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# Guide to Pavement Technology Part 4B

Asphalt

Austroads

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Austroads

Sydney 2014

# Guide to Pavement Technology Part 4B: Asphalt

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First edition published May 2007

**Second edition published June 2014**

This second edition includes major structural changes incorporating details previously contained in a number of Austroads technical reports that are now superseded. It also incorporates the outcomes of a thorough review of asphalt mix design levels and design methodology.

ISBN 978-1-925037-67-8
Austroads Project No. TP1054 and TT1849
Austroads Publication No. AGPT04B-14

Pages 139



**Abstract**

This Guide has been prepared as part of the Austroads Guide to Pavement Technology to provide an introduction to the nature of asphalt as a material and its application in road pavements. Further publications in this Guide provide supporting detail for the placing of asphalt as well as the selection of materials for particular applications.

**Keywords**

asphalt, pavements, mixing/asphalt, paving (asphalt), asphalt mix design, dense graded asphalt, hot mix asphalt, stone mastic asphalt, open graded asphalt, fine gap graded asphalt, warm mix asphalt, gyratory compaction, Marshall compaction

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- promote improved practice and capability by road agencies.
- promote consistency in road and road agency operations.

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**Acknowledgements**

The authors wish to acknowledge the assistance of members of the steering group of the Asphalt Research Working Group (ARWG):

| | |
|---|---|
| Jason Jones | Department of Transport and Main Roads, Queensland |
| Hugo van Loon | Department of Planning, Transport and Infrastructure, South Australia |
| Paul Morassut | Roads and Maritime Services, New South Wales |
| Steve Halligan | Main Roads Western Australia |
| Warren Carter | Downer Infrastructure. |

# Summary

This guide is part of the Austroads *Guide to Pavement Technology* and provides an introduction to the nature of asphalt as a material and its application in road pavements. *Part 4b: Asphalt* was first published in May 2007. This update includes major changes to the document structure which incorporate detail previously contained in a number of Austroads technical reports that are now superseded. It also incorporates the outcomes of a thorough review of asphalt mix design levels and design methodology. Outcomes of the Australian asphalt research program were first published in 1997 as APRG Report No.18 *Selection and Design of Asphalt Mixes: Australian Provisional Guide*. The provisional guide was subsequently revised and included as an appendix to the first edition of this Guide in 2007. Mix design procedures are now incorporated in the updated Guide while a series of appendices provide practical guidance on material selection, determination of the volumetric properties and performance testing.

Austroads technical reports that are now superseded by the Guide to Pavement Technology include:

- AP-T62-06 *Introduction to asphalt mix design*
- AP-T63-06 *Asphalt characterisation for pavement design*
- AP-T64-06 *Asphalt manufacture*
- AP-T65-06 *Asphalt paving*
- AP-T66-06 *Asphalt recycling*
- AP-T67-06 *Maintenance of asphalt surfacings*.

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# 1. Introduction

## 1.1 General

The purpose of this publication is to provide a guide to the principal types of asphalt, selection of asphalt mix type, selection of component materials, asphalt mix design, performance characterisation, and manufacture and placing of asphalt.

Asphalt is widely used in the construction and surfacing of roads in Australasia. The properties of asphalt are complex and its performance requirements vary considerably with the application. Engineers responsible for the design of works incorporating asphalt have a responsibility to acquire an adequate understanding of the properties of asphalt and appropriate usage as well as an understanding of the application of specifications and construction requirements.

**Figure 1.1: Arterial road surfaced with asphalt**

## 1.2 Asphalt Mix Types

In basic terms, asphalt is a mixture of coarse and fine aggregates, filler and bituminous binder. The most common type of asphalt is a dense graded mixture that is manufactured and placed hot (typically 150–170 °C) and commonly referred to as dense graded asphalt (DGA). In this form it is the basis for most structural applications of asphalt in construction of new pavements and strengthening of existing pavements as well as a versatile surfacing material for pavements with traffic levels ranging from pedestrians and light cars up to the most heavily trafficked urban arterial roads.

Different traffic levels, however, require different combinations of size, type, and proportion of aggregate, filler and binder to provide appropriate levels of structural stiffness, deformation resistance, flexibility, permeability, surface texture and durability. Selection of component materials, optimisation of volumetric properties for different levels of traffic and characterisation of resultant performance properties form the basis of asphalt mix design procedures (Section 4).

Other asphalt mix types for particular applications, mostly as surfacing materials, include stone mastic asphalt, open graded asphalt and fine gap graded asphalt.

Stone mastic asphalt uses a high proportion of coarse aggregate to increase texture for reduced noise and water spray while achieving high deformation resistance, but with increased materials cost and construction complexity.

The permeable surface of open graded asphalt reduces surface water spray and tyre road noise, providing a safer and quieter surface but with reduced durability and structural stiffness.

Fine gap graded mixes contain a large proportion of fine aggregate and may be used in combination with high binder contents to provide smooth textured, durable, and easily compacted asphalt mixes for light traffic situations.

As well as standard classes of bitumen, multigrade bitumen and modified binders may be used to increase performance standards such as flexibility, deformation resistance or binder cohesion for particular applications.

A further modification of the properties of asphalt mixes is the concept of ‘warm mix asphalt’ that enables the manufacture and placing of asphalt at lower temperatures than that normally associated with hot mix asphalt.

## 1.3 Manufacture and Placing

The manufacture of hot mix asphalt is generally carried out in large fixed plants operating in capital cities and major provincial centres. Transportable plants are also used for project work in both major centres and rural locations.

Placing of hot mix asphalt on major works usually involves specialist paving crews or independent contractors operating in association with asphalt manufacturers (Figure 1.2). Placing of asphalt on minor works, such as maintenance patching, domestic driveways, sports grounds, car parks, etc., is particularly the province of smaller independent contractors and road maintenance crews.

The most common applications for asphalt are on public roads and hence subject to public authority specifications. Asphalt work is generally undertaken by contract in a quality systems environment.

Important issues are therefore:

- specification requirements for asphalt type, design requirements and standards of completed work
- contractor’s quality system, including
  - manufacturing procedures
  - manufacturing process control
  - asphalt spreading and compaction procedures
  - occupational health and safety
  - environmental management system
- specification requirements for sampling and testing
- audit and surveillance of contract works.

**Figure 1.2: Asphalt paver in operation**

## 1.4 Sustainability

'Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (World Commission on Environment and Development 1987).

In the context of this document, sustainability refers to:

- use of recycled materials in the manufacture of new asphalt
- ability to re-use asphalt pavement materials, either in situ or in further re-use as reclaimed asphalt pavement
- lowering of greenhouse gas emissions through use of warm mix asphalt.

Aggregates and binder in reclaimed asphalt pavement (RAP) may be re-used in the manufacture of new hot mix asphalt, recycled in situ in hot or cold processes or cold recycled as a plant mixed pavement material. Other recycled materials, including crumb rubber, slag, crushed glass, crushed concrete and foundry sand may also be incorporated in the manufacture of asphalt. Fly ash and cement kiln dust are by-products regularly used as asphalt filler materials.

Existing asphalt pavement layers can be overlaid with asphalt and incorporated in the rehabilitated or strengthened pavement structure, subject to the in-place performance of the existing asphalt layers, or reclaimed and re-used in the manufacture of new asphalt or recycled as pavement base material.

Long-term performance studies of pavements constructed with full depth and deep strength asphalt have demonstrated the concept of 'long-life pavements'. Low asphalt strains associated with thick asphalt layers result in long lasting pavements that have minimal long-term structural deterioration and which can be maintained by periodic replacement of the surfacing.

Warm mix asphalt (WMA) technologies are additives and/or processes that can allow a reduction in the temperatures at which asphalt mixes are produced and placed. Typically, WMA is produced at temperatures that are 20–50 °C below that of normal hot mix asphalt.

# 2. Asphalt Applications and Mix Types

## 2.1 Applications

The applications for which asphalt may be used include:

- construction of new pavements
- maintenance or rehabilitation of an existing pavement, involving one or more of
  - patching to correct pavement deficiencies
  - strengthening by overlay with additional asphalt layer(s)
  - correction of surface irregularities
  - provision of a new wearing surface.

The selection of the appropriate asphalt treatment depends on the following and may involve a combination of several factors, including:

- pavement design
- structural performance requirements
- strengthening requirements
- condition of the existing pavement
- operating environment
- surface characteristics required
- construction requirements
- whole-of-life costs.

Consideration of the above factors will lead to selection of:

- type of asphalt mix
- nominal size of mix
- layer thickness
- type of binder
- type of aggregate.

## 2.2 Design of New Pavements

Design of new pavements, including reconstruction, should determine:

- total pavement thickness
- composition and thickness of various pavement courses.

Information on the design of pavements is provided in the *Guide to Pavement Technology Part 2: Pavement Structural Design* (Austroads 2012).

## 2.3 Structural Performance of Asphalt

The structural performance of an asphalt pavement, or its ability to withstand the destructive effects of traffic and environment, is defined in terms of the engineering properties of the mix.

The engineering properties of asphalt in pavements consider:

- the load deformation or stress-strain characteristics in terms of elastic modulus (stiffness)
- the performance characteristics in terms of the two primary structural distress modes
  - fatigue (cracking)
  - excessive permanent deformation (rutting).

The elastic response and fatigue life of a mix are primarily dependent on:

- the stiffness of the binder
- inter-particle friction of aggregates
- the volumetric composition of the compacted mix (usually expressed by its volume of voids in mineral aggregate, binder and air voids).

Factors influencing asphalt mix stiffness, fatigue life and deformation resistance may be in conflict. An understanding of asphalt mix design and performance characteristics is an important element of design of asphalt pavements and rehabilitation treatments. It is essential that the pavement designer is well informed about the impact of asphalt mix design on pavement design, and that the choice of asphalt type and design parameters is appropriate to the overall pavement. A detailed guide to the determination of asphalt characteristics for structural design applications is provided in Austroads (2012).

Tests for the determination of stiffness, fatigue and deformation characteristics are described in Appendix D, Appendix E and Appendix G.

## 2.4 Rehabilitation

### 2.4.1 General

In rehabilitation work there are a number of treatments available depending on the situation. Selection of the appropriate treatment relies on:

- identifying the pavement distress
- investigation and evaluation of existing pavements
- determining mode and cause of distress (or failure).

A more detailed guide to identifying pavement distress and miscellaneous treatments is provided in the *Guide to Pavement Technology Part 5: Pavement Evaluation and Treatment Design* (Austroads 2011).

### 2.4.2 Treatment Types

Rehabilitation may involve the provision of structural overlay to improve the strength of the pavement or a non-structural overlay where the primary purpose is to provide a new wearing surface without significantly changing the strength of the pavement.

Overlay treatments can be combined with a strain alleviating membrane interlayer (SAMI) to waterproof the pavement or reduce reflective cracking prior to placing the overlay.

Other available forms of pre-treatment include:

- milling to remove unstable or deficient materials, correcting surface shape or matching the new surface to existing adjacent surfaces
- minor patching to correct localised defects
- major or heavy patching to correct structural defects
- crack sealing
- regulation or application of a corrective course to improve shape, ride quality or rut filling.

Further asphalt rehabilitation treatment options include:

- in situ recycling
- patching without overlay
- geogrid reinforcement to delay reflective cracking.

## 2.5 Operational Environment Factors

Operational environment factors affecting the selection of asphalt mix type may be external or relate to the required characteristics of the finished surface.

Factors that affect selection include:

- traffic
- site conditions
- finished surface texture requirements
  - surface friction
  - tyre/road noise
  - conspicuity of road markings
  - water spray
- climate and weather
- whole-of-life costs
- user expectations.

A detailed guide to the effect of the operational environment and required surface characteristics on the selection of road surfacing type, including factors leading to the choice between asphalt and alternative surfacings, is provided in the *Guide to Pavement Technology Part 3: Pavement Surfacings* (Austroads 2009a).

## 2.6 Types of Asphalt Mixes

### 2.6.1 General

The primary division between mix types is in terms of particle size distribution (generally referred to as grading). Within each grading type, there are variations in terms of binder type as well as types and proportions of component materials for particular applications. Further variations to asphalt mix types include mixes for specific application such as ultra-thin surfacing or warm mix asphalt.

The principal mix types based on particle size distribution are:

- dense graded asphalt (DGA), also called asphaltic concrete (AC)
- stone mastic asphalt (SMA)
- open graded asphalt (OGA), also called open graded porous asphalt (OGPA) and open graded friction course (OGFC)
- fine gap graded asphalt (FGGA).

Figure 2.1 indicates typical particle size distributions for the principal mix types. An indication of the relative proportion of components is shown in Figure 2.2.

**Figure 2.1: Typical particle size distributions for various mix types**

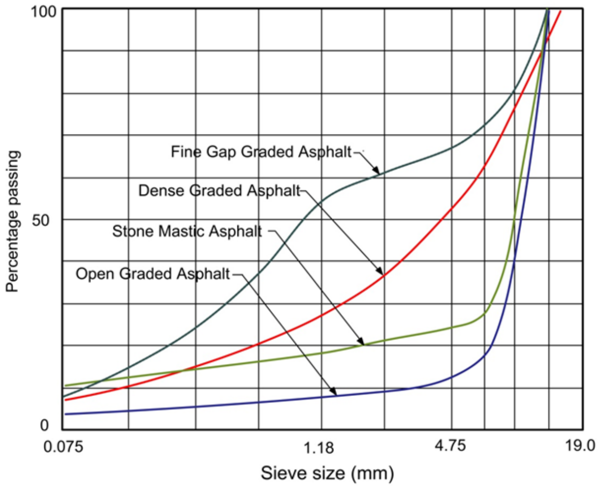
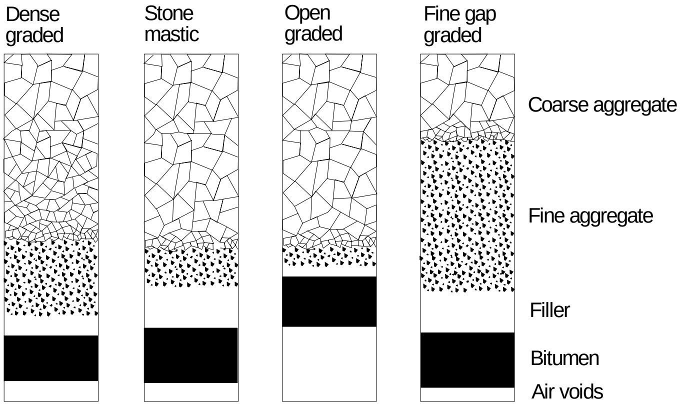



**Figure 2.2: Typical mix components by volume**



### 2.6.2 Dense Graded Asphalt (DGA)

A dense graded asphalt mix has a continuous distribution of aggregate particle size and filler (i.e. evenly distributed from coarse to fine) and a low design air voids content, generally in the range of 3 to 7%. Dense graded mixes represent the most widely used form of asphalt. This type of mix provides the greatest load carrying capacity for structural layers as well as a range of other properties appropriate to a wide variety of wearing course applications.

The durability and resistance to environmental degradation of DGA is largely determined by in situ air voids and binder content, and it is important that these be optimised for service conditions as described in Section 4. Binder type, aggregate characteristics, filler type, and use of additives, all contribute to structural stiffness, fatigue, deformation resistance, surface texture and workability. The effect of materials and assessment of performance properties are covered in Sections 3 and 4.

Dense graded mixes are usually mixed, spread and compacted while hot, although mixes incorporating cutback bitumen or bitumen emulsion binders may be mixed, placed and compacted at, or slightly above, ambient temperatures.

### 2.6.3 Stone Mastic Asphalt (SMA)

SMA is a gap graded mix with a high proportion of coarse aggregate providing an interlocking stone-on-stone skeleton that resists permanent deformation. The coarse aggregate skeleton is filled with a mastic of binder, filler and fine aggregate. Generally, fibres are used to prevent drainage of the relatively high binder content during transport and placing.

SMA generally has the following characteristics:

- high durability
- low permeability
- low traffic noise
- high resistance to reflection cracking
- high deformation resistance.

SMA is used in applications where a well textured mix is required for good skid resistance and reduced tyre noise. Compared to open graded asphalt, it provides greater durability and may be suitable for use at intersections and other areas of high traffic stress. Materials cost is generally higher than other mix types but SMA provides enhanced texture depth in a durable, rut resistant mixture.

SMA mixes of nominal size 7, 10 and 14 mm have been used in Australia although the use of 14 mm nominal size has diminished in line with European trends to smaller sized SMA mixes. The smaller nominal sizes provide lower surface-noise levels, reduced risk of segregation and enable reduced layer thickness while retaining a well textured surface.

### 2.6.4 Open Graded Asphalt (OGA)

The particle size distribution of an OGA mix is characterised by a large proportion of coarse aggregate and only small amounts of fine aggregate and filler.

OGA has relatively high air voids, generally in the range 18 to 25%, and relies largely on mechanical interlock of aggregate particles for stability. High air voids lead to reduced durability although the impact of reduced durability can be lessened with the use of high binder contents to increase the binder film thickness around the individual aggregate particles and the use of modified binders. Coarse textured aggregates with angular shape are desirable for surface texture and stability.

When used as a wearing course the characteristics of OGA include:

- good skid resistance
- smooth riding surface
- reduced light reflection (glare)
- reduced tyre noise
- reduced water spray.

As OGA mixes are permeable, it is important that they are placed on a base that is:

- waterproof to minimise vertical movement of moisture into the pavement
- free draining to provide lateral drainage to the edges of the pavement.

The principal applications of OGA are as surfacing on high speed multi-lane facilities, particularly in urban areas where the combination of low tyre noise and increased safety are important attributes.

OGA is not recommended for use at intersections due to relatively low shear resistance and potential for oil droppings to soften the binder and fill the voids, reducing drainage ability.

OGA may also be used in certain special applications such as a drainage layer or as a base material for cement grout filled macadam.

### 2.6.5 Fine Gap Graded Asphalt (FGGA)

FGGA is a dense (low air voids) mix but with intermediate sized fractions replaced by finer fractions. It may also contain more filler.

Fine gap graded mixes rely on the stiffness of the fine aggregate/filler/binder mixture for stability. When used in residential streets and other lightly trafficked applications, they provide a fine textured surface and a workable mix that is readily compacted to low in situ air voids. The combination of low air voids and relatively high binder content provides an extremely durable surface as well as good fatigue resistance.

FGGA mixes are not generally used as a wearing course in heavily trafficked applications in Australasia due to poor rutting resistance at high surface temperatures. In the United Kingdom, FGGA in the form of 'hot rolled asphalt' was formerly widely used as a wearing course although its use is now being largely replaced by SMA. Hot rolled asphalt incorporates hard grades of binder to provide mix stiffness, while polish resistant bitumen-coated coarse aggregates are spread and rolled into the surface during placing to provide adequate texture depth and surface friction at high speeds.

FGGA mixes are not used in base applications due to higher cost and reduced stiffness.

## 2.7 Asphalt Courses

### 2.7.1 General

Asphalt may be used at almost any location within a pavement:

- wearing or surface course
- intermediate course
- basecourse
- regulating, levelling or corrective course.

In general, a course may consist of more than one layer (although most wearing courses comprise only one layer).

### 2.7.2 Wearing or Surface Course

Where DGA or SMA is placed as a wearing course in conjunction with an asphalt base or intermediate course, they form part of the structural medium. In contrast, open graded asphalt used as a wearing course is often discounted as a structural layer due to relatively low flexural stiffness and the need for more frequent replacement. As a maintenance treatment, a wearing course may be used to recondition the surface of the pavement without changing the structural condition of the pavement.

A wearing course may also be used, with or without additional intermediate or basecourse layers, as a structural overlay.

The selection of wearing surfaces is discussed in detail in Austroads (2009a).

### 2.7.3 Intermediate Course

The term ‘intermediate course’, also referred to as ‘binder course’, is sometimes used to describe the layer immediately below the wearing course to distinguish it from other basecourse materials that may comprise a different size or type of asphalt or other base material. In other respects the term is synonymous with basecourse.

### 2.7.4 Basecourse

Asphalt basecourses are the elements of flexible pavements that provide structural strength to the pavement.

### 2.7.5 Regulating, Levelling or Corrective Course

This is an asphalt course used to correct irregularities in the surface of an existing sealed pavement prior to subsequent surfacing.

### 2.7.6 Deep Strength and Full Depth Asphalt

A deep strength asphalt pavement is one where asphalt wearing and basecourses are used in conjunction with an unbound, stabilised or cemented granular basecourse, to form the structural layers of the pavement.

A full depth asphalt pavement is one where all the structural layers above the subgrade or improved subgrade are constructed of asphalt. Generally, an improved subgrade or working platform of granular materials is required to enable placing and compaction of the base asphalt layer.

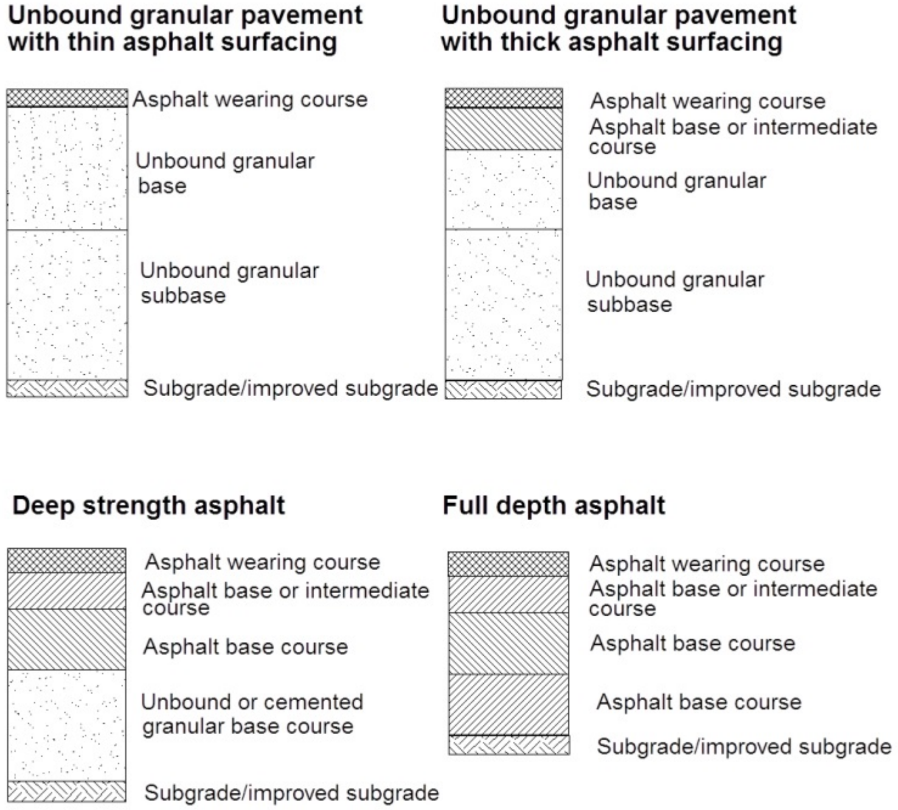
For some heavily trafficked asphalt pavements a high bitumen content asphalt fatigue layer at the bottom of full depth asphalt pavements has been used (Austroads 2012). A minimum thickness of cover of 100 mm of dense graded asphalt should be adopted to prevent the likelihood of instability and permanent deformation under heavy traffic. Such high binder content mixes should be limited to no more than 25–30% of the total pavement thickness, or not exceed 75 mm in thickness.

Some advantages of full depth and deep strength asphalt are:

- greater speed of construction results in less inconvenience to the road users, and lower overhead costs
- subgrade or subbase is waterproofed at an earlier stage reducing the risk or water damage or delays in wet weather
- reduced risk of structural deterioration due to moisture infiltration into base and subbase materials
- compared to granular pavements, excavation depth is reduced, often alleviating the need to relocate services
- low maintenance costs throughout the life of the pavement
- pavements can be designed as long life pavements subject to periodic replacement of the wearing course
- construction and maintenance is generally cost-effective compared to other forms of pavement construction.

An indication of asphalt courses and pavement types is provided in Figure 2.3.

**Figure 2.3: Pavement types**




## 2.8 Mix Size and Layer Thickness

### 2.8.1 Nominal Mix Size

The nominal size of an asphalt mix is an indication of the maximum particle size present and is usually expressed as a convenient whole number above the largest sieve size to retain more than 0% and less than 10% of the aggregate material (AS 2150).

The selected nominal size of the mix will be determined by:

- location of asphalt course in the pavement
- proposed compacted thickness of the layer
- functional requirements of the asphalt layer.

Table 2.1 indicates typical nominal mix sizes for different applications.

**Table 2.1: Typical mix sizes for various applications**

| Application | Typical mix size |
|---|---|
| Dense graded wearing course<br>▪ lightly trafficked pavements<br>▪ medium to heavily trafficked pavements<br>▪ highway pavements<br>▪ heavy duty industrial pavements | <br>7 or 10 mm<br>10 or 14 mm<br>Generally 14 mm (also 10 mm)<br>14 or 20 mm |
| Dense graded intermediate course | In general it is better to use the largest size practicable where the wearing course is dense graded asphalt. Where the asphalt surface is open graded asphalt, the largest size mix used in this application is typically 14 mm |
| Dense graded basecourse | Normally 20 mm. 28 mm may also be used depending on layer thickness and availability. 40 mm has been used in the past but now largely discontinued through difficulties associated with increased segregation in larger sized mixes and general unavailability |
| Dense graded corrective course | 5, 7, 10, 14 or 20 mm |
| Stone mastic asphalt wearing course | 7, 10 or 14 mm |
| Open graded wearing course | 10 or 14 mm |
| Open graded basecourse (drainage layers) | 14, 20 or 28 mm |
| Fine gap graded asphalt | Generally 10 mm (also 7 mm) |
| Minor patching<br>Major patching | 10 mm (also 5, 7, 14 and 20 mm)<br>All sizes as appropriate |

### 2.8.2 Layer Thickness

Generally, asphalt should be placed in layers with a compacted thickness of not less than 2.5 times and preferably 3 times the nominal size of mix in order to facilitate compaction and to avoid tearing or poor mechanical interlock of aggregate particles.

A minimum layer thickness of at least three times the nominal size is particularly important in assisting compaction of harsher and coarse graded asphalt mixes, including stone mastic asphalt and mixes with heavily modified binders.

Minimum layer thickness may not apply to placing of ultra-thin asphalt where a suitable seal coat or bond coat is used to effectively bond the new layer to the underlying pavement and improve waterproofing effectiveness.

The maximum compacted layer thickness is generally limited to between four and five times the nominal mix size. Where the layer thickness exceeds four times the nominal size, it is often more cost-effective to use a larger nominal size mix, which may also provide greater flexural stiffness and deformation resistance.

A guide to typical layer thickness is shown in Table 2.2.

**Table 2.2: Typical asphalt layer thickness**

| Nominal mix size (mm) | Compacted layer thickness (mm) |
|---|---|
| 5 | 15 to 20 |
| 7 | 20 to 30 |
| 10 | 25 to 40 |
| 14 | 35 to 55 |
| 20 | 50 to 80 |
| 28 | 70 to 110 |

### 2.8.3 Ultra-thin Asphalt Surfacing (UTA)

Ultra-thin asphalt (UTA) provides an exception to the minimum layer thicknesses shown in Table 2.2 and generally refers to asphalt placed to a compacted thickness of 20 mm or less. A variety of asphalt mix types can be used for ultra-thin surfacing, including small nominal size mixes of all the above types, or specially developed mixes, typically a variation of OGA or SMA with a grading somewhere between the two.

Most of these UTA mixes are permeable and can lack the independent integrity associated with thicker layers. Placing is usually accompanied by a bond coat of modified bitumen emulsion to provide both a bond to the underlying layer and a reasonably waterproof surface. The bond coat application rate generally involves the use of a purpose-built paving machine to spray the bituminous emulsion bond coat and place the asphalt mix in the one operation.

## 2.9 Warm Mix Asphalt

Warm mix asphalt (WMA) technologies are additives and/or processes that can allow a reduction in the temperatures at which asphalt mixes are produced and/or placed. Typically, WMA is produced at temperatures that can be up to 20–30 °C below that of hot mix asphalt (HMA) although lower manufacturing temperatures may not be required where the WMA technology is being applied to enable longer haul distances or improved workability.

Claimed benefits associated with the use of WMA technologies compared to HMA include improved working conditions (less fumes and lower mat temperatures), reduced emissions and energy usage, decreased binder aging during production, improved operational efficiency (early site opening), wider paving conditions (cool-weather paving at night and during the winter), improved workability (compaction aid for stiff mixes), longer haul distances, and improved compaction (more consistent field density).

# 3. Materials

## 3.1 Introduction

Asphalt is a mixture of coarse and fine aggregates, and filler, bound with a bituminous binder.

Aggregates form up to 96% by mass of an asphalt mix. The function of aggregate is to:

- impart stability to the mix by the interlock of aggregate particles through their frictional resistance to displacement
- provide a surface texture which will maintain skid resistant properties and not polish excessively under traffic
- form a durable, abrasion resistant material which will withstand environmental degradation and accommodate imposed loads without failure
- spread the wheel loads to the lower layers of the pavement.

