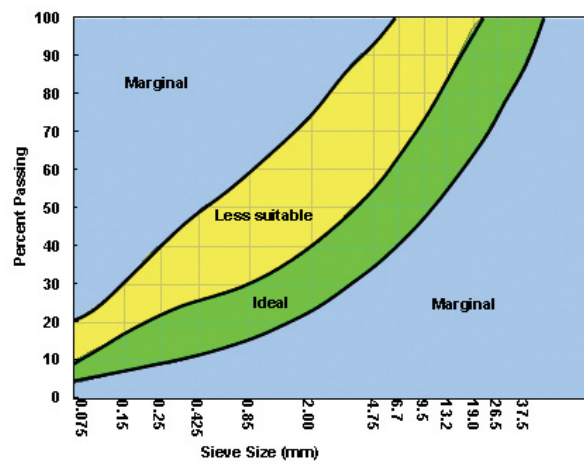
**Notes:**

1. CS = crushed stone, NG = natural gravel, GS = gravel soil, SSSC = sand, silty sand, silt, clay; 98%, 95%, 93%, 90% are Mod. AASHTO densities.
2. Diameter of specimen.



Table A.9 Rating of Indicators and Tests for Classification of Bitumen Stabilised Materials

Test or Indicator	Material <sup>1</sup>	Rating				CF
		1	2	3	4	
Grading (see Figure A.5)	CS	Ideal	Less suitable		Marginal	0.4
	NG		Ideal	Less suitable	Marginal	
	GS		Ideal	Less suitable	Marginal	



Sieve Size (mm)	Percent Passing			
	BSM-Emulsion		BSM-Foam	
	Ideal	Less suitable	Ideal	Less suitable
50	100		100	
37.5	87 – 100		87 – 100	
26.5	77 – 100	100	77 – 100	100
19.5	66 – 99	99 – 100	66 – 99	99 – 100
13.2	67 – 87	87 – 100	67 – 87	87 – 100
9.6	49 – 74	74 – 100	49 – 74	74 – 100
6.7	40 – 62	62 – 100	40 – 62	62 – 100
4.75	35 – 56	56 – 95	35 – 56	56 – 95
2.36	25 – 42	42 – 78	25 – 42	42 – 78
1.18	18 – 33	33 – 65	18 – 33	33 – 65
0.6	12 – 27	27 – 54	14 – 28	28 – 54
0.425	10 – 24	24 – 50	12 – 26	26 – 50
0.3	8 – 21	21 – 43	10 – 24	24 – 43
0.15	3 – 16	16 – 30	7 – 17	17 – 30
0.075	2 – 9	9 – 20	4 – 10	10 – 20

The differences between the grading zones of BSM-emulsion and BSM-foam are small enough that the differences cannot be discerned on the figure.

Figure A.5 Interpretation of Grading to Quantify Relative Conformance to Grading (BSM)



## APPENDIX A: Material Classification System

### A.4.3. Cement Stabilised Materials

The classification of cement stabilised materials focuses on the degree of cementation still present. The material is classified as a rating, from 1 to 3. This rating scheme has the following relationship between the rating and the material classes as defined in TRH14 (1985).

- » **Rating 1:** Indicates condition similar to recently constructed C1, C2, or C3 material.
- » **Rating 2:** Indicates condition similar to recently constructed C4 material.
- » **Rating 3:** Indicates material is either ineffectively stabilised, or has deteriorated to an equivalent granular state. These materials should be regarded as unbound granular materials and the classification guidelines in Section A.4.1 should be applied.

The indicators and tests for the classification of cemented materials are detailed in Table A.10, and the relevance of the test or indicator is explained. The interpretation of the test results are given in Table A.11. The values shown have been validated and provide consistent, reasonable results (Long, 2009).

**Table A.10 Indicators and Tests for Classification of Cement Stabilised Materials**

Test or Indicator	Relevance for Material Classification	Rating	Comments
DCP Penetration	Indicator for overall shear strength. Sensitive to density, moisture content, particle strength, grading and plasticity.	Table A.11	Test relevance and interpretation is based on experience and ranges published Kleyn (1984).
FWD Backcalculated Stiffness	Provides a direct but relative indication of the stiffness under dynamic loading. Likely to be highly correlated to shear strength at small strains for most materials.	Table A.11	Test relevance and interpretation ranges based on experience in southern Africa.
Consistency Rating	Provides a rough indication of the degree of cementation of the material.	Table A.11	Rating based on material consistency evaluation from test pits and on the SANRAL M1 Manual (SANRAL, 2004)
Evidence of Active Cement	Quantifies the confidence that material is acting as a cohesive, cement stabilised layer.	Table A.11	None



Table A.11 Interpretation of Indicators and Tests for Classification of Cemented Materials from Field Observations

Test or Indicator	Rating			CF
	1	2	3	
	Indicates condition similar to recently constructed C1, C2 or C3 material	Indicates condition similar to recently constructed C4 material	Indicates material is either ineffectively stabilised, or deteriorated to an equivalent granular state	
Consistency	Hand-held specimen can be broken with hammer head with single firm blow. Similar appearance to concrete.	Material crumbles under firm blows of sharp geological pick point. Grains can be dislodged with some difficulty under a knife blade.	Some material can be crumbled by strong pressure between fingers and thumb. Disintegrates under a knife blade to a friable state.	0.2
	Firm blows of sharp geological pick point.	Cannot be crumbled between strong fingers. Some material can be crumbled by strong pressure between thumb and hard surface. Disintegrates under light blows of a hammer head to a friable state.		
DCP Penetration (mm/blow)	< 1.50	1.5 to 3.0	> 3	0.4
FWD Backcalculated Stiffness (MPa)	> 1 200	500 to 1 200	< 500	0.3
Evidence of Active Cement	Clearly visible in material colour and consistency. Clear indication of active cement, based on chemical tests.	No cementation visible, slight indication of active cement, based on chemical tests.	No indication of active cement, either in material colour and consistency or from chemical tests.	0.3

## A.5. CONFIDENCE ASSOCIATED WITH ASSESSMENT

The confidence in the certainty associated with the material classes depends on the number of tests or indicators used and the certainty factors associated with the tests and indicators. The strength of confidence in our assessment is thus quantified by the certainty of the assessment, and this is an indirect indicator of the reliability of any design which is based on this assessment. Table A.12 provides some guidelines to assess the confidence associated with the material classification.

Table A.12 Relative Confidence of Materials Classification

Final Value of C(H E)	Confidence in Classification
< 0.3	<b>Very low confidence.</b> It is strongly recommended that more data be gathered to enable a more confident assessment to be made.
0.3 to 0.5	<b>Low confidence.</b> Suitable only for situations where the existing pavement condition and age is such that structural rehabilitation will not be considered or is very unlikely.
0.5 to 0.7	<b>Medium.</b> Suitable or situations where the existing pavement condition and age is such that structural rehabilitation is unlikely, or for which the condition and/or other factors predetermines the treatment type.
> 0.7	<b>High.</b> This is the minimum recommended certainty for situations where structural rehabilitation is likely, and for which the rehabilitation design will rely completely on the quality and state of existing pavement layers.



## APPENDIX A: Material Classification System

### A.6. WORKED EXAMPLE

The following paragraphs illustrate the application of the method described in Section A.3. This example uses data from an actual pavement rehabilitation investigation, but with some slight adjustments to clearly illustrate the concepts of the method. The example involves an assessment of an upper subbase layer for the eastbound lane of a planned rehabilitation project 18 km long.

Based on the condition of the road, the construction history and the deflection patterns, the road was designated as a single uniform design section. All available results are therefore assessed together. The available information consists of the following:

- » **Materials test data from nine test pits.** Available test data include: material description, relative density, moisture content, DCP penetration, grading analyses, CBR and PI.
- » **173 FWD deflections** with backcalculated stiffnesses for all layers.

Table A.13 summarizes some of the test indicators. The grading analyses are summarized in Figure A.6. In the test pits, the material was described as a dense weathered dolerite natural gravel in all instances and therefore the classification system for granular materials is appropriate.

**Table A.13 Example Materials Test Data**

Station (Km)	Relative Density	CBR (%)	% Passing 0.075 mm Sieve	Moisture as % of Optimum	GM	PI	Consistency Rating <sup>1</sup>	Grading Rating <sup>2</sup>	DCP Pen (mm/blow) <sup>3</sup>
1.5	1.03	70	11	70	2.34	9	4	4	1.8
2.7	0.87	24	4	108	2.7	10	4	6	4.8
4.3	0.94	64	5	91	2.67	9	4	5	-1
4.9	1	66	6	96	2.65	7	4	5	-1
7.9	1	70	13	67	2.17	8	4	4	-1
9.2	1	100	3	75	2.68	8	4	5	-1
12.5	1	90	12	63	2.24	5	4	4	2.4
14.3	0.98	80	6	72	2.59	8	4	4	1.4
17.5	0.94	N/R	10	48	2.24	6	4	5	-1
10 <sup>th</sup> Percentile	<b>0.93</b>	<b>52</b>	3.8	<b>60</b>	<b>2.2</b>	<b>6</b>	4	4	<b>-1.0</b>
Median	<b>1.00</b>	<b>70</b>	6.0	<b>72</b>	<b>2.6</b>	<b>8</b>	4	5	<b>-1.0</b>
90 <sup>th</sup> Percentile	<b>1.01</b>	<b>93</b>	12.2	<b>98</b>	<b>2.7</b>	<b>9</b>	4	5	<b>2.9</b>
Observations	<b>9</b>	<b>8</b>	9	<b>9</b>	<b>9</b>	<b>9</b>	9	9	<b>9</b>

- Note:**
1. Consistency rating determined from Table A.4 and Table A.6.
  2. Grading rating determined from Table A.4 and Figure A.4.
  3. For DCP penetration, a value of -1 indicates refusal.

The backcalculated stiffnesses for the subbase were as follows:

- » 10<sup>th</sup> Percentile = 189 MPa
- » Median = 466 MPa
- » 90<sup>th</sup> Percentile = 581 MPa

For most of the available tests, the results can be directly evaluated by means of the interpretation guidelines provided in Section A.4. However, for the consistency and grading, the test results first have to be converted to a rating, to facilitate a numerical evaluation of results. The ratings assigned for these indicators are summarized in Table A.13.



APPENDIX A: Material Classification System

Once all the tests have been quantified, we can summarize the available tests, their certainty factors and their sample statistics. For this example, the certainty factors from Table A.3 were adopted. Since the sample size exceeds six for all tests, the adjustment factor for sample size (from Table A.1) is 1.0 in all cases. The available test data and certainty factors are summarized in Table A.14.