Coarse aggregate is that portion retained on a 4.75 mm sieve and fine aggregate is that portion passing a 4.75 mm sieve and retained on a 0.075 mm sieve.

Filler is that portion of mineral matter passing a 0.075 mm sieve, and includes rock dust derived from coarse and fine aggregate fractions and any other materials such as ground limestone, hydrated lime, fly ash, cement kiln dust, etc., added to supplement the quantity and properties of filler in the mix.

Bitumen binders are obtained from the refining of crude oil. Binders may be modified by additional processing or the addition of polymers. Binders may also be cut back or emulsified to enable production of cold mixes and other specialty applications.

Asphalt mixes may be further modified by the addition of adhesion agents, fibres, bitumen flow modifiers, coloured pigments or other additives used to modify the binder or asphalt mix behaviour.

## 3.2 Aggregates

### 3.2.1 Sources of Aggregate

Aggregate may be produced from:

- crushed and screened quarry products
- natural sands and gravels
- manufactured aggregates
- recycled materials.

Igneous rocks are the most common source of processed quarry aggregate, and may include basalt, dolerite, andesite, granite, porphyry, rhyolite, diorite, etc.

Metamorphic rocks such as hornfels, schists, gneisses, and quartzites are also used as asphalt aggregates.

Sedimentary rocks and low grade metamorphic rocks encompass a large range of sources of various composition and properties. Use of sedimentary aggregates in asphalt is dependent on material of adequate hardness and absence of planes of weakness as well as factors of availability and particular application.

Natural sands and gravels may be crushed and screened, washed and screened, or obtained as untreated bank run or pit sand.

Manufactured aggregates may be either the by-products of an industrial process, such as industrial slag, calcined bauxite, or products specially manufactured for use as aggregates.

Recycled materials for use in the manufacture of asphalt include reclaimed asphalt pavement (RAP), recycled concrete, crushed glass, etc.

A general guide to suitability of various source rock types for asphalt is shown in Table 3.1.

**Table 3.1: Desirable aggregate properties for asphalt use**

| Rock type | Mechanical strength | Durability | Chemical stability | Surface characteristics | Hardness, toughness | Surface texture | Crushed shape |
|---|---|---|---|---|---|---|---|
| Igneous | | | | | | | |
| Granite | Good | Good | Good | Good | Fair | Fair | Fair |
| Syenite | Good | Good | Good | Good | Good | Fair | Fair |
| Dolerite | Good | Good | Good | Good | Good | Fair | Good |
| Basalt | Good | Good | Good | Good | Good | Good | Good |
| Diabase | Good | Fair | Questionable | Good | Good | Good | Good |
| Peridite | Good | Fair | Questionable | Good | Good | Good | Good |
| Metamorphic | | | | | | | |
| Gneiss, schist | Good | Good | Good | Good | Fair | Good | Good |
| Quartzite | Good | Good | Good | Good | Good | Good | Fair |
| Marble | Fair | Good | Good | Good | Poor | Fair | Fair |
| Serpentine | Fair | Fair | Good | Fair to poor | Good | Good | Good |
| Amphibolite | Good | Good | Good | Good | N/A | Fair | Fair |
| Slate | Good | Good | Good | Poor | Good | Fair | Fair |
| Sedimentary | | | | | | | |
| Limestone/dolomite | Good | Fair | Good | Good | Poor | Good | Poor |
| Sandstone | Fair | Fair | Good | Good | Fair | Good | Good |
| Chert | Poor | Poor | Fair | Good | Poor | Good | Good |
| Conglomerate/breccia | Fair | Fair | Good | Good | N/A | N/A | N/A |
| Shale | Poor | Poor | Poor | Good | Poor | Fair | Fair |

A general outline of the desirable properties of aggregates for use in asphalt is provided below. A more detailed guide to Australasian practice in the selection and testing of source rock for pavement construction materials is provided in the *Guide to Pavement Technology Part 4J: Aggregate and Source Rock* (Austroads 2008a).

### 3.2.2 Aggregate Properties

It is the physical properties and, to a much lesser extent, the chemical properties that determine the suitability of aggregates for use in asphalt mixes. These properties reflect both the mineralogy of the source material and the processes to which the material has been subjected to produce the aggregate.

The physical properties of aggregates include:

- particle size and grading
- particle shape
- surface texture
- resistance to polishing
- abrasion resistance
- durability
- strength

- cleanliness
- particle density
- absorption.

Further properties that are largely dependent on the chemical composition of the source rock include:

- affinity for bitumen
- colour.

***Particle size and grading***

The particle size and grading of an aggregate are controlled by the crushing and subsequent screening process which produce a series of so-called 'one-sized' aggregate fractions, each of which has a narrow grading of particle sizes. Each fraction is designated by its 'nominal' size, which is the size of the sieve through which at least 95% of the particles will pass. In the production of asphalt mixes these aggregate 'fractions' are combined to give the desired distribution of particle sizes.

Aggregate fractions in which the majority of particles are retained on the 4.75 mm sieve are termed 'coarse aggregates'. Those in which the majority of particles pass through the 4.75 mm sieve and are retained on the 75 μm are termed 'fine aggregates'.

Consistent grading through good process control of aggregates is essential if quality control is to be maintained in asphalt production. Most mix specifications specify grading limits of aggregate components to maintain a product within job mix grading limits. Supply of component aggregates to a grading standard which can satisfy job mix requirements and the capabilities of the manufacturing plant being used, becomes a matter of production control based on limits established between the asphalt manufacturer and the aggregate suppliers. A typical delivery tolerance would range from ±15% for a 26.5 mm sieve to ±5% for a 4.75 mm sieve.

***Particle shape***

The shape of the aggregate particles has an important influence on the mechanical stability of an asphalt mix. In general, particles with angular, near-cubicle shape rather than flaky, elongated or rounded shapes are preferred because they provide a skeleton structure with greater interlock and hence resistance to deformation under traffic. Rounded particles are used to provide more workable mixes which require less compactive effort to achieve the required density but such mixes may continue to densify under traffic, leading to rutting due to low air voids and plastic flow. Flaky and elongated particles in a mix impede compaction and, hence, may produce a mix which lacks strength due to high in situ air voids and is more prone to deterioration due to aging of the binder or stripping.

***Surface texture***

Particle surface texture, like particle shape, influences the strength and workability of asphalt mixes. It is determined principally by the grain sizes of the mineral constituents of the source material. Rough textured particles produce high internal friction which generates higher strength than that produced by smoother particles. Also, while smoother particles are more easily coated by the binder film, rougher particles usually form stronger mechanical bonds with the binder. The microtexture of the aggregate particle is also an important influence on the low-speed skid resistance behaviour of a wet surface.

***Resistance to polishing***

All aggregates polish under traffic. The degree of polishing depends on the type of aggregate, traffic conditions and road geometry. Polishing of coarse aggregates can result in a loss of surface friction and minimum requirements are usually specified for all medium and heavily trafficked wearing course applications.

***Abrasion resistance***

The abrasion resistance of aggregate particles is essential to the maintenance of particle interlock and skid resistance under the action of traffic. In addition, aggregates must be able to withstand the crushing and abrasive wear to which they are subjected during manufacture, placing and compaction of asphalt mixes.

***Durability***

A property of aggregate which is both chemical and physical/mechanical is its durability, a measure of the aggregate's ability to perform its intended function for the required service life subject to the load and environmental conditions experienced during that service life. As a chemical property, durability is a measure of the resistance of the aggregate to decomposition (chemical changes) at the surface of individual particles as a result of the interaction between the aggregate and the adjacent environment. In terms of a physical property it is a measure of the resistance to disintegration caused by fracturing along planes of weakness (joints, foliations) which leads to a reduction in particle size. The process of disintegration is aided by the presence of water and some salts and by thermal expansion and contraction.

Decomposition results from the action of water, oxygen or carbon dioxide which, in addition to dissolving water soluble constituents in the aggregate, also causes the release of silica and cations. The surface layers of the rock become unstable with the further release of atomic units (ions or molecules) and the process accelerates as more of the aggregate particle surface is exposed to attack. The atomic units removed from the surface settle in a coherent fashion to form what are termed 'secondary minerals', typically clay minerals. The process is a particular problem in igneous rocks which rely on the strong interlock between constituent crystals for their strength. In these rocks even a small amount of decomposition can seriously weaken this interlock.

The minerals which formed in igneous rocks when the original magma had almost solidified are also classified as secondary minerals.

***Strength***

The strength of an aggregate is important for assessing the suitability of an aggregate for use in asphalt mixes subjected to high traffic intensity, high tyre pressures or heavy wheel loads. This is particularly so where the mixes are to be used in the upper pavement layers where stresses are very high. In general, the strongest aggregate (other properties permitting) should be used in asphalt mixes for wearing courses on freeways, airfields and container handling facilities.

***Cleanliness***

The cleanliness/soundness of aggregates describes the absence of foreign or deleterious materials (such as secondary minerals in igneous rock). These materials include weak or weathered particles, friable particles, clay lumps and organic matter. Clay coatings and excessive dust from the crushing operation influence the cleanliness of aggregates. Weak and weathered particles occur in quarrying operations where the intended source rock for the aggregate is interbedded with weaker rocks, such as millstones, or where the rock is highly jointed or fractured. Clay lumps and organic matter occur as a result of inadequate removal of overburden.

The presence of these materials in aggregates used for asphalt mixes can cause premature ravelling, stripping or surface pop-outs as the weak particles disintegrate under traffic loading or cyclic wetting and drying.

***Density***

The particle density of an aggregate is not a property which influences the suitability of the aggregate for use in asphalt mixes but it is the essential property in the mix design procedure.

***Absorption***

Absorption of water by an aggregate provides an indication of porosity. Good quality asphalt aggregates should be dense and of low porosity. Control of mix voids is difficult with excessively absorptive aggregates, particularly if the degree of porosity is not consistent. A porous aggregate will absorb more binder and tend to produce an asphalt mix which is dry or less cohesive. As a result, additional binder must be incorporated to compensate for the binder absorbed by the aggregate. Therefore, the use of highly absorptive aggregates is not desirable unless the aggregate has other beneficial properties (such as a high resistance to polishing) which outweigh the potential problems arising from its high absorption.

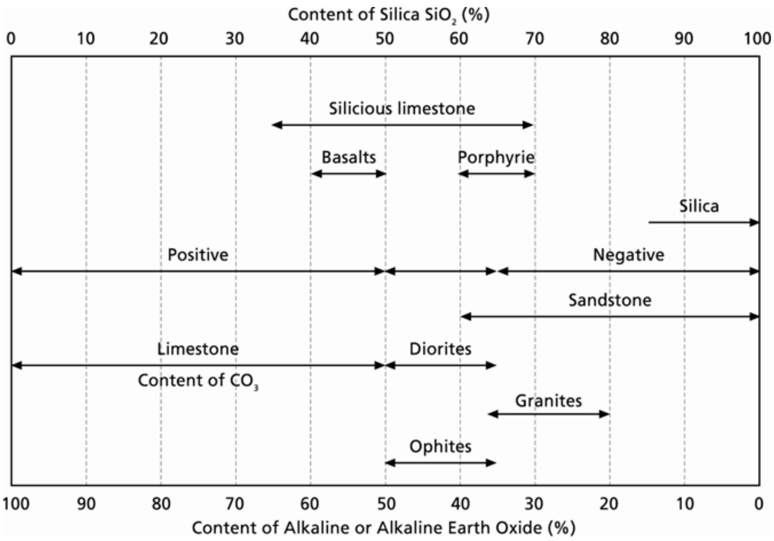
In many cases highly absorptive aggregates will fail to meet other acceptance criteria, i.e. crushing value, but this is not always so. Some authorities therefore qualify or exclude the use of absorptive aggregates. For example, aggregates with a water absorption value of 2 to 4% are classified as absorptive. Lower voids in the total mix and higher voids filled with bitumen ranges are specified for mixes manufactured from these aggregates. Aggregates with absorption values in excess of 4% are classified as excessively absorptive and are not accepted.

### *Affinity for bitumen*

The primary chemical property of an aggregate which influences its use in asphalt is its affinity for bitumen which is related to the surface chemistry of the aggregate. Bitumen must wet the aggregate surface, adhere to the aggregate and resist stripping in the presence of water. Stripping in asphalt is not a new phenomenon but the mechanisms which lead to its occurrence are still not well understood although it has been firmly established that the mineralogy and chemical composition of the aggregate are of primary importance. Some aggregates have a greater affinity for water than for bitumen and the binder film on these aggregates may become detached upon exposure to water. These aggregates, which are termed 'hydrophilic' (water-loving), tend to be acidic while those which have a greater affinity for bitumen are termed 'hydrophobic' (water-hating) and tend to be derived from basic rocks.

This difference in behaviour has been related to the different electrical charges which develop on the surface of the minerals in the presence of water. Most silicious aggregates (e.g. granites, sandstones) become negatively charged while calcareous aggregates become positively charged. A classification of aggregates by surface charge is shown in Figure 3.1.

**Figure 3.1: Classification of aggregates by surface charge**




### *Colour*

Colour of aggregates is dependent on the source rock type. The surface appearance of asphalt will be influenced by the natural colour of the coarse aggregates exposed after a period of wear and weathering. In most cases this is accepted without any specific requirements. Aggregates may be selected on the basis of colour for particular applications, for example the use of red coloured aggregates in conjunction with red pigmented binder to provide a durable red colour for delineation of bus lanes or for an aesthetic effect.

A general description of the principal tests used in the evaluation of aggregate properties is provided in Appendix A and the *Guide to Pavement Technology Part 4J: Aggregate and Source Rock* (Austroads 2008a). Specific details of tests are contained in the Australian Standard series AS 1141 *Methods for sampling and testing aggregates*.

Typical limits for the range of tests are given in road transport agency specifications and in Australian Standard AS 2758.5 *Aggregates and rock for engineering purposes, coarse asphalt aggregates.*

### 3.2.3 Reclaimed Asphalt Pavement

Reclaimed asphalt pavement (RAP) is a valuable source of pre-processed road-making material. When used in the manufacture of hot mix asphalt it provides savings in both new crushed aggregate and bituminous materials. It also assists in preserving landfill space.

The most important use of RAP is as a component in the manufacture of new hot mix asphalt. A small amount is used in cold recycling, with the remainder used in base or subbase materials or landfill.

Other processes for the recycling of asphalt include:

- in situ, using hot processes
- in situ, using cold processes
- cold plant mixing of RAP material.

RAP may be obtained from the milling of existing asphalt surfaces or excavation of road pavements. Milled materials require a minimum of reprocessing by crushing and screening to remove oversized particles and separate into size fractions suitable of use in asphalt manufacture. Greater processing is required for excavated materials.

The maximum size of RAP particles should not exceed the nominal size of the asphalt being produced. Further separation of RAP stockpiles into coarse and fine fractions allows greater control of the particle size distribution of the manufactured asphalt, particularly where larger proportions (20% or more by mass of the total mix) are being added.

As RAP materials are obtained from previously manufactured asphalt, a high degree of confidence can be used in assessing aggregate quality, although some specifications exclude RAP from wearing-course mixes for heavy duty applications on the basis of undetermined effect on the polishing characteristics of the component aggregates.

For most applications, testing of RAP is limited to grading and binder content. Testing of binder viscosity may be required where adjustment of the binder grade is required to compensate for the hardening of bitumen binder in RAP.

Additional information on the recycling and re-use of RAP is provided in Sections 4.7.6 and 5.4.13.

### 3.2.4 Other Recycled Materials

Other recycled materials that may be used in asphalt include crumb rubber, slag, recycled concrete, crushed glass, fly ash, cement kiln dust and foundry sand.

Details of the use of crumb rubber in asphalt mixes are included in the description of polymer modified binders in Section 3.4.3.

Slags typically have the properties of igneous rocks and a structure which can vary from glassy to vesicular. Both steel and blast furnace slags have been used successfully in asphalt mixes, although the latter are generally unsuitable due to poor strength and abrasion resistance. Steel furnace slags are designated in accordance with the process from which they are derived, namely the basic oxygen slag (BOS) and the electric-arc furnace (EAF).

BOS and EAF slag produced in the manufacture of steel from molten iron or scrap metal are similar in characteristics. When cooled slowly they produce a hard, dense material. The density may be 20% greater than normal aggregates. They have good resistance to abrasion and polishing and have the potential for use in situations where high levels of surface friction are required.

Crushed recycled concrete can be used as aggregates in asphalt manufacture although, in practice, these materials are largely used as road base rather than asphalt.

Crushed glass, or glass cullet, is a hard, granular material suitable for use as fine aggregate. In terms of its physical and mechanical properties, crushed glass cullet behaves in a very similar manner to sand, having a similar particle density. As such, it can be used in place of natural sand in asphalt. Suitability includes an appropriate nominal size, particle size distribution, particle shape and limits on the extent of foreign matter such as paper, plastics, aluminium foil and container residues.

Coal fly ash and cement kiln dust are products that can be used as added filler as described in Section 3.3.

Foundry sand is derived from the metals casting industry. It has the potential for use in asphalt and is regularly used in some states in the USA. Some trial projects undertaken in Australia have shown it to be feasible but not necessarily commercially attractive.

An essential factor in considering recycled materials for use in asphalt is that of future recyclability. Reclaiming and reuse of asphalt pavements is well established in Australia and it is important not to incorporate materials that could preclude future recycling due to adverse effects on health and safety or asphalt properties.

Further details on the use of recycled materials in asphalt are provided in the *Guide to Pavement Technology Part 4E: Recycled Materials* (Austroads 2009b).

## 3.3 Filler

Mineral filler is that portion of mineral matter passing a 0.075 mm sieve which can be derived as a portion of the coarse and fine aggregate grading, from the recycling of the dust extracted from the crushing and screening plant or from the dryers or drums of asphalt plants or as added material. The most common added fillers are:

- hydrated lime
- Portland cement
- cement kiln dust
- ground limestone
- ground slag
- fly ash
- baghouse dust.

Fillers can be used to achieve a range of requirements for asphalt mixes. They fill voids and, hence, reduce the optimum binder content. They enable the specified aggregate grading to be met. They increase the strength by stiffening the binder mastic but may also decrease workability. Some fillers, such as hydrated lime, improve the bond between the aggregate and bitumen.

The filler/binder ratio is defined as the percentage by mass of aggregate passing the 75 μm sieve to the effective binder content expressed as a percentage by mass of the total mix and is generally in the range 0.6 to 1.2%. These limits have been established to provide a balance between too little filler, which leads to a mix with low strength, and too much filler, which reduces the voids in the mineral aggregate to a level at which sufficient binder for a durable mix cannot be added. The appropriate proportion for a particular asphalt mix is, however, very dependent on the size, surface area and particle density of the filler.

Unless a particular filler material is specified, fillers are normally evaluated on the relative costs of purchasing, hauling and handling the material. Some fillers store and handle well whilst others cause problems, particularly in wet weather and where used spasmodically. A summary of the advantages and disadvantages of the various added fillers is shown in Table 3.2.

**Table 3.2: Common fillers – advantages and disadvantages**

| Filler type | Advantages | Disadvantages |
|---|---|---|
| Hydrated lime | Consistency of product, availability, ease of handling, improved resistance to stripping, high surface area | Relatively high cost, restricted availability in bulk, reduces workability |
| Portland cement | Consistency of product, availability | High cost, difficult to handle |
| Ground limestone | Easy handling, relatively low cost | Variable grading, restricted availability |
| Cement kiln dust | Relatively low cost | Restricted availability outside capital cities, variable bulk density |
| Fly ash | Low cost, easy to handle | Restricted availability, variable characteristics, promotes bitumen hardening in low binder content mixes |
| Ground slag | Low cost | Properties depend upon production process |
| Baghouse dust | Low cost, readily available | Variable characteristics |

The primary function of the filler is to increase the resistance of the binder mastic to flow, although hydrated lime has been shown to both improve resistance to stripping and the durability of the bitumen (Dickinson 1984).

The properties which are important when considering the use of added fillers in asphalt mixes are defined in Australian Standard AS 2150, *Hot mix asphalt: a guide to good practice* and include:

- particle size distribution
- moisture content
- particle shape (specific surface)
- water solubility
- loss on ignition
- clay content
- plasticity index
- compacted void content.

Other relevant properties are the particle density and the free lime content.

The grading of the filler is important in controlling the amount of oversize material including lumps. Also, the grading in association with the particle shape and texture influences the percentage of air voids in the compacted material and, hence, in the asphalt mix. Fillers with a finer grading tend to produce higher air voids on compaction and those with a high proportion of material finer than 20 to 30 μm may act as a binder extender rather than a filler.

Since the proportion of filler is controlled on the basis of a ratio of percentages by mass of filler to effective binder, fillers with low particle density will represent a greater volume of material.

The particle shape, as characterised by the surface area to volume ratio (specific surface), influences the binder film thickness and binder viscosity. Fillers with a high specific surface reduce the binder film thickness for a given binder content for adequate fatigue resistance of the asphalt mix and binder durability. The exception is hydrated lime which, despite having a high specific surface has been shown to improve binder durability. The improvement appears to stem from the action of the hydrated lime in absorbing the products formed as part of the bitumen oxidation process, thereby preventing further oxidation reaction. The effect of filler on binder viscosity has been shown to be related both to the specific surface of the filler and to its affinity for bitumen.

Some fillers, notably cement flue dust and fly ash, can contain a significant percentage of material which is soluble in water and likely to deteriorate in the pavement. Therefore, it is important that the percentage of such materials is limited.

Added fillers that have active lime are able to alter the surface polarity of aggregates and thus improve their bitumen affinity. The 'active' lime content is the free calcium oxide and hydroxide which occurs in hydrated lime, cement flue dust and Portland cement and will readily hydrolyse to form hydroxides.

Most of the commercially available materials used as added filler are produced to standards that reflect their primary use for other applications, or are by-products of other processes. Specific requirements for use in asphalt are included in AS 2150 as well as some asphalt specifications.

An outline of the test used for the evaluation of filler properties is provided in Appendix A.

## 3.4 Binders

### 3.4.1 Bitumen

Bitumen is a visco-elastic material derived from the processing of crude oil. It is temperature susceptible, i.e. gradually softening when heated and returning to its initial state on cooling.

The characteristics of bitumen, which make it most suitable for use in road surfacing, are:

- strong adhesion which produces cohesive mixes with aggregate
- water resistance
- flexibility and ductility
- durability or resistance to weathering.

The classes of bitumen used in asphalt in Australia, and complying with AS 2008, are shown in Table 3.3. In AS 2008, bitumen is classified in terms of viscosity at 60 °C measured in Pascal seconds (Pa.s).

**Table 3.3: Bitumen classes**

| Formal grade designation | Informal name | Viscosity at 60 °C (Pa.s) | |
|---|---|---|---|
| | | Pre RTFO treatment | Post RTFO treatment |
| Class 170 | C170 | 140–200 | N/A |
| Class 240 | C240 | 190–280 | N/A |
| Class 320 | C320 | 260–380 | N/A |
| Class 450 | C450 | N/A | 750–1150 |
| Class 600 | C600 | 500–700 | N/A |
| Multigrade 500 | M500 | 400–600 | N/A |
| Multigrade 1000 | M1000 | N/A | 3500–6500 |

Source: AS 2008.

Class 320 bitumen is predominantly used in asphalt manufacture. Class 170 bitumen is used to provide workable and durable mixes for lower traffic applications and cooler climate zones or to compensate for hardened binder in RAP when adding high proportions (> 20%) of RAP to the asphalt mix. Class 450 is a slightly stiffer grade used in heavy traffic applications or warmer climates in some states only. Class 600 bitumen may be used to provide greater stiffness in basecourse mixes or increased rutting resistance in wearing and intermediate course mixes.

In some countries, including New Zealand, bitumen is classified by penetration at 25 °C.

Bitumen in New Zealand is generally produced in two basic grades of 40–50 and 180–200. Intermediate grades such as 60–70, 80–100 and 130–150 are supplied for specific applications by blending of the two basic grades. Bitumen penetration grades used in New Zealand are specified in NZ Transport Agency *Specification for roading bitumens NZTA M1*, as shown in Table 3.4.

**Table 3.4: Bitumen grades (NZ)**

| Grade | Penetration (at 25 °C, 100 g, five seconds) | Viscosity (Pa.s at 60 °C, minimum) |
|---|---|---|
| 180–200 | 180–200 | 36 |
| 130–150 | 130–150 | 58 |
| 80–100 | 80–100 | 115 |
| 60–70 | 60–70 | 190 |
| 40–50 | 40–50 | 330 |

Source: NZ Transport Agency (2011).

Applications of penetration grades are generally:

- 180**–**200 **–** mostly used in sprayed seal work only
- 80**–**100 – used in general asphalt work
- 60**–**70 and 40**–**50 – harder grades for stiffer and more deformation resistant mixes.

The type and grade of bituminous binder is usually defined in job specifications. Greater detail on the production, handling, characteristics and selection of bituminous binders can be found in the *Guide to Pavement Technology Part 4F: Bituminous Binders* (Austroads 2008b).

### 3.4.2 Multigrade Bitumen

Multigrade bitumen is less susceptible to temperature changes (i.e. the viscosity changes less with temperature) than conventional bitumens. It can thus provide improved deformation resistance at high service temperatures while retaining the desired level of flexibility at low temperatures.

The grades and classes of multigrade bitumen are set out in AS 2008 and guidelines are covered in the *Guide to the Selection and use of Polymer Modified Binders and Multigrade Bitumens* (Austroads 2013a).

The classification system for multigrade bitumens is based on the range of properties expected at both high and low service temperatures and related to the standard grades of binder specified in AS 2008.

The Class M500 grade, developed for both sprayed sealing and asphalt applications, has properties similar to Class 600 bitumen at the classification temperature of 60 °C and low temperature properties similar to Class 170. The harder Class M1000 asphalt grade has properties significantly harder than a Class 600 at the classification temperature of 60 °C while retaining low temperature properties similar to Class 320.

### 3.4.3 Polymer Modified Binder

Polymer modified binders (PMBs) are generally used to enhance the properties of bituminous binders in order to improve performance on heavily trafficked pavement surfaces, areas of high shear stresses and in some cases, greater flexibility. Performance gains include increased elasticity, improved cohesion, and reduced temperature susceptibility thus improving flexibility, cohesion or resistance to deformation of asphalt mixes at high temperatures.

A wide range of polymer types can be successfully incorporated into bitumen. In practice, a relatively small range of synthetic polymers, as well as crumbed rubber, are used in bituminous materials in Australasia.

The grades and classes of modified binder are set out in the *Specification framework for polymer modified binders* (Austroads Test Method AGPT/T190) and guidelines are covered in Austroads (2008b) and Austroads (2013a).

### 3.4.4 Epoxy Modified Bitumen and Polyurethane Materials

Modification of bitumen with thermosetting epoxy resins produces extremely tough resilient binders. Bitumen extended epoxy binders have been used as asphalt binders in specialty applications such as the surfacing of steel bridge decks where materials are required to exhibit extreme flexibility as well as a strong bond to the steel surface. They can, however, be very difficult to handle due to the need to place materials before the epoxy reaction is completed.

Polyurethane can also be used as a bitumen modifier or as a total binder. This provides a binder with exceptional adhesion, toughness, and flexibility with similar applications to epoxy modified bitumen.

### 3.4.5 Cutback Bitumen

Cutter and flux oils are used for specific purposes in asphalt production. They decrease the viscosity of the bitumen and hence prolong the available time between manufacture and placing of the mix.

Cutback and/or fluxed bitumen may be produced in the refinery, but more commonly in conjunction with asphalt manufacture, by mixing petroleum oils with the bitumen. Standard manufactured grades of cutback bitumen should comply with AS 2157 *Cutback bitumen*.

The addition of low volatility flux oil, such as distillate, has a long-term effect on the viscosity of the binder. It is used to allow an asphalt mix to remain workable at lower temperatures but also reduces the stiffness and deformation resistance of the mix for a substantial period in-service. The quantity of flux oil employed is variable up to about 20% (of binder), and a figure of 12% is commonly used for cold-mix maintenance patching materials that are stockpiled for later use at ambient temperatures (see AS 4283).

Cutback bitumen containing cutter oil such as kerosene will cure at a faster rate than fluxed bitumen but still remains in the asphalt binder for a significant period after placing.

The use of cutback or fluxed bitumen in asphalt is generally applicable to temporary works or emergency repairs. Typical uses are:

- cold mix for maintenance patching
- long distance haulage situations
- packaged mixes to be stored for future use.

### 3.4.6 Bituminous Emulsion

Emulsification of bituminous materials provides binders that can be sprayed or mixed with aggregates with little or no heating. Emulsions are two-phase systems consisting of two immiscible liquids: bituminous binder and water. The binder is dispersed throughout the continuous water phase in the form of discrete globules, which are held in suspension by electrostatic charges.

Standard grades of bituminous emulsion are classified in AS 1160, *Bituminous emulsions for the construction and maintenance of pavements*, by:

- type
- grade
- class of bitumen.

There are two common types of bituminous emulsion – anionic and cationic.

Anionic emulsions have an alkaline emulsifier and a negative surface charge, and are most suitable for use in dry conditions or as slow setting grade in soil stabilisation.

Cationic emulsions have a positive surface charge. They are more commonly used than anionic types due to better performance under adverse conditions and suitability for a much greater range of aggregates (especially acidic aggregates).

Care should be taken not to mix anionic and cationic emulsions, as they will break immediately producing solid bitumen.

Emulsion grades are also based on setting (or breaking) times, into rapid setting (RS), medium setting (MS) or slow setting (SS) grades. Rapid and medium setting emulsions are used for tack coating. Slow setting emulsions are used for cold mix, to allow mixing and spreading before the emulsion breaks.

Typical uses for bitumen emulsion include:

- binder for cold recycled asphalt
- binder for stabilised granular materials
- binder for cold mixed granular base materials
- binder for cold mix maintenance patching materials
- tack coating prior to placing asphalt.

Design of cold recycled asphalt is referred to in Section 4.7.6. A further guide to the use of cold recycled materials is provided in the *Guide to Pavement Technology Part 4E: Recycled Materials* (Austroads 2009b).

A guide to the use of bitumen emulsion in pavement stabilisation is provided in the *Guide to Pavement Technology Part 4D: Stabilised Materials* (Austroads 2006).

Emulsion mixes to be stockpiled are usually manufactured with cationic aggregate mixing (CAM) grade emulsion that contains flux oil to enable it to remain workable in storage. Design of cold mix maintenance patching materials is referred to in Section 4.7.7.

Bitumen emulsion used for tack coating is generally a rapid setting cationic type, although medium setting cationic emulsions and anionic emulsions may also be used if conditions are suitable. Anionic emulsions are generally only suitable for tack coating in warm and dry conditions.

## 3.5 Additives

### 3.5.1 General

Additives are materials that are either added to bitumen to alter the physical characteristics of the binder or added to the asphalt mixture. Modification of binder by the addition of polymers (including crumb rubber), cutter oils and flux oils has already been discussed as has the addition of recycled materials and added filler.

Other types of additives that may be blended with the binder or added to the asphalt mix include adhesion agents, bitumen flow modifiers, fibres, natural asphalt modifiers, rejuvenating agents and coloured pigments.

### 3.5.2 Adhesion Agents

The use of adhesion (anti-stripping) agents aims to increase the physio-chemical bond between the binder and aggregate. Adhesion agents are generally not required for establishing aggregate bond in asphalt manufacture but may, however, reduce in-service moisture sensitivity of particular aggregate types in some circumstances. Rock types with high silica content are usually classified as a poor performer with regard to moisture sensitivity, which is a result of the low adhesion between the bitumen and the rock source. In this case the incorporation of adhesion agent may improve the mix performance.

### 3.5.3 Bitumen Flow Modifiers

Additives used to modify bitumen flow characteristics are used in warm mix asphalt technologies to enable production and/or placing of asphalt at temperatures less than standard hot mix asphalt. Typically, temperature reductions of up to 20 to 30 °C may be achieved depending on the type of additive applied and the technology being employed.

Organic additives, usually waxes, lower the viscosity of the binder at mixing and compaction temperatures thus increasing the workability of the mix without compromising performance at in-service temperatures. They are usually supplied in granular form and can be added either to the mixture or to the binder. However, they are more effective when dispersed in the binder prior to mixing with asphalt.

Chemical additives are generally surfactants that do not change the bitumen viscosity, but act to regulate and reduce the frictional forces at the microscopic interface of the aggregates and the bitumen making it possible to mix the bitumen and aggregates, and to compact the mix, at lower temperatures. Depending on the product, the chemical additives can be added directly to the binder or mixed with water to form a liquid so that it can be injected into the binder stream just before the mixing chamber.

Combined chemical and organic systems include a chemical additive (e.g. sulphur or Trinidad Lake asphalt) to improve the performance of the binder combined with organic additives to lower the viscosity of the binder at mixing and at compacting temperatures. They are usually supplied in pellet form that can be added to the mixture or mixed with the binder.

Water-bearing additives involve the addition of zeolite (containing about 20% crystallised water) to the mix at the same time as the binder. At a mix temperature of about 130–135 °C, zeolite slowly releases water to create foamed bitumen and, hence, provides greater workability.

### 3.5.4 Fibres

Fibre may be used as an additive in asphalt, particularly SMA and OGA mixes to enable high binder contents without binder drain-off during transport and placing. Types of fibre include:

- cellulose
- glass
- polymer
- rock wool.

Cellulose is the most commonly used. Other materials such as polyester and polypropylene fibres have also been shown to be feasible as fibres in asphalt but are not generally commercially viable.

### 3.5.5 Natural Modifiers

Naturally occurring binder modifiers include Trinidad Lake asphalt and Buton Rock asphalt, sulphur and gilsonite, with gilsonite being the only product used in Australasia at this time.

Gilsonite occurs as a rock-like material in veins ranging from a few centimetres to a few metres thick and extending to depths of up to 300 metres. It is a hydrocarbon which is similar in appearance to coal or hard asphalt but its chemical properties are very different and its behaviour is unique.

It is usually supplied in a powder form that can be blended with bitumen to increase binder stiffness or produce the equivalent of a harder grade of bitumen.

### 3.5.6 Rejuvenating Agents

Rejuvenating agents (also called recycling oils), are used in some recycled asphalt applications to reduce binder viscosity or restore the recycled bitumen to optimum characteristics.

Rejuvenating agents are usually proprietary products comprising low viscosity and low volatility oils derived from crude oil. The may be supplied in emulsified of non-emulsified form or as a blend in bitumen.

### 3.5.7 Coloured Pigments

Asphalt may be coloured by the addition of colour pigments. The most common colour is red derived from iron oxide.

The intensity of the colour depends on the proportion of added pigment. In asphalt mixes made with conventional bitumen binder and dark coloured aggregates, the intensity will eventually reduce due to weathering and wear of the surface binder to expose the natural aggregate colour. The use of red coloured aggregates in conjunction with red colour pigment will provide a durable red colour.

A greater intensity of colour in asphalt, as well as a wider choice of colours can be obtained by combining coloured pigments with specialty colourless (pigmentable) binders, although at a much higher cost.

# 4. Mix Design

## 4.1 Introduction

### 4.1.1 General

The process of asphalt mix design involves the choice of aggregate type, aggregate grading, binder type, and determination of a binder content that will optimise the engineering properties in relation to the desired behaviour in-service.

Asphalt mix performance is also influenced by manufacturing and construction standards.

Asphalt mix design involves the following basic steps that are similar in concept, regardless of the actual tests and procedures used:

1. selection of mix type
2. selection of component materials
3. combination of aggregates to achieve a design grading
4. selection of target binder content or range
5. mixing and compaction of asphalt mix to a density that is representative of in-service conditions
6. measurement of volumetric properties of compacted mix
7. mechanical testing of compacted samples
8. verification of design properties on samples of manufactured asphalt, if required
9. selection of job mix.

Procedures for designing asphalt mixes have been generally developed around testing of hot dense graded mixes and determination of optimum binder content, although most tests can be used for other mix types with suitable interpretation of results.

## 4.2 Design Process

### 4.2.1 Background

A major objective of asphalt research and development programs in Australia and overseas, since the late 1980s, has been the development and implementation of simple fundamental and simulative tests for characterisation of asphalt mixes to supplement or replace empirical tests that did not directly relate to road performance. In Australia, this has resulted in the implementation of asphalt mix design procedures based on gyratory compaction as well as a series of performance-related tests.

In the USA, research programs have resulted in the implementation of 'Superpave' (SUperior PERforming asphalt PAVEment). The volumetric design concepts used in Australia are similar to Superpave. The main difference in the Australian developed procedure is the adoption of locally developed, more affordable equipment for compaction and mechanical testing of asphalt.

The aim of the Australian program was the development of a mix design procedure that:

- is performance-related
- enables the in-service performance of mixes to be predicted
- is relatively affordable (in terms of new equipment cost)
- is rapid and easy to use.

Outcomes of the Australian research program were first published in 1997 as APRG Report No.18 *Selection and Design of Asphalt Mixes: Australian Provisional Guide.* This was subsequently revised in 1998 and 2002, republished as Austroads Technical Report AP-T20-03, and included as an appendix to the first edition of this Guide in 2007. Updates of the design procedure, sometimes referred to as the Austroads mix design procedure, are incorporated in this Guide.

The driving force in the adoption of gyratory compaction was the belief that it achieves alignment of aggregate particles that is more representative of field placement of asphalt and is preferred where performance properties are to be measured.

While a number of road agencies in Australia and New Zealand have adopted the use of gyratory compaction for sample preparation and volumetric mix design, others continue to use Marshall compaction for volumetric properties or allow optional use of Marshall or gyratory compaction. The Modified Hubbard-Field Method for compaction or design of asphalt mixes has, however, been almost totally discontinued.

The Marshall method of compaction (i.e. impact compaction) remains in wide use due to its simplicity. It is recognised that the mechanical tests (i.e. stability and flow) used in the Marshall method of asphalt mix design are not necessarily good performance predictors, especially for heavy duty applications, due to the lack of correlation between the tested properties and the in-place performance. Procedures for measurement and interpretation of Marshall stability and flow are included in this publication as they form part of the optimisation of volumetric properties. Additional performance testing (Level 2) using the procedures described in this Guide may, however, be undertaken on mixes designed by the Marshall method.

The status of adoption of alternative mix design procedures by road agencies at the time of preparation of this Guide is described in *Implementation of Austroads Mix Design Procedures* (Austroads 2013b).

### 4.2.2 Selection of Mix Type and Component Materials

Selection of mix type for particular performance conditions will set the parameters for aggregate grading, binder type, volumetric properties, and the general performance characteristics of the mix.

The selection of materials must be appropriate to the mix type and performance environment.

Design parameters and component material requirements are usually defined by the relevant specification. It should be understood that specifications developed around the need for well textured, deformation resistant mixes for heavily trafficked roads may be less suitable for more lightly trafficked applications where other factors such as handling properties, fatigue resistance, durability and asphalt permeability may also need to be considered.

### 4.2.3 Recipe Criteria

Recipe criteria may be used to define some or all of the components and characteristics of an asphalt mix where characteristics of the mix cannot be readily defined or optimised by conventional tests. Such criteria can also be used for simple mixes for minor applications. Examples include:

- setting grading parameters for dense graded asphalt, stone mastic asphalt, open graded mixes, gap graded mixes, ultra-thin mixes and other special mix types
- setting binder content ranges for the preceding mix types
- setting the binder type or additives in any mix type where particular attributes are desired
- using mixes of similar composition to those that have been determined to perform satisfactorily in practice
- cold-mixes.

In many cases, volumetric properties and mechanical performance tests may still be determined to ensure compliance with voids targets or other performance criteria.

### 4.2.4 Preparation and Compaction of Trial Mixes

A variety of methods of sample preparation and compaction for laboratory testing of asphalt mixes are used.

In most cases, trial mixes are prepared that combine aggregates with different proportions of binder to allow selection of a binder content that optimises the desired volumetric properties. If these are not met at a suitable binder content, the source or proportions of aggregates may be altered and the process of sample preparation and compaction is repeated.

### 4.2.5 Volumetric Properties

Volumetric proportions and characteristics are the basis of asphalt mix design and largely determine the in-service performance of the mix.

For some applications, the asphalt mix design process ends at this point.

### 4.2.6 Mechanical Testing

Ideally, the mechanical properties of asphalt in situ are required for pavement design purposes. In situ conditions will vary with a range of factors including temperature, loading time, stress conditions and degree of compaction. Reproduction of in situ stress conditions in the laboratory is difficult, hence simplified tests are used to indicate certain aspects of the in situ behaviour.

Procedures for the mechanical testing of asphalt mixtures may be considered in three groups:

- Fundamental (performance based) tests for stiffness and fatigue
  - repeated load indirect tensile test
  - repeated flexural bending.
- Simulative (performance-related) tests for resistance to deformation and moisture damage
  - wheel tracking test
  - moisture sensitivity.
- Empirical tests for design of asphalt mixes
  - Marshall test (stability and flow).

### 4.2.7 Workability

Workability is the ease with which a material may be handled, placed and compacted to a dense, uniform mat.

The major factors influencing workability are:

- binder viscosity
- binder content
- filler type and content
- nominal size of mix
- aggregate grading
- aggregate shape (crushed or rounded)
- temperature of placing and compaction.

There are no defined tests for workability although an indicator of workability may be obtained from the behaviour of a mix under gyratory compaction.

Workable mixes are indicated by mixes that undergo rapid volume change and increase in density after a few cycles of gyratory compaction and then a slower rate of increase in density to the refusal density condition.

Harsh mixes, with poor workability, are indicated by mixes that do not increase as rapidly in the earlier stages of gyratory compaction but continue to increase in density with further compaction cycles. Such mixes require greater effort to achieve field density targets.

#### 4.2.8 Job Mix

The final selected mix is called the job mix, also referred to as job mix formula (JMF) or nominated mix in some agencies.

The job mix will nominate the type and source of components, target grading, binder content and volumetric properties of the mix. These are used as the basis for manufacturing process control. Production tolerances allow for variations in the mix composition due to changing feed rates, raw material fluctuations, sampling and testing limitations and other factors.

Manufacturing process control may be applied to grading and binder content only, although most agencies also require volumetric testing, and possibly some mechanical testing, to monitor consistency of production.

Any change in the type or source of components, or significant variation in the proportion of any component, generally requires redesign of the mix and determination of a new job mix.

Where there are no other changes requiring redesign of the mix, a job mix may remain valid for a period of time, typically two years, before the need to re-confirm design properties. Verification of design properties may not require a new mix design if the supplier can demonstrate that the components have not changed and that the target volumetric and mechanical properties of the mix are still being achieved. This could be shown by testing undertaken as part of quality assurance programs.

#### 4.2.9 Implementation and Verification of Mix Properties

It is generally recommended that volumetric properties obtained on laboratory prepared samples be verified on asphalt mix sampled from actual production. This may require minor adjustments to grading or binder content targets before adoption of a job mix for subsequent production.

In some cases, design properties of asphalt mixes may also be verified by mechanical tests on samples of plant-manufactured or field materials before adoption of a job mix. Such testing should not be confused with process control and assurance testing of asphalt production.

## 4.3 Volumetric Properties

#### 4.3.1 General

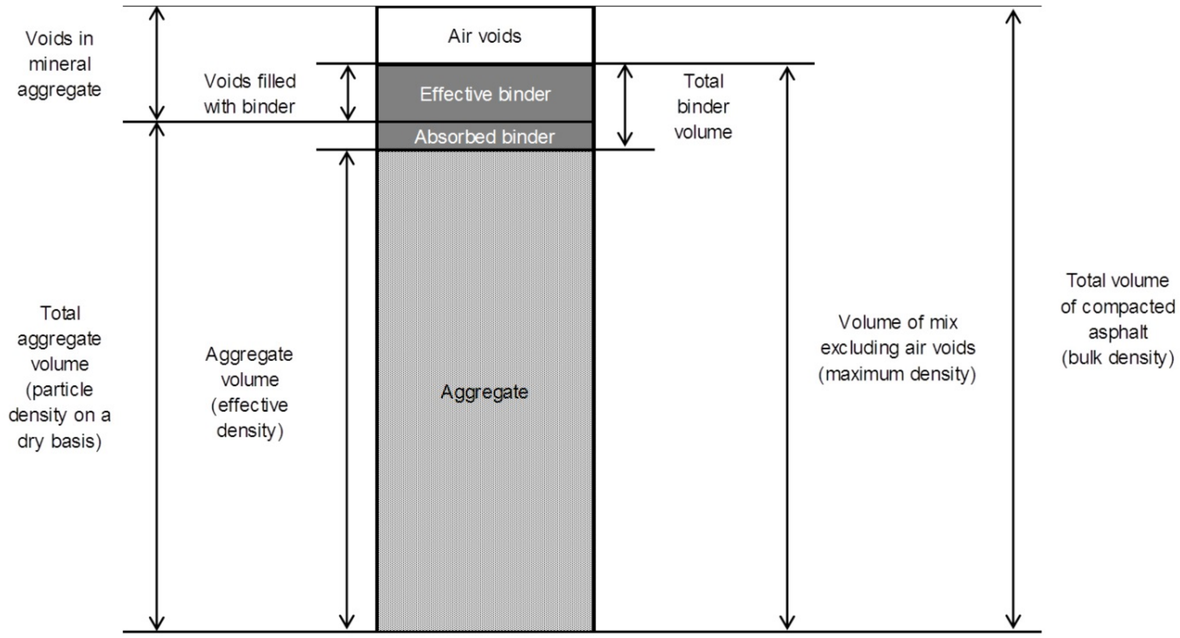
Asphalt mix design is essentially a volumetric process although, for convenience of manufacture and process control, it is simpler to measure the mix proportions by mass.

Important measures of volumetric properties are:

- bulk density
- maximum density
- voids in the mineral aggregate (VMA)
- air voids
- absorbed binder
- effective binder content
- voids filled with binder (VFB)
- binder film thickness.

Volumetric relationships are illustrated in Figure 4.1 (Appendix C).

**Figure 4.1: Constituents of a compacted asphalt mix**




Source: AS 2150.

### 4.3.2 Determining Density of Components

Calculation of asphalt volumetric properties requires determination of the density of components.

By definition, density is the mass per unit volume. Density is usually expressed as tonnes per cubic metre. Before metrication and adoption of SI units of measurement in Australia in the 1970s, the term 'specific gravity' was used to describe the weight-volume relationship of materials. Specific gravity is the ratio of the weight of a unit volume of the material to the weight of an equal volume of water at a standard temperature. The term is still commonly used in many countries and reference texts, particularly in non-metric countries. In practical use, the terms are largely synonymous, but when used in scientific calculations the two will always differ by the density of water at the test temperature (0.997 t/m$^3$ at 25 °C).

The terms 'density' (mass per unit volume) and 'specific gravity' must never be confused or test values mixed when calculating volumetric properties of asphalt mixes.

Accurate determination of densities is important in asphalt design as small differences can have a significant impact on the measurement of properties such as bitumen absorption, effective bitumen content and air voids.

If not available from the bitumen supplier's test certificate for the batch of bitumen to be used for the laboratory mix the bitumen density should be determined in accordance with AS 2341.6 or AS 2341.7.

The density of coarse aggregates is determined by AS 1141.6.1 or AS 1141.6.2 and fine aggregates by AS 1141.5. Apparent particle density of filler is determined according to AS 1141.7.

The test methods provide for three measures of particle density:

- **Particle density on a dry basis** is the mass per unit volume of particles where the volume includes both the permeable and impermeable voids inherent in the particles. It is determined from the ratio of the mass of an oven dry sample to the volume of water displaced by the sample mass in a saturated surface dry condition. In common usage, the term 'bulk density' refers to this condition of test.

- **Apparent particle density** is the mass per unit volume of the impermeable portion of the aggregate particles (inaccessible to water by 24-hour soaking). It is determined from the ratio of the mass of an oven-dried sample to the volume of water displaced by that sample after 24-hour soaking. In common usage, the term 'apparent density' refers to this condition of test.
- **Particle density on a saturated surface dry basis** is the mass per unit volume including both the permeable and impermeable voids. It is determined from the ratio of the mass of a saturated surface dry sample to the volume of water displaced by that saturated surface dry sample.

For determination of the volumetric properties of asphalt, particle density on a dry basis (bulk density) is generally used. Calculations in AS 2891.8 are based on dry density.

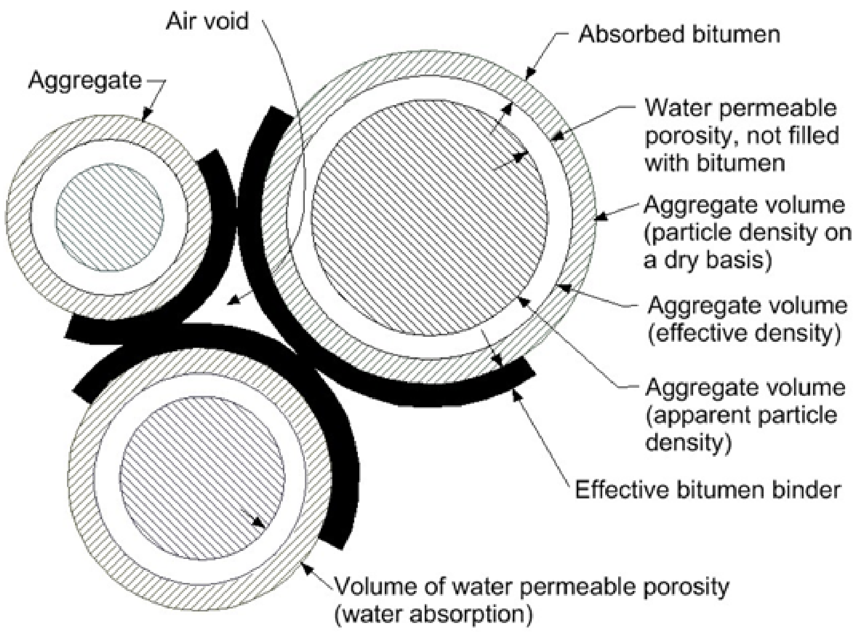
A further measure of aggregate density is that of effective density, being the overall volume of aggregate including the volume of water permeable voids (apparent density), but excluding the volume of larger voids which absorb asphalt (see also Appendix A.2).

Good quality asphalt aggregates should be dense and have low porosity. The porosity of an aggregate is generally indicated by the amount of water it absorbs. The water absorption of aggregates should ideally be less than 2%. Water absorption is the ratio of the mass of water held in the permeable voids of the aggregate particles brought to the saturated surface dry condition, to the oven dry mass of material. Water absorption of coarse aggregate is determined by testing in accordance with AS 1141.6.1 or AS 1141.6.2 and that of fine aggregate by AS 1141.5.

The absorption of binder into porous aggregates must be allowed for in asphalt mix design to ensure an adequate effective binder content.

A diagram indicating the influence of aggregate density and bitumen absorption is shown in Figure 4.2.

**Figure 4.2: VMA, air voids and effective bitumen content in compacted asphalt mixtures**



### 4.3.3 Bulk Density of Asphalt

Bulk density is the weight per volume of the compacted mix including internal air voids. Bulk density is the basis for calculation of voids relationships.

AS 2891.8 refers to three methods of determining bulk density of compacted asphalt; AS 2891.9.1 to AS 2891.9.3 provides the test details for these three methods. Each method will give slightly different results depending on the surface texture and water permeable voids and this must be considered in both the selection of test method and interpretation of test results:

- **Presaturation (AS 2891.9.2)** method is suitable for dense mixes with low permeability and internal air voids that are largely inaccessible to moisture (generally a maximum of 2% absorption for dense graded mixes and 1% for SMA mixes).
- **Waxing (AS 2891.9.1)** procedure eliminates the effect of water permeable voids by sealing the surface with a layer of wax. It is used for dense mixes where it is desirable to avoid the influence of water permeable voids on the measurement of bulk density. Removal of wax can be difficult for samples that are to be used for further testing. An alternative to waxing is the use of silicone to seal the external surface of the sample against the entry of water. Silicone allows easy removal from bitumen-coated surfaces of laboratory compacted samples but is not so readily removed from cut surfaces of field cores.
- **Mensuration (AS 2891.9.3)** method refers to determination of the volume of the specimen by direct measurement of the external dimensions. It is generally used for open graded and other porous mix types.

In addition, some states specify the use of sealing methods to determine the bulk density of OGA and SMA mixes. These include silicone sealing by a Queensland test method and vacuum sealing by a Western Australian test method.

### 4.3.4 Maximum Density

Maximum density, also termed ‘voids free bulk density’, is the density of the mix excluding air voids. AS 2891.7.1 provides the test details for determining the maximum density.

Testing is performed by determining the volume of water displaced by a loose sample of mix after removal of all air under vacuum.

Maximum density determined in this manner is also sometimes referred to as maximum theoretical density, i.e. the maximum density to which a mix could be theoretically compacted if there were no air voids present. In Australia, the term ‘maximum theoretical density’ is usually applied to the calculation of density from the combined density of all the components, and not the measurement of maximum density by test.

The proportional difference between maximum density and bulk density provides the basis for calculation of air voids in the mix.

### 4.3.5 Voids in Mineral Aggregate (VMA)

The voids in the mineral aggregate (VMA) is the total volume of voids within the mass of compacted aggregate. It is a function of the particle size distribution, the shape and surface texture of the aggregate and packing characteristics of the aggregate particles.

VMA is the combination of air voids in the compacted mix and the volume occupied by effective binder (total binder less any binder absorbed into the aggregate).

It is important that the VMA be large enough to:

- allow space for sufficient binder so that the mix will be durable
- allow sufficient air voids in the compacted mix to ensure the mix is stable.

Typical values of VMA in dense graded mixes can be 13 to 20%, depending on the nominal size of the mix.

The VMA affects the performance of the mix as follows:

- VMA too low
  - potential for over-filling of voids with binder resulting in flushing or bleeding or instability
  - insufficient binder for cohesion and durability.
- VMA too high
  - high air voids
  - increased binder volume to satisfy air voids requirements resulting in a mix that is more costly to produce.

Increases in VMA may be obtained by:

- Changing the particle size distribution. For dense graded asphalt, moving away from a maximum density curve or moving to a coarser exponent of maximum density (see Section 4.5) will increase VMA. Generally, it is preferable to maintain a uniform particle size distribution rather than introduce gaps in the grading.
- Reducing the minus 0.075 mm (filler) fraction. This will also increase the binder film index but may reduce stiffness of the mix.
- Changing one or more of the aggregate fractions for one that has different shape and/or surface texture characteristics and hence different packing properties.

Decreases in VMA may be obtained by:

- changing the particle size distribution to move closer to a maximum density relationship or a finer grading with a lower exponent of maximum density
- increasing the filler content
- changing one or more of the aggregate fractions for one that has different shape and/or surface texture characteristics and hence different packing properties.

The calculation of VMA is provided in AS 2891.8.

#### 4.3.6 Air Voids

The air voids content in a mix is a function of:

- VMA
- binder content
- level of compaction.

The air voids content of a mix affects mix stiffness, fatigue resistance and durability. In general, mixes should be designed to have the lowest practical air voids value in order to reduce:

- the ageing (oxidation) of the binder
- the possibility of water penetration, and hence stripping of binder from the aggregate.

If the air voids content of asphalt in-service is too low (less than about 2%), plastic flow may occur resulting in flushing, bleeding, shoving or rutting of the pavement.

An indication of the maximum density (lowest air voids) that mixes may reach in-service is provided by compaction to maximum cycles in the gyratory compactor. Minimum air voids at maximum cycles for heavy duty mixes may be specified for either 250 or 350 cycles. Values for minimum voids at maximum cycles should only be applied to asphalts designed for heavy traffic applications.

The calculation of air voids content is provided in AS 2891.8.

### 4.3.7 Binder Content

In general, the optimum binder content is a balance between being high enough to ensure durability and life for the pavement but not so high that the mix becomes unstable.

The binder content has a major influence on the volumetric and mechanical properties of an asphalt mix.

The optimum design binder content is dependent on:

- aggregate type
- aggregate particle size distribution
- compaction level of the mix
- design air voids content.

Asphalt performance depends on its effective binder content, excluding any binder absorbed by the aggregate, and not its total binder content.

Binder absorption is generally determined from the measured maximum density of the mix and a theoretical maximum density determined from the combined bulk density of aggregates, filler and binder. Accurate measurement of the density of aggregates and filler is an essential part of the estimation of absorbed binder. A negative value calculated for binder absorption indicates an error in density determinations or calculations.

The proportion of binder absorbed by aggregate depends on the porosity of the aggregate and the type of binder. Typically, the amount of binder absorbed by aggregate is 0.3 to 0.7 times the water absorption of the aggregate.

### 4.3.8 Voids Filled with Binder (VFB)

Voids filled with binder (VFB) is the proportion of VMA occupied by effective binder and its calculation is provided in AS 2891.8. This is generally in the range of 65 to 80%.

At low VFB values, approximating 60%, the mixes become dry, lacking cohesion, durability and fatigue resistance. Mixes with low VFB may also be more permeable.

When VFB approximates 85% or more, mixes can become unstable and susceptible to rutting.

For a given air voids target, high VFB is generally associated with high VMA while a low VFB is an indicator of low VMA. Adjustments to VMA may be achieved as indicated in Section 4.3.5.

### 4.3.9 Binder Film Index

Binder film index is calculated as a function of the surface area of the aggregates and filler, and the effective binder content. The calculation of the film index is based on standardised surface area factors for each particle size (Austroads Test Method AGPT/T237 *Binder film index*). In practice, surface area is influenced by aggregate shape and texture so that the calculation of the binder film index should be taken as indicative only, and not an accurate representation of actual binder film thickness.

Consideration of the minimum binder film index at the volumetric design stage is a guide to the incorporation of sufficient binder in the asphalt mix to ensure adequate cohesion, durability, fatigue resistance, and resistance to the effects of moisture.

The binder film index may be increased by:

- changing the particle size distribution to increase the proportion of coarse to fine material
- reduction of the amount of filler
- increasing the VMA and hence increasing the binder content for the same air voids.

Alternative specification measures for ensuring adequate binder volume include the minimum percentage of binder by volume (rather than mass) or the proportion of voids filled with binder (VFB).