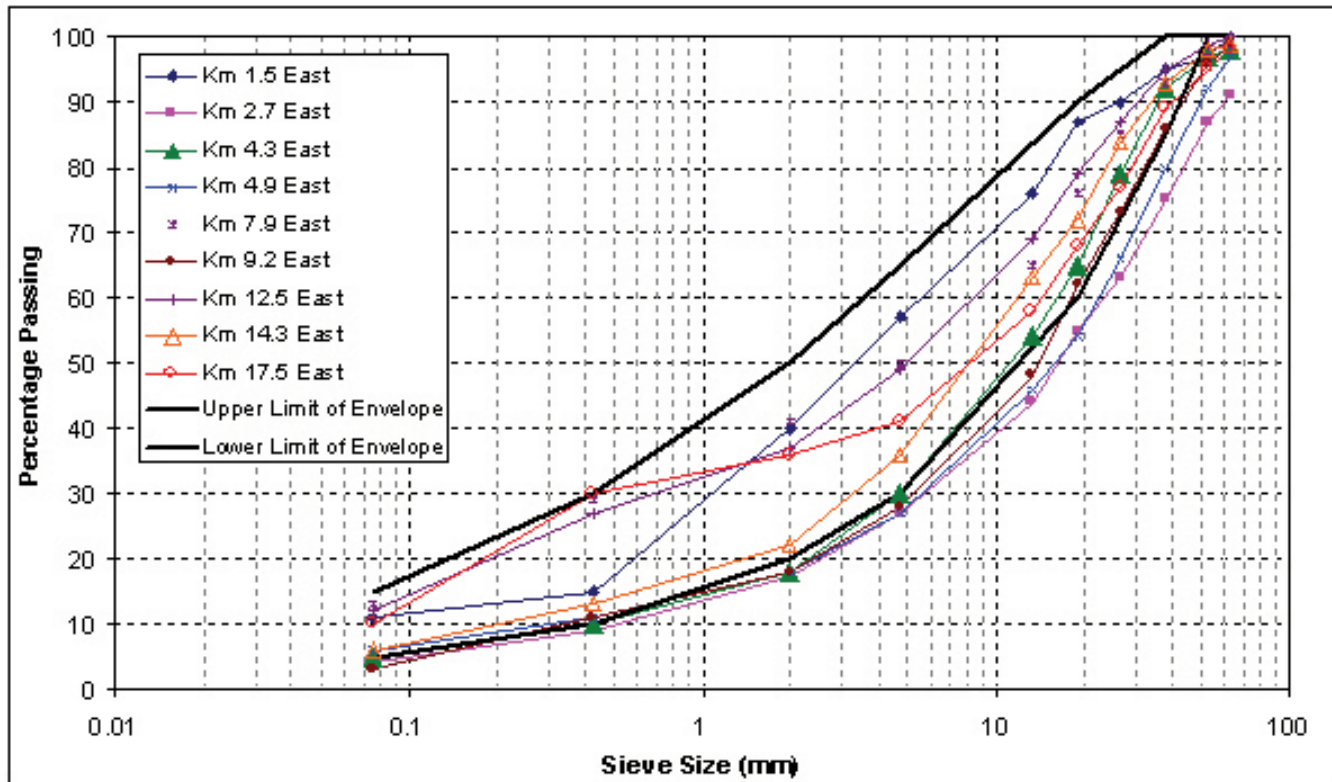


Figure A.6 Grading Analyses for Worked Example

Table A.14 Worked Example, Summary of Test Data and Certainty Factors

Test	CF	CF'	10 <sup>th</sup> %	Median	90 <sup>th</sup> %	C(E) DE-G4	C(E) DE-G5	C(E) DE-G6
DCP Penetration	0.4	0.4	-1.0	-1.0	2.9	0.05	0.00	0.00
CBR (NG)	0.4	0.4	52	70	93	0.18	0.79	0.0
P0.075 (NG)	0.3	0.3	3.8	6.0	12.2	0.92	0.0	0.0
Relative Density	0.3	0.3	0.93	1.00	1.01	0.20	0.21	0.02
FWD Stiffnesses	0.3	0.3	189	466	581	0.30	0.11	0.00
Consistency Rating	0.2	0.2	4	4	4	1.0	0.0	0.0
PI (NG)	0.4	0.4	6	8	9	0.0	1.0	0.0
Rel. Moisture (NG)	0.3	0.3	60	72	98	0.33	0.54	0.08
Grading Rating	0.4	0.4	4	5	5	0.25	0.75	0.0
GM (NG)	0.2	0.2	2.2	2.6	2.7	0.44	0.50	0.06
Column	1	2	3	4	5	6	7	8

In Table A.14, CF is the certainty factor related to the test type, and CF' is simply CF adjusted to take account of sample size. In this case, CF' is equal to CF because the sample size is greater than 6 in all cases. Columns 6, 7 and 8 represent the relative certainty that the test evidence points to a DE-G4, DE-G5 or DE-G6 design equivalent material class.



APPENDIX A: Material Classification System

The factors C(E) are determined using the method described in Section A.3.1. Figure A.7 shows an example of the detailed calculation of C(E) for FWD Backcalculated Stiffness. This calculation relies on the FWD stiffness limits recommended in Table A.3 and on the sample statistics shown highlighted for FWD stiffness in Table A.14.

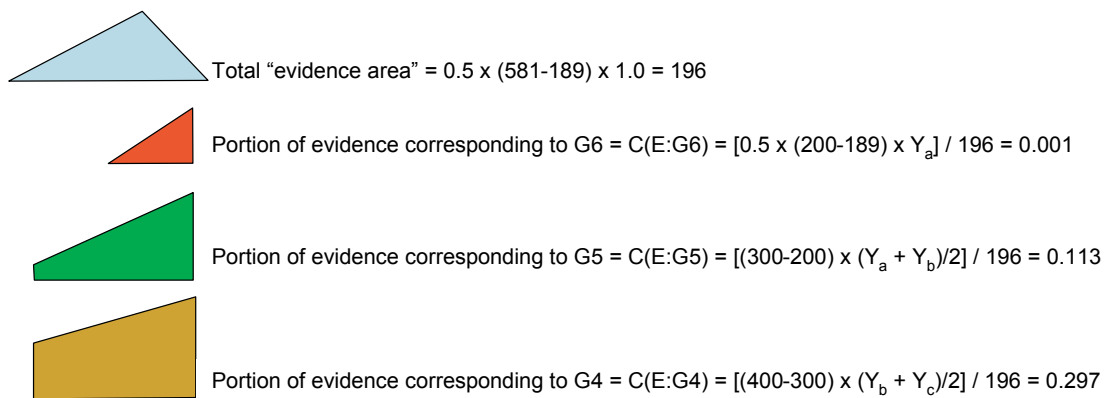
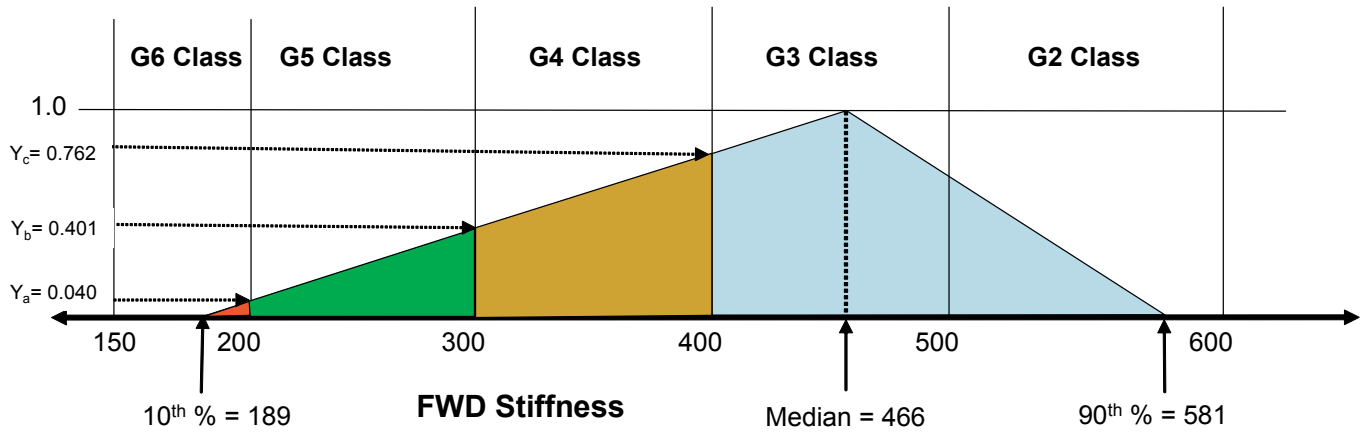


Figure A.7 Example of C(E) Calculations for FWD Backcalculated Stiffness Sample

Table A.15 shows the final adjusted certainty factors (CF') for a DE-G4, DE-G5 and DE-G6 material, and also the cumulative certainty that the material is a DE-G4, DE-G5 or DE-G6 (i.e. C(H|E)). The final cumulative certainty for these three material classes is shown in the bottom row. The classification method shows that most of the evidence points to the material being a DE-G5, and some evidence also points to a DE-G4. In comparison to a DE-G4 and DE-G5, there is comparatively little information to suggest that the material is a DE-G6.



Table A.15 Worked Example, Summary of Certainty Associated with DE-G4, DE-G5 and CE-G6

Test	CF'			C(H-DEGX E)		
	DE-G4	DE-G5	DE-G6	DE-G4	DE-G5	DE-G6
DCP Penetration	0.02	0.00	0.00	0.02	0.00	0.00
CBR	0.00	0.40	0.00	0.02	0.04	0.00
P0.075	0.28	0.00	0.00	0.29	0.4	0.00
Relative Density	0.13	0.11	0.02	0.38	0.47	0.02
FWD Stiffnesses	0.09	0.03	0.00	0.44	0.49	0.02
Consistency Rating	0.20	0.00	0.00	0.55	0.49	0.02
PI	0.00	0.40	0.00	0.55	0.69	0.02
Measured Moisture	0.06	0.13	0.09	0.58	0.73	0.11
Grading Rating	0.10	0.30	0.00	0.62	0.81	0.11
GM	0.16	0.09	0.20	0.68	0.83	0.29
<b>Final Assessment of Relative Certainty for</b>				<b>DE-G4 = 0.68</b>	<b>DE-G5 = 0.83</b>	<b>DE-G6 = 0.29</b>
<p><b>Most likely Materials Class is a G5 Design Equivalent Class</b>  <b>Relative Certainty associated with this outcome = 0.83</b>            Confidence associated with this outcome is <b>High</b>.            Assessment is suitable for situations where structural rehabilitation is required, or for which the rehabilitation design will rely completely on the state of existing layers.</p>						

**Note:** CF' calculated with Equation A.1  
 C(H-G4/G5/G6|E) calculated with Equation A.2, A.3 or A.4



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## APPENDIX B: LABORATORY TESTS

Test	Test Method		
	Website <sup>1</sup>	TMH1	Other
Atterberg Limits		A1, B4	
Bulk Relative Density		B14	
California Bearing Ratio (CBR) - Soaked		A8	
Dilution Test for Bitumen Emulsions	Method 1		
Dynamic Cone Penetrometer (DCP)			TMH6
Dry density vs moisture curve		A7	
Durability Mill Index (DMI)			CSIR TS/20/85
Bitumen emulsion type » Anionic » Cationic			SANS 308 SANS 548
Expansion Ratio	Method 2		
Fractured Faces			ASTM D5821-01
Grading Modulus			TRH14
Half-life	Method 2		
Indirect Tensile Strength (ITS)	Method 3		
Indirect Tensile Strength – wet (ITS <sub>wet</sub> )	Method 4		
Laboratory Pugmill Mixing	Method 6		
Preparation of field cores for testing	Method 9		
Preparation of field material for manufacture of specimens	Method 10		
Retained Cohesion (MIST)	Method 7		
Modified AASHTO compaction		A7	
Moisture contents	Method 8	A7	
Plasticity Index		A1, B4	
Sieve Analysis / Grading		A1, B4	
Simple Triaxial Test » Cohesion » Friction Angle » Tangent Modulus	Method 7		
Unconfined Compressive Strength (UCS)	Method 5		
Vibratory Hammer Compaction	Method 8		

**Note:** 1. These tests are available for download on [www.asphaltacademy.co.za/bitstab](http://www.asphaltacademy.co.za/bitstab).



## APPENDIX C: Pavement Number Structural Design System

# APPENDIX C: PAVEMENT NUMBER STRUCTURAL DESIGN METHOD

## C.1. INTRODUCTION

The basic principle of pavement design is to provide structural layers to protect the pavement subgrade against the stresses imposed by traffic. The combined system, consisting of the structural layers and the subgrade, should then function as a unit in a balanced system to achieve the desired design structural capacity. In essence, pavement balance requires that there should be a gradual decrease in strength from the top to the bottom pavement layers and that the strength of the structural pavement layers should not greatly exceed that of the subgrade. The exception to this is the use of inverted pavement structures in South Africa, although the structural layers typically have more strength than the subgrade.

The structural design of pavements incorporating Bitumen Stabilised Materials uses a knowledge based approach, termed the Pavement Number (PN). The PN is based on the Structural Number concept, which was used in the original AASHTO methods (AASHTO, 1996).

However, some of the shortcomings of the Structural Number have been overcome in the PN method. The PN method was chosen for several reasons.

- » **Data from in-service pavements** were used to develop the method. The type and detail of the data suggests the use of a relatively simple method and precludes the use of a Mechanistic-Empirical design method.
- » The method gives a **good fit** to the available field data.
- » The method is **robust**, and cannot easily be manipulated to produce inappropriate designs.

The development and validation of the PN method are described in Jooste, *et al* (2007) and Long (2009). The method is applicable to all pavement materials commonly used in southern Africa. This method relies on basic points of departure, or rules-of-thumb, which reflect well-established principles of pavement behaviour and performance, and which will ensure an appropriate pavement design solution in most situations. The concepts in the rules-of-thumb are quantified into specific rules with constants or functions associated with each rule. The rules-of-thumb are described in the next section.

The PN method was calibrated by calculating the PN value for several pavements extracted from the TRH4 catalogue (TRH4, 1996), and for which the structural capacities were known with some certainty from experience. Using these data, the quantified rules-of-thumb were adjusted to optimize the correlation between PN and structural capacity. The final rules were then validated using observed pavement performance data. The development of the rules-of-thumb and the calibration and initial validation processes are described by Jooste and Long (2007). The additional validation process and final values for the rules-of-thumb are described by Long (2009).

The constants shown for the PN method included in this guideline were the values used at the time of publication of the guideline. Although these values were well validated (Long, 2009), it may be necessary from time to time to make changes to improve the system. If changes are made, the modified values will be reflected on [www.asphaltacademy.co.za/bitstab](http://www.asphaltacademy.co.za/bitstab). It is therefore recommended that before commencing a Pavement Number calculation, the website is checked for any changes in values or tests.

The PN method is designed to be used in conjunction with the material classification system described in Appendix A. The method is applicable to both new construction and rehabilitation. For rehabilitation projects, the material class would be the design equivalent material class (DEMAC). For brevity, in this Appendix, the term material class is used for both new construction and rehabilitation, but it should be understood that the term implies the DEMAC for rehabilitation projects.