## 4.4 Mechanical Testing

### 4.4.1 General

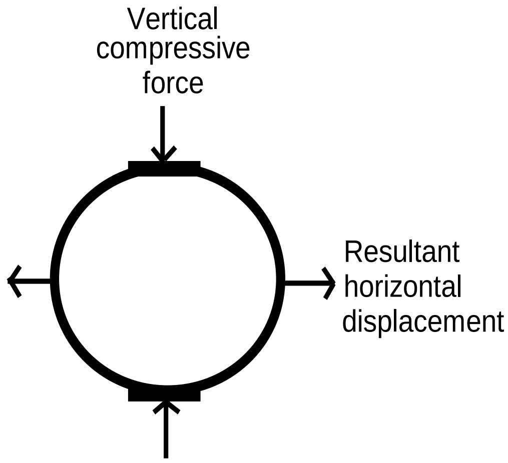
Mechanical tests used for determination of performance-related and empirical properties include:

- AS 2891.13.1 determination of resilient modulus of asphalt – indirect tensile test
- AGPT/T231 deformation resistance of asphalt mixtures by the wheel tracking test
- AGPT/T232 stripping potential of asphalt – tensile strength ratio
- AGPT/T233 fatigue life of compacted bituminous mixes subject to repeated flexural bending
- AS 2891.5 determination of stability and flow – Marshall procedure.

### 4.4.2 Resilient Modulus

The Australian Standard test for the determination of the resilient modulus of asphalt (AS 2891.13.1) is based upon an indirect tensile measurement. A repeated vertical compressive force is applied acting parallel to and along the vertical diametrical plane and the horizontal displacements are measured mid-height through the horizontal diameter (Figure 4.3).

**Figure 4.3: Indirect tensile test**




Further information on the application of AS 2891.13.1, including guidance on the effect of variables and interpretation of results, is provided in Appendix D.

### 4.4.3 Wheel Tracking

Wheel tracking is used to indicate the resistance of the candidate mix to deformation under traffic.

The wheel tracking test procedure is available as Austroads test method AGPT/T231.

Further information on the application of this test method including guidance on the effect of variables and interpretation of results is provided in Appendix E.

### 4.4.4 Moisture Sensitivity (Stripping Potential)

***General***

Moisture sensitivity relates to the potential for loss of adhesion between the binder and aggregate in the presence of moisture. This loss of adhesion is commonly referred to as stripping. Stripping in asphalt is a complex mechanism. Where stripping occurs it is often a combination of more than one of the following factors:

- environment – climate and traffic
- asphalt mix permeability
- type and class of binder
- poor coating of aggregates due to poor mixing or presence of clay or dust contamination on aggregates
- aggregate affinity for bitumen
- asphalt mix design including binder content, type of filler and use of other additives.

Stripping can only occur if there is moisture in the pavement. The most critical situations arise where the asphalt mix becomes saturated with water. The potential for saturation is often a combination of the selection of asphalt mix types for various layers, field construction standards and permeability of individual layers. The greatest risk occurs where there is a combination of a permeable surface layer allowing the entry of moisture from the surface, and an impermeable lower layer holding moisture adjacent to the interface. Saturated asphalt is particularly susceptible to stripping when subject to high traffic loadings.

The risk of an asphalt mix becoming saturated can also be related to the air voids in the mix. Low air voids contents in dense graded mixes (less than about 6%) tend to result in discrete, non-interconnected voids that are largely impermeable to water. Higher air voids (up to about 12%) result in partly interconnected voids that allow water to become trapped in the layer. Above about 12% air voids, such as in open graded mixes, the asphalt becomes permeable to the extent that moisture can move freely through the mix. This leads to the concept of 'pessimism air voids' of in situ materials in the range of 6–12% or possibly, more critically, in the range of 7–9%.

Increased risk of stripping tends to be associated with high ambient temperatures, possibly due to lower binder stiffness. The type of binder can also have an influence as stiffer binders tend to have greater resistance to stripping.

Drying of aggregates, mixing temperature and efficiency of mixing are factors in achieving a good bond during manufacture. The adequacy of binder coating and adhesion can be adversely affected by the presence of clay, dust or other deleterious coating on the aggregate.

As previously indicated in Section 3.2, the affinity of aggregates to bitumen is influenced by the mineral composition of the aggregate. As bitumen is slightly acidic, better adhesion is generally achieved with basic aggregates (e.g. basalt).

***Testing for moisture sensitivity***

A variety of tests have been used that attempt to identify the moisture sensitivity and binder stripping potential of asphalt mixes.

Tests such as the plate stripping test, which were essentially developed around sprayed seal work and establishment of initial adhesion, do not necessarily consider the more complex behaviour of asphalt mixtures. AGPT/T232 *Stripping potential of asphalt: tensile strength ratio*, adapted from ASTM D 4867-94 and AASHTO T 283 (commonly known as the Modified Lottman Test) is a preferable test for assessing the moisture sensitivity of asphalt. The optional freeze-thaw cycle provided for in AGPT/T232 is generally recommended for asphalt for use in high traffic loadings.

Further information on the application of this test method is provided in Appendix F.

### 4.4.5 Fatigue

Fatigue of an asphalt mix is a very important property since it relates to the ability of a mix to withstand cracking under traffic loading. Whilst the importance of fatigue has been recognised for a long time, suitable and affordable equipment to measure fatigue has only recently become widely available. The Australian manufactured pneumatic test device has enabled fatigue characterisation to be carried out on a more routine basis than was possible in the past. Procedures for fatigue testing are described in Austroads Test Method AGPT/T233.

In the absence of this equipment, for a given mix type, fatigue properties may be estimated from the volumetric properties using the formula described in the *Guide to Pavement Technology Part 2: Pavement Structural Design* (Austroads 2012). A further quick check to avoid producing mixes likely to fatigue prematurely under the action of traffic is specification of a minimum binder content or film index (Section 4.3).

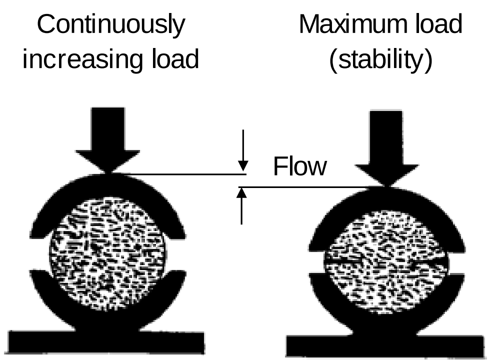
Further information on the application of AGPT/T233 including guidance on the effect of variables and interpretation of results is provided in Appendix G.

### 4.4.6 Marshall Stability and Flow

Testing for the properties of stability and flow are integral to the use of the Marshall method for determining optimum values for volumetric properties of samples compacted by the Marshall procedure.

Preheated specimens are loaded diametrically in the Marshall apparatus and the maximum load resisted and the vertical deformations are recorded and reported as the stability and flow (Figure 4.4). Some specifications also require the calculation of the Marshall quotient (ratio of stability to flow).

**Figure 4.4: Testing of cylindrical asphalt specimen for Marshall stability and flow**



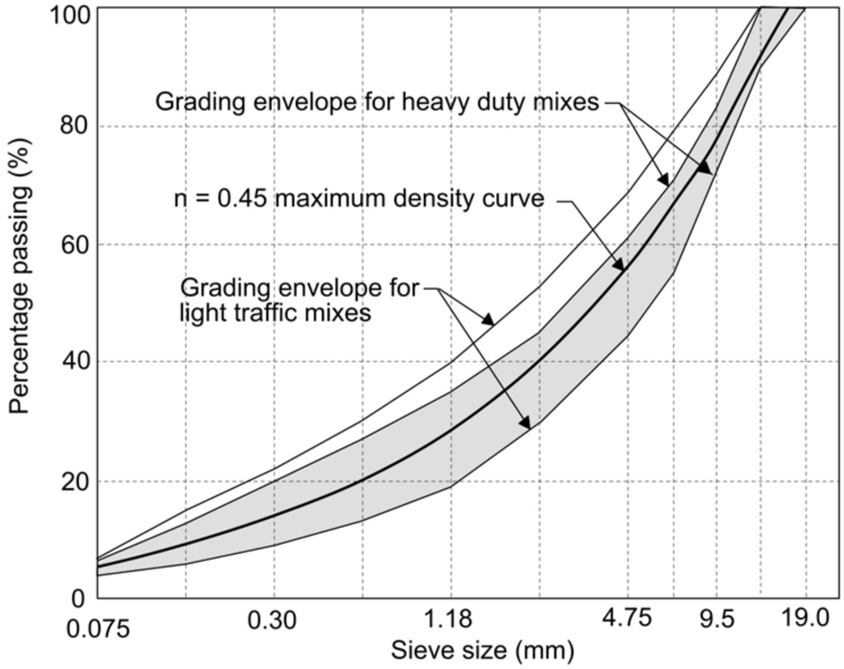

## 4.5 Combining Component Materials

### 4.5.1 Selecting a Target Grading

The selection of mix type largely defines the aggregate grading envelope within which the asphalt mix is to be designed. Most specifications specify the grading envelope for each mix type. Where not otherwise specified, typical grading envelopes may be found by reference to AS 2150.

Typical grading limits for 14 mm nominal size mixes, based on AS 2150, are depicted in Figure 4.5.

**Figure 4.5: Typical grading envelope for 14 mm dense graded mix**




Aggregate grading and binder content ranges such as those recommended in AS 2150 are usually accepted as indicative targets for design purposes and selection of a job mix. In such cases, application of production tolerances may result in actual production being outside the design envelope. Alternatively, some specifications require that the production range must also remain within the specified envelope.

Mixes designed within grading envelopes can still vary widely in performance. The target grading should not move widely from one side of the grading envelope to the other but maintain a uniform distribution of aggregate sizes taking into account the grading of available materials and any adjustments necessary to achieve the desired volumetric properties.

In the absence of experience with the materials and mixes intended use, the mid-point of the grading envelope provides a suitable target grading for initial trial mixes. Where there is experience with the materials being used, or where particular characteristics are being optimised, mixes alternative grading targets may be adopted, provided that the relevant specification requirements are maintained.

### 4.5.2 Maximising Packing Properties of Dense Graded Mixes

Dense graded asphalt mixes use a continuous grading to facilitate packing of aggregate particles to achieve:

- flexibility
- durability
- structural stiffness
- deformation resistance
- low permeability.

The maximum density grading gives the theoretical densest particle packing and minimum voids in the mineral aggregate (VMA) condition of the mix (the total voids within the mass of compacted aggregate).

For a particular maximum aggregate size, the maximum density grading may be determined by the Fuller equation (Equation 1).

$$P = 100\left(\frac{d}{D}\right)^n \qquad 1$$

where

P = total percentage passing a given sieve

d = size of sieve opening

D = maximum size of aggregate

n = grading exponent

The original Fuller equation used a grading exponent of 0.5. Further work has determined that an exponent of 0.45 provides the greatest density and lowest VMA. Increasing the exponent to say 0.6 provides an asphalt mix with slightly increased VMA and coarser texture. Decreasing the exponent also increases VMA but results in a finer textured mix. Higher exponents such as 0.8 or 0.9 tend towards an open graded mix.

The Fuller equation has proved to give impractical proportions of filler for some mixes. Another equation has been developed to adjust for the percentage filler content (Equation 2).

$$P = \frac{(100 - F) * (d^n - 0.075^n)}{(D^n - 0.075^n)} + F \qquad 2$$

where

F = the percentage of filler

P, d, D and n = are as above

Maximising the density of the mix with a particle size distribution that closely follows the maximum density relationship may result in a VMA that is too low. A low VMA may not provide enough space for the required air voids and a reasonable volume of binder to provide cohesion, durability and fatigue resistance in the mix. Overfilling the VMA with binder in such circumstances can lead to mixes with low air voids and poor rutting resistance.

Deviations from the maximum density curve generally result in higher VMA. Significant deviations from the maximum density curve can, however, result in a reduction in mix stability. It can also result in a significant change in finished surface texture by becoming 'gap' graded. It is desirable, therefore, that changes to the aggregate grading combination to achieve higher VMA maintain a continuous distribution and interlock of aggregate particle sizes.

### 4.5.3 Combining Aggregates to a Target Grading

The proportioning of the selected aggregate fractions, together with the filler, may be determined by trial and error, graphically, arithmetically or by computer spreadsheet.

Determining the combined grading of the aggregates is achieved arithmetically using the following formula (Equation 3):

$$P = A * a + B * b + C * c \qquad 3$$

where

| | | |
|---|---|---|
| P | = | the percentage of material passing a given sieve for the combined aggregate fractions A, B, C, etc. |
| A, B, C, etc. | = | percentage of material passing a given sieve for each of the aggregates A, B, C, etc. |
| a, b, c etc. | = | proportion of aggregates A, B, C, etc. used in the combination and where the total of a, b, c, etc. = 1.00 |

In practice, most organisations undertaking regular asphalt mix design have developed spreadsheets that enable matching of available aggregate fractions to target gradings. Spreadsheet programs may also provide for input of the density of components and hence estimation of key volumetric data for the combined materials. Such programs can significantly reduce the amount of trial and error in preparing laboratory mixes to achieve specific volumetric targets.

Table 4.1 provides an example calculation demonstrating a combination of seven aggregate fractions to meet a target grading for a 20 mm nominal size mix complying with AS 2150.

**Table 4.1: Combination grading calculation**

| **Type** | **20 mm** | **14 mm** | **10 mm** | **7 mm** | **Dust** | **Sand** | **Filler** | **Combined grading** | **Grading target** | **Range (AS 2150)** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Source** | **Quarry A** | **Quarry A** | **Quarry A** | **Quarry A** | **Quarry A** | **Quarry B** | **Cement kiln dust** | | | |
| % | 19 | 14 | 18 | 10 | 21 | 17 | 1 | 100 | | |
| Sieve (mm) | | | | | | | | | | |
| 26.5 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 19.0 | 98 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 99 | 90–100 |
| 13.2 | 23 | 94 | 100 | 100 | 100 | 100 | 100 | 85 | 83 | 71–86 |
| 9.5 | 3 | 9 | 95 | 100 | 100 | 100 | 100 | 68 | 68 | 58–75 |
| 6.7 | 2 | 1 | 28 | 97 | 100 | 100 | 100 | 54 | 54 | 46–64 |
| 4.75 | 2 | 0 | 7 | 51 | 100 | 97 | 100 | 45 | 47 | 37–55 |
| 2.36 | 2 | 0 | 2 | 14 | 90 | 84 | 100 | 36 | 36 | 24–42 |
| 1.18 | 1 | 0 | 0 | 2 | 63 | 70 | 100 | 27 | 27 | 15–32 |
| 0.600 | 1 | 0 | 0 | 0 | 44 | 59 | 100 | 20 | 20 | 10–24 |
| 0.300 | 1 | 0 | 0 | 0 | 30 | 47 | 100 | 15 | 14 | 7–17 |
| 0.150 | 1 | 0 | 0 | 0 | 20 | 5.4 | 100 | 6 | 7 | 4–12 |
| 0.075 | 1 | 0 | 0 | 0 | 14 | 2 | 96 | 4 | 4.2 | 3–6 |

## 4.6 Laboratory Mixing and Compaction of Asphalt Mixes

### 4.6.1 Sample Preparation and Conditioning

An important aim of sample preparation procedures is to ensure that specimens prepared in the laboratory have properties as close as possible to asphalt placed in the road.

Design procedures based on gyratory compaction include a laboratory conditioning step that simulates the binder hardening that occurs during manufacture and placing of the mix and around the first two years of field service. This step is important in preparing samples for mechanical tests such as resilient modulus and fatigue as stiffness of the binder has a significant impact on test results.

Procedures for mixing, quartering and conditioning of laboratory samples are described in AS 2891.2.1 (Appendix B).

### 4.6.2 Compaction

Methods used for compaction of samples for volumetric and mechanical testing may include:

- gyratory compaction
  - Gyropac
  - Servopac
- Marshall compaction
- slab compaction.

Preparation of samples for volumetric testing and certain performance tests is generally based on either gyratory or Marshall compacted specimens. Both methods produce cylindrical samples suitable for volumetric testing and resilient modulus. The gyratory compactor may also be used to prepare cylindrical samples to a defined air voids for moisture sensitivity testing or to continue compaction to maximum cycles to simulate the effect of long-term heavy traffic.

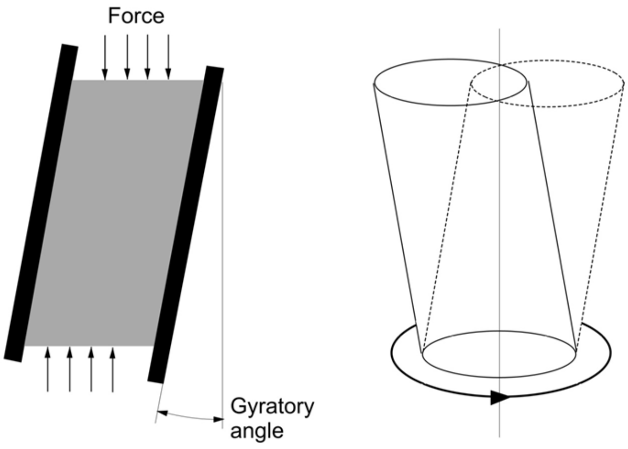
Where larger samples are required for wheel tracking or fatigue tests, a variety of methods are used involving compaction in rectangular moulds or large slabs that simulate the field placement of asphalt. Compaction devices include the slab compactor (segmental rolling wheel), compaction of slabs with a footpath roller, and the rectangular 'shear box compactor'. Large rectangular samples can also be cored for use in tests that require cylindrical samples. Preparation of asphalt slabs is described in Austroads Asphalt Test Method AGPT/T220 – *Sample preparation: compaction of asphalt slabs*.

The temperature at which laboratory specimens are compacted is dependent upon the viscosity of the binder, the type of mix and whether an additive or mixing process has been used to either reduce production temperatures of asphalt or change the workability of the asphalt. Asphalt mixes prepared with Class 320 bitumen binder are typically compacted at 150 °C. Higher compaction temperatures may apply to polymer modified binders and stiffer grades of bitumen. Lower compaction temperatures may apply to open graded mixes, lower viscosity binders or warm mix asphalt.

### 4.6.3 Gyratory Compaction

The principle of gyratory compaction is illustrated in Figure 4.6. Compaction is achieved by shearing forces obtained by the application of a constant vertical compressive force to the asphalt confined in a cylindrical mould while the mould is rotated about its vertical axis through a small angle. The angle should remain constant throughout the compaction process.

**Figure 4.6: Principle of gyratory compaction**




Compaction can be terminated after a set number of cycles or at a set height representing a predetermined volume and density of asphalt. Monitoring the height of the cylinder during the process enables the density to be estimated at different numbers of cycles. This data can be used to determine density at different compaction levels and provide an indicator of mix workability.

Two forms of gyratory compactor are commonly used in Australia and New Zealand, the Gyropac and the Servopac. Both are considered suitable for mix design and production testing, subject to the requirements outlined in AS 2891.2.2. The Gyropac (Figure 4.7) is used for routine mix design and monitoring tests. The Servopac (Figure 4.8) is a more advanced version that includes more options and greater control over the compaction process that make it suited to both routine design and research applications. The Servopac generally achieves increased compaction per cycle over the Gyropac and therefore lower air voids.

Voids and density properties are determined as described in Section 4.3.

For routine mix design, the level of compaction depends on the traffic level as follows:

- light traffic – 50 cycles
- medium traffic – 80 cycles
- heavy traffic – 120 cycles
- voids at maximum cycles – 250 or 350 cycles.

Test procedures are described in AS 2891.2.2.

**Figure 4.7: Gyropac**

**Figure 4.8: Servopac**

### 4.6.4 Marshall Compaction

The Marshall compaction method involves the manufacture of cylindrical specimens, 101.6 mm diameter by 63.5 mm high, using a standard compaction hammer (Figure 4.9) and a cylindrical mould as described in AS 2891.5. For most applications, 50 blows of the hammer are applied to each face of the cylinder. A higher standard of compaction, involving 75 blows per face, is used for airfield work and some heavy duty road pavements. A compaction level of 35 blows is sometimes used for paths and residential streets.

**Figure 4.9: Automated Marshall compaction hammer**

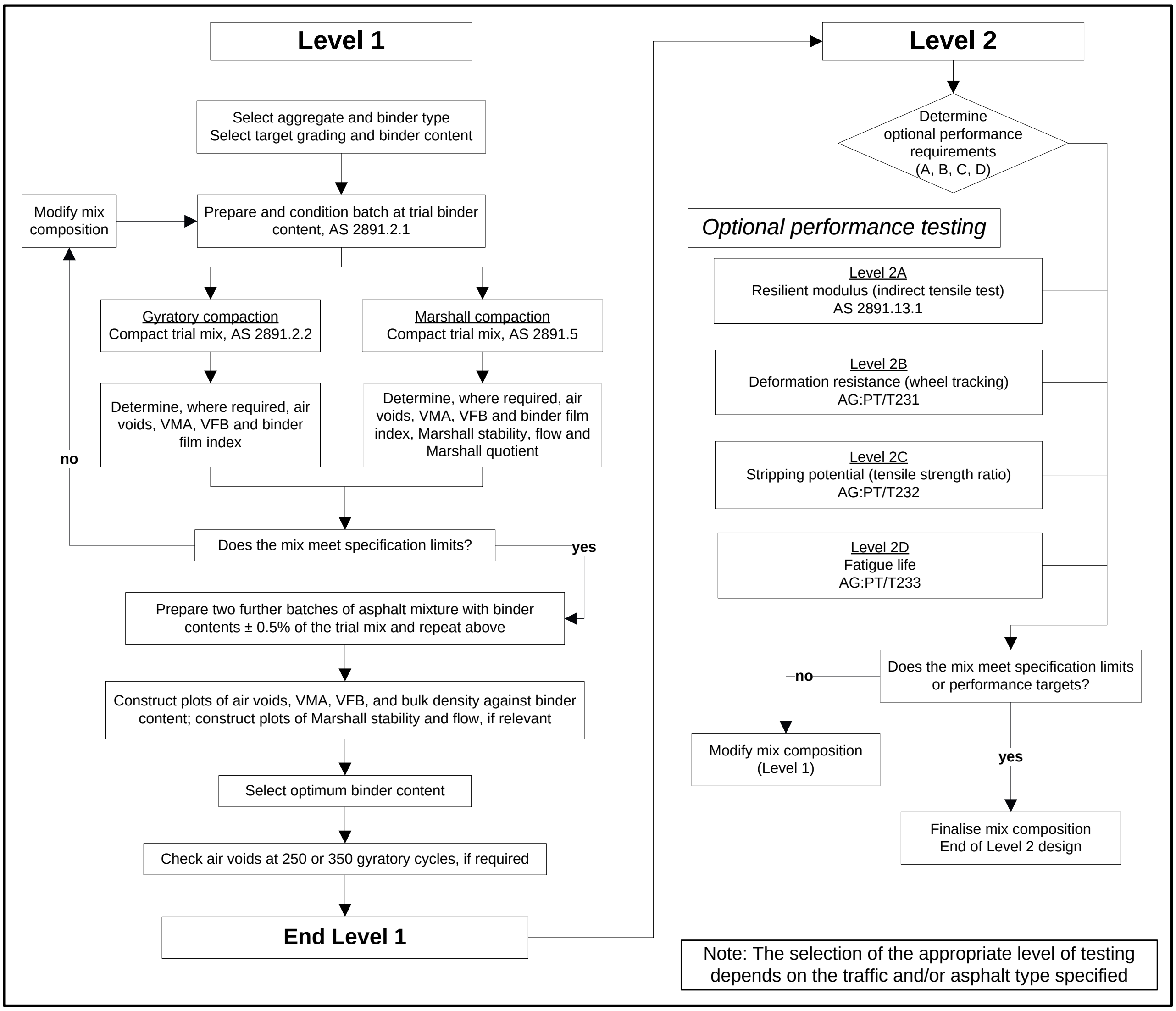
Marshall compaction, as described in AS 2891.5, is applicable to asphalt mixes not exceeding 20 mm nominal size although some agencies have their own procedures for compacting mixes of larger nominal size.

## 4.7 Mix Design Procedure for Dense Graded Mixes

### 4.7.1 General

The design procedure for dense graded mixes is based on two levels as shown in Figure 4.10.

**Figure 4.10: Austroads mix design procedure**




Level 1 involves:

- selection of mix type and component materials likely to satisfy the relevant specification and/or performance requirements
- selection of target grading and binder content
- mixing of materials
- conditioning of mix to specified compaction temperature and conditioning time
- compaction of trial mix
- determination of volumetric properties including air voids, bulk density, VMA and VFB (if required); binder film index is also determined at this stage
- determination of stability and flow (Marshall compaction only) and calculation of Marshall quotient (ratio of stability to flow) if required
- comparison of volumetric and Marshall properties with specified requirements.

Where all relevant requirements are satisfied, and no further testing is required, Level 1 testing may be concluded at this point. Acceptance of mix properties from a single trial mix particularly applies to mix designs that are based on an existing mix that has been previously subject to full design testing or where volumetric properties are to be further confirmed by testing of plant production mix.

Where further testing is required for the selection of an optimum binder content, or for determination of the influence of variation in binder content on volumetric properties, Level 1 testing continues with the following:

- preparation and compaction of two further mixes with the same grading as the initial trial mix and with binder contents ±0.5% of the initial mix
- determination of volumetric properties and Marshall properties (if required) and preparation of a graphical presentation of the results with variation in binder content
- selection of optimum binder content satisfying required specified parameters.

For mixes intended for use under very heavy traffic, a further set of samples is prepared at the design binder content and duplicate samples compacted in the gyratory compactor to a maximum of either 250 or 350 cycles as specified.

Some specifications require preparation and compaction of further mixes to determine the influence on volumetric properties arising from potential variations to bitumen content and/or grading within the tolerances permitted for asphalt production.

Level 2 testing includes a number of optional performance-related tests which may be used to determine:

- mechanical properties used for structural design: resilient modulus (stiffness) and fatigue life (resistance)
- resistance to permanent deformation: wheel tracking
- moisture sensitivity: resistance to stripping.

It should be noted that the selection of the appropriate level of testing depends on the asphalt application and/or specified requirements.

***Presentation of the results***

The results of the following tests may be presented graphically as shown in Figure 4.11:

- air voids
- VMA
- bulk density
- maximum density
- VFB
- Marshall stability
- Marshall flow.

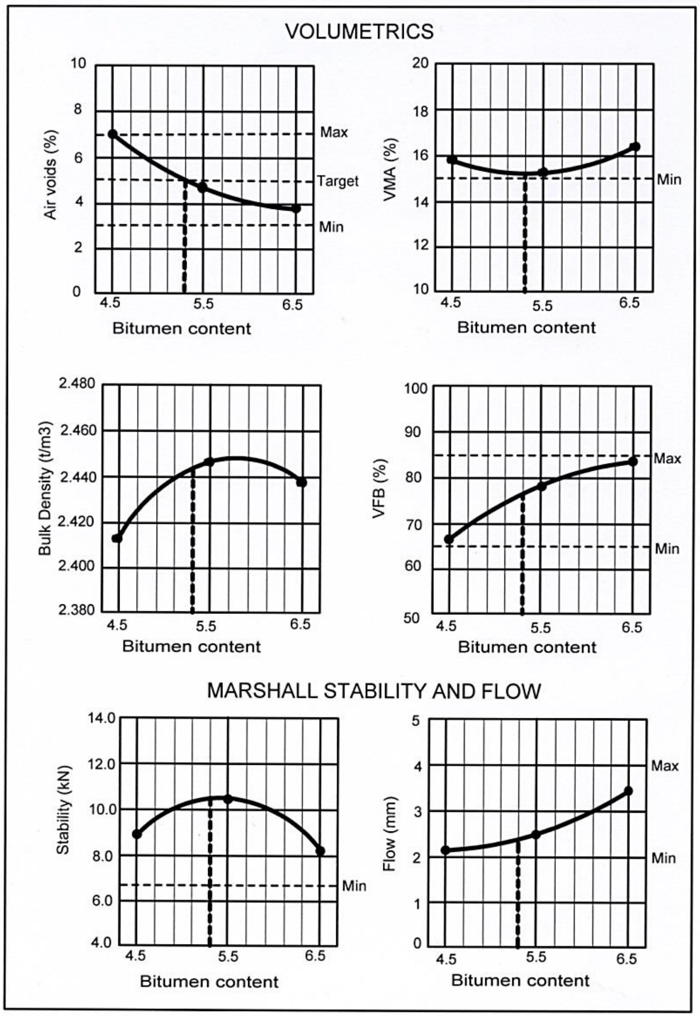
These results are used to select the final binder content that should:

- have air voids within the specified limits
- be near the minimum value for VMA.

Further requirements for mixes designed by the Marshall method are for a binder content that is:

- close to maximum values for stability and bulk density
- within the specified limits for flow.

**Figure 4.11: Typical volumetric properties and Marshall test results**




### *Summary of design procedure*

Table 4.2, Table 4.3 and Table 4.4 provide a summary of the mix design procedure. The prefix in the 'number' column corresponds to the design level.

The following design procedures are based on laboratory-mixed samples. Testing of all design properties may also be undertaken on asphalt-plant manufactured samples sampled in accordance with AS 2891.1.1.