## C.2. APPLICABILITY AND LIMITATIONS OF THE PAVEMENT NUMBER METHOD

Before the calculation of the pavement number is started, the designer should check to ensure that the design method is applicable to the pavement situation and that none of the following situations apply:

- » **Design traffic greater than 30 MESA.** The PN method was calibrated using a knowledge base which was limited to pavements that had accommodated less than 30 million standard axles (MESA). Thus, in such a design situation, the design must be checked using more in-depth analysis.



## APPENDIX C: Pavement Number Structural Design System

- » **Presence of thin, weak lenses.** If thin, weak lenses of material exist below the surfacing, or between stabilised layers, then zones of high slip and shear will develop, and routine design calculations will not apply. In such instances, the structural capacity assessment of the PN method will not be appropriate, and special treatment of the affected weak lens must be undertaken. The PN design method cannot be applied to situations where such lenses still exist within the pavement structure, especially where such lenses are located within the upper 400 mm of the pavement structure.
- » **Design traffic less than 1 MESA.** In cases where the design traffic is less than 1 MESA, the designer should use the design catalogues in Chapter 5.
- » **Subgrade CBR less than 3%.** The knowledge base on which the PN method was calibrated did not include any pavements that had a subgrade CBR less than 3%. The PN method should therefore not be used in cases where the subgrade CBR is less than 3% at a depth less than 600 mm below the surface.

### C.3. RULES OF THUMB / DEPARTURE POINTS

This section presents a discussion of the basic rules-of-thumb underlying the method for calculating PN. These rules-of-thumb reflect well-established principles of pavement behaviour and performance. The following rules-of-thumb were adopted as the points of departure for the calculation of the Pavement Number:

#### Rules Relating to the Pavement System In General:

1. The structural capacity of a pavement is a function of:
  - The combined long term load spreading potential of the pavement layers.
  - The relative quality of the subgrade on which the pavement is constructed.
2. The relative quality and stiffness of the subgrade is the departure point for design, as the subgrade is a key determinant in the overall pavement deflection and in the relative degree of bending and shear that will take place in overlying pavement layers.
3. For pavements with thin surfacings, the base layer is the most critical component, and failure in this layer effectively constitutes pavement failure. Experience can guide the relative confidence in different material types to serve as base layers under heavy traffic.

#### Rules Relating to Specific Pavement Layers:

4. The load spreading potential of an individual layer is a product of its thickness and its effective long term stiffness under loading.
5. The Effective Long Term Stiffness (ELTS) of a layer depends on the material type and on its placement in the pavement system.
6. Fine-grained subgrade materials act in a stress-softening manner. For these materials, the ELTS is determined mainly by the material quality and by the climatic region. Owing to the stress softening behaviour, subgrade materials will generally soften with decreased cover thickness.
7. Coarse-grained, unbound layers act in a stress-stiffening manner. For these materials, the ELTS is determined mainly by the material quality and the relative stiffness of the supporting layer. The ELTS of these materials will increase with increasing support stiffness, by means of the modular ratio limit, up to a maximum stiffness which is determined mainly by the material quality.
8. Cement stabilised materials initially act as a stiff, glassy material, but gradually deteriorate into a material consisting of loose clumps or separate blocks that can be solid or deteriorated into a granular state. For a specific DEMAC, the rate of deterioration depends mainly on the thickness of the layer and on the stiffness of the support.
9. Thin asphalt surfacings act as either stiff, glassy material, or as semi-stiff, rubbery material. The material state depends primarily on the temperature and bitumen content. Over time, the material is subject to deterioration owing to ageing and fatigue. Fatigue breakdown is primarily dependent on the stiffness of the supporting layer.
10. Bitumen stabilised materials with low cement contents ( $\leq 1\%$ ) are assumed to act in a similar way to coarse granular materials, but with a higher cohesive strength. The cohesive strength is subject to breakdown during loading, and thus some softening over time can occur. The rate of softening is mainly determined by the stiffness of the support, which determines the degree of shear in the layer. However, owing to the higher cohesive strength in bituminous stabilised materials, these layers are less sensitive to the support stiffness than unbound granular materials, and thus can sustain higher modular ratio limits.

The above-noted rules-of-thumb introduce several concepts, like the ELTS, Modular Ratio Limit and Stress-stiffening behaviour. These aspects will be discussed in more detail in the following subsections.



## APPENDIX C: Pavement Number Structural Design System

### C.3.1. The Effective Long Term Stiffness (ELTS)

The ELTS is a model parameter which serves as a relative indicator of the average long term in situ stiffness of a pavement layer. As such, the ELTS averages out effects of long term decrease of stiffness owing to traffic related deterioration, as well as seasonal variations in stiffness. Thus the ELTS does not represent the stiffness of a material at any specific time.

The ELTS is not a stiffness value that can be determined by means of a laboratory or field test. It is a model parameter, which is calibrated for use in the PN design method and it may therefore differ from stiffness values typically associated with material classes. (e.g. Theyse *et al*, 1996).

The ELTS concept is especially needed in the case of cement stabilised materials, where a significant change in the effective stiffness of the material can be expected during the course of a pavement's design life (de Beer, 1990; Theyse *et al*, 1996; TRH4, 1996). This concept is illustrated in Figure C.1, which shows the reported breakdown of a cement stabilised material under traffic, with the ELTS representing an *average effective long term stiffness*.

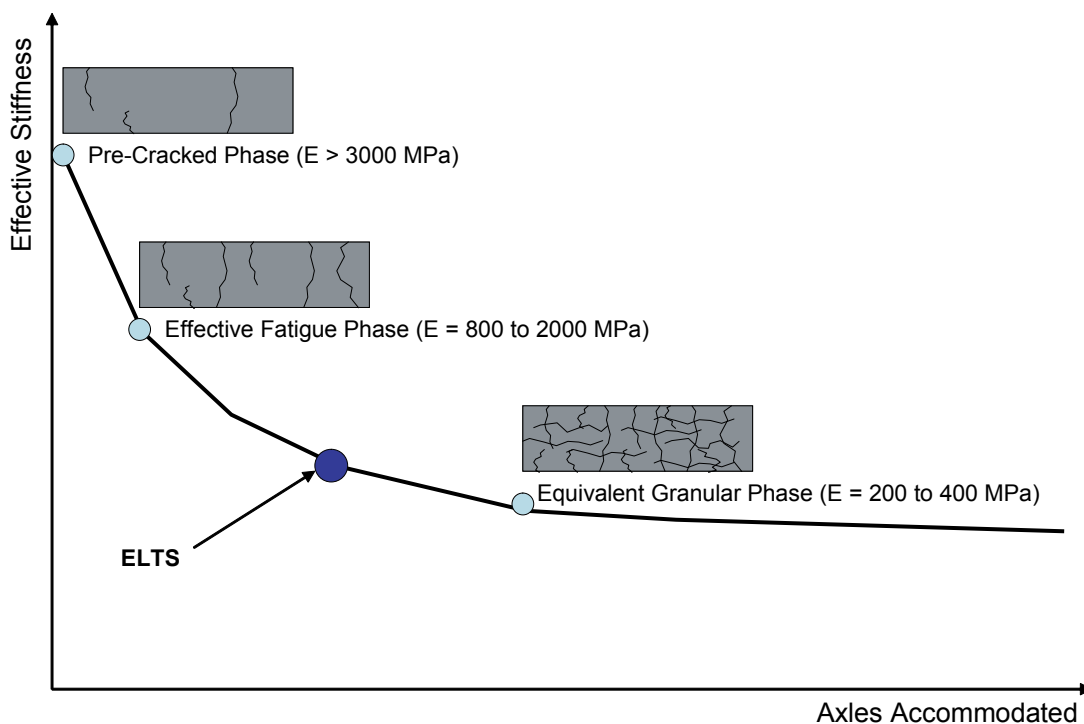


Figure C.1 Application of the ELTS Concept for Cement Stabilised Materials

### C.3.2. Modelling of Subgrade Materials

Characterization of the support condition is critical to the pavement design. For new construction, the TRH4 procedure for delineation of the in situ subgrade and for importing selected subgrade material, if the structural strength of the in situ subgrade is insufficient, applies to the PN method. For rehabilitation projects, the guidelines in TRH12 (1997) for evaluating and designing for changing support conditions should be followed in conjunction with the PN method.

The first step in the calculation of the PN-value is the determination of the subgrade material class. To do this, specific guidelines are provided in Appendix A.

Once the subgrade class has been determined, the ELTS for the subgrade is calculated. This involves the following steps:

1. Assignment of a basic long term stiffness based on the materials class.
2. Adjustment of the basic long term stiffness for different climatic regions (wet, dry or moderate).
3. Adjustment of the stiffness determined in step 2 to take account of depth of subgrade cover.



The adjustment of the subgrade stiffness to take account of the depth of cover takes account of the stress-softening tendencies of fine grained materials, in which these materials tend to soften under load. The relationship between the cover depth and the adjustment to the subgrade stiffness is given in Section C.4.

### C.3.3. The Modular Ratio Limit and Maximum Stiffness

The modular ratio is defined as the ratio of a layer's stiffness relative to the stiffness of the layer below it. Thus, if the stiffness of a base layer is 300 MPa, and the stiffness of the support below it is 200 MPa, then the modular ratio of the base layer would be 1.5.

The modular ratio accounts for the stress-sensitive stiffness of granular materials, which causes the stiffness of a granular material to decrease when the material is placed over a weaker (less stiff) support. This decrease in stiffness occurs because, in situations where the support layer is soft, the overlying layers tend to bend more into the support, thereby increasing the tendency to develop higher shear and tensile forces in the overlying layers. This effect limits the stiffness that can be obtained in an unbound layer placed over a weaker support. By placing a limit on the modular ratio that can be sustained for a specific material, it is ensured that the stiffness value assumed for that layer is realistic, given the material quality and stiffness of the support. In essence, the concept of a limiting modular ratio for granular materials ensures that stress-sensitive stiffness behaviour is implicitly taken into account.

The modular ratio that a material can sustain will vary over the life of a pavement. The concept of pavement balance, as discussed by Maree (1982) and Kleyn (1984) essentially assumes that the modular ratio of different unbound layers in a pavement system will decrease over time, as the traffic moulds and densifies the material into a more uniform or balanced system.

Thus while it is possible for a high quality crushed stone to maintain a modular ratio of 4 to 5 right after construction, over time the material will be moulded and weakened by traffic into a more balanced state where a modular ratio of 3 or less is likely to be observed. It is thus important to note that the use of a modular ratio limit, as defined for the PN method, pertains to the overall long term stiffness that a material can maintain over time.

Under the action of loading, there is a maximum stiffness that materials can achieve. As with the modular ratio, the maximum stiffness depends on the quality of the material, and less dense and angular materials cannot develop very high stiffnesses under loading, regardless of the stiffness of the support.

In the PN model, the modular ratio limit and the maximum allowed stiffness are used extensively to determine realistic ELTS values. These parameters are used in the following way:

1. The stiffness of the supporting layer is first determined. Thus the PN calculation process starts from the subgrade and proceeds upward toward the surfacing.
2. The modular ratio limit and maximum allowed stiffness are determined based on the DEMAC.
3. The ELTS for a layer is determined as the minimum of
  - The support stiffness multiplied with the modular ratio limit.
  - The maximum allowed layer stiffness.

In the case of base layers, the ELTS is further adjusted by means of a base confidence factor, which is discussed in more detail in Section C.4. The use of the modular ratio limit and maximum allowed stiffness is also applied to cement stabilised and hot mix asphalt materials, as explained below.

#### C.3.3.1. Modular Ratio Limit for Cement Stabilised Materials and Hot Mix Asphalt

Modular ratio limits do not normally apply to cohesive materials such as cement stabilised layers and hot mix asphalt. This is because of the high cohesion inherent in such materials, which effectively removes the stress-sensitivity and ensures that these materials can maintain a relatively high stiffness under loading, even over weak support.

However, when the long term stiffness of these materials is considered, then the stiffness of the support again becomes relevant. This is because weaker support layers will lead to increased fatigue and hence faster breakdown of stabilised layers. Thus, when these materials are used in a simplified model, the modular ratio limit can serve to mimic the long term fatigue effect that will lead to quicker reduction of the stiffness when these materials are placed over softer support.



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This effect is illustrated schematically in Figure C.2, which shows a case where the same cement stabilised material is placed over a stiff and soft support. Because the cement stabilised material is the same in both instances, the initial and final stiffness values are the same. However, the material on soft support experiences more rapid stiffness reduction, and thus the effective stiffness over the long term is lower than for the material on the stiff support.

Another factor which determines the rate and degree of breakdown in cement stabilised materials is the thickness of the layer. To mimic the influence of layer thickness on the rate of deterioration, the PN model adjusts the ELTS of cement stabilised layers for layer thickness. Details of this adjustment are provided in Section C.4.