**Table 4.2: Design procedure, material properties**

| **Material properties** | | |
|---|---|---|
| **No.** | **Action** | **Comment** |
| 0-1 | Determine binder density. | Needed for binder absorption calculation which in turn is needed for binder film index. Also required for VMA. |
| 0-2 | Measure bulk densities of filler, fine aggregate and coarse aggregate according to AS 1141.5, AS 1141.6.1 or AS 1141.6.2 and AS 1141.7. | Needed for binder absorption calculation which in turn is needed for binder film index. Also required for VMA. Particle density determined on dry basis should be used in all cases unless other density specifically requested. |
| 0-3 | Determine particle size distribution (grading) of all components (AS 1141.11). Store enough of each component to carry out full design procedure, allowing for possible iteration to meet compliance requirements. | Needed to determine combined grading. Introducing additional aggregates halfway through the mix design process can increase the variability of the process. |

**Table 4.3: Design procedure, Level 1 testing**

| **Level 1** | | |
|---|---|---|
| **No.** | **Action** | **Comment** |
| 1-1 | Choose trial grading and binder content. | Trial binder content can be based on experience or minimum binder content to give required film index. Film index estimated by AGPT/T237. May require assumed values for bitumen absorption and aggregate breakdown due to mixing. |
| 1-2 | Prepare and condition batch of material at trial binder content (AS 2891.2.1). Prepare sufficient material for triplicate specimens and for duplicate maximum density (MD) determinations. | Preparation of a single trial mix as a preliminary to testing at a range of binder contents can avoid unnecessary testing if the initial testing indicates that a satisfactory mix is unlikely to be achieved with the selected combination of components. Conditioning (AS 2891.2.1) is not critical for mixes to be compacted by the Marshall method. |
| 1-3 | Compact mix in accordance with selected compaction method (AS 2891.2.2 or AS 2891.5) and compaction effort. Put aside uncompacted mix for MD (AS 2891.7.1). | Compaction method and compaction effort are selected in accordance with specification and intended application. |
| 1-4 | Measure bulk density of compacted specimens according to AS 2891.9 and MD according to AS 2891.7.1. | Alternative methods for determination of bulk density include AS 2891.9.1, AS 2891.2 and AS 2891.3. |
| 1-5 | Calculate air voids content of each specimen (AS 2891.8). | See Section 4.3 for information on volumetric properties. |
| 1-6 | Optional check, binder film index (AGPT/T237). | Compare value with any specification requirement. Minimum values are generally applied to ensure adequate cohesion and durability. |
| 1-7 | For asphalt mixes compacted by the Marshall method complete testing for stability and flow (AS 2891.5). | Marshall stability and flow are usually included as specification parameters for asphalt mixes designed by the Marshall method as well as providing information used in determining optimum binder content. |
| 1-8 | Compare results with specification requirements or intended application. | Results outside of acceptance limits require adjustment of proportions of components or selection of alternative components and preparation of a further trial mix. |
| 1-9 | Where further testing is required for selection of optimum binder content or measurement of the influence of variations to binder content on volumetric properties, prepare two further batches of asphalt mixture with binder contents ±0.5% of the trial mix and repeat steps 1.3 to 1.7. | Additional mixes enable selection of optimum binder content. |
| 1-10 | Construct plots of air voids, VMA, VFB and bulk density against binder content. Construct plots of Marshall stability and flow, if relevant. | Visual aid to help in understanding mix design relationships. |
| 1-11 | Design binder content is selected to meet the specified value of air voids and other volumetric properties. | Required air voids content is obtained from relevant specification. |
| 1-12 | If required, check air voids for the design binder content at 250 or 350 cycles (maximum cycles) meet the relevant specification minimum value. | A check on the value of air voids at maximum cycles is normally made at this stage before proceeding with mechanical testing of additional performance properties. |

**Table 4.4: Design procedure, Level 2 testing**

| **Level 2** | | |
|---|---|---|
| **No.** | **Action** | **Comment** |
| 2-1 | Optional resilient modulus testing (AS 2891.13.1). Manufacture one set of specimens at design bitumen content. Mix sufficient material for triplicate specimens and for duplicate maximum (voids free) density (MD) determination. | Use gyratory compaction (AS 2891.2.2) to a set density procedure. |
| 2-2 | Measure resilient modulus according to AS 2891.13.1. | Standard resilient modulus conditions are 5% voids and 25 °C. |
| 2-3 | Check that the values of modulus at the design binder content meet any specified requirements for climate and traffic. If not return to start of 1-1. | May need extra testing to indicate sensitivity to binder content and/or air voids. |
| 2-4 | Optional wheel tracking testing (AGPT/ T231). Prepare, compact, test and evaluate samples in accordance with test procedure. | Prepare and compact samples using procedures given in Austroads Test Method AGPT/T220. Standard test conditions are 5% voids and 60 °C. |

| Level 2 | | |
|---|---|---|
| **No.** | **Action** | **Comment** |
| 2-5 | Optional moisture sensitivity testing (AGPT/T232). Manufacture, test and evaluate samples in accordance with test procedure. | Asphalt mixes produced in the laboratory are prepared and compacted in accordance with AS 2891.2.1 and AS 2891.2.2. Standard test conditions are 8% voids and 25 °C. An optional freeze-thaw conditioning cycle is generally applied to heavy duty applications. |
| 2-6 | Optional fatigue testing (AGPT/T233). Manufacture, test and evaluate samples in accordance with test procedure. | Prepare and compact samples using procedures given in Austroads Test Method AGPT/T220. Standard test conditions are 5% voids and 20 °C and a strain level of 400 $\mu\varepsilon$. Testing at other strain levels can lead to a more complete understanding of the mix behaviour. |

### 4.7.2 Improving Mix Performance

At some stage in the design process, the designer may become aware that the mix is deficient in one or more performance areas. In this section, some advice is given on how such a deficiency may be addressed by changes in mix composition. It must be remembered, however, that a change in composition to improve one property may have a detrimental effect on other properties. The mix designer must use best endeavours to reach an optimum solution.

Air voids content is an important mix design parameter. In particular, very heavily trafficked mixes should not be below a specified voids value after maximum gyratory cycles. Generally, a designer will aim to produce a mix that achieves all the design parameters, including air voids, at the most economical binder content. Grading combinations matching the mid-point of the specified grading envelope provide a useful starting point. Adjustments that may be made in order to increase or decrease voids in the mineral aggregate, and hence the binder content required for the target air voids, include the following:

- Making the mix coarser or finer and/or more gap graded. Generally, the mid-point of specified grading envelopes provides target gradings that are close to a maximum density curve. Moving a portion of the grading either coarser or finer will generally increase voids. Caution must be exercised, however, due to the effect on mix stiffness and surface texture.
- Changing the percentage of fines (material passing the 2.36 mm sieve) – effect as above.
- Increasing or decreasing filler content has a direct effect and decreases or increases the voids respectively.
- Changing particle shape, particularly of the fine aggregate component. Use of smooth, rounded particles increases workability (the mix is easier to compact) and thus reduces voids. Note that this may decrease mix stiffness.
- Increasing the natural sand content may increase voids due to void spaces occurring between sand grains.

***Deformation resistance***

A lack of deformation resistance will lead to rutting. Deformation resistance can be improved by:

- selecting a larger nominal size mix
- using an angular or textured aggregate
- using a stiffer binder or a binder modified to increase the elastic strain component of the total strain
- adopting a coarser grading
- reducing air voids, provided that it does not result in air voids below a critical limit at maximum cycles
- increasing filler content.

Each of these actions, however, will have an impact on other characteristics. For example, using more angular and textured aggregate will reduce workability, and increasing filler content can produce a mastic which lacks flexibility thereby reducing fatigue resistance. Figure 4.12 shows a typical rutting.

***Fatigue resistance***

Fatigue resistance is improved by:

- using binders with elastic properties
- increasing binder content
- reducing air voids.

However, the latter two measures will reduce deformation resistance. The high binder content mixes which are used as the lower layer in the basecourse of modified full depth asphalt pavements as a fatigue layer have poor deformation resistance (Section 2.7.6). The binder content should not exceed 1% above normal mix requirements.

Crocodile cracking (Figure 4.13) may be due to lack of fatigue resistance.

**Figure 4.12: Typical rutting**

**Figure 4.13: Typical crocodile cracking**

***Durability***

Durability is improved by:

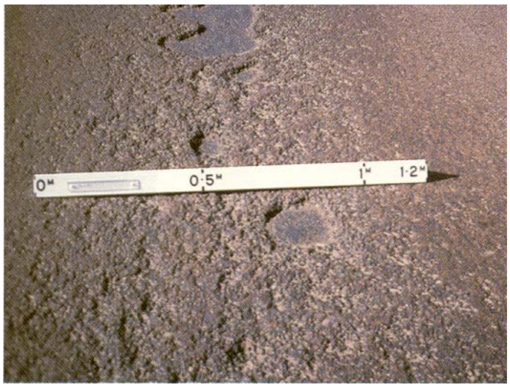
- reducing air voids
- using softer grade binders
- increasing the binder film thickness.

A reduction in air voids can be achieved by increasing the proportion of rounded particles at the expense of crushed particles, but this would also reduce the deformation resistance which could be an important consideration in other than light-duty pavements.

The use of a softer grade of binder can improve durability but will invariably reduce the rutting resistance of the mix.

The binder film index for a given binder content is increased by adopting a coarse grading, thus reducing the total particle surface area. This action, however, can result in an increase in the voids in mineral aggregate and, for a given binder content, an increase in air voids. A lack of durability may be evidenced by ravelling (Figure 4.14).

**Figure 4.14: Typical ravelling**




***Workability***

Workability, which is the ease with which the mix can be spread and compacted, can be improved by:

- increasing voids in the mineral aggregate
- using higher binder content
- using softer binder
- reduction in filler content
- using more rounded aggregate.

The use of higher binder content, a softer binder and more rounded aggregate will tend to increase the potential for rutting.

***Moisture sensitivity***

Resistance to moisture-induced damage can be improved by:

- incorporating hydrated lime in the filler as 1 to 2% of the total mix
- reducing permeability
- inclusion of an adhesion agent
- using an aggregate with a greater affinity for bitumen
- use of clean aggregates
- adequately drying aggregate
- effectively mixing and coating the aggregates
- adequate mixing times
- appropriate binder/filler ratio
- selection of compatible components
- controlling the dosage of additives
- using harder grades of binders or polymers, etc.

Non-silicious aggregates usually have a better affinity for bitumen, thus reducing the potential for displacement of the binder film from the aggregate surfaces.

The addition of hydrated lime (typically 1–2% of the total mix) has been shown to reduce the potential for stripping.

### 4.7.3 Warm Mix Asphalt

WMA mix designs may utilise the same asphalt binder type and grade, aggregate and RAP sources and material gradations as identically formulated hot mix asphalt (HMA), which should show little difference in volumetric properties. Greater variation may be found, however, in Level 2 properties of resilient modulus, resistance to deformation and moisture sensitivity.

Laboratory preparation of WMA mixes for the determination of mix design volumetric properties may require additional laboratory equipment for the preparation of mixes, depending on the particular WMA technology being used.

Where WMA manufacturing processes require mixing and conditioning procedures that cannot be effectively simulated in the laboratory, volumetric properties may be verified on samples taken from asphalt plant produced mix.

Similarly, plant produced asphalt mix may also be used for preparation of samples for Level 2 testing as described in Section 4.7.1.

Mixing, and compaction temperatures of WMA as well as any additional conditioning, should follow the recommendations of the additive supplier or WMA technology provider.

### 4.7.4 Polymer Modified Binders

Dense graded asphalt containing polymer modified binders can be designed in accordance with the standard procedures already described.

In substituting modified binders for unmodified bitumen in asphalt mixes, the factors discussed below are commonly considered.

The direct substitution of more highly modified binders for bitumen will often result in slightly higher air voids due to reduced workability. Achievement of the same compacted air voids in the same mineral aggregate combination may require up to 0.3% of additional binder. Substitution of binders of intermediate property modification such as multigrade bitumen should not require any adjustment to binder content for the same volumetric properties.

Further improvement in durability and fatigue resistance can be obtained by the use of higher binder contents, softer binders or modified binders, or a combination of these. The presence of the polymer reduces the tendency for further compaction under traffic or bleeding in hot weather as might occur with conventional bitumen, thus enabling the use of higher binder contents and/or lower air voids for improved durability and fatigue resistance without compromising deformation resistance.

### 4.7.5 Crumb Rubber Asphalt Mixes

Crumb rubber blended into bitumen provides a binder with performance characteristics similar to an elastomeric PMB. Crumb rubber may be added to asphalt mixes using either the ‘dry process’ or ‘wet process’.

In the dry process, crumb rubber is added directly to hot aggregate in an asphalt mixer, prior to addition of bitumen. Following the addition of bitumen, an extended mixing time or increased storage prior to placement is required to ensure adequate reaction time between crumb rubber and bitumen. Use of the fine (size 30 mesh) grade of crumb rubber is important in order to achieve a reasonable level of digestion in the binder in the short time that the material remains hot.

The wet process refers to a crumb rubber modified binder produced as a factory blended material or mixed on site in a separate blending and storage unit prior to addition to the aggregates in the asphalt mixing plant.

Principal variations of crumb rubber asphalt mixes include:

- Dense graded asphalt with crumb rubber modified binder as an alternative PMB. For example, laboratory trials with a pre-blended crumb rubber modified binder similar to sealing grade S45R (Austroads Test Method AGPT/T190) showed similar fatigue and rutting resistance to that associated with SBS modified binders but at higher binder contents (Austroads Pavement Research Group 1999). Increased costs associated with high binder contents and availability of blending facilities have inhibited further commercial development at this time.
- Dense graded asphalt with very high binder content (10–12% by mass of the total mix) comprising a blend 25% of crumb rubber in bitumen. These mixes are generally produced using the dry process referred to above. Aggregate gradings are adjusted to achieve normal dense graded mix air voids. The presence of the rubber largely avoids instability and bleeding that would normally be associated with such high binder contents. These mixes have exceptional flexibility and high resistance to reflective cracking.

### 4.7.6 Reclaimed Asphalt Pavement (RAP)

***Hot mix asphalt***

The addition of up to 15% RAP has little impact on the properties of a dense graded asphalt mix with conventional bitumen binders. Little change is required to asphalt mix design procedures or production methods other than the preparation of separate mix designs for the required proportion of RAP and establishment of suitable protocols for handling, stockpiling and adding RAP.

Where the proportion of RAP exceeds around 15% of the total mix, the bitumen grade may need to be adjusted to compensate for the stiffness of the aged binder in the RAP.

Modified asphalt plants that provide for improved heat transfer, reduced emissions and effective mixing of recycled materials, are generally desirable for higher proportions of RAP addition. Higher proportions of RAP also require greater control over the uniformity of RAP materials, and crushing and screening into separate size fractions is generally recommended.

Guidelines for manufacture of asphalt containing RAP are provided in Section 5.

Specifications generally prescribe the maximum proportion of RAP permitted in particular mix types and applications as well as specific test requirements for mix design or quality assurance purposes.

***Hot-in-place recycling***

Hot-in-place recycling involves heating and scarifying or milling of asphalt surface material, mixing with fresh binder or rejuvenator, and re-laying, generally in one operation. Fresh asphalt may also be added during the hot recycling process to improve asphalt properties or supplement the layer thickness.

Mix design procedures for in situ recycling are not as well established as those for conventional recycled hot mix. Unlike conventional recycled hot mix where the RAP usually comprises no more than 40% of the mixture, in situ recycled materials may involve up to 100% recycled material.

In general the design steps for hot-in-place recycled asphalt are:

1. Characterisation of the in situ asphalt
   - binder content
   - penetration, softening point and ductility or, alternatively, viscosity of recovered binder
   - grading and quality of the aggregate.
2. Determination of the need for, and proportions of, additional mix.
3. Selection of the type and quantity of rejuvenating agent.
4. Mix preparation and testing for optimum combination of in situ materials and added aggregates, binder and rejuvenating agent, using standard mix design criteria.

Assessment of the material properties of the existing asphalt pavement, including binder content, binder viscosity and aggregate grading is the first part of the process. This information is used to determine any adjustments to aggregate grading to develop the required voids in mineral aggregate (VMA) and selection of the appropriate viscosity binder or rejuvenating agent.

The process of determining the correct type and quantity of rejuvenating agent or blended bitumen binder is largely iterative.

Table 4.5 provides a guide to typical target values of rejuvenated binder for design purposes. These values are intended to provide a binder of similar consistency to freshly mixed asphalt.

Consistency may be measured as viscosity, apparent viscosity using a sliding plate viscometer, or penetration.

The penetration of Class 170 bitumen is initially between 65 and 90 and drops to about 40 during the manufacture of new asphalt. The penetration values of recovered binder from old pavements are often as low as 10 or 20, and a target penetration of 35 to 40 is recommended for the recycled binder.

**Table 4.5: Typical requirements for rejuvenated binder**

| Property | Requirement | |
|---|---|---|
| | Min | Max |
| Penetration at 25 °C | 35 dmm | – |
| Viscosity at 60 °C | 350 Pa.s | 900 Pa.s |
| Viscosity at 45 °C (heavy traffic) | – | 4.5 log Pa.s |
| Viscosity at 45 °C (light traffic) | – | 4.2 log Pa.s |
| Softening point | 52 °C | 56 °C |

The quantity of rejuvenating agent required, or grade of fresh added binder, may be calculated by various methods including nomographs for individual products or estimated using Equation 4.

$$r = \frac{\log(V + 3) - \log(T + 3)}{\log(V + 3) - \log(R + 3)} \qquad 4$$

where

r = the mass fraction of the total binder in the mix that is rejuvenating agent or fresh bitumen

R, T and V = viscosity (log Pa.s) at a single temperature that is usually either 45 or 60 °C

R = viscosity of the rejuvenating agent

T = target viscosity of the final product

V = viscosity of the bitumen extracted from the RAP

Rejuvenation is a physical-chemical phenomenon that takes time under field conditions, as follows:

- fluxing of the existing binder takes place gradually by migration
- fluxing is speeded up by compaction, traffic and higher temperatures
- there is a maximum amount of rejuvenating agent that can be assimilated by a bitumen binder.

The rejuvenating process continues to occur after mixing, leading to further softening of the bitumen. The extent of this post-mixing softening depends on the materials used and the type and quantity of the rejuvenating agent. Full rejuvenation is usually achieved in about three to six months after the completion of the recycling.

The amount of rejuvenating agent that can be added in hot-in-place recycling is limited by the air voids of the existing asphalt. When the air voids content of the old mix is too low to accommodate sufficient recycling agent for proper rejuvenation or softening of the old asphalt without mix flushing, it may be necessary to add additional fine aggregate or improve the mixture with fresh hot mix to open up the mix or increase the air voids. The selection of the appropriate addition (either fine aggregate or add-mix) and the amount to be added are determined by conventional hot mix asphalt design methods. Similarly, criteria used for the testing and evaluation of hot recycled mix construction are generally the same as those used for comparable hot mix asphalt types.

***Cold recycled asphalt***

Cold recycling of asphalt may be undertaken in situ or as plant mixed materials.

Cold in situ recycling involves milling of in situ asphalt, mixing with fresh binder or rejuvenator, and re-laying. Filler or other additives may also be used to improve mix properties.

Plant mixing comprises crushed and screened RAP blended with fresh bitumen of rejuvenating agent. Fresh bitumen is usually in the form of bitumen emulsion of foamed bitumen. Additional crushed aggregate, natural sand or mineral filler, as well as moisture, may be added to the mixture to improve grading, strength, handling and curing properties of the mixture.

Typical design steps for cold recycled asphalt are:

1. Characterisation of the in situ asphalt or RAP.
2. Determination of the need and proportions of additional aggregates or filler.
3. Estimation of the quantity and type of new binder (or rejuvenating agent).
4. Mix preparation and testing for optimum combination of RAP, aggregates, filler and binder or rejuvenating agent.

Selection of optimum content of additional binder or rejuvenating agent is somewhat different to the procedure described for hot recycled mixes. Generally, it is not intended to restore the binder to the condition of fresh asphalt. Bitumen emulsion and foamed bitumen have minimal effect on the viscosity of the existing binder in the RAP. Optimum binder content is generally determined as a result of stiffness measurement such as the indirect tensile test.

The optimum amount of added binder or rejuvenator is selected as a combination of economics and minimum resilient modulus of cured materials. Typical proportions of design binder content are shown in Table 4.6.

A further difference in the design of cold recycled mixes is the use of water as an essential component to facilitate dispersion of binders and workability and compaction of the mix.

Mixtures only develop their full strength after a period of curing. The rate of curing and strength development depends on the type of binder or rejuvenator, moisture content and curing conditions. Accelerated curing for laboratory testing is typically undertaken in a fan-forced oven for three days at 40 °C. Development of full strength in the field may take several months, or even longer, depending on ambient conditions and ability of moisture to drain or evaporate from the mixture. The rate of cure of field materials can also be significantly influenced by the choice of added filler.

**Table 4.6: Design binder content for cold recycled asphalt**

| Binder type | Added binder content (% by mass of total mix) |
|---|---|
| Foamed bitumen | 2.0 to 4.0 |
| Bitumen emulsion | 1.5 to 3.5 (residual binder) |

Further details of cold recycled materials are provided in Austroads (2009b).

### 4.7.7 Cold Mix

The term ‘cold mix’, also referred to as premix, applies to asphalt materials that are manufactured warm or cold and designed to be placed cold. Cold mix asphalt may be designed for immediate use, stockpiled for later use or supplied as a packaged material.

The design of cold mix asphalt is generally based on limits for grading, binder type and binder content developed from experience for particular applications. Cold mix, particularly packaged materials, can also be supplied as commercial products manufactured to proprietary formulations.

Binders for cold mix may be either cutback bitumen or bitumen emulsion. The proportion of flux and/or cutter oils in cutback bitumen binders is usually selected on the basis of required storage time, storage conditions and climatic conditions at the time of use. Cutback bitumen binders for mixtures intended for stockpiling and later use may, typically, contain up to 20% of flux oil. Lesser proportions of flux oil or, alternatively, medium curing cutter oils may be used in binders for mixtures intended for immediate use or faster curing.

Dense graded mixes using fluxed or cutback bitumen binders require heating and drying of aggregates for efficient mixing of binder and fine aggregates. Heating and drying is less essential when manufacturing open graded or coarse graded mixtures that have only small proportions of finer aggregate particles. Open graded and coarse graded mixes also provide for more rapid curing of flux and cutter oils after placing and compaction.

Similarly, open and coarse graded mix types are usually used with bitumen emulsion binders in order to achieve efficient mixing of bitumen emulsion binder with fine aggregates and to allow ready curing of the bitumen emulsion binder. CAM bitumen emulsion binders are generally used in mixes to be stored for later use, but other bitumen emulsion types may be used where the mix is intended to be placed within a short period of time after mixing (AS 4283).

## 4.8 Stone Mastic Asphalt (SMA)

### 4.8.1 Characteristics of SMA

SMA is a gap graded mix with a high coarse aggregate content, high filler content, and high binder content.

The high proportion of coarse aggregate in SMA interlocks to form a high stability skeleton (structural matrix) with good internal friction, while the bitumen-filler-fine aggregate mastic substantially occupies the voids in the coarse aggregate to provide low permeability.

SMA has a high filler and bitumen content. The coarse aggregate skeleton must be able to contain all the mastic binder while maintaining the stone-to-stone contact essential for rutting resistance. Too much mastic will result in flushing, bleeding and loss of pavement shear deformation resistance. Too little mastic will result in high air voids, increased permeability and reduced pavement durability.

Optimum performance is considered to be obtained when the fine aggregate just fills the void space in the coarse aggregate particles while still retaining inter-particle contact of the larger particles.

### 4.8.2 Design Procedure

The design of SMA follows the same procedure as that described for dense graded mixes in Section 4.7.1, but with specific requirements on aggregate grading, filler and binder contents. Volumetric testing (Level 1) may also incorporate checks for optimising aggregate packing properties and a check of binder drain-off.

Particular consideration must be given to the characteristics of SMA in the selection of components and laboratory design procedures. Issues requiring special attention include:

- aggregate grading, particularly aggregate interlock and relationship between coarse and fine aggregates
- influence of added filler type, and combination of added filler and binder type on the stiffness, workability and moisture sensitivity of the SMA mixture
- influence of laboratory compaction procedures on laboratory compacted density and relationship to density of field compacted materials
- control of binder drain-off during storage, transport and placing
- accurate measurement of bulk density of samples containing high levels of surface voids.

It is important to recognise these factors in order to minimise the risk of underperformance arising from high in situ voids, increased permeability, increased moisture sensitivity or, at the other end of the scale, flushing and instability.

### 4.8.3 Design Requirements

The essential characteristics of SMA are defined by limits on aggregate grading, filler and binder contents.

SMA originated in Europe, largely based on standardised grading, filler and binder content limits. The extension of SMA to other countries has seen the development of a range of procedures for optimising these limits, including packing properties of coarse and fine aggregates and filler/binder relationships.

Grading and binder content limits for the design of SMA mixes, as well as volumetric and performance requirements are included in relevant specifications of individual agencies.

As a general guide, typical grading control points for European SMA (EN 13108-5) are shown in Table 4.7. Typical design limits for binder content based on the range of specification requirements used by Australian agencies are shown in Table 4.8.

**Table 4.7: Typical grading control limits for European SMA**

| AS sieve (mm)[1] [2] | SMA7 | | SMA10 | | SMA14 | |
|---|---|---|---|---|---|---|
| | Lower limit | Upper limit | Lower limit | Upper limit | Lower limit | Upper limit |
| 19.0 | | | | | 100 | |
| 13.2 | | | 100 | | 90 | 100 |
| 9.5 | 100 | | 90 | 100 | | |
| 6.7 | 90 | 100 | | | | |
| 2.36 | 20 | 40 | 20 | 35 | 15 | 30 |
| 0.075 | 7 | 13 | 7 | 13 | 7 | 12 |

1 Values are approximate, based on nearest comparable AS sieve size to EN standard sieve sizes.
2 Specification limits imposed by individual agencies may vary from the values shown.

**Table 4.8: Typical limits for binder content**

| Type | Minimum binder content (mass% of the total mix)[1] | Maximum binder content (mass% of the total mix)[1] |
|---|---|---|
| SMA7 | 6.0 | 7.5 |
| SMA10 | 6.0 | 7.5 |
| SMA14 | 6.0 | 7.0 |

1 Specification limits imposed by individual agencies may vary from the values shown.

### 4.8.4 Aggregates

Typically, the aggregates that are used in SMA are relatively cubical in shape and of high quality to resist crushing of coarse aggregate during compaction. For heavy traffic applications, where a high degree of rutting resistance is required, wholly crushed fines are generally used. Australian agencies do not currently allow the use of RAP in SMA.

Aggregate grading, and consequent aggregate-particle interlock, is critical to the performance of SMA. Trial gradings for determination of volumetric properties can be selected from within standard grading envelopes or optimised using one of several methods developed in Australia and overseas.

Procedures developed overseas for optimising aggregate grading include the voids in coarse aggregate procedure detailed in AASHTO test methods M325-08 and R46-08 and the Bailey method as detailed in *Bailey Method for Gradation Selection in Hot-mix Asphalt Mixture Design* (Transportation Research Board 2002).

The voids in coarse aggregate (VCA) procedure involves tamping the coarse aggregate (without any binder) using a specific rod and cylinder and then calculating the density which can be used to derive the VCA. The VCA can be used to estimate the proportion of fine aggregate, filler and bitumen required, which can then be verified by determination of the volumetric properties of the compacted SMA. Provided the VCA in the compacted asphalt samples does not exceed the VCA in the compacted aggregate, then it is assumed that a stone-on-stone aggregate skeleton exists in the asphalt sample.

The Bailey method of mix design is applied to a range of asphalt mix types including SMA. It imposes ratios to the gradation to ensure that there is sufficient space for the various aggregate sizes. One of the major concepts in the Bailey method is that the size of the space between particles is about 22% of the size of the particles that confine the space. The method also divides a mix into coarse and fine aggregates with the division between the two being defined as the sieve closest to 0.22 times the nominal maximum particle size. The fine aggregate portion is divided into two sizes and the division is again defined by 0.22 times the sieve size that divided the coarse and fine aggregates.

Other concepts used in Australia for design of SMA include the dilation method (Oliver 1998a and 1998b) and the packing triangle concept (Butcher & van Loon 2013).

The dilation method involves the introduction of the fine aggregate component incrementally into the coarse aggregate skeleton until the coarse aggregate is dilated by the addition of fine aggregate. The dilation point can be determined from volumetric measurements or by the change in some physical property such as modulus. Although initially promising, the dilation point method has fallen into disuse through difficulty in defining the dilation point and a tendency to result in coarse mixes that carry a greater risk of high permeability for small increases in air voids.

The packing triangle concept is an extension of earlier work on the packing of materials, combined with filler/binder interactions to assist in determining an optimum material combination from various combination scenarios.

### 4.8.5 Fillers and Binders

Good quality fillers are typically used in SMA, although it should be appreciated that very fine fillers, characterised by high (more than about 45%) voids in dry compacted filler, will have a greater stiffening effect on the binder.