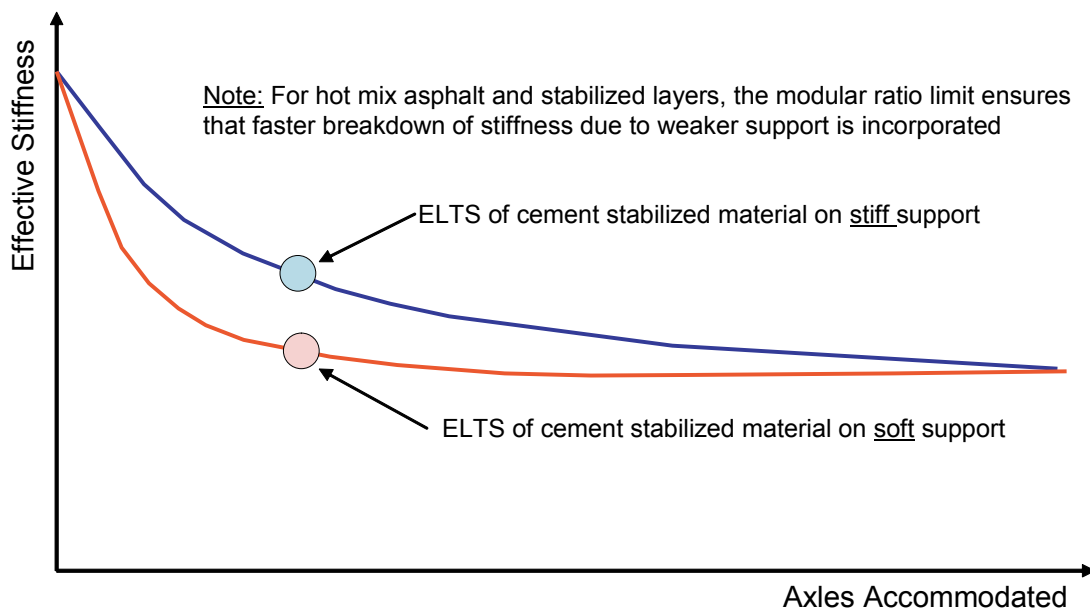


Figure C.2 Modular Ratio Limit for Cement Stabilised Materials

### C.3.3.2. Modular Ratio Limit for Bitumen Stabilised Materials

The modular ratios of BSMs and the ELTS values are higher than that of granular materials for the reasons given in Section C.3, Rule 10.

### C.3.4. The Base Confidence Factor

The type of material in the base layer is an important determinant of the performance of the pavement because the base is the main load bearing element in the pavement system, and failure of the base effectively constitutes pavement failure. Experience has shown that there is a limit on the types of base materials that can be considered for any given design traffic. In particular, suitable design options are significantly limited as the design traffic increases.

In the PN method, the appropriateness of the base material is controlled by the Base Confidence Factor (BCF). The BCF is used to adjust the ELTS value for the base layer. This is done simply by multiplying the initial ELTS for the base with the BCF.

## C.4. PAVEMENT NUMBER CALCULATION

In this section, the stepwise method for calculating the PN is detailed. Details relating to different steps or concepts in the method are discussed in the subsections that follow. In a pavement design situation, the steps described are applied for each uniform design section. For rehabilitation design situations, it is thus presumed that the designer will have detailed information on the existing pavement layer properties for each uniform section.

- Step 1:** Check to ensure that the design method is applicable for the design situation (see Section C.2 for details). If the design method is not applicable, a more detailed analysis should be performed, and the PN method should not be used.
- Step 2:** Determine the layer thicknesses, and available material properties for each layer. Use the material properties to obtain a DEMAC for each layer (see Appendix A for details). To prevent the use of unrealistic layer thickness assumptions, maximum and



## APPENDIX C: Pavement Number Structural Design System

minimum practical design thickness are prescribed for different material types. The limits are also constrained by the data used to calibrate and validate the PN method (Long, 2009). The layer thickness limits are shown in Table C.1.

- Step 3:** Combine layers with similar properties to obtain a five layer pavement system, including the subgrade (see Section C.4.1 for details). Check that the layer thicknesses do not exceed the maximum for design purposes (see Table C.1 for details).
- Step 4:** Determine the basic stiffness of the subgrade by means of Table C.2. Adjust the stiffness for climatic region (Table C.3) and depth of subgrade cover (Figure C.3) by multiplying the basic stiffness by the climate adjustment factor and adding the subgrade cover adjustment factor. The resulting stiffness is the ELTS for the subgrade.
- Step 5:** For each layer above the subgrade, determine the modular ratio limit and maximum allowed stiffness from Table C.4.
- Step 6:** Use the modular ratio limit and maximum allowed stiffness to determine the ELTS for each layer by working up from the subgrade (see Section C.4.2 for details on the process).
- Step 7:** For the base layer, determine the Base Confidence Factor (BCF) from Table C.4. For cement stabilised layers, also determine the adjustment factor based on thickness from Figure C.4.
- Step 8:** For each layer, calculate the layer contribution by multiplying the ELTS with the layer thickness and dividing this by 10 000. For the base layer multiply this product with the BCF, and for any cement stabilised layers, multiply with the thickness adjustment factor.
- Step 9:** Add the layer contributions for each layer to get the PN.

The constants shown in Table C.2 to Table C.4 and the relationships in Figure C.3 and Figure C.4 were obtained through an iterative calibration process. The values are specific to the PN method and should not be adjusted by the designer.

**Table C.1 Recommended Layer Thickness Limits for Design Calculations**

Material Type	Layer Situation	Thickness Limits Allowed for PN Calculation (mm)	
		Minimum	Maximum
Hot Mix Asphalt	Surfacing Layers	20	50
Surface Seals	Surfacing Layers	5	5
Bitumen Stabilised Layers	Base and Subbase	100	350
Cement Stabilised Layers	Subbase	100	400
All Unbound Materials (G1 to G10)	Subbase	100	300
	Selected Layer(s)	100	300

**Table C.2 Stiffness Determination for the Subgrade**

Design Equivalent Material Class for Subgrade	Stiffness Value (MPa)
G6 or better	180
G7	140
G8	100
G9	90
G10	70

Note: Subgrade stiffness value should be adjusted for climate (Table C.3) and cover depth (Figure C.3).



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**Table C.3 Climate Adjustment Factors**

Climate and Weinert N Values (after TRH4, 1996)	Adjustment Factor
Wet (Weinert N < 2)	0.6
Moderate (Weinert N = 2 to 5)	0.9
Dry (Weinert N > 5)	1.0

**Table C.4 Modular Ratio Limit and Maximum Allowed Stiffness for Pavement Layers**

General Material Description	Material Class <sup>1</sup>	Modular Ratio Limit	Maximum Allowed Stiffness (MPa)	Base Confidence Factor
Hot mix asphalt (HMA) surfacing and base material	AG, AC, AS, AO	5.0	3500	1.0
Surface seals	S1, S2, S3, S4, S5, S6	2.0	800	N/A
High strength bitumen stabilised material, normally using crushed stone or reclaimed asphalt (RA) source material	BSM1	3.0	600	1.0
Medium strength bitumen stabilised material, normally using natural gravel or RA source material	BSM2	2.0	450	0.7
Crushed stone material	G1	2.0	700	1.1
	G2	1.9	500	0.8
	G3	1.8	400	0.7
Natural Gravel	G4	1.8	375	0.2
	G5	1.8	320	0.1
	G6	1.8	180	-2.0
Gravel-soil blend	G7	1.7	140	-2.5
	G8	1.6	100	-3.0
	G9	1.4	90	-4.0
	G10	1.2	70	-5.0
Cement stabilised crushed stone	C1 and C2	9	1500	0.8
Cement stabilised natural gravel	C3	4	550	0.6
	C4	3	400	0.4

**Note:** 1. Design equivalent material class (DEMAC) for rehabilitation projects.



APPENDIX C: Pavement Number Structural Design System

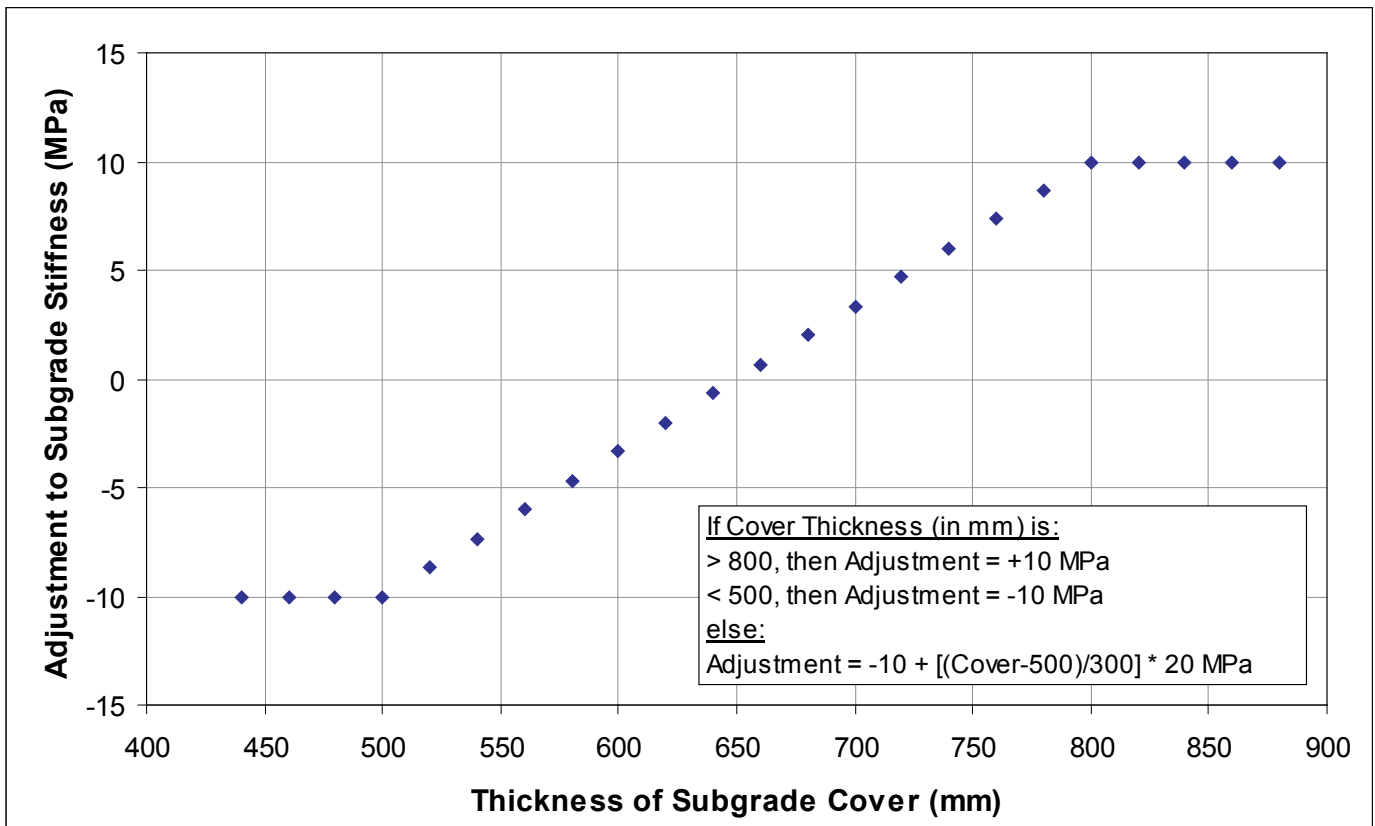


Figure C.3 Adjustment of Subgrade Stiffness Based on Cover Thickness

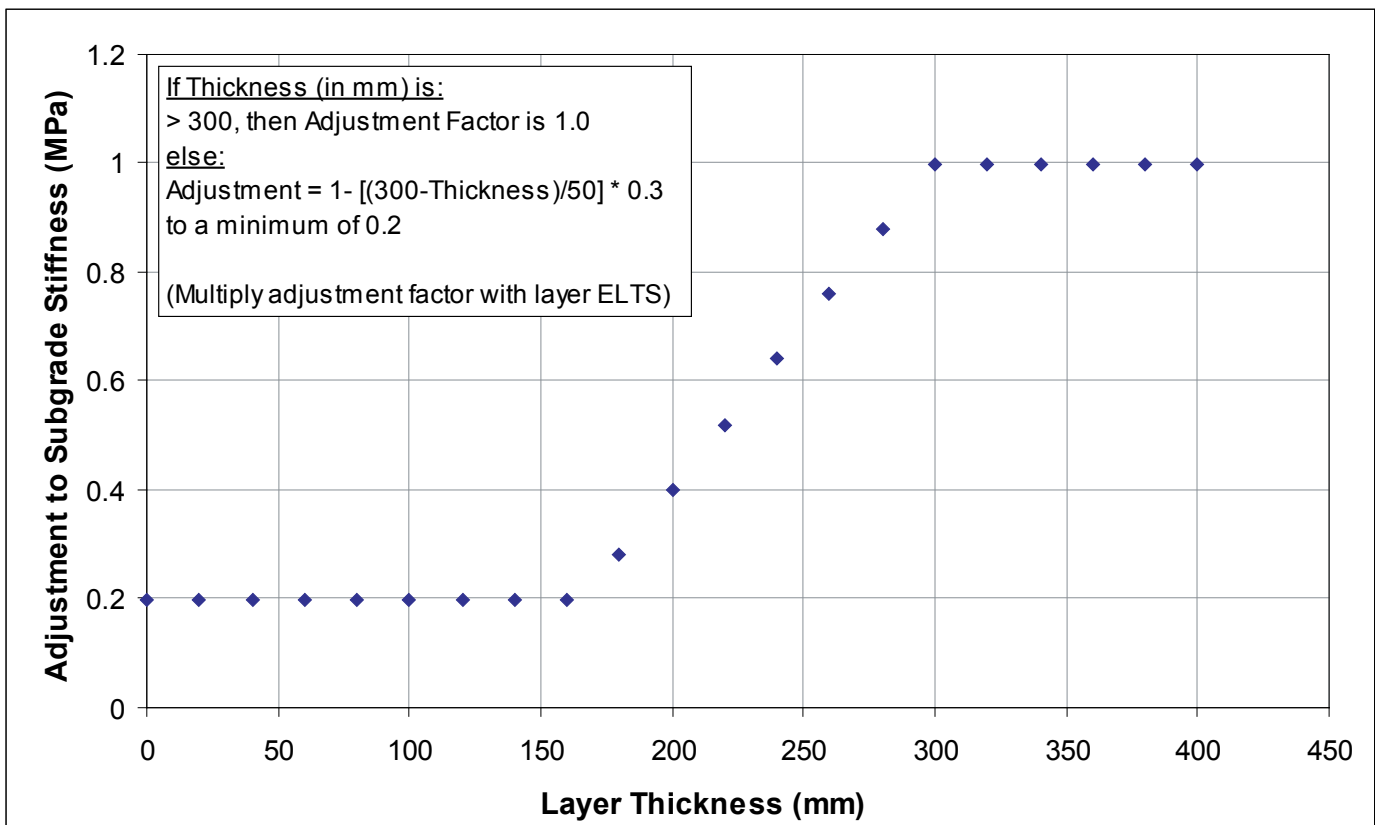


Figure C.4 ELTS Adjustment Factor for Cement Stabilised Layers based on Layer Thickness



## APPENDIX C: Pavement Number Structural Design System

### C.4.1. Combining Pavement Layers to Form a Five Layer Model

By definition, the PN consists of the sum of the load spreading contributions of four pavement layers above the subgrade. To apply this definition consistently, the pavement model used in the PN calculation must consist of four pavement layers plus the subgrade. In cases where the pavement consists of more than four layers, two or more layers will need to be combined. To do this, the following guidelines should be adhered to:

- » Only combine layers that consist of the same general materials class. In this respect, the following general material classes can be used:
  - Hot mix asphalt and surfacing seals
  - Crushed stone material
  - Natural gravel material
  - Cement stabilised material
  - Bitumen stabilised material
  - Gravel-soil, silt or clay materials
- » The surfacing should be modelled as a separate layer in all cases. A surface seal should be modelled as a 5 mm thick layer.
- » Where there is a need to combine pavement layers, the designer should first combine sub-layers below the subbase, followed (if needed) by sub-layers in the subbase zone.
- » The material class assigned to the combined layer should be the class of the thicker of the two layers. Thus, if a 150 mm G6 is combined with a 120 mm G7, then the material assigned to the 270 mm combined layer should be G6.
- » Where the two layers to be combined are of equal thickness, the lower material should be assigned to the combined layer. Thus, if a 150 mm G7 is combined with a 150 mm G8, then the material class assigned to the 300 mm combined layer should be G8.
- » When a pavement layer is combined with the apparent natural subgrade, the material class of the combined subgrade layer should be the class of the uppermost layer.
- » When a pavement consists of only two or three pavement layers, a four layer pavement system should be constructed by subdividing the top of the subgrade into two or more layers, each with a thickness of 100 mm. The material class assigned to these sub-layers should be that of the subgrade.
- » The thickness of the combined layers should not exceed the limits given in Table C.1. These thickness limits are only applicable to the design calculations.

Figure C.5 shows an example in which there are several selected layers that are combined to form a five layer system. This example also shows the application of the limiting thickness to the selected layers, which also determines the amount of cover on the subgrade for modelling purposes. Even with the above guidelines taken into account, some pavement situations will allow more than one approach to the combination of layers. In such cases, the designer should experiment with different approaches and adopt the most conservative model for design purposes.

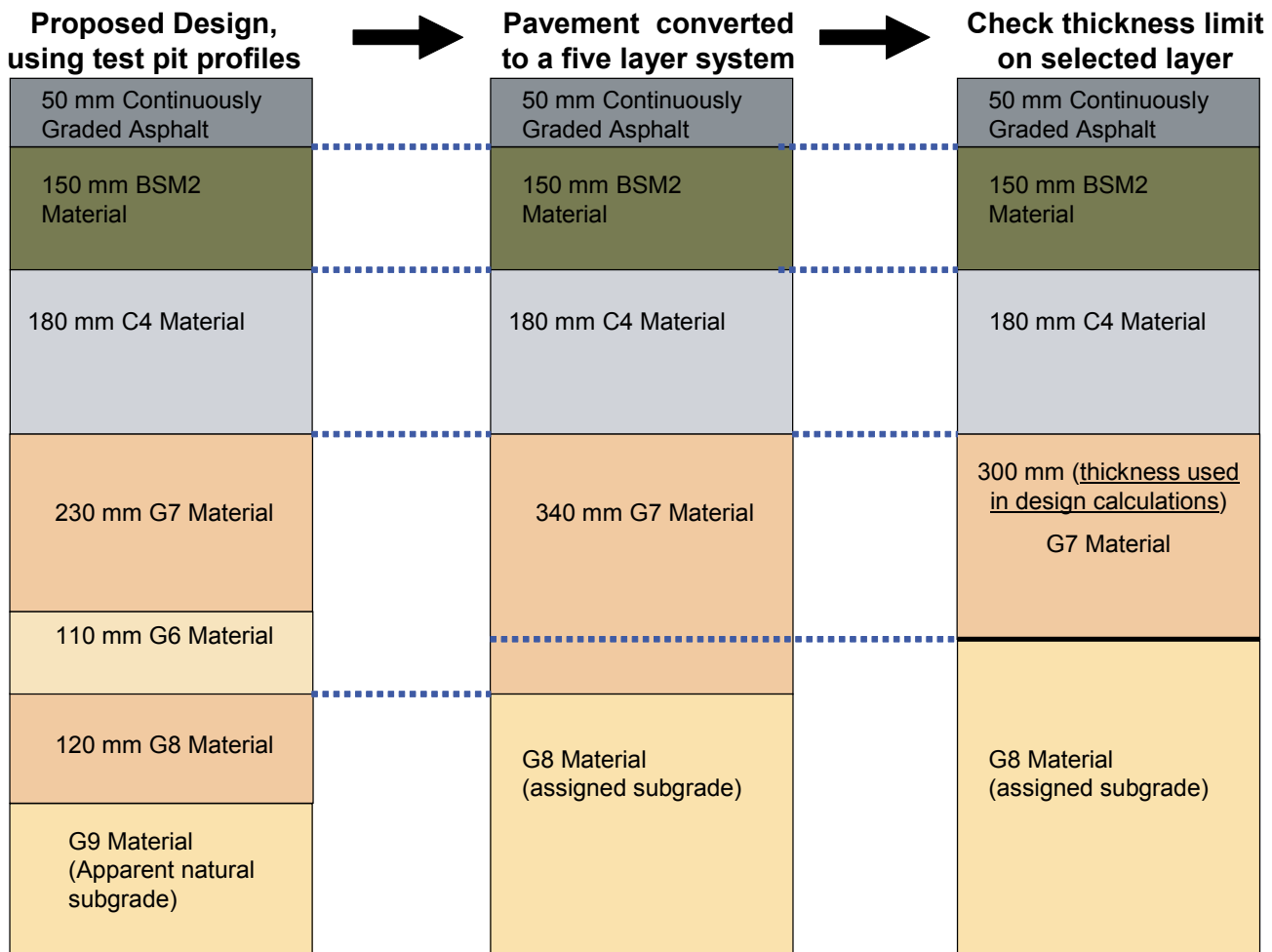


Figure C.5 Example of the Combining of Pavement Layers to Form a Five Layer Model

#### C.4.2. Determining Effective Long-Term Stiffness (ELTS) Values

The ELTS and modular ratio limit are essential to the PN-method. For the subgrade, the ELTS is first determined using the material class. This value is then adjusted for climate and for depth of subgrade cover.

The climate adjustment of the subgrade stiffness takes into account the increased frequency and risk of having a soft subgrade in wet regions. The climate adjustment factors are shown in Table C.3 and are multiplied by the ELTS associated with the material class.

The adjustment for subgrade cover takes into account the behaviour of finer-grained materials which tend to soften under increased stress. A relative adjustment (decrease) of the subgrade stiffness is therefore made to simulate the effect of stress-softening for pavements with less subgrade cover (i.e. where shear stresses are greater). The adjustment of the subgrade stiffness for depth of cover is shown in Figure C.3 and is added to the ELTS that has already been adjusted for climate.

For pavement layers above the subgrade, the maximum allowed stiffness and modular ratio limit for each material are obtained from Table C.4 using the assigned material class. The stiffness can then be determined by working from the subgrade upwards, using the modular ratio limit and the maximum allowed stiffness. The assigned ELTS is determined as the minimum of the maximum allowed stiffness, and the stiffness of the support layer multiplied by the modular ratio limit.

An example of this procedure is shown in Figure C.6 and Figure C.7 for a structure in a wet and dry climate, respectively. A comparison of these figures shows the impact of climate on the subgrade, and the subsequent impact on pavement layer stiffnesses. These examples show how the modular ratio effectively takes into account the stiffness of the support layer, thereby reducing the assigned ELTS when the support stiffness reduces, even though the material class remains unchanged.



APPENDIX C: Pavement Number Structural Design System

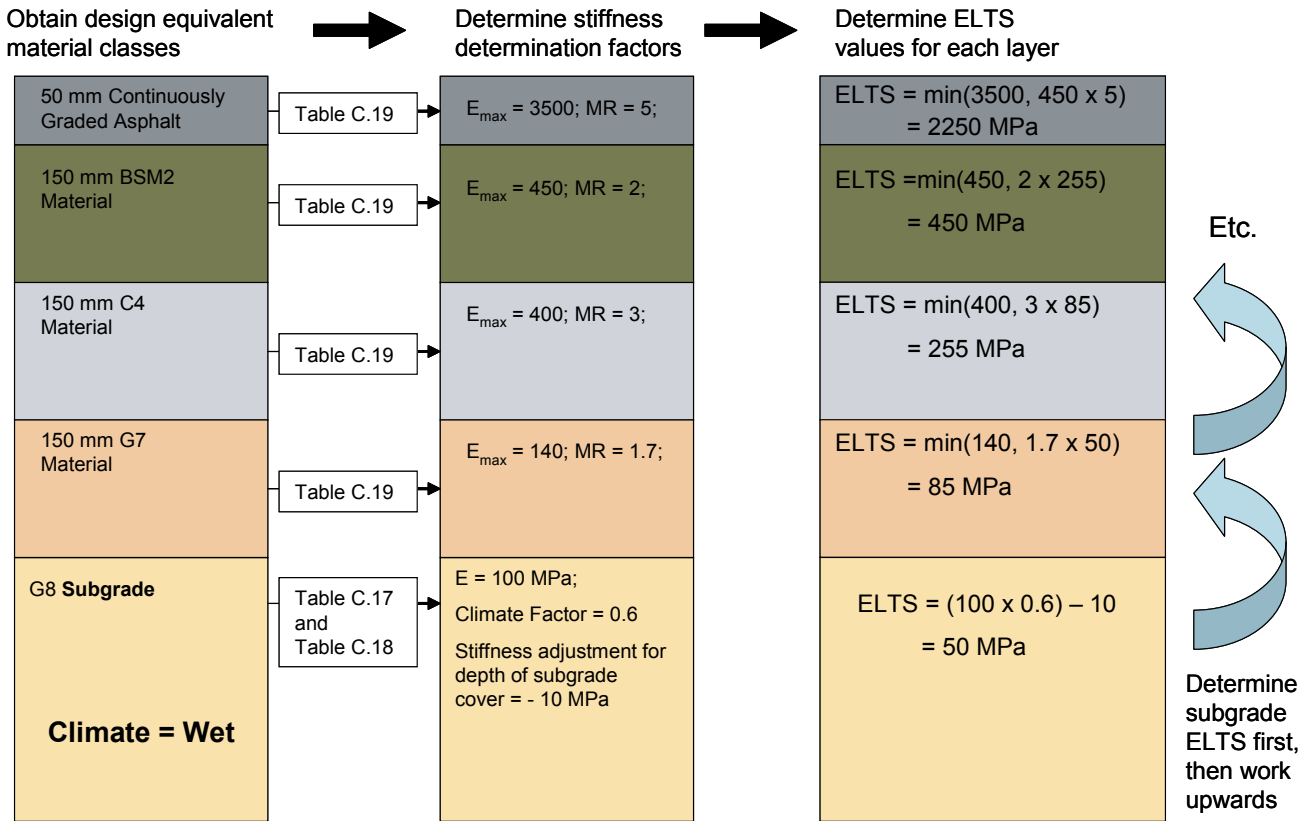


Figure C.6 Example of ELTS Determination (Wet Climate)