Particular attention should be given to the effect of added fillers with high values of dry compacted voids (AS 1141.17) such as fly ash, hydrated lime and some sources of baghouse dust. The resultant stiffening effect on the combined filler properties can make placement and compaction of the mix more difficult as well as masking the influence of an inappropriate aggregate grading on laboratory testing for stiffness modulus and deformation resistance.

Where added fillers with high values of dry compacted voids are being considered, it is recommended that a risk analysis for production and compaction for the selected bitumen-filler combination should be performed. If the mastic combination can be mixed only at unacceptable temperatures and/or provides unacceptable risk for compaction, it is recommended that consideration be given to the selection of a different binder. Some agencies require the addition of hydrated lime to improve the aggregate-binder bond and avoid stripping of the material. An alternative to the use of hydrated lime is addition of an adhesion agent.

Binders used in SMA can be C320 bitumen, multigrade bitumen or PMB. PMBs with higher levels of polymer modification such as A15E and A10E are often specified to enhance deformation resistance of SMA although it needs to be recognised that these binders, in combination with many common fillers, provide the highest risk in terms of production due to the required elevated temperature for mixing and placing and reduced workability. A20E, A35P and C320 binders provide less risk through a wider window for normal mixing temperatures (Austroads 2013c). If flexible granular pavements are surfaced with a single layer SMA, PMBs with higher levels of polymer modification may also be used to enhance fatigue resistance.

If there is a concern about the stiffening effect of the filler or filler/binder combination, European standard EN 13179-1 may be used to assess this property. Large increases of delta ring and ball values may increase the risk of an unworkable mix.

Alternatively, warm mix asphalt (WMA) technologies may be applied to SMA to assist in manufacture and placing.

### 4.8.6 Sample Preparation

The laboratory compaction procedure of SMA is crucial as the selected volumetric properties are based on the laboratory results, which should replicate similar volumetric properties that are achieved in field compaction.

Australian experience (Austroads 2013d) provides the following general guidelines:

- The Gyropac compactor is not capable of achieving the same level of compaction (i.e. air voids content) as the Servopac and may be less reliable for laboratory compaction of SMA mixes, particularly when using more highly modified PMB binders.
- The Servopac compactor provides the most reliable compaction with good indication of densities achievable in field compaction.
- Marshall compaction at 50 blows also provides reliable indication of field conditions, comparable with that achieved using typical field compaction procedures.
- Laboratory compaction temperatures should be selected on the same basis as dense graded mixes.

### 4.8.7 Binder Drain-off

The high binder content of SMA increases the risk of binder drain-off although this risk may be reduced with stiffer binders resulting from fine filler materials or modified binders.

The most effective method for controlling binder drain-off is the addition of cellulose fibre. Determination of the potential for binder drain-off and the proportion of fibre additive can be evaluated using Austroads test method AGPT/T235. Typically, 0.3% of cellulose fibre by mass of total mix provides effective protection against binder drain-off at normal mixing and placing temperatures.

### 4.8.8 Measurement of Bulk Density

Accurate determination of bulk density and hence air voids is an important part of design procedures as well as assessment of field performance. Measurement of bulk density of SMA needs to consider both the surface texture of compacted samples as well as the possibility of interconnected air voids and hence high permeability for relatively small increases in air voids.

The following guidelines may be applied to the effectiveness of different methods for measurement of bulk density (Austroads 2013e):

- Mensuration (AS 2891.9.3) provides the lowest value of bulk density through overestimating air voids by inclusion of all surface voids and should not be used.
- The vacuum sealing method also tends to include negative surface air voids and is an unreliable indication of internal air voids for SMA.
- Presaturation (AS 2891.9.2) provides reliable values of bulk density and air voids provided that air voids do not exceed approximately 7%. Above 7% air voids, SMA mixes tend to become highly permeable reducing the reliability of measurement of bulk density by presaturation.
- Waxing (AS 2891.9.1) provides a reliable measure of bulk density provided that the wax does not penetrate internal air voids of samples with high air voids (more than about 10%). Risk of wax penetrating internal voids can be reduced by dipping and rotating the sample rather than full immersion. Alternatively, the use of silicone in place of wax can provide reliable measurement.

## 4.9 Open Graded Asphalt (OGA)

### 4.9.1 Characteristics of OGA

OGA is characterised by a large proportion of coarse aggregate and only small amounts of fine aggregate and filler. This provides an asphalt mix with relatively high air voids, generally in the range 18 to 25%, and relies on a combination of mechanical interlock of coarse aggregate particles and binder cohesion for shear and deformation resistance.

High air voids and the porous nature of OGA leads to reduced durability compared to DGA or SMA wearing courses, although the impact of reduced durability can be lessened with the use of high binder contents to increase the binder film thickness around the individual aggregate particles and the use of modified binders.

### 4.9.2 Design Procedure

There is no universal rational design system for OGA. Basic parameters are usually established by specified requirements for materials, volumetric properties and any additional performance tests. Determination of volumetric properties (Level 1 testing) follows the same procedure as that described for dense graded mixes in Section 4.7.1.

Compaction to maximum cycles is not applicable to OGA. Level 2 performance tests applied to dense graded mixes are also not usually applied to OGA.

Additional performance tests with specific application to OGA include AGPT/T235 – *Asphalt binder drain-off* and AGPT/T236 – *Asphalt particle loss*.

### 4.9.3 Design Requirements

Design requirements are usually defined by individual agency specifications.

Design limits for grading and binder content or a target grading and binder content are basic specification requirements for all OGA mixes. Specification requirements may also include the type of binder and properties of combined filler or type and proportion of added filler.

Other design requirements can include one or more of the following:

- Range or minimum value of air voids. Where values for volumetric properties are not specified, they may still be measured and reported for use in monitoring of manufacture and placing.
- Minimum binder volume or binder film index. High values of binder volume or film index are an important contribution to durability.
- Maximum value for binder drain-off (AGPT/T235).
- Maximum particle loss (AGPT/T236).

Test procedures developed for moisture sensitivity of dense graded asphalt are not applicable to OGA as these mixes do not develop the moisture saturation condition that is the basis of the moisture sensitivity test (AGPT/T232). Separate aggregate/binder adhesions tests may be undertaken to determine the need for the addition of adhesion agents.

***Component materials***

Typically, the aggregates that are used in OGA are relatively cubical in shape and of high quality to resist crushing of coarse aggregate during compaction.

Polymer modified binders are frequently used in OGA mixes to provide greater cohesion and durability. They may also assist in reducing the risk of binder drain-off although, where binder drain-off is an issue, it is more effectively controlled by the addition of cellulose fibres.

OGA may also incorporate crumb rubber (see also Section 4.7.5), in conjunction with a high binder content, for increased durability or to provide lower surface noise characteristics.

Some specifications require the addition of a minimum proportion of hydrated lime filler to improve aggregate binder adhesion and reduce moisture sensitivity. The filler component in OGA has a further role in reducing binder drain-off and thereby ensuring an adequate binder film thickness around the coarse aggregates. High values of dry compacted voids in the combined filler fraction also assist in retention of binder in the mix.

***Sample preparation***

Sample preparation and laboratory compaction procedures are the same as that applied to dense graded mixes except that lower compaction temperatures are usually applied to OGA.

***Air voids and volumetric properties***

High air voids in OGA are desirable to maximise the benefits of reduced tyre surface noise and improved safety through reductions in water spray and increased skid resistance. Air voids requirements must be balanced against the need for sufficient binder for cohesion and durability as well as resistance to surface shear forces. OGA generally has low resistance to shearing forces in situations of high traffic stress such as signalised intersections and tight radius curves. Increasing the proportion of fine aggregate improves the resistance to traffic but at the expense of air voids and porosity.

Air voids in OGA are increased by:

- increasing the proportion of coarse aggregate for a more open graded property
- decreasing binder content
- decreasing filler content.

Decreases to air voids are obtained by:

- increasing binder content
- increasing the proportion of fine, intermediate aggregate sizes
- increasing filler content.

***Measurement of bulk density***

Bulk density of compacted OGA specimens is usually measured by mensuration (AS 2891.9.3). An alternative method used in Australia is the vacuum sealing method (Main Roads Western Australia 2008).

***Binder drain-off***

The asphalt binder drain-off test (AGPT/T235) can be used to establish the maximum amount of binder that can be used without excessive drain-off of binder or to evaluate the influence of different binder types or additives. The test may also be used to establish the maximum temperature for mixing and transport for a given binder type and binder content.

Excessive binder drain-off can be reduced by:

- lowering of temperature for OGA manufacture
- using a higher viscosity binder
- decreasing the binder content
- increasing filler content or changing the type of added filler
- including fibres in the mix.

***Asphalt particle loss***
The asphalt particle loss test (AGPT/T236) measures the loss of aggregate particles of a sample subject to tumbling in a Los Angeles abrasion loss test apparatus (Appendix H). It gives an indication of the cohesion of the asphalt mix and hence a guide to the effectiveness of binder type and content in resisting particle loss during service.

Reductions in aggregate particle loss can be achieved by:

- increasing the binder content (decrease air voids content)
- including more intermediate sized aggregates (decrease air voids content)
- using a binder with improved cohesive properties.

## 4.10 Fine Gap Graded Asphalt (FGGA)

FGGA mixes are intended to provide highly durable mixes in light traffic situations through low in situ voids while still retaining sufficient resistance to low levels of traffic stress, typically in residential streets and other light traffic situations. A high proportion of fine aggregate and high binder content provide good workability and ease of compaction to the desired field density and in situ air voids.

The procedure for FGGA is similar to dense graded asphalt. General limits for particle size distribution are established from specified grading targets or nominated proportions of coarse and fine aggregates, mineral filler and binder. Volumetric properties may be evaluated on samples prepared using either gyratory or Marshall compaction.

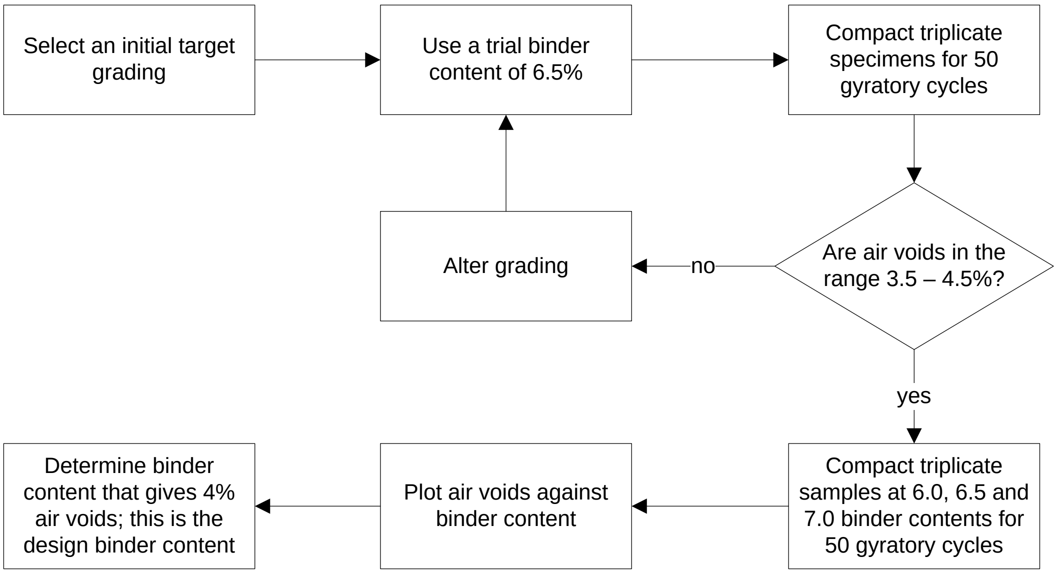
Generally, compaction is based on 50 cycle gyratory or 35 blows Marshall. A low air voids content, typically between 3.5 and 4.5%, and a high bitumen content, typically not less than 6.5%, are desirable in order to achieve highly durable asphalt mixes

The relationship between performance under traffic and laboratory properties (air voids and shape of the gyratory compaction curve) built up from experience should permit a mix designer to improve the composition of the mix or alter it to meet different traffic loading conditions.

An outline of a design procedure using the gyratory compactor is shown in Figure 4.15.

Greater information containing detailed design procedures and a worked example are provided in Oliver (1995).

**Figure 4.15: Laboratory design of fine gap graded asphalt**



# 5. Asphalt Manufacture

## 5.1 Introduction

The primary functions of an asphalt mixing plant are to:

- dry and heat the aggregate
- combine the aggregates, filler and binder in the correct proportions
- mix binder and aggregates
- discharge the mix in good condition for transport, placing and compaction.

The methods of production should:

- supply a homogeneous, consistent product
- limit segregation of the asphalt and loss of materials
- meet required environmental standards for emissions and site management
- be conducted in a sustainable and safe manner.

The safe and efficient use of the mixing plant can have a significant effect on the quality and suitability of the asphalt produced. Different types of plants are available for the production of asphalt and these are discussed in the following sections.

## 5.2 Types of Mixing Plants

### 5.2.1 General

Mixing plants are generally categorised as:

- batch plants
- continuous mixing plants.

In a typical batch plant, the combined dried and heated aggregates are elevated to a screen deck where they are rescreened into separate hot aggregate bins. Hot aggregates and other components are weighed separately and mixed together in predetermined batch sizes in a pugmill mixer.

Batch plants are considered to offer greater flexibility than continuous mixing plants in the ease of changing from one size of mix to another without wastage.

In Australia, continuous mixing plants are mostly of the drum mixing plant type. The earliest form of drum mixers were of the parallel flow type in which aggregates are introduced into the dryer/mixer drum at the same end as the burner and drying, mixing and coating of the aggregate with binder takes place simultaneously in a revolving drum. These gained popularity through low capital and maintenance costs and ready portability and were considered particularly applicable to the continuous production of one type of mix and are capable of very high outputs.

Subsequent development of the drum mixing concept has seen improvements in control systems and alternative configurations such as counterflow mixers and drum within a drum (double drum mixer). Alternative drum mixing configurations offer greater mixing and thermal efficiency, improved flexibility, as well as facilitating the effective use of higher proportions of RAP in the asphalt mixture.

Other forms of continuous mixing plants include the separate heating or drying of aggregates, similar to a batch mixing plant, prior to feeding the hot aggregate mixture into a separate pugmill or rotating drum mixing chamber for mixing with remaining components.

A further variation of the continuous mixing plant is the feeding and metering of raw materials direct from storage bins to a continuous pugmill mixer.  This type of plant is used for manufacture of cold mixes, cold recycling and stabilised materials where heating of aggregates is not required.

#### 5.2.2 Sites for Mixing Plants

Plants can be further classified as:

- stationary (fixed)
- portable (units which can be easily relocated)
- fully mobile plants (on wheels).

Many factors are important in selecting a plant site, including:

- environmental considerations
- sufficient working space
- proximity to the job
- traffic considerations
- availability and sources of materials and services
- well drained, level ground conditions
- town planning (zoning).

### 5.3 Raw Material Supply and Storage

#### 5.3.1 Aggregate Supply

Consistency of grading of aggregates supplied to the mixing plant is essential if a mix of uniform quality is to be produced.

#### 5.3.2 Aggregate Stockpiles

Stockpile sites should be selected and arranged to minimise wastage on the ground and facilitate the use of mechanical loading plant.  Aggregates should be kept as dry as possible, to avoid unnecessary demand on the heating capacity of the dryer and to ensure consistency in the drying process.  Covered storages may be considered as a means of managing moisture.

The stockpile area should be well drained and preferably paved, and there should be ample clearance to fences, trees, poles, overhead wires, etc.

Separate stockpiles should be provided for the various aggregate fractions.  These should be separated by walls or adequate clearance of at least 10 m (if in stockpiles) to avoid contamination between stockpiles.

Unnecessary handling should be avoided in order to reduce segregation.

#### 5.3.3 Stockpiling and Handling of RAP

Incoming RAP materials generally require crushing and/or screening to remove oversize materials and break up agglomerations in order to ensure a consistent grading and provide a free-flowing product.

Separation into different sized fractions further assists control of combined grading of the asphalt mix.  The process of reclamation and crushing tends to produce an increase in fines in RAP compared to the original asphalt mixture.  Separation into separate size fractions assists in recombining materials to a particular grading target, particularly if the content of RAP exceeds around 20% of the mixture.  Screening into separate sizes is essential if the RAP is to be used in mixes with special grading requirements such as stone mastic asphalt, open graded asphalt or fine gap graded asphalt.

Materials should be inspected or tested for contamination and suitability for recycling. Materials containing tar are not suitable due to the risk of fuming. Aggregates that are rounded or polished may only be suitable for basecourse applications.

Stockpiles of RAP should be carefully controlled to:

- identify and keep separate, different quality or sizes of RAP materials
- avoid consolidation of large stockpiles
- avoid moisture retention.

RAP materials can retain a great deal of moisture and undercover storage can reduce subsequent heating and drying costs.

#### 5.3.4 Mineral Filler Storage

Mineral filler added in asphalt production may be either (or both) a commercially available filler and/or collected baghouse dust.

Commercially available fillers are usually delivered in bulk and stored in elevated waterproof silos.

All fillers form lumps when wet and can cause blockages. Therefore, it is essential to ensure that the storage and handling equipment is waterproof. Filler systems should be checked regularly to ensure that there are no obstructions that will affect uniform feeding.

#### 5.3.5 Binder Storage

Tanks for the storage of binder should have provision for heating and circulating, and be provided with an insulated circulating system to the mixer. Thermostatic control is highly desirable to ensure that the binder can be held at the required mixing temperature.

Sufficient numbers of tanks should be provided to ensure that different binder types can be stored without risk of mixing or contamination.

Binders should be stored in accordance with the manufacturer's directions. Particular attention should be applied to any special requirements for the storage of polymer modified binders. Tanks for modified binders should be fitted with stirrers to keep the binder within the tank continuously moving and the binder should be maintained at the lowest practical temperature for operational use.

Binder storage should include a facility to sample the binder from the tank discharge line.

#### 5.3.6 Storage of Additives

Additives supplied in bulk are stored and handled similarly to added filler. Packaged materials should be carefully stored to protect containers from damage. Powdered and granular materials, in particular, require waterproof storage for protection from moisture.

Hazardous materials must be stored and handled in accordance with relevant regulations and occupational health and safety standards.

### 5.4 Batch Mixing Process

#### 5.4.1 General

The components of a batch plant as shown in Figure 5.1 are:

- cold aggregate bins fitted with feeders to meter the aggregate onto a belt conveyor
- bins or hoppers to hold recycled materials
- conveyor
- a rotating steel drum dryer

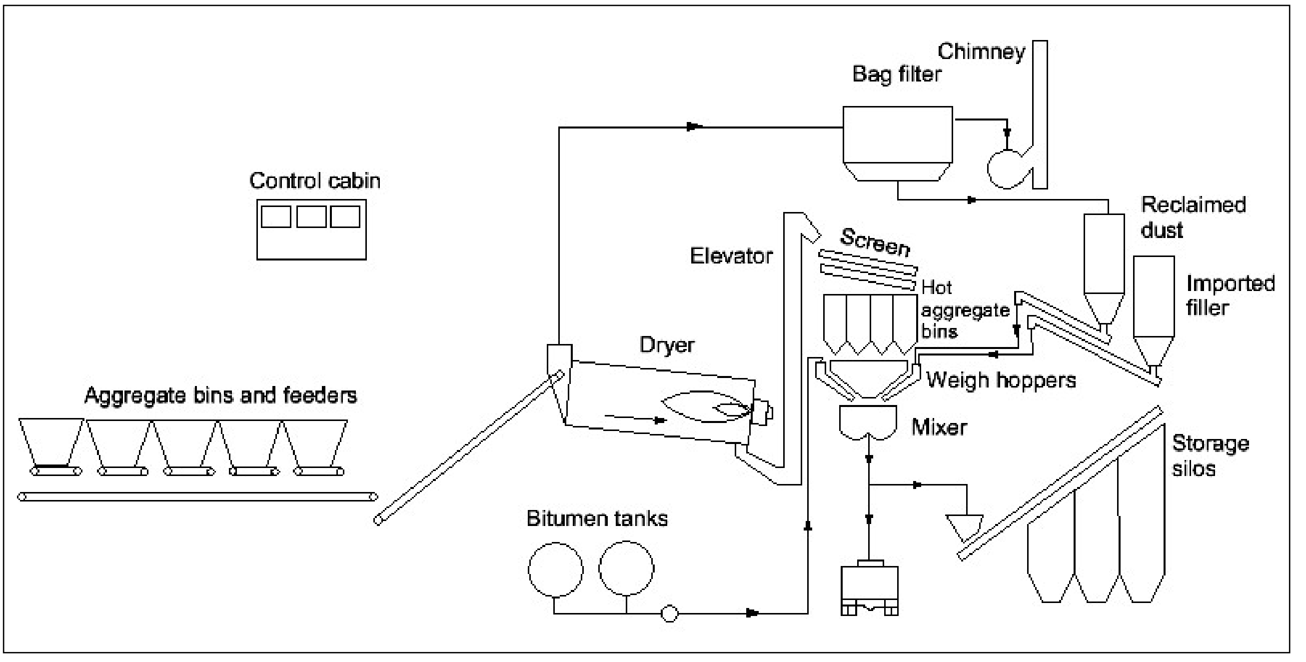
- a dust collection system
- a hot elevator
- screens to separate the hot aggregate into various fractions
- a number of bins to hold hot aggregate
- a filler storage bin and feeder system
- binder storage tanks and feeding system
- a weigh batching system
- a pugmill mixer
- storage silos or surge bins
- a manual, semi-automatic or automatic control system.

In the batch plant process, aggregates are fed from cold storage bins in controlled amounts and passed through a rotating dryer where they are dried and heated to approximately 170 °C (although this temperature depends on numerous factors including the type of asphalt being produced, the type of binder being used, the RAP content of the mix, whether a warm mix technology is used, etc.). This aggregate is elevated to a screen deck where it is separated into different sized fractions and deposited into hot storage bins. The aggregates and filler(s) are weighed and discharged into the pugmill which are then dry mixed. The bitumen is weighed in a separate hopper and then sprayed into the pugmill and wet mixed. Finally, the mix is either discharged directly into trucks, or into a skip hoist or slat conveyor for transfer to hot storage.

Batch plants are rated on their mixer capacity and are generally 350 to 7000 kg. The actual production capacity of the plant depends on a combination of factors including:

- moisture content of the aggregate
- capacity of the dryer
- screening capacity
- batch weighing capacity for aggregates, binder, filler or additives
- length of mixing and discharge cycles
- hot bin storage capacity and/or availability of trucks.

**Figure 5.1: Typical batch plant**




Under normal conditions, based on a typical mixing cycle of 55 to 60 seconds, a 3000 kg plant is capable of producing about 170 to 180 tonnes of asphalt per hour.

### 5.4.2 Cold Aggregate Bins

Aggregate is fed into the plant from either:

- open-topped bins fed by a front-end loader
- bins fed by trucks either directly or via a conveyor system
- conveyor tunnel under open stockpiles separated by walls.

The number of bins necessary will depend on the mixes being produced and the available aggregate sizes. Commonly, three or four bins are used for coarse aggregate and two for fine aggregates (e.g. sand and crusher dust).

When charging the cold bins, care should be taken to minimise aggregate segregation and degradation.

**Figure 5.2: Batch plant**

### 5.4.3 Cold Aggregate Feeding

Each size of aggregate must be metered out by the cold feeders in the correct proportions. Close control of the cold feed is needed to avoid:

- variations in grading
- uneven flow through the dryer causing variations in temperature and moisture content of the dried aggregate
- overloading of screens
- overfilling or starving of the hot bins
- layering of sizes in the hot bins.

Any of these factors can produce variations in the final mix.

Proper control requires an adequate number of cold bins for the various sizes of aggregate. The flow rates from the cold bins should be individually calibrated.

To ensure that the correct quantity of each aggregate is fed to the dryer, the cold bins should be supplied with materials of uniform grading and moisture content and the levels in the bins should be kept constant.

Regular inspection of the cold feeding operations is required to overcome:

- clogging of the coarse aggregate feed
- arching of the fine aggregate feed
- slipping of the feed belt to dryer.

Blockages can be reduced by using oversize screens (grizzlies) above the cold bins and fitting of vibrators to the fine aggregate bins.

### 5.4.4 Aggregate Heating and Drying

The dryer is a rotating drum that uses forced air in conjunction with an oil or gas burner to heat and dry the aggregates. It is equipped with longitudinal flights that lift the aggregate particles and cascade them through the hot burner gases. The dryer performs the two functions of removing moisture from the aggregate and heating it to the required mixing temperature.

Dryers may vary in size (and capacity) from 1 to 3 m in diameter and from 5 to 16 m in length. It is important that the dryer's capacity to heat and remove moisture from the materials is matched to the plant mixing capacity. The amount of aggregate passing through the dryer should be such that it can be heated to a temperature slightly higher than the mixing temperature.

In plants using baghouse dust collectors, the controlling operational factor is the temperature of the exhaust gases carrying the extracted dust. If the exhaust gas temperature is below the dew point temperature of the gas stream, moisture vapour will condense and turn the dust cake into mud on the airbag fabric. This will significantly affect the efficiency of the baghouse filtration. Conversely, excessive temperatures can cause damage to the fabric filters.

A temperature probe is provided to measure the temperature of the discharged aggregate. A check should be kept on the temperature at all times to ensure that it is within the manufacturer’s specified range. Overheating of the aggregate may cause oxidation damage and premature hardening of the binder.

Automatic control of the burner maintains the required aggregate temperature. The temperature of the aggregate leaving the dryer should be suited to the temperature requirements of the completed mixture. Higher aggregate temperatures may be required for mixes with RAP to achieve appropriate heat transfer to the added RAP material.

### 5.4.5 Dust Extraction

Some airborne dust is carried away from the dryer in the exhaust. Sound environmental practice requires that this dust is collected. It may be returned direct to the hot elevator and/or retained in a silo for use as added filler, provided that it does not contain excessive silt or clay.

A typical dust collection system is comprised of a primary dust collector of the cyclone type, and a secondary dust collector, which may be a wet scrubber or a dry baghouse.

The combination of dry cyclone and wet scrubber or baghouse removes about 99% or more of airborne dust.

### 5.4.6 Screening of Hot Aggregates

Aggregate from the dryer is transported by the hot aggregate elevator to screens mounted over the hot bins. The screens separate the aggregate into selected sizes for subsequent proportioning and reject oversize particles.

Vibrating screen decks are most commonly used.

For efficient screening, the screens should be:

- of adequate effective area
- of the correct size opening
- clean and in good condition
- properly arranged and at the correct slope
- vibrating in the correct manner.

The selection of the screen-opening sizes can have a significant effect on the actual particle size distribution of the mix. Trials should be undertaken to determine the most appropriate screen (mesh) sizes, and combination of sizes, for each production mix. The surface area of the hot screens must be balanced with the output from the dryer and the capacity of the mixer.

The capacity of a screen for a particular operation will be influenced by many factors, including:

- area of screen
- gradation of material from the cold feed
- screen load versus amount passing
- size of screen wire
- vibration amplitude and frequency.

Screens are subject to wear and tear, which can allow oversized material to enter a bin for finer material. This will produce a mix coarser than specified.

If a screen is blocked, fine material will not pass through the screen efficiently resulting in some finer aggregate going into coarser bins. This will produce a mix finer than specified.

Regular (daily) inspection of the cleanliness and wear of the screens is desirable to ensure correct aggregate proportioning. Worn screens should be removed and replaced.

### 5.4.7 Hot Aggregate Bins

The number of bins required to hold the hot aggregate will depend on the type and size of mixes being produced, but is generally not less than four.

They should be of adequate capacity to enable continuity of production at maximum output.

The levels of the materials in the bins should be kept uniform by regulating the cold feed. If the cold feed is not properly controlled, over-filling or under-filling of the hot bins may occur and may adversely affect the specified particle size distribution of the final mix. Efficiency and the production rate may also be affected.

The hot aggregate bins should have individual thermometers, level indicators, sampling gates, and overflow outlets to ensure that any excess will not spill into an adjoining bin.

### 5.4.8 Filler Feeding

Added filler is fed directly into the mixer and not passed through the dryer as the air flow would carry it away to the dust collector. Therefore, it is not heated but the small proportion of filler in the total mix results in very little cooling effect.

Filler is generally proportioned by mass. Filler may be weighed in a separate weigh hopper or cumulatively with aggregates. Separate weighing provides greater accuracy for the relatively small quantities involved.

### 5.4.9 Aggregate Proportioning

Normally, all aggregates are weighed cumulatively on one set of beam-type scales. Weighing may be carried out manually or automatically.

The hot aggregate bins discharge into the weigh hopper, which empties directly into the mixing chamber. Gates should be shut off cleanly, allowing no dribble of aggregate.

Dust in the lever system, knife-edges, bearings, etc. or faulty electronic components may result in inaccurate batching. Zero adjustment of the scales should be checked daily before operating, and the scale calibrated periodically.

### 5.4.10 Binder Proportioning

Binder is weighed in a special bucket on a separate measuring scale and should be distributed over the full length of the pugmill, generally by spray bar.

The binder cut-off valve must be checked frequently, to ensure that it is operating efficiently.

The binder content of the mix is critical to quality mix production, and it is imperative that the binder content is within the specified tolerance.