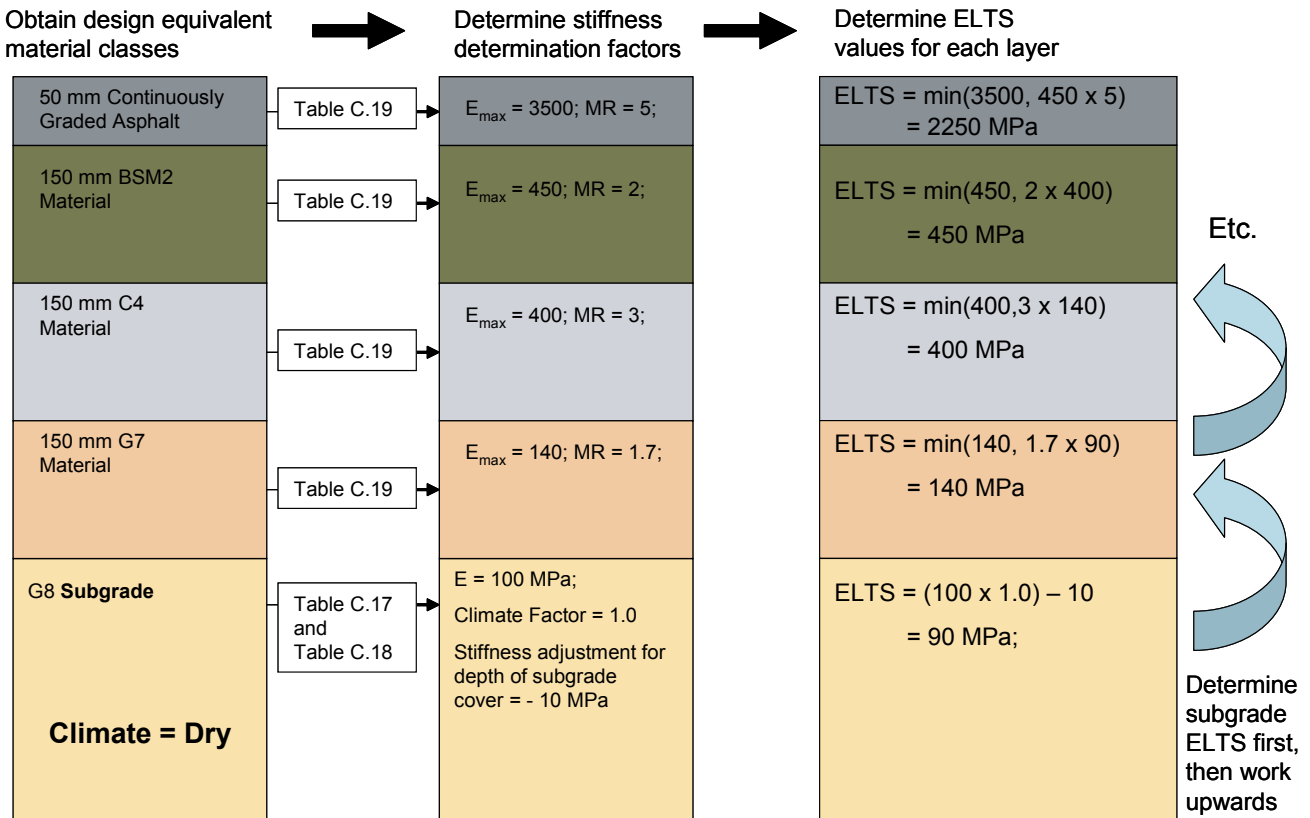


Figure C.7 Example of ELTS Determination (Dry Climate)



## C.5. PAVEMENT CAPACITY CALCULATION

The calculation of the pavement capacity depends on the Pavement Number and the Road Category. The relationship in Equation C.1 is used, in conjunction with the constants in Table C.5 or Table C.6. The relationship between the PN and the pavement capacity does not give a pavement life prediction, but rather provides a lower limit for which the pavement should carry the desired traffic sufficiently. The criteria are only applicable to Category A and B roads and for design capacities between 1 and 30 MESA. For Category C and D roads, a catalogue of design is recommended, see Chapter 5.

$$N_{\text{allow}} = N_1 + (PN - PN_1) \times \text{Slope} \quad (\text{C.1})$$

Where:

$N_{\text{allow}}$	=	Allowed pavement capacity (MESA)
$N_1$	=	Lower limit for the capacity range from Table C.5 or Table C.6
PN	=	Calculated pavement number
$PN_1$	=	Lower limit for the PN range from Table C.5 or Table C.6
Slope	=	Slope for the PN range from Table C.5 or Table C.6

The values  $N_1$ ,  $PN_1$  and Slope are obtained from Table C.5 or Table C.6 (depending on the Road Category), after first determining the range within which the calculated PN falls. Figure C.8 shows the criteria in a graphical format.

**Table C.5 PN Criteria for Category A Roads**

PN Range	N1	PN1	Slope
PN < 15	Less than 3 MESA, not suited for Category A roads		
15 < PN ≤ 23	3	15	0.00
23 < PN ≤ 25	3	23	3.50
25 < PN ≤ 32	10	25	0.00
32 < PN ≤ 35	10	32	6.67
PN > 35	30	35	0.00

**Table C.6 PN Criteria for Category B Roads**

PN Range	N1	PN1	Slope
PN < 3	Less than 1 MESA, use Design Catalogue (Figure 5.1)		
3 < PN ≤ 8	1	3	0.00
8 < PN ≤ 11	1	8	0.67
11 < PN ≤ 15	3	11	0.00
15 < PN ≤ 25	3	15	0.70
PN > 25	Use Category A Criteria		



APPENDIX C: Pavement Number Structural Design System

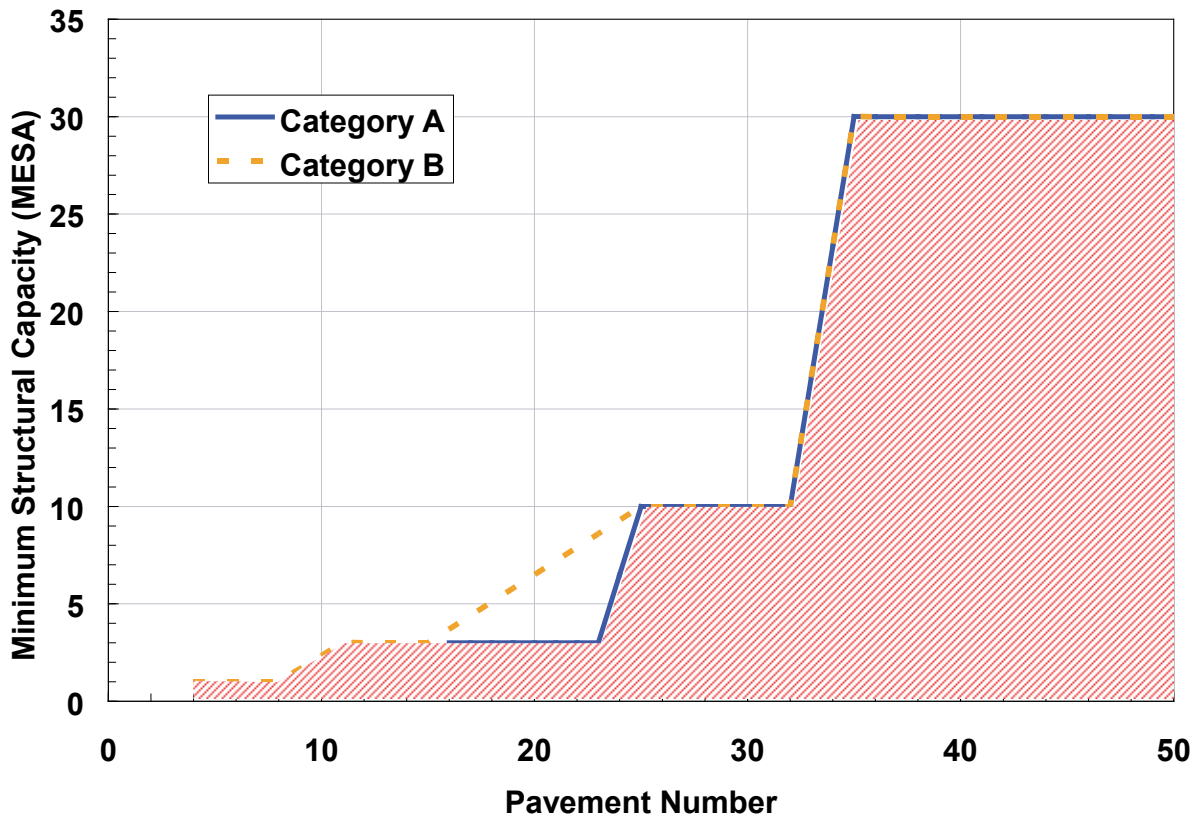


Figure C.8 Criteria for Determining Allowed Capacity from PN

C.6. WORKED EXAMPLE

An example of the PN calculation is shown in Figure C.9. In the figure, the assumed values are shown in yellow, values obtained from tables and figures are shown in green and calculated values are shown in blue.

For the example, the following information was assumed:

- Climate:** Moderate
- Pavement Structure:**
  - 30 mm Asphalt Surfacing
  - 175 mm BSM2 (Bitumen Stabilised Natural Gravel)
  - 200 mm G6 (Gravel Soil Blend)
  - 180 mm G7 Selected Layer
  - G8 Subgrade

**Step 1. Check the number of pavement layers and thicknesses**

The pavement has five layers including the subgrade, and does not need adjustment using the guidelines in Section C.4.1. The layer thicknesses are within the specified limits for each material type given in Table C.1.

**Step 2. Calculate the Subgrade ELTS**

This is shown in the topmost section of Figure C.9. The initial stiffness is first determined from Table C.2, multiplied by the climate adjustment factor (Table C.3) and then the cover depth adjustment factor (using Figure C.3) is subtracted. The subgrade ELTS is then entered into the last row of column 4 of the lower table in Figure C.9.



APPENDIX C: Pavement Number Structural Design System

**Step 3. Calculate the ELTS for each layer**

First, the modular ratio limit and maximum allowed stiffness are determined from Table C.4. The ELTS is then calculated as the minimum of:

- The maximum allowed stiffness.
- The stiffness of the support layer multiplied by the modular ratio limit.

The calculation starts at the subgrade and then moves upward. For example, the ELTS of the selected layer is the minimum of 146 (i.e.  $86 * 1.7$ ) and the maximum allowed stiffness of 140 MPa.

**Step 4. Determine the Thickness Adjustment Factor and Base Confidence Factor**

The thickness adjustment factor is determined from Figure C.4 and entered in column 5. This factor applies only to cement stabilised materials and is therefore shown as 1.0 for all layers in this example. The BCF for the base layer is determined from Table C.4 and is only valid for the base layer.

**Step 5. Calculate Layer Contribution**

The layer contribution in column 7 is calculated for each layer by multiplying the thickness, the ELTS, the thickness adjustment factor and the BCF (where applicable). This product is then divided by 10 000 to scale the number to a realistic value. For example, the base layer contribution is  $(175 * 360 * 1 * 0.7) / 10\ 000 = 4.4$ .

**Step 6. Calculate the Pavement Number**

The layer contributions are added to obtain the PN ( $5.4 + 4.4 + 3.6 + 2.5 = 15.9$ ).

**Step 7. Determine the Pavement Capacity**

Equation C.1 and the constants given in Table C.5 for Category A roads or Table C.6 for Category B roads are used to calculate the pavement capacity. For example, for Category B, the pavement capacity is  $3 + (15.9 - 15) * 0.7 = 3.6$  MESA.