### 5.4.11 Mixing

The mixing unit normally consists of a pugmill mixing chamber with two shafts holding blades or paddles rotating in opposite directions.

The maximum batch size used should be based on the manufacturer's recommended rating. The chamber should not be filled to a greater depth than the maximum height of the revolving blades (called the pugmill 'live zone'). Material that is above the level of the revolving paddles tends to float and will not be properly mixed. On the other hand, when the pugmill is under-filled, the paddles have insufficient material to carry around.

There is usually a clearance of only about 10 mm between the paddle tips and pugmill liner to ensure there are no dead spots that are not properly mixed.

The functions of the pugmill are to mix constituents sufficiently to ensure:

- mix homogeneity
- that all aggregate particles are completely coated with binder.

The pugmill mixing cycle has three phases:

- dry mixing phase
- wet mixing phase
- discharge phase.

The dry mixing of aggregate and filler materials is normally for a period of 5 to 15 seconds. Pelletised or granulated additives may need longer dry mixing times to ensure complete dispersion.

The wet mixing phase begins as the binder is introduced into the mixing chamber, and has a duration of between 30 and 50 seconds.

During the wet mixing, the hot binder is exposed to air in relatively thin films that make it subject to oxidation. Excessive mixing, therefore, can tend to degrade the binder and mixing time should be carefully controlled so that the process is carried out in the shortest time required to uniformly coat aggregate particles.

Mixing temperatures should also be carefully controlled to avoid overheating of the binder that can also result in excessive oxidation. In general, mixing should be carried out at the lowest practicable temperature at which satisfactory coating of the aggregate can be obtained. For hot mixes, this is generally in the range of 135 to 165 °C although lower temperatures may apply to particular warm mix asphalt technologies.

When mixing is complete, the pugmill discharge gate must open quickly to allow the mixed batch to be discharged as a mass, thereby avoiding segregation.

The mixed material is discharged directly into the delivery vehicle or transported by skip or slat conveyor to a hot retention system (surge or storage bin).

#### 5.4.12 Controls

Although control of the process of feeding, drying, weighing, mixing, etc., may be manual it is more commonly semi-automatic or automatic.

In semi-automatic plants, the dry mixing time, binder feeding, wet mixing time and pugmill discharge are under automatic cycle control.

In a fully automatic system (Figure 5.3) the following controls may be pre-set:

- proportions of aggregates, for a number of different mixes
- batch size
- number of batches required
- the entire weighing cycle.

Automatic controls increase consistency of manufacture as well as raising productivity and reducing operator fatigue.

The burner controls may also be automated to maintain the temperature of aggregate leaving the dryer.

Temperature monitoring is required for aggregate leaving the dryer, in each hot bin and in the binder supply line to ensure that materials are at the appropriate temperature for effective mixing and placing, and to avoid overheating.

#### 5.4.13 Reclaimed Asphalt Pavement (RAP)

The mixing process for incorporating RAP into asphalt mixes in batch mixing plants involves heat transfer from superheated aggregates. Practical considerations generally limit the proportion of RAP that can be recycled by this method to about 30% of the total mix although higher proportions may be achievable by pre-heating the RAP.

RAP is generally transferred via a cold feed bin and weigh hopper so that it enters the pugmill at ambient temperature.

**Figure 5.3: Asphalt plant control room**


Alternatively, RAP may be added to aggregates at discharge from the dryer. This provides for more efficient heat transfer during retention in hot bins, although clogging of screens can be a problem that requires regular inspection and cleaning.

The new materials are dried, heated, screened and conveyed to the hot bins in the usual manner except that aggregates are heated to higher than normal temperatures to provide for heat transfer to the RAP.

Heat is transferred from the superheated aggregates to the RAP in the hot bins or pugmill. Increased dry mixing times may be required to ensure adequate softening of the binder in the RAP for thorough mixing of the RAP and the new material.

The temperature to which the new aggregate must be heated depends on a number of factors, including:

- the percentage of RAP added
- the temperature of the RAP
- the moisture content of the RAP
- the desired temperature of the manufactured mix.

The rate of heat transfer must be closely controlled so as to avoid evaporation of light oil fractions of the binder film, which would be discharged into either the baghouse or to the atmosphere. In addition, exhaust gases with high temperatures (over 230 °C) can cause further oxidation and hardening of the RAP binder as well as deterioration of the fabric bags in a baghouse dust collector.

Complete temperature equilibrium in the hot recycled mixture is usually not attained until some time after the mix has been discharged from the pugmill. Hot asphalt storage bins help in this respect.

A homogeneous mix is only achieved using this method if the duration of the mixing cycle and the proportion of RAP in the total mix are tightly controlled. The longer the mixing time used the higher the proportion of RAP that may be used. It is usual to increase the mixing time by 5 to 20 seconds and to limit the proportion of RAP to about 30% (maximum) of the total mix.

## 5.5 Continuous Mixing Plants

### 5.5.1 General

Continuous mixing plants differ from batch plants in that there is no further screening and recombining of aggregates after heating and drying thus eliminating the need for:

- hot elevator
- vibrating screens
- hot aggregate storage bins
- weigh hopper.

Drum mixing plants may be parallel or counterflow. In a parallel flow mixer, the burner (either oil or gas) is located at the aggregate inlet end of the drum and hot bitumen is added near the outlet end of the drum, furthest from the burner. Addition of RAP in such mixing plants is generally by a collar, part way along the drum.

Counterflow drum mixing plants generally employ an extended burner to shield the binder and RAP from direct contact with the burner flame.

Other forms of the drum mixing plant include:

- use of internal drum(s) to separate heating and mixing processes (double drum mixer)
- tandem drum mixers to separate heating and mixing processes.

Continuous mixing of asphalt can also be undertaken with a pugmill mixer. Some batch plants incorporate a bypass chute that enables heated and dried aggregates to be fed directly to the pugmill mixer. A configuration similar to that of the tandem drum mixer using a pugmill in place of the second drum may also be used. Both these forms of continuous mixing plant are rarely used for the production of hot mix asphalt in Australia. The more common application of continuous pugmill mixing plants (Section 5.5.6) is in the manufacture of cold mixes, cold recycled asphalt and cold stabilised materials where no heating and drying of aggregates is required.

### 5.5.2 Parallel Flow Drum Mixer

***General***

The following description of the parallel flow drum mixer (Figure 5.4) incorporates a number of features that are common to all continuous mixing plants, particularly the proportioning and control of aggregate feed rates. Variations specific to other types of continuous mixing plant are described in the following sections.

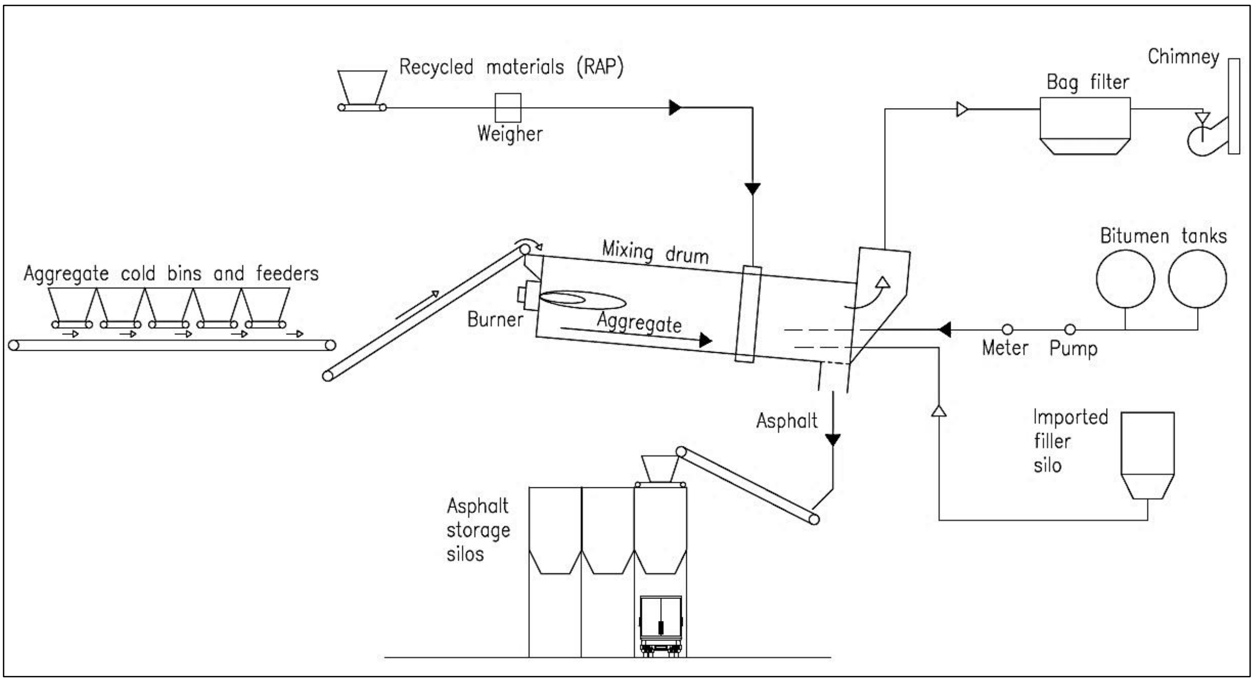
The capacity of a parallel flow drum mixer (Figure 5.5), in tonnes per hour, depends primarily on the drum size, but the effective production rate is also influenced by moisture content of the aggregate. The single most important factor affecting the production rate of a particular size of drum mixing plant is the moisture content of the aggregate entering the mixing drum.

***Cold aggregate bins and feeding***

Accurate calibration and control of the cold feed is of great importance in all continuous mixing processes. Proportioning is carried out with damp aggregates and compensation must be made for the moisture content of the aggregate.

Proportioning of individual aggregates in this system is controlled by variable-speed belt feeders on each individual cold feed bin. The area of the opening above the feed belt may be further regulated by means of an adjustable gate opening that is set or locked into position. The mass of cold feed aggregates may be determined from weigh cells on each individual belt feeder, which also control the individual aggregate feed rate, or from a single load cell for the combined aggregates on the cold feed conveyor. Electronic scales for the aggregate feed rate are interlocked with a variable speed bitumen pump so that a pre-set bitumen content is constantly maintained.

**Figure 5.4: Diagram of a typical parallel flow drum mix plant**




Particular care must be taken to remedy flow deficiencies such as:

- coning of the aggregate in the bin
- blockages of the opening at the belt feeder
- emptying of the bin i.e. running out of the raw material
- variation in the moisture content of the aggregate
- sudden changes in the head of material in the bin.

Warning devices must be fitted to indicate a lack of material and continuous monitoring is essential.

**Figure 5.5: Typical parallel flow drum mixing plant**

***Mineral filler feeding***

The mineral filler is fed by an enclosed screw feeder powered by a variable-speed motor that is operated and controlled in a similar manner to the cold aggregate.

Some older drum mixing plants deposit the filler on the belt at a point where it will be almost immediately covered by aggregate. This is designed to minimise loss of filler entering the dryer drum but some loss may still occur through the gas extraction system and allowance for this must be made in the proportioning of ingredients.

The preferred method of feeding mineral filler is to feed the filler directly into the dryer drum in a similar manner as the binder. This has the advantage that it minimises the potential loss of added filler through the dust collection system.

***Binder feeding***

Positive interlock is provided between the flows of aggregate, mineral filler and binder, so that the relative proportions can be maintained independently of variation in the total feed rate.

The binder is generally introduced from a feed pipe extending around one-third of the distance from the outlet end of the drum.

***Mixing***

Mixing takes place in the rotating dryer drum. The time taken for material to pass through the drum may vary from three to five minutes.

Parallel flow drum mixers are designed so that binder does not come into direct contact with the burner flame and so that mixing is accomplished in an inert atmosphere of water vapour and spent gases of combustion. These factors combine to lessen hardening of the binder.

Mixed material leaves the end of the drum and is conveyed into a surge bin from which it is loaded into trucks.

***Dust collection***

As the aggregate is coated with binder as it is dried, most of the fines are trapped in the mix. There will however be some airborne dust which must be collected in a similar manner to that previously described for batch mixing plants.

***Addition of RAP***

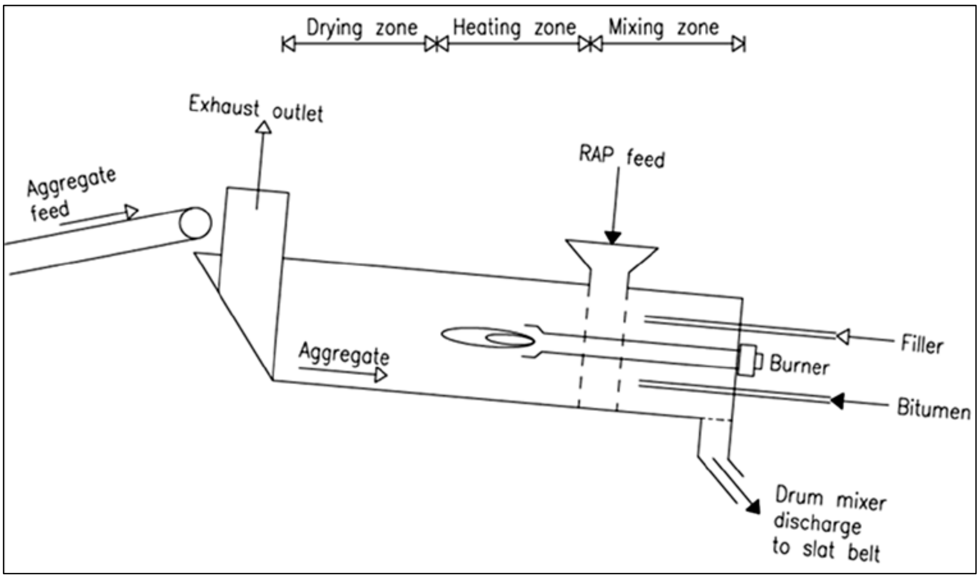
The most common method of adding RAP to a parallel flow drum mixing plant is the use of a split feed with separate inlets for new materials and RAP. RAP is fed into the drum part way along the drum using a special collar (Figure 5.4).

Addition of RAP requires drum flight systems to be modified to ensure that the virgin aggregate forms a shield between the flame and the RAP, preventing overheating.

### 5.5.3 Counterflow Drum Mixer

The counterflow drum mixing system uses an extended burner that is mounted at the discharge end of the drum to isolate the mixing zone from the drying zone (Figure 5.6). The combined aggregates pass through the drying zone before entering the mixing chamber where the bitumen and filler are added. Thus, in this system the bitumen does not come in contact with the flame. When RAP materials are included in the mix, they are added directly to the mixing chamber via a collar similar to that of a parallel flow drum mixer. The design of the plant provides improved emission levels over that of a standard drum mixer and enables high proportions (up to 50%) of RAP to be used.

**Figure 5.6: Counterflow drum mixer**




### 5.5.4 Drum within a Drum (Double Drum Mixer)

In this system a second, smaller diameter, inner drum is used to heat and dry the new aggregate. RAP is introduced into the outer drum through a second chute. The heated aggregate and RAP meet at the discharge point of the inner drum along with bitumen and filler (Figure 5.7 and Figure 5.8). It is a clean and efficient process with a potential ability to produce mixes containing up to 50 to 60% RAP although, in practical terms, most production is limited to around 30 to 40% RAP.

**Figure 5.7: Schematic view of a double drum mixer**

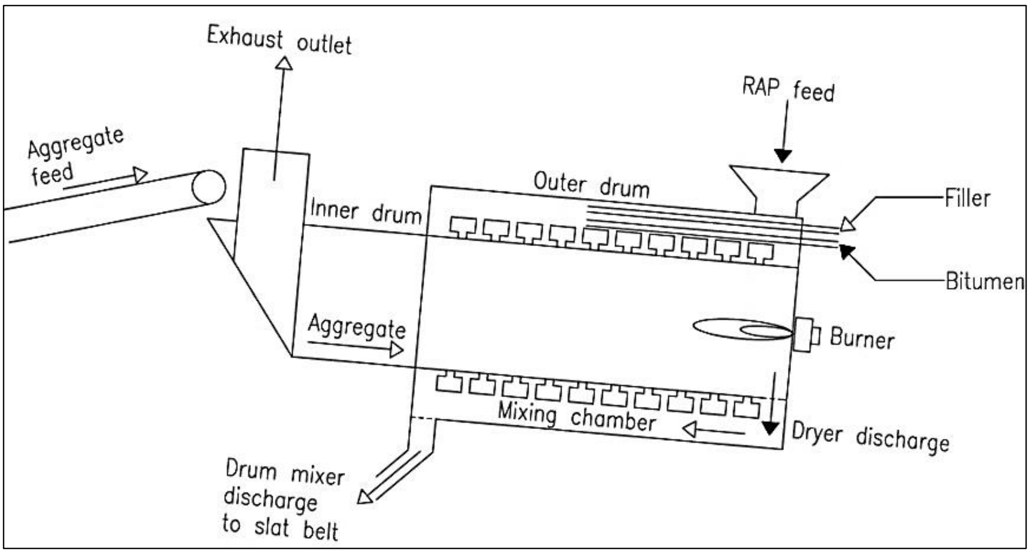


**Figure 5.8: Double drum mixer**


### 5.5.5 Tandem Drum Mixers

This plant consists of two drums in series (Figure 5.9 and Figure 5.10). The first drum is an aggregate dryer, which superheats the new aggregate. The second drum mixes the new material with the RAP, filler and binder. This drum may also heat the RAP using the exhaust gases from the first drum. This method may be used to produce mixes with up to about 50% RAP.

**Figure 5.9: Tandem drum mixer**

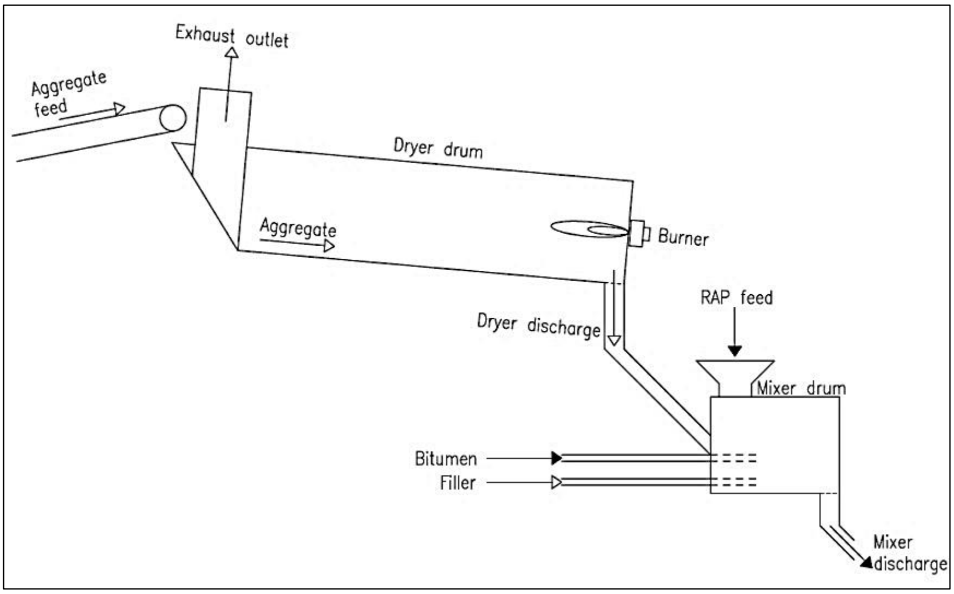
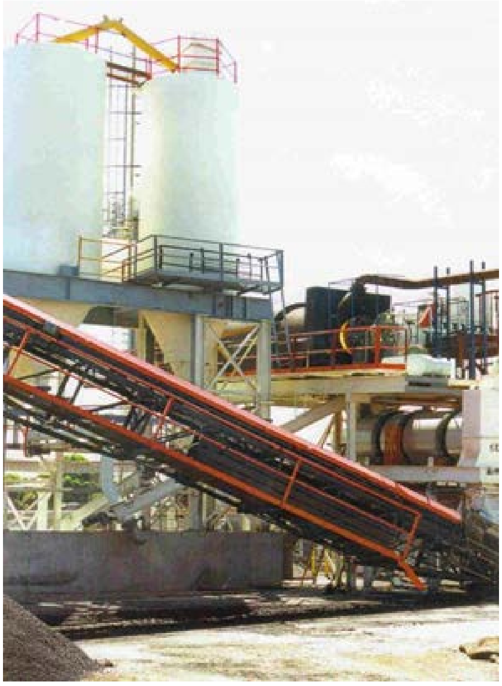


**Figure 5.10: Tandem drum mixer at an asphalt plant**



### 5.5.6 Cold Mixing Plant

***General***
This type of plant is used for cold mix and stabilising operations where no heating and drying of aggregates is involved. Such plants are generally transportable for use in temporary locations.

***Component proportioning***
Aggregates are proportioned by means of calibrated feed gates.

Positive interlock between the controls for binder, aggregate, mineral filler and any other additive feeders is essential for a uniform mix. The positive interlock ensures that components are supplied in constant proportions, even if the total output varies.

Binder proportioning is achieved by use of constant displacement pumps that are interlocked to the aggregate feed system. Since the proportioning is by volume, the temperature of the binder must be controlled within close limits to maintain correct proportions. The binder is sprayed onto the stream of aggregate as it enters the pugmill.

***Mixing chamber***
The pugmill in a continuous plant is similar to that in a batch plant, except that it is usually longer and narrower. To move the mix forward most of the paddles are sloped in one direction, except the last few are usually reversed to prevent the mix from being discharged too rapidly.

The mix is discharged over a level-control gate at one end of the pugmill. Mixing time is controlled by this gate which, when raised or lowered, increases or decreases the amount of material in the pugmill and consequently the time taken for the mix to pass through. The height of material should not be above the paddle tips, except for the last set of paddles.

Mixing efficiency may be improved by raising the gate to provide a longer mixing time, or by reversing the slope of some of the paddles.

Actual mixing time should be sufficient to provide thorough mixing and full coating of the aggregate particles with binder. Mixing time can be determined by dividing the pugmill capacity by the output rate. It should be not less than 30 seconds.

## 5.6 Warm Mix Asphalt

A range of warm mix asphalt technologies can be applied to the manufacture of warm mix asphalt. In general terms they may be considered in four major categories:

- additives blended with the binder before addition to the mixer
- additives added direct to mixer at the same time as addition of binder
- binder foaming using water-based mechanical systems
- sequential aggregate coating and binder foaming techniques.

Additive-based warm mix asphalt technologies require no modifications to asphalt mixing plant other than facilities for handling, dosing and blending of additives.

Binder foaming using mechanical-based systems requires appropriate modifications to the asphalt mixing plant for foaming of binder at the point of addition to the mixer. Although generally used in conjunction with continuous mixing plants, they can also be incorporated in a batch mixing process, including retro-fitting to existing plants.

The sequential aggregate coating and binder foaming technology requires a specific configuration of asphalt mixing plant.

## 5.7 Asphalt Surge and Storage Bins

Surge bins (Figure 5.11) are used for the temporary retention of asphalt (generally from a few minutes to a few hours).

The advantages of surge bins are:

- the plant can be operated more economically by producing at a continuous steady rate
- fluctuations in demand can be evened out and overall production increased
- truck loading is much faster, so there is less waiting time
- quantities of asphalt can be stored for delivery outside normal plant operating hours.

Surge bins can be of any capacity from 10 to 400 tonnes. The bins are usually insulated and do not require heating, except in the vicinity of the discharge gate.

Storage bins are used for holding asphalt for longer periods, which under controlled conditions may be up to 48 hours, but generally not more than 24 hours. Bins for extended storage usually require heating as well as insulation.

The allowable storage time in heated storage bins depends on mix type and binder type. Generally, mixes containing PMB binders, or high binder contents susceptible to binder drain-off (i.e. OGA and SMA) should not be stored for extended periods.

Surge and storage bins are a potential source of segregation in asphalt. Particular points requiring care include the charging of bins using batching devices or rotating chutes, the dimensions and operating range of asphalt within the bin, and operation of discharge gates when loading delivery trucks. Bins must be designed and operated correctly to minimise or avoid segregation.

**Figure 5.11: Asphalt surge bins**

## 5.8 Cold Mix

Cold asphalt mixes, commonly referred to as cold mix or premix, are produced in a similar manner to hot mixed asphalt except that they may be manufactured at ambient temperature or no more than about 100 °C.

Cold mixes are generally intended to remain workable at ambient temperatures and may be designed and manufactured for either immediate use, stockpiling for up to several months, or packaged in bags or pails.

Cold mixes may also be produced with bitumen emulsion binders, in which case no heating is necessary. Stockpile mixtures are made with a slow setting cationic emulsion containing an oil distillate to improve storage life and maintain workability when stockpiled.

## 5.9 Cold Recycling of Asphalt and Bituminous Stabilisation

Cold recycling is a process in which the RAP is mixed with a rejuvenating agent or binder to produce an asphalt mixture placed cold but with properties approaching that of hot mix asphalt after a suitable period of curing. The binder can be bitumen emulsion or foamed bitumen. Cold recycled asphalt mixtures may also incorporate added filler or other additives to adjust grading or assist in curing (Austroads 2009b) (see Section 4.7.2 of the current Guide).

Cold asphalt recycled mixtures are generally produced as plant mixed materials although it is also feasible to undertake in situ recycling by milling and adding a rejuvenating/stabilising agent.

Bituminous stabilising of unbound granular materials may also be undertaken using in situ recycling or plant mixed materials. A guide to bituminous stabilised materials and in situ recycling is provided in Austroads (2006) and Austroads (2009c).

Mixing plants for plant mixing of cold recycled and bituminous stabilised materials are generally continuous mixing plants of the type described in Section 5.5.6.

## 5.10 Routine Inspections

Routine inspection should be carried out to check materials and ensure that all components of the plant are being operated correctly, efficiently and in balance with each other. The checklists shown in Table 7.1 and Table 7.2 may be used as a guide for the purpose.

# 6. Asphalt Paving

## 6.1 General

Good organisation is required to ensure efficiency and smoothness of asphalt paving work. Equipment must be suitable to the task and personnel trained and skilled to achieve the required standards of workmanship. Surfaces must be adequately prepared. Transport, spreading and compaction must be completed while materials are sufficiently hot to achieve the required standards of density and surface finish. Greater detail is provided in the *Guide to Pavement Technology Part 8: Pavement Construction* (Austroads 2009c).

## 6.2 Planning

Preliminary planning activities for an asphalt job should include:

- site inspection to assess the site conditions and the basic requirements of the job
- arrangement of contracts for supply of asphalt, where appropriate
- arrangement of paving trials, if appropriate
- planning of traffic control arrangements
- advertising and advance warning to occupiers of adjoining properties, if necessary
- issuing of instructions to supervisory personnel
- assessment of plant requirements
- assessment of field organisation required.

The site should be inspected well in advance of the proposed start date for the work to confirm:

- the appropriate treatment
  - type(s) of mix
  - nominal size(s) of mix
  - compacted thickness of layer(s)
- any remedial treatment required to restore the pavement to a condition suitable for the asphalt treatment
- cold milling requirements
- the manner of executing the work
- staging of work
- the traffic control requirements for the work
- the need for public utility adjustments and treatment adjacent to the utility
- tie-in to existing work.

Detailed site planning should include:

- a site risk assessment
- correct position of longitudinal joints
- planning of optimum length of each run and minimisation of transverse joints
- method of level control
- optimum use of labour, equipment and delivery trucks
- adoption of good practices in all aspects of work
- sketches and/or plans of the work, if appropriate.

## 6.3 Surface Preparation

### 6.3.1 Cleaning

Before the asphalt is placed, the existing surface should be dry, and thoroughly swept to remove any loose stones, dirt and foreign matter. Sweeping should be carried out with a rotary road broom or suction cleaner. It should extend at least 300 mm beyond each side of the area to be paved.

Any foreign matter adhering to the pavement and not swept off by broom should be removed by other means. Any areas affected by minor oil contamination should be cleaned by an appropriate method. Any area significantly affected by oil, and which has softened to an appreciable degree or has ravelled, should be removed and reinstated with asphalt.

### 6.3.2 Correction of Defects

Prior to commencement of the paving operation, any defects should be corrected, as follows:

- filling of potholes and depressions with asphalt or approved patching material; cold-mix containing flux oil should not be used as it may lead to bleeding or flushing
- removal of excess binder from fatty patches
- crack filling; caution should be exercised as some crack filling products may contain cutting oils leading to bleeding or flushing
- repair of edge breaks
- cleaning and repairing of any joints
- removal and replacement of unstable materials
- removal and replacement of cold-mix patches
- shape correction.

Where the surface is badly out of shape, a correction (regulating) course of asphalt should be applied first. This will reduce the effects of differential compaction of subsequent layers and enable the best possible riding quality to be achieved. Alternatively, cold milling may be used to correct surface shape, as well as remove any unsuitable or unstable materials.

A guide to pavement rehabilitation is provided in the *Guide to Pavement Technology Part 5: Pavement Evaluation and Treatment Design* (Austroads 2011). Further information on routine maintenance of asphalt pavements is also included in *Guide to Pavement Technology Part 7: Pavement Maintenance* (Austroads 2009d).

### 6.3.3 Tack Coating

A tack coat is a light application of bituminous binder that provides a bond between the existing surface and the new asphalt layer.

Generally, rapid setting cationic bitumen emulsion is used for tack coating although medium setting grades and anionic emulsions may be used in dry conditions.

## 6.4 Transport

Asphalt should be transported in such a way as to minimise the loss of heat, segregation of the mix or contamination by foreign matter.

The mix should be delivered at a uniform rate, within the capacity of the spreading and compacting equipment, to enable a continuous paving process. To reduce the cooling of the mix, deliveries should be made by the shortest practical route, and waiting time and delays on site should be minimised.

## 6.5 Spreading

### 6.5.1 General

Asphalt should be spread and compacted uniformly in order to:

- limit segregation
- produce a homogeneous product
- achieve a density that delivers the intended design performance of the asphalt
- provide the specified thickness of asphalt
- achieve the specified riding quality.

Spreading may be carried out by self-propelled paver, grader or hand methods. Wherever possible, self-propelled pavers should be used as they provide greater control during spreading and will deliver a superior surface finish. Paver operations are generally quicker and more economical.

### 6.5.2 Material Transfer Vehicle

The use of a material transfer vehicle (MTV) (Figure 6.1) assists in uniform transfer of asphalt into the asphalt paver by reducing segregation, and variations in temperature and rate of flow of asphalt to the asphalt paver.

**Figure 6.1: Material transfer vehicle**

### 6.5.3 Spreading by Asphalt Paver

Pavers used for spreading of asphalt operate on a ‘floating screed’ principle (Figure 6.2). During paving, the screed is supported by the asphalt being spread. This also provides partial compaction of the asphalt. The thickness of the asphalt layer is determined by the height of the towing arm and angle of attack of the screed. Changes to thickness are achieved by changing the height of the tow point and/or changing the angle of the screed relative to the tow arm. Changing the angle of attack of the screed produces a gradual change in asphalt thickness until a new equilibrium state is achieved.

Adjustments to the tow point and screed angle (Figure 6.3) may be made manually, or controlled automatically by sensors referenced to an adjoining paved surface, levelling (or averaging) beam attached to the paver, fixed reference line or by computer-programmed level data.

Minor changes to the finished level will also be introduced by changes in the head of the material in front of the screed, changes in paver forward speed, and changes in asphalt stiffness due to changes in mix temperature. Smooth, continuous operation is therefore an important factor in achieving high standards of ride quality. The rate of delivery of the asphalt should be arranged so that the paver can operate at a uniform speed. Paving should not commence until sufficient asphalt is on site to ensure continuous operation.

**Figure 6.2 Asphalt paver**

### 6.5.4 Joints

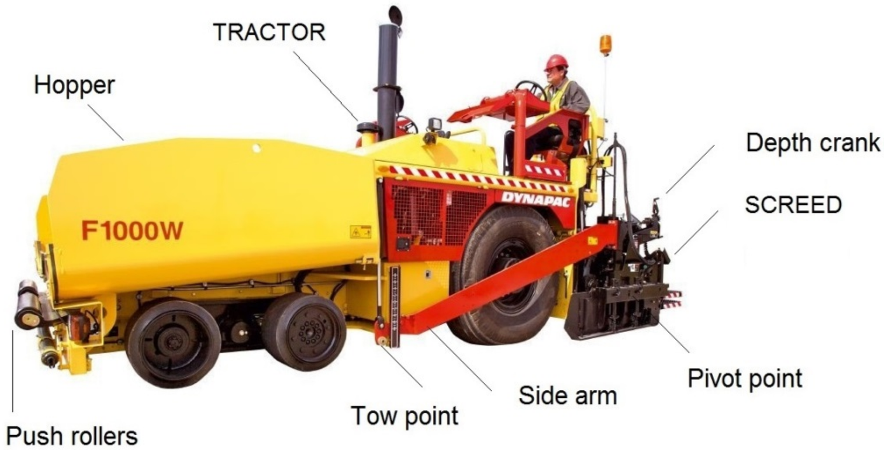
Construction joints in an asphalt layer are planes of weakness and imperfection that can be the first locations to deteriorate. Generally, this is due to initial separation of the joint, the ingress of water, and cracking and ravelling.

Joints that are more permeable than the rest of the asphalt mat can lead to the ingress of moisture into the pavement during periods of wet weather.

The number and extent of joints in asphalt layers should be kept to a minimum and the paving pattern should be designed accordingly in advance of the work. Generally, longitudinal joints should be placed away from wheel paths and all joints should be offset between layers.

Correct jointing technique will ensure that the two mats are joined in such a way as to minimise differences in density, texture, shape and level and also minimise the extent of joints.

**Figure 6.3: Asphalt paver components**



## 6.6 Compaction

### 6.6.1 General

During the paving operation, compaction is a two-stage process, as follows:

- primary compaction by the paver screed
- secondary compaction by rollers.

Adequate compaction of asphalt is essential to ensure that the design performance of the mix and expected service life are achieved. The compaction should be uniform and achieve a high density.

The main factors influencing the successful compaction of asphalt are:

- Type and numbers of rollers or other compaction equipment – requirements vary with rate of spreading, layer thickness, rate of cooling and workability of asphalt mix.
- Rolling procedures and techniques – rolling sequence, rolling speed and number of passes.
- Temperature of the mix – compaction must be completed while asphalt remains workable. Asphalt will cool more rapidly in thin layers and cool ambient conditions. Lower placing and compaction temperatures may apply when using warm mix asphalt technologies.
- Mix properties – workability is a function of internal friction of mix and binder stiffness. Binder stiffness is a function of binder type grade and, where applicable, the use of warm mix asphalt technologies is an aid to workability.
- Soundness and stiffness of the underlying base – must adequately support compaction equipment without distortion of the asphalt layer.

### 6.6.2 Compaction Equipment

The compaction equipment for asphalt work includes:

- vibratory steel-wheeled rollers – most commonly used for initial rolling and basic compaction
- pneumatic-tyred rollers – used for secondary compaction and sealing of the surface
- impact compactors such as vibratory plates, hand tampers, etc. – generally only used for areas inaccessible to rollers, and minor works.

## 6.7 Finished Surface Properties

Finished surface properties of asphalt include:

- placing to desired layer thickness and/or finished surface levels
- placing to required longitudinal and transverse shape
- smooth longitudinal profile for good riding quality
- compaction to uniform high standards of density.

Tolerances on thickness, level and shape, minimum standards of ride quality (if relevant) and minimum standards of compacted density are generally included in relevant specifications.

# 7. Quality of Asphalt

## 7.1 General

Quality requirements for the production and placing of asphalt require the application of a quality management system (QMS). Contract specifications typically require the contractor to implement a QMS complying with AS/NZS ISO 9000.

AS/NZS ISO 9000 describes fundamentals of quality management systems. Essential elements of a quality system include quality assurance (QA) and quality control (QC). Quality assurance is defined in the *Austroads glossary of terms* (Austroads 2010) as 'the systematic action necessary to give confidence of satisfactory quality'. Quality control is defined as 'those tests necessary to determine the control of the quality of the product being produced'.

Inspection and test requirements for quality assurance purposes are generally included in contract specifications. In most road construction contracts, quality control is considered the responsibility of the contractor within an overall quality assurance context.

A general guide to the application of quality systems in road construction is provided in Austroads (2009c).

Control of asphalt quality involves control of inputs, operating/production processes and product testing. While a contractor's quality system will incorporate that testing done for assurance inspection purposes, a contractor undertaking the manufacture and placing of asphalt should not rely solely on those tests as measures of process quality control.

Elements of process quality control include:

- testing of raw materials
- control and monitoring of the production process
- testing of manufactured product
- control and monitoring of asphalt placing
- testing of finished properties of asphalt.

Procedures for testing of raw materials, control and monitoring of asphalt manufacture and testing of manufactured product are outlined below.

Procedures for the control and monitoring of asphalt paving properties are described in Austroads (2009c).

Testing of finished properties of asphalt can include:

- compacted density
- surface shape and level
- ride quality
- permeability
- surface texture.

Testing of finished properties of asphalt are also outlined in Austroads (2009c).

In addition to assurance inspection undertaken by the contractor, a supervising authority may also undertake surveillance and auditing of a contractor's procedures and analysis of records to ensure that quality requirements are being met.

Auditing is defined in AS/NZS ISO 9000 as a systematic, independent and documented process for obtaining records and other information and evaluating it objectively to determine the extent to which the policies, procedures and/or requirements are fulfilled.

Audits may take the form of quality system audits, quality audits, product quality audits, or technical procedure audits and may be undertaken by an auditing team from within or outside the organisation being audited.

Surveillance is the continuing evaluation of the status of procedures, methods, conditions, products, processes and services, and analysis of records to ensure that the quality requirements are being met. Surveillance is normally undertaken by officers appointed by the principal or supervising authority to observe and monitor a particular contract performance.

Surveillance of contract activities may also include separate or parallel sampling and testing by the principal or independent testing agency.

## 7.2 Control and Monitoring of Asphalt Manufacture

### 7.2.1 Tests on Raw Materials

These tests should be carried out on a routine basis. The frequency of sampling and testing will depend on the nature of the production operation. For a job using a portable plant in a remote location, the checking of raw materials may need to be more frequent than an established plant using raw materials from known sources or with a process known to be under control.

***Aggregate supply***

The grading and moisture content of each aggregate should be checked frequently. Monitoring of moisture content of aggregates is particularly important in continuous mix plants to maintain correct proportions of aggregates and binder.

Properties such as abrasion resistance, soundness, particle shape, etc., should be checked against the specification requirements at a frequency great enough to ensure compliance.

***Mineral filler***

If testing is carried out at the point of production and a certificate of compliance with the specification is supplied, then occasional checks on dry compacted voids and moisture content may be all that is necessary.

Recovered baghouse filler should also be checked periodically.

***Binder***

Tests are generally performed by the supplier to ensure conformance with the specification. Spot checks may be necessary to ensure that binders conform to specified requirements and have not deteriorated or been contaminated in transport and storage.

### 7.2.2 Production Process

***Cold aggregate feeders***

Aggregate feeders should be calibrated and maintained regularly to ensure accurate feed rates. The rate of feed of the various cold aggregates should be checked and adjusted as necessary to ensure the right proportions are maintained. Feed stoppages or variability must be avoided and a watch kept on fine aggregates for 'arching' or 'funnelling' in bins.

All belt systems should be fitted with a 'no flow' alarm.

***Cold aggregate feeder weighing devices***
These should be regularly calibrated and checked for faults or interference. These devices are often very sensitive and should be treated accordingly.

***Drum/dryer mixer***
The condition of drum flights should be checked regularly as part of plant maintenance along with the functioning of the burner. Check the temperature and moisture content of aggregates/mix after drying/mixing.

***Screens and hot bins***
Check screens for wear, pegging of screens or irregular carryover. Hot bin level indicators should be cleaned and adjusted as necessary. Hot bin sample gradings performed on a regular basis will indicate problems with the screens.

***Batch weighing hoppers***
Periodically, test weights should be applied to the weigh hoppers to ensure accuracy.

***Batching and mixing***
Regular checks should be performed to cover the weighing or measuring, mixing times, efficiency of the mixing, and temperature of the mix.

In addition to controlling and testing of production, visual checks should be made to pick up any problems such as unevenly mixed materials, high temperature, moisture, insufficient or excessive binder content, etc.

Items to be observed in visual inspection include:

- unevenly mixed or poorly coated particles
- condition of tips and paddles
- evidence of incomplete dispersion of fibres or granular additives
- evidence of excessive moisture seen as a dull brown appearance, slumping and a distinct 'crackling' sound
- evidence of overheating seen as blue smoke or fuming from the asphalt mix
- evidence of inadequate temperature seen as a stiff appearance of the mix
- evidence of excessive binder – rich or glossy appearance (more than usual)
- evidence of too little binder – mix with lean, granular appearance, tending to dull brown colour
- evidence of excess coarse or excess fine aggregate
- segregation from storage bins or loading
- contamination.

### 7.2.3 Sampling and Testing
Asphalt should be sampled in accordance with AS 2891.1.1 and at the minimum frequency required by contract specifications or the supplier's quality plan.

Representative sampling is important as test results from a poor sample will not be a good indicator of the properties of the mix being produced.

Compliance with the job mix is generally assessed in terms of grading and binder content. Samples taken from production may also be compacted to monitor and verify volumetric and performance properties of the manufactured product.

Testing for grading and binder content may be determined using solvent extraction (AS/NZS 2891.3.1, AS/NZS 2891.3.2 or AS/NZS 2891.3.3) or ignition oven (Austroads AGPT/T234). Grading analysis is then performed on the remaining aggregates (AS 1141.11).

Maximum density of a loose sample of manufactured asphalt (AS 2891.7.1) is determined as a reference density for compaction control, as an aid to process control or to determine the volumetric properties. When used as an aid to process control, it is a relatively simple test that provides an indicator of variation in binder content through a change in density of the mixture, thus reducing the need for full analysis of the mixture and allowing a reduction in the frequency of full analysis.

All tests should be conducted by experienced testing officers in a laboratory accredited by the National Association of Testing Authorities (NATA) for the appropriate test methods and endorsed in accordance with the NATA registration for that laboratory. Laboratories for the testing of asphalt production should be located on or near the site of the manufacturing plant.

#### 7.2.4 Statistical Process Control

A valuable tool in monitoring of production process is statistical process control. Statistical monitoring can be used as an aid to:

- ensuring that the asphalt meets the specified mix properties
- ensuring the uniformity of the mix
- detecting at an early stage any real variations in the process or the product and allowing adequate corrective measures to be taken to minimise potential non-compliance of the end product
- identifying and monitoring periods of consistent production that can be used as a basis for continuous improvement of the process.

Guides to statistical process control systems are provided in *Asphalt Plant Process Control Guide* (AAPA 1997) and AAPA Pavement Work Tip No. 15 *Asphalt Statistical Process Control.*

A typical statistical process control system utilises control charts and action guidelines for interpretation of data.

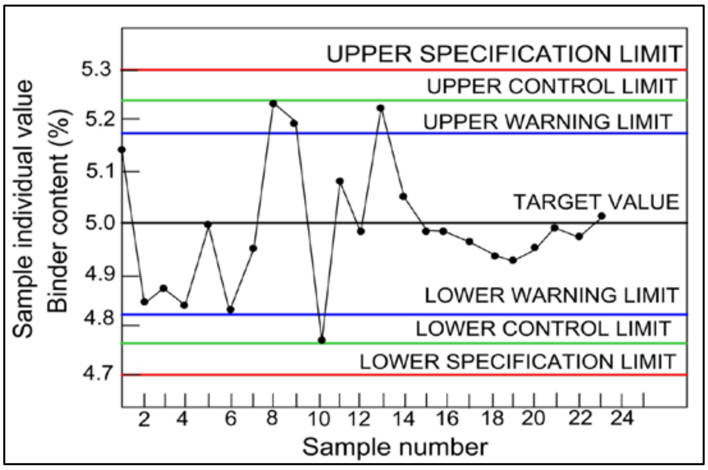
Control charts are graphical plots that highlight the average performance of data series and the variation around this average, of each process that is required to be monitored.

Control charts are developed from a series of samples taken from the manufacturing process. As samples can never be more than a spot check, the value of control charts lies in the ability to analyse the results of a number of samples over a period of time.

This enables relatively small changes in production that occur with time to be monitored and a cumulative impression of the effective control or otherwise of the process to be gained.

The simplest form of control chart provides a plot of the results of individual samples as shown in Figure 7.1.

**Figure 7.1: A typical control chart**




This example shows upper and lower 'control limits' (also termed 'action limits') and 'warning limits'. Results outside the control limits require immediate action to prevent the process moving out of specification while warning limits give a statistical indication that something significant may have changed in the process that may be beginning to become unstable.

Values obtained outside the warning limits may require action in the form of an increased frequency of sampling to determine if the fluctuations observed are random events or not.

It should be noted that the warning limits and control (or action) limits are determined from the statistical variation of the process being monitored and not the specified production tolerances although specification or tolerance limits are usually plotted on charts to monitor compliance. However, if the process is to be capable of consistently achieving the required tolerances, the control limits should not exceed the appropriate specification tolerances.

Other types of charts include a moving range showing the simple difference between two consecutive results or the moving (or rolling) average of a number (e.g. 2 or 5) of consecutive results. Charts may also be used to plot the average of groups of results and the range or standard deviation of results in those groups. Typically, this type of chart is usually applied to the results of in situ compaction testing.

Monitoring of asphalt production processes typically includes tests for grading (one sieve below the nominal mix size, the 2.36 mm and the 0.075 mm sieves), binder content and maximum density.

Investigation and correction of assignable causes should be taken when either of the following occurs:

- one point lies outside the control limits
- two out of three points lie outside the warning limits.

Investigation of possible assignable causes, and the need for corrective action, should be undertaken if:

- nine consecutive points are above or below the target
- six consecutive points are steadily increasing or decreasing
- two out of three points lie outside the warning limits.

## 7.3 Checklists

Checklists for routine inspection of both batch and continuous drum mixing plants are provided in Table 7.1 and Table 7.2 respectively.

**Table 7.1: Routine inspections for batch mix plants**

| Process | Checklist |
|---|---|
| Cold feed | ▪ Stockpile construction, separation, labelling and handling<br>▪ Source of aggregate<br>▪ Stockpile contamination<br>▪ Aggregate gradation and moisture content<br>▪ Aggregate levels in bins<br>▪ Calibration and setting of cold feeders<br>▪ Rate of feed in relation to the rest of the plant |
| Dryer and dust collector | ▪ Accuracy of temperature measuring device<br>▪ Efficiency of the dust collection system and either the disposing of collected fines or feeding uniformly into the mix at the predetermined rate<br>▪ Temperature of aggregate |
| Screens and hot bins | ▪ Screen capacities in relation to the rest of the plant<br>▪ Pegged or clogged screens<br>▪ Damage (including holes) and degree of wear of the screens<br>▪ Excessive or irregular carryover<br>▪ Operation of overflow vent<br>▪ Bin levels<br>▪ Sampling point<br>▪ Temperature of aggregate<br>▪ Moisture content of aggregate |
| Binder heating, circulation and storage | ▪ Quality of binder<br>▪ Quantity of binder in storage<br>▪ Temperature of binder<br>▪ Sampling point<br>▪ Leakage in lines and at pump flanges<br>▪ Circulation system (including continuous stirring within the tank only for modified binder) |
| Proportioning and mixing | ▪ Maintenance, calibration, accuracy and sensitivity of scales<br>▪ Tare mass of binder bucket<br>▪ Temperature of aggregates and binder<br>▪ Proportioning of materials<br>▪ Binder cut-off valve<br>▪ Leakage from binder bucket or aggregate weigh hopper<br>▪ Batching sequence and size<br>▪ Introduction of filler<br>▪ Aggregate distribution in the mixer<br>▪ Uniformity of distribution of binder into the mixer<br>▪ Dry mixing time<br>▪ Wet mixing time<br>▪ Pugmill condition and operation, including paddle tips and dead spots<br>▪ Appearance of the mix<br>▪ Confirmation of grading and other target properties of the asphalt |

**Table 7.2: Routine inspections for continuous plants**

| Process | Checklist |
|---|---|
| Cold feed | ▪ Stockpile construction, separation, labelling and handling<br>▪ Source of aggregate<br>▪ Stockpile contamination<br>▪ Aggregate gradation and moisture content<br>▪ Aggregate levels in bins<br>▪ Calibration and setting of cold feeders<br>▪ Rate of feed in relation to the rest of the plant |
| Dryer and dust collector | ▪ Accuracy of temperature measuring device<br>▪ Efficiency of the dust collection system and either the disposing of collected fines, or whether they are being fed uniformly into the mix at the predetermined rate |
| Binder heating, circulation and storage | ▪ Quality of binder<br>▪ Quantity of binder in storage<br>▪ Temperature of binder<br>▪ Sampling point<br>▪ Leakage in lines and at pump flanges<br>▪ Circulation system (including continuous stirring within the tank only for modified binder) |
| Proportioning and mixing | ▪ Calibration and setting of aggregate and mineral filler feeders<br>▪ Calibration and setting of binder pump<br>▪ Temperatures of aggregate and binder<br>▪ Interlock of aggregate and binder feeders<br>▪ Temperature of produced mix<br>▪ Appearance of mix<br>▪ Confirmation of grading and other target properties of the asphalt |

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36. *Sprayed seals: pre-spraying to correct surface texture*, 2003.
37. *Cape seals*, 2003.
38. *Sprayed sealing: surface enrichment*, 2003.
39. *Dust laying with bitumen emulsion*, 2003.
40. *Sprayed sealing: volume temperature correction*, 2004.
41. *Coring of asphalt pavements*, 2004.
42. *Nuclear density testing of asphalt pavements*, 2004.
43. *Primersealing of pavements*, 2010.
44. *High pressure water retexturing*, 2004.

45. *Skin patching*, 2006.

46. *Asphalt cooling rates*, 2006.

47. *Sprayed sealing of drought & salt-affected pavements*, 2008.

48. *Treatment of flushed seals using chemical solvents*, 2010.

49. *Preparation of pavements for priming and primersealing*, 2013.

# Appendix A Testing of Components

## A.1 Introduction

Guidelines for the application and conduct of the test procedures described in this and the following appendices are for information only. They may be used to assist in understanding test procedures but should always be read in conjunction with the relevant current Australian Standards or Austroads Test Methods as such test methods undergo review from time to time.

## A.2 Aggregates

The suitability of aggregates for use in asphalt mixes is evaluated by a series of tests which are described in Australian Standard AS 1141.0, *Methods for sampling and testing aggregates: list of methods*. Typical limits for the range of tests are given in road authority specifications and in Australian Standard AS 2758.5, *Aggregates and rock for engineering purposes: coarse asphalt aggregates.*

The grading of aggregate particles is determined from a dry sieving method (Figure A 1), as described in AS 1141.11.1, *Methods for sampling and testing aggregates: particle size distribution: sieving method*. Wet sieving is preferable if the aggregate has a significant percentage of clay or silt fines.

**Figure A 1: Equipment used to determine grading and plasticity index of fines**

The test most commonly used to evaluate particle shape is the flakiness index test (AS 1141.15). The index is defined as the percentage by mass of particles, the least dimension of which is less than 60% of the mean dimension. The misshapen particles test is considered an alternative to the flakiness index test. Another aspect of particle shape is the measurement of the number of crushed faces, i.e. fresh faces which have been produced by the action of the crusher operation. The greater the proportion of crushed faces on an aggregate particle, the more angular it will be.

There is no test available to estimate surface texture prior to construction, although there are a number of tests to evaluate the loss of texture due to the polishing of the aggregate under traffic. These tests include:

- polished stone value (PSV) (EN 1097-8)
- polished aggregate friction value (PAFV) using the vertical road-wheel machine (AS 1141.40)
- polished aggregate friction value (PAFV) using the horizontal bed machine (AS 1141.41)
- pendulum friction test (AS 1141.42).

The PAFV procedure of preparing polished aggregate samples using either a vertical or horizontal bed polishing machine was developed in Australia as an alternative to the British PSV test (now EN 1097-8) although the results may not be directly comparable. All three laboratory polishing methods determine the friction value of the polished aggregate specimen using the pendulum friction test.

The pendulum tester measures the loss of energy when a rubber slider, mounted on the end of a pendulum, is propelled across the surface of a polished aggregate specimen. The pendulum is released from the horizontal and the energy absorbed is indicated by the highest position reached on the upswing. The test is repeated five times and the polished aggregate friction value (PAFV) number is the mean of the last three swings.

The pendulum tester may also be used for testing of pavement surfaces (Figure A 2).

**Figure A 2: Pendulum friction test**

The hardness or abrasion resistance of an aggregate is most commonly determined using the Los Angeles abrasion test (AS 1141.23). The abrasion value is the mass of material passing the 1.7 mm sieve, as a percentage by mass of the original test sample, produced when a ‘single-size’ aggregate sample is subjected to 500 rotations in a standard ball mill.

The strengths can also be evaluated by the aggregate crushing value test (AS 1141.21) or a modification of that test known as the wet-dry strength variation test (AS 1141.22). The aggregate crushing value is determined by placing a sample of aggregate passing the 13.2 mm sieve and retained on the 9.5 mm sieve in a cylinder fitted with a plunger. The plunger is loaded at a uniform rate of 40 kN per minute up to a maximum load of 400 kN. The aggregate crushing value is the percentage by mass of the sample which passes the 2.36 mm sieve after application of the load.

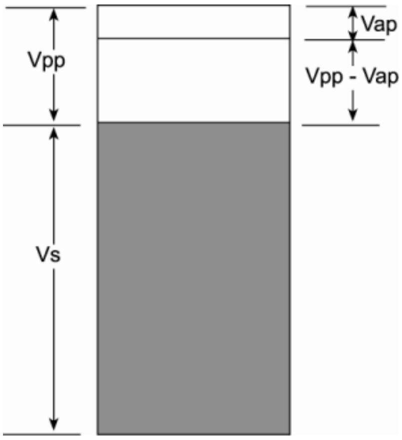
The wet-dry strength determines the variation in strength for aggregate tested under oven dried and saturated surface dry only conditions. The wet-dry strength is defined as the force required to produce 10% of the sample passing the 2.36 mm sieve.

The durability of an aggregate can be evaluated using the unsound particles (AS 1141.30.1) or friable particles (AS 1141.32) test. The unsound particles (i.e. clay lumps, weak particles) are those which when wet will deform under finger pressure. These particles are removed and the loss of such particles is reported as a percentage by mass of the original test portion. The test portion is the aggregate fraction which is retained on the 4.75 mm sieve.

Particle density and water absorption of coarse and fine aggregates are determined in accordance with procedures described in AS 1141.6.1 and AS 1141.5, respectively. In some cases tests are carried out to determine the bitumen absorption characteristics of aggregates. The test, however, is a difficult one to execute and the water absorption value is generally used to specify absorption limits.

There are three different aggregate particle densities used in designing asphalt mixes (Figure A 3) apparent particle density, bulk particle and effective bulk density.

**Figure A 3: Relationship between different aggregate particle densities**




In Equations A1 to A3 following, the variables are defined as follows:

$W_S$ = oven dry mass of aggregate

$\rho_W$ = density of water

$V_S$ = volume of solids

$V_{pp}$ = volume of permeable pores

$V_{ap}$ = volume of pores absorbing bitumen

$V_{pp} - V_{ap}$ = volume of water permeable pores not absorbing bitumen

**Apparent particle density** includes only the volume of the aggregate particle; it does not include the volume of any pores or capillaries which become filled with water after 24 hours of soaking, but does include internal pores which are impermeable to water. Therefore, where these voids occur, reducing the size of the aggregate particle by crushing exposes these voids and thus increases the apparent particle density.

$$\text{Apparent particle density} = \frac{W_S}{V_S * \rho_W} \qquad \text{A1}$$

**Bulk particle density** includes the overall volume of the aggregate particle including the volume of the water permeable and impermeable pores.

$$\text{Bulk particle density} = \frac{W_S}{(V_S + V_{pp}) * \rho_W} \qquad \text{A2}$$

**Effective bulk density** includes the overall volume of the aggregate including the volume of water permeable pores but excluding the volume of the larger pores which absorb asphalt.

$$\text{Effective bulk density} = \frac{W_S}{(V_S + V_{pp} - V_{ap}) * \rho_W} \qquad \text{A3}$$

The moisture sensitivity of an asphalt is best evaluated from testing on compacted samples of the mix using a variation of the modified Lottman test (AGPT/T232).

The rigorous evaluation of the durability of an aggregate or its source material for a particular application can only be made through observation of the performance of that aggregate in a pavement subject to the same loading and environmental conditions as would occur in the proposed application. However, rarely, if ever, would there be a perfect coincidence of loading and environmental conditions for any two pavements. Therefore, various authorities in Australia have adopted and developed test methods or sets of test methods for the assessment of the durability of aggregates. The specified limits for these are based upon comparisons between the observed durability of aggregates in-service and the results of their assessment procedures.

Each of these procedures has been shown to be valid for a limited range of rock sources located primarily within the areas of control of the authority which uses a particular procedure. If aggregate is to be supplied from a source for which no experience is available with any of these assessment methods, the works specification should include the assessment procedure considered most appropriate for that source.

The tests available for the assessment of durability include:

- sodium sulphate soundness test (AS 1141.24)
- degradation factor (AS 1141.25.1, AS 1141.25.2 and AS 1141.25.3)
- wet/dry strength variation test (AS 1141.22)
- secondary minerals content in basic igneous rocks (AS 1141.26).

In the soundness test, the aggregate is subjected to alternate wetting, by immersion in a solution of sodium sulphate in water, and drying. This process causes the growth of sulphate crystals in the pores of the aggregate particle which is intended to reproduce the disruptive forces caused by freezing water. Since few areas in Australia experience temperatures sufficiently low to freeze wet aggregate, the test is probably over-severe relative to field performance, but probably distinguishes between good and poor performance in a relatively short period.

The degradation test has been designed for use with spalls or drill core, although modified versions are available which test coarse or fine aggregate samples. The test sample is subjected to self-abrasion, in a shaker in the presence of water, and the fines (i.e. finer than 75 μm) produced are dispersed