<b>Subgrade Class</b>	G8	
<b>Initial Stiffness</b>	100	(from Table C.2)
<b>Climate</b>	Moderate	
<b>Climate Adjustment</b>	0.9	(from Table C.2)
<b>Cover Depth</b>	585 mm	(sum of layer thicknesses above subgrade)
<b>Cover Adjustment</b>	- 4	(from Figure C.3)
<b>Subgrade ELTS</b>	86	$(100 * 0.9 - 4)$

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9
Layer	Thickness (mm)	material class	Modular Ratio (Table C.4)	Maximum Stiffness (MPa) (Table C.4)	ELTS (MPa)	Thickness Adjustment (Figure C.4)	BCF (Table C.4)	Layer Contribution
Surfacing	30	AC	5.0	3500	1 800	1.0	N/A	5.4
Base	175	BSM2	2.0	450	360	1.0	0.7	4.4
Subbase	200	G6	1.8	180	180	1.0	N/A	3.6
Selected	180	G7	1.7	140	140	1.0	N/A	2.5
Subgrade	N/A	G8	N/A	N/A	86	Pavement Number =		15.9
							Pavement Capacity = (Equation C.1)	3.0 MESA (A) 3.6 MESA (B)

Figure C.9 Example Showing Determination of the Pavement Number



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## APPENDIX D: CONSTRUCTION CONTROLS FOR BITUMEN TREATMENT

### D1. Essential Requirements for a successful recycling operation using recyclers

#### D2. Pre-start check lists (example sheets)

- D2.1 In situ recycling: BSM-foam
- D2.2 In situ recycling: BSM-emulsion
- D2.3 In plant treatment: BSM-foam

#### D3. Daily reports for in situ recycling (example sheets)

- D3.1 BSM-foam
- D3.2 BSM-emulsion
- D3.3 Active filler control

### D.1. ESSENTIAL REQUIREMENTS FOR A SUCCESSFUL RECYCLING OPERATION USING RECYCLERS

The following are some of the essential requirements for a successful recycling operation:

- » **Operator and supervisor training.** Recycling should never be undertaken by a work crew that has not received the necessary training. In addition to technical aspects of the work, safety is a major factor when working with large machinery. This is compounded when working with the hot bitumen required for BSM-foam. Everyone involved in the operation must be adequately trained to use all the equipment properly, and all the risks must be emphasised to prevent accidents.
- » **Operating procedures.** These must be strictly adhered to, particularly those relating to start-up. Feed lines require bleeding and checks must be carried out to ensure that the spraybars are free of internal blockages. Blockages are frequently experienced when these procedures are not followed. External blockages caused by material build-up inside the milling chamber must be checked and removed where necessary. In addition, the various settings i.e., drum rotation speed, breaker-bar setting, rear-door pressure, etc. should be preset as per those established during the construction of the Trial Section, as dealt with in Section 6.7. Computer input data, such as material density and application rates, need to be set and checked.
- » **Connecting tankers to the recycler.** Before coupling a bitumen tanker to the recycler, the valve at the rear of the tanker should always be carefully opened to allow a small quantity of bitumen emulsion or hot bitumen to flow out into a drum. This is an important procedure as it prevents a plug of cold bitumen from entering and blocking the feed line. Although such cold plugs are more often experienced when working with foamed bitumen, this check will also draw attention to bitumen emulsion that has broken prematurely in the tanker.
- » **Temperature checks.** The following temperature checks should be routinely undertaken:
  - **Material prior to treatment.** Where low temperatures are suspected (normally estimated from the surface temperature) the temperature of the material being recycled can be measured soon after starting work by lifting the drum and using a hand-held digital thermometer focused on the cut face. Where the temperature is below the minimum recommended (Section 4.2.1.5), work should not proceed.
  - **Hot bitumen or bitumen emulsion.** The temperature of the bitumen in each tanker load should be checked before connecting to the recycler. When the temperature is below the minimum specified, the tanker must be sent off site. Temperature gauges permanently fitted to tankers are notoriously inaccurate. A hand-held digital thermometer should therefore be used to measure the temperature of the contents of the tanker through the filling hatch.
  - **The mixed product.** A hand-held digital thermometer should be used to measure temperature variations across the width of treatment immediately behind the rear door of the milling chamber. Ensure that the laser “spot” (location of temperature reading) is kept off coarse particles. The temperature readings should not vary by more than 5 °C across the recycled width. Any decrease of more than 5 °C is an indicator of under application by a blocked nozzle. Since recyclers do not move material more than 200 mm in the transverse direction, the offending nozzle can be isolated and the cause of the problem addressed.



**APPENDIX D: Construction Controls for Bitumen Treatment**

<b><i>BSM-emulsion</i></b>	<b><i>BSM-foam</i></b>
Not relevant.	An increase in temperature indicates a lack of foaming since unfoamed hot bitumen is being applied.

- » **Lateral joints.** Joints are formed at right-angles to the direction of travel every time the recycling process is stopped and, similar to all other stabilising processes, continuity across these joints is an important factor in avoiding localised failures. To ensure continuity of treatment, it is essential that the operating characteristics of the application system being used are fully understood, particularly the bitumen application system. As the recycler accelerates from stationary to the normal operating speed, the bitumen application system needs to respond continuously to ensure that the correct application rate is achieved and maintained. Where the system only starts functioning above a minimum advance speed (thereby ensuring sufficient pressure on the spraybar), the recycler must be positioned at least 1 metre back into material that has already been treated to ensure continuity of bitumen treatment. When the recycler moves forward, the minimum advance speed is generally attained within the first metre and the application system starts functioning. Failure to adhere to this simple requirement can result in a patch of untreated material.
- » **Containing the recycled material.** Recycled material exits the recycler in a loose state and must be compacted immediately back into the cut from whence it came. Bulking will result in this material being proud of the adjacent un-recycled road surface. Material must not be spread into the path of the adjacent un-recycled cut because this will result in double dosage and saturation when the next cut is recycled.
- » **Thickness control.** Although recyclers are usually equipped with automatic sensors, the depth of recycling is critical and should therefore be regularly checked and any necessary adjustments made. To ensure that the correct layer thickness is achieved, the same survey reference poles used for cutting final levels should be utilised, employing a pointed T-bar as a probe, as illustrated in

A trench, 0.5 m, wide should be dug through the entire layer of loose BSM across the full cut width at least once every 500 m. When opened, the condition of the top surface of the underlying in situ material can be checked as well as the layer thickness and the quality of the recycled and treated mix. These trenches must be dug, inspected, measured, viewed, recorded and closed before the primary roller makes the first pass.



**Figure D.1.** Where check measurements are taken on the side face of the cut, cognisance must be taken of the increase in surface elevations of recycled material caused by bulking.



APPENDIX D: Construction Controls for Bitumen Treatment

- » **Speed of advance.** The quality of the recycled and bitumen treated mix is a function of the advance speed of the recycler. Although the recycler may be capable of working at far higher speeds, experience has shown that optimal mixing is achieved at forward speeds of between 7 and 10 metres per minute, depending on the nature of the material to be recycled and the depth of cut.
- » **“Bulldozing” the active filler.** Where active filler is pre-spread on the road surface ahead of the recycler, the rubber flap fitted to the bottom of the front door of the milling chamber must be lifted to prevent it from acting as a dozer blade, spilling a windrow of the active filler on either side of the chamber. This windrow tends to be buried by fines thrown forward through the sides of the front door and not easily visible. If not detected and eliminated, such a concentration of active filler will not be properly dispersed when recycling the adjacent cut and can be the cause of a longitudinal crack that follows the line of the joint.
- » **Change in recycling conditions.** Should unforeseen conditions arise that result in slow operating speeds or variations in the recycled and treated material, the recycler can always be stopped and the drum lifted for a quick inspection.
- » **Moisture control.** As explained in Section 6.2.2.4 in Chapter 6, it is impractical to attempt to accurately predict variations in the moisture content of materials in the pavement layers, regardless of how many tests are done in advance. On most recycling projects, the required moisture content of the recycled material is approximated by varying the addition of water whilst recycling and constantly “measuring” the material “by feel”. This requires the operator to vary the amount of water added, only upon instruction of a supervisor who has sufficient experience to be able to gauge moisture content. Equipping the supervisor and operator with walkie-talkie radios allows instant communication.
- » **Visual observations whilst the recycler is working:**
  - The **consistency in the colour** of the material immediately behind the recycler will usually indicate whether or not the machine is set up properly. A gradual change in colour across the width normally indicates that one end of the drum is lower than the other. A lighter appearance indicates dilution (under-application of water and bitumen stabilising agent) caused by the drum not penetrating too deep into the pavement. A darker colour indicates an over-application due to the drum not penetrating to the required depth.
  - Bitumen treated material is **not sticky** and should therefore not adhere to the rear wheels of the recycler. The left picture in Figure D.2 illustrates what should be seen behind the recycler. The right picture shows material sticking to the rear wheels indicating that the treated material is poorly mixed. This operation should be stopped immediately to determine the cause. Such poorly mixed material will also stick to the drum of the roller, causing material build-up and further problems.

<b>BSM-emulsion</b>	<b>BSM-foam</b>
This is not usually a problem with BSM-emulsion.	Material sticking to the rear wheels of the recycler indicates a poor mix. This is the consequence of the bitumen not foaming or too few fines are available to disperse the amount of added bitumen.



Minimal material sticking to the wheels of the recycler

Material sticking to the wheels of the recycler

Figure D.2: Observations behind the recycler

- » **The ball test.** This simple test requires a round specimen the size of a fist to be made from a sample of material picked up from behind the recycler and firmly squeezed between both hands. Once a ball has been formed, the following visual observations can be made:



APPENDIX D: Contruction Controls for Bitumen Treatment

<p><b>BSM-emulsion</b></p> <p>Place the ball in the sun and leave to dry for at least 30 minutes to allow the bitumen emulsion to break before carrying out the “test” described below.</p>	<p><b>BSM-foam</b></p> <p>Clean all loose material from the palms of the hands and observe the bitumen spots. The warmth of the hands and pressure applied will permit the bitumen to stick. Lots of tiny spots indicate good dispersion whilst larger “blobs” are the stringers resulting from poor dispersion. The ball does not need curing and can be tested immediately as described below.</p>
---	--

The “test” consists of holding the ball between the thumb and index finger and gently applying pressure on opposite sides of the ball to gauge the cohesiveness of the material. The ball should deform before falling apart. Inspect the face of the broken ball too see how well the bitumen has dispersed. If no bitumen can be seen, the mix is perfect. The more bitumen blobs or stringers there are that can be observed, the worse the quality of the mix.

D.2. PRE-START CHECKLISTS

The following checklists are examples of the kinds of checks that should be followed prior to starting the recycling.

D.2.1. In situ recycling: BSM-foam

**IN SITU RECYCLING / FOAMED BITUMEN**      S/visor: EXAMPLE SHEET

**PRE-START CHECK LIST**      Date: 23 March 2009

**RECYCLER** (Start of shift)      Machine ID: Wirtgen 2500 S # 0059.

- Check the bitumen system heaters are operational
- Check the temperature of the road surface (digital thermometer) 18°C 07:00
- Check that the foam-water tank is full
- Remove and clean the foam-water filter
- Remove and clean the bitumen filter
- Lift machine / lower drum / open chamber doors for visual inspection  
Check: all foamed bitumen nozzles clear   
all water injection nozzles clear
- Check each expansion chamber for blockages using "pre-water" function

Switch # 1 2 3 4 5 6 7 8

Nozzle # 1 & 3 2 & 4 5 & 7 6 & 8 9 & 11 10 & 12 13 & 15 14 & 16

Note any blockages: # 15 blocked. Removed water jet, cleaned dirt from jet

- Obtain loading / weighbridge certificate for bitumen tanker 21.96 tons
- Calculate cut lengths / finalise cut plan (with the operator)
- Reset the on-board computer, enter data and check  
Density 2150 Cut depth 200mm Application width 2.5m

Bitumen application rate 2.20% Foam water 2.50%

**SETTING UP THE RECYCLING TRAIN** (Each new cut / tanker load)

- Check cut guideline and position recycler on first cut
- Check bitumen temperature in tanker (loading hatch) 17.3°C
- Check bitumen tanker for leaks. Crack valve, check for cold plug
- Check water tanker is full and free of leaks
- Couple up bitumen tanker and bleed air from system
- Check that the bitumen foams using test nozzle Good
- Couple up water tanker and bleed air from system
- Check all supply lines and feed pipes for leaks
- Confirm cut plan / check computer settings & nozzle closure  All open
- Check solenoid lights controlling spraybars / nozzle closure #4 ait (water)
- Close front & rear doors. Lower recycling drum to cut depth
- Lift drum and measure tempereure of material on cut face N/A
- Roller in place. Drivers ready. Level control team standing by



### D.2.2. In situ recycling: BSM-emulsion

<b>IN SITU RECYCLING / BITUMEN EMULSION</b>		S/visor: <u>EXAMPLE SHEET</u>
<b>PRE-START CHECK LIST</b>		Date: <u>25 February 2009</u>
<b>RECYCLER</b> (Start of shift)	Machine ID: <u>Wirtgen 2100 DCR #0593</u>	
1. Check the bitumen emulsion system has been flushed		<input checked="" type="checkbox"/>
2. Check the temperature of the road surface (digital thermometer)	<u>19°C</u>	<u>07:20</u>
3. Lift machine / lower drum / open chamber doors for visual inspection		
Check: all bitumen emulsion nozzles clear		<input checked="" type="checkbox"/>
all water injection nozzles clear		<input checked="" type="checkbox"/>
4. Obtain loading / weighbridge certificate for bitumen tanker	<u>21.62</u>	<u>tons</u>
5. Calculate cut lengths / finalise cut plan (with the operator)		<input checked="" type="checkbox"/>
6. Reset the on-board computer, enter data and check		<input checked="" type="checkbox"/> <b>check</b>
Density <u>2060</u> Cut depth <u>150mm</u> Application width <u>2.1m</u>		
Emulsion application rate <u>3.33</u> (percentage emulsion)		
<b>SETTING UP THE RECYCLING TRAIN</b> (Each new cut / tanker load)		
1. Check cut guideline and position recycler on first cut		<input checked="" type="checkbox"/>
2. Check emulsion temperature in tanker (loading hatch)	<u>59°C</u>	
3. Check emulsion tanker for leaks. Crack valve, check flow		<input checked="" type="checkbox"/>
4. Check water tanker is full and free of leaks		<input checked="" type="checkbox"/>
5. Couple up emulsion tanker and bleed air from system		<input checked="" type="checkbox"/>
6. Couple up water tanker and bleed air from system		<input checked="" type="checkbox"/>
7. Check all supply lines and feed pipes for leaks		<input checked="" type="checkbox"/>
8. Confirm cut plan / check computer settings & nozzle closure		<input checked="" type="checkbox"/>
9. Check solenoid lights controlling spraybars / nozzle closure		<input checked="" type="checkbox"/>
10. Close front & rear doors. Lower recycling drum to cut depth		<input checked="" type="checkbox"/>
11. Lift drum and measure temperature of material on cut face	<u>OK</u>	
12. Roller in place. Drivers ready. Level control team standing by		<input checked="" type="checkbox"/>



APPENDIX D: Construction Controls for Bitumen Treatment

D.2.3. In plant treatment: BSM-foam

<b>IN PLANT TREATMENT / FOAMED BITUMEN</b>		S/visor: <u>EXAMPLE SHEET</u>
<b>PRE-START CHECK LIST</b>		Date: <u>Friday 20 March 2009</u>
<b>MIXING PLANT</b> (Start of shift)	Machine ID: <u>Wirtgen KMA 200 #0063</u>	
1. Check the bitumen system heaters are operational		<input checked="" type="checkbox"/>
2. Check the temperature of the material stockpiles		<input type="text" value="17"/> °C
3. Check that the water tank is full		<input checked="" type="checkbox"/>
4. Remove and clean the foam-water filter		<input checked="" type="checkbox"/>
5. Remove and clean the bitumen filter		<input checked="" type="checkbox"/>
6. Aggregate feed bins. Check for material packing / blockages		<input checked="" type="checkbox"/>
Bin # 1. Material: <u>&lt; 6.7mm crusher dust</u>	Setting	<input type="text" value="15"/> %
Bin # 2. Material: <u>&lt; 19mm Screened RAP</u>	Setting	<input type="text" value="85"/> %
7. Check the active filler bin and auger feed system		<input checked="" type="checkbox"/>
8. Open pugmill hatch and visually inspect for blockages		<input checked="" type="checkbox"/>
Check: all foamed bitumen nozzles clear		<input checked="" type="checkbox"/>
all water injection nozzles clear		<input checked="" type="checkbox"/>
9. Check each expansion chamber for blockages using "pre-water" function		
Nozzle #	<input checked="" type="checkbox"/> 1	<input checked="" type="checkbox"/> 2
	<input checked="" type="checkbox"/> 3	<input checked="" type="checkbox"/> 4
	<input checked="" type="checkbox"/> 5	<input checked="" type="checkbox"/> 6
Note any blockages:	<u>All clear</u>	
10. Obtain loading / weighbridge certificate for bitumen tanker		<input type="text" value="Bulk"/>
11. Check delivery conveyor is clean and running free		<input checked="" type="checkbox"/>
12. Reset the computer, enter data and check		<input checked="" type="checkbox"/>
Material density	<input type="text" value="2150"/>	Active filler: <u>Lime</u> Application rate: <input type="text" value="0.7"/> %
Bitumen application rate	<input type="text" value="1.9"/> %	Foam water <input type="text" value="2.0"/> %
<b>SETTING UP THE PLANT FOR MIXING</b> (Each new batch / tanker load)		
1. Check bitumen temperature in tanker (loading hatch)		<input type="text" value="181"/> °C
2. Couple up bitumen tanker and bleed air from system		<input checked="" type="checkbox"/>
3. Check that the bitumen foams using test nozzle		<input type="text" value="Good"/>
4. Water supply. Open valves and bleed air from system		<input checked="" type="checkbox"/>
5. Check all supply lines and feed pipes for leaks		<input checked="" type="checkbox"/>
6. Check ancillary plant and equipment is ready for mixing		<input checked="" type="checkbox"/>
NOTES	<u>Two wheel loaders. Material run to stockpile</u>	



APPENDIX D: Construction Controls for Bitumen Treatment

### D.3. DAILY REPORTS FOR IN SITU RECYCLING

The following are examples of report that should be completed daily during recycling operations.

#### D.3.1. BSM-foam

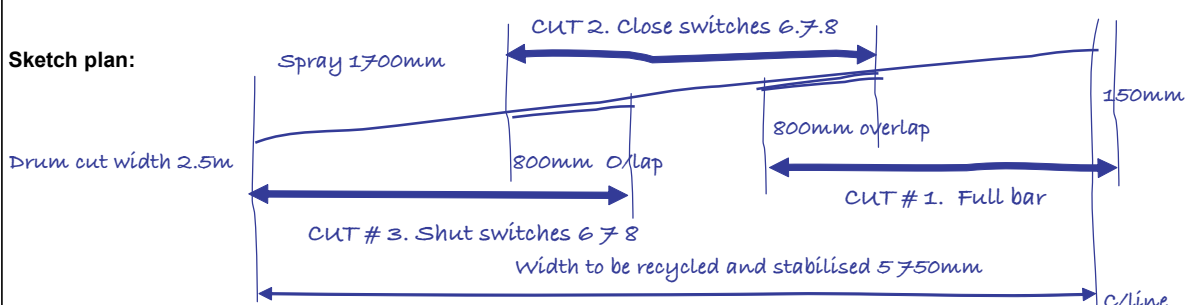
<b>Project:</b> Rehab of N2 Section 21, Kokstad		<b>Date:</b> 23 March 2009		<b>DAILY FOAMED BITUMEN APPLICATION RECORD</b>					
Recycler make / model Wirtgen 2500 S		Machine Serial No. 06-WR-593-067		Type of Bitumen 80 / 100 Pen					
Weather conditions Sunny and warm		Producer / Batch No Engen, Durban, 0067/338/21							
Lane (see sketch)		LHS	LHS	LHS	LHS				
Cut no. (see sketch)		1	2	3	3				
Supply tanker ID / bitumen temp		ND 635 / 170C	NP 4439 / 165C	? same	ND 4004 / 170C				
Weighbridge ticket mass		19.60 tons	19.38 tons	? same	9.86 tons				
Time		09:20	11:45	13:15	15:30				
Road surface temp	°C	18°C	23°C	26°C	27°C				
Bitumen temp (flowmeter)	°C	185°C	172°C	168°C	166°C				
Active filler	Type / %	OPC / 0.7%	OPC / 0.7%	OPC / 0.7%	OPC / 0.7%				
Bitumen consumption reading (computer)	Start	Reset 0	19 900	33 800	39 500				
	Finish	19 900	33 800	39 500	47 500				
Distance covered (chainage markers)	Start	32+410	32+410	32+410	32+755				
	Finish	33+240	33+240	32+755	33+240				
Length of section	m	830	830	345	485				
Application width	m	2.5	1.7	1.7	1.7				
Recycling depth	m	0.2	0.2	0.2	0.2				
Volume of section	m <sup>3</sup>	415.0	282.2	117.3	164.9				
Density of material	kg/m <sup>3</sup>	2150	2150	2150	2150				
Mass treated	tons	892.25	606.73	252.2	354.54				
Emulsion consumed	litres	Computer	Actual	Computer	Actual	Computer	Actual		
		19 900	19 600	13 900	Part	5 700	Part	8 000	Part
Bitumen application rate	%	2.23	2.2	2.29	tanker	2.26	tanker	2.26	Tanker
Design requirement	%	2.2		2.2		2.2		2.2	

Remarks: Tanker # 3 sent away with about 2 tons remaining (computer says 1.86 tons)

Total bitumen used ± 47 tons for 830m. (38.98 + 8 approx) Average application for day : 2.29%

Total pockets of cement spread : 280 (14 tons). Average application for day 0.68%

Sketch plan:





APPENDIX D: Construction Controls for Bitumen Treatment

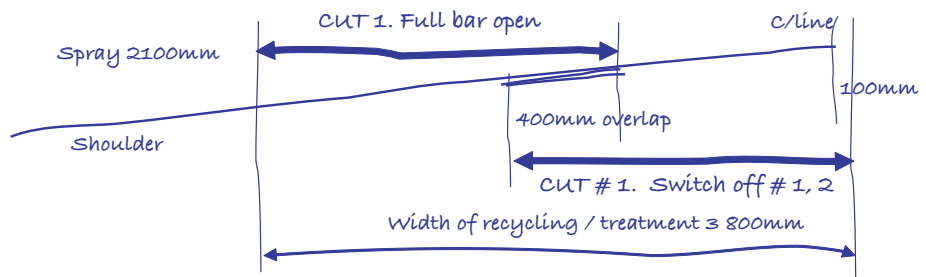
D.3.2. BSM-emulsion

Project:		Date		DAILY BITUMEN EMULSION APPLICATION RECORD							
Rehab of Munyawaneŋi Road, Durban		25 February 2009									
Recycler make / model		Wirtgen 2100 DCR		Machine Serial No.		03-WDC-00593					
Type of Emulsion		CSS-60		Producer / Batch No		JJ Emulsions, Durban, 3/2009/593					
Weather conditions		Partly cloudy and windy									
Lane (see sketch)		LHS		LHS							
Cut no. (see sketch)		1 °C		2 °C							
Supply tanker ID / emulsion temp		ND 123 / 62		NP 456 / 61							
Weighbridge ticket mass		21.62 tons		20.93 tons							
Time		07:20		10:10							
Road surface temp		19°C		24°C							
Emulsion temp (flowmeter)		59°C		64°C							
Active filler		Type / %		OPC / 1.0%		OPC / 1.0%					
Emulsion consumption reading (computer)		Start		Reset 0		21 400					
		Finish		21 400		38 900					
Distance covered (chainage markers)		Start		0+340		0+340					
		Finish		1+340		1+340					
Length of section		m		1000		1000					
Application width		m		2.1		1.7					
Recycling depth		m		0.15		0.15					
Volume of section		m³		315		255					
Density of material		kg/m		2060		2060					
Mass treated		tons		648.9		525.3					
Emulsion consumed		Computer		Actual		Computer		Actual			
		litres		21 400		21620		17 500		Part	
Emulsion application rate		%		3.30		3.33		3.33		tanker	
Residual bitumen content		%		60		60		60			
Bitumen application rate		%		1.98		2.00		2.00			
Design requirement		%		3.33 / 2.0 net		3.33 / 2.0 net					

Remarks: Tanker # 2 not emptied - about 3 tons remaining (computer indicates 3.43 tons)  
 Total emulsion used 38.9 tons for 1000m. Average application for day 3.31% (1.99% residual)  
 Total cement spread by hand: 220 pockets (11 tons). Average application for day 0.94%

Sketch plan:

Drum cut width 2.1m





APPENDIX D: Construction Controls for Bitumen Treatment

D.3.3 Active filler control

<b>Project:</b> Rehab of N2 Section 21, Kokstad		<b>Date:</b> 23 March 2009		<b>DAILY ACTIVE FILLER APPLICATION RECORD</b>	
<b>CONTROL SHEET FOR SPREADING BY HAND</b>					
Type of Active Filler		OPC in 50kg pockets		Source	
Wind conditions		Light NE		NPC, Durban	
Lane (see sketch)		LHS	LHS	LHS	
Cut no. (see sketch)		1	2	3	
Required application rate		0.70%	0.70%	0.70%	
Length of section	m	830	830	830	
Application width	m	2.5	1.7	1.7	
Recycling depth	m	0.2	0.2	0.2	
Volume of section	m <sup>3</sup>	415.0	282.2	282.2	
Density of material	kg/m <sup>3</sup>	2150	2150	2150	
Mass treated	tons	892.25	606.73	606.73	
Active filler required	tons	6.25	4.25	4.25	
Mass per pocket	kg	50	50	50	
Pockets required	No	120	80	80	
Spacing per pocket	m	6.92	10.38	10.38	
Total pockets for day	No	280			
Total tonnage used	tons	14.0			
Total volume treated	m <sup>3</sup>	$830 \times 5.75 \times 0.2 = 954.5$			
Tons of material treated	tons	$954.5 \times 2.15 = 2,052.2$			
Tons of cement required	tons	$2,052.2 \times 0.007 = 14.37$			
Difference	tons	$14.37 - 14.0 = 0.37$ UNDER APPLIED			
Actual application rate	%	$14.0 / 2052.2 \times 100 = 0.68\%$			
<b>Remarks:</b>					
<b>Sketch plan:</b>					

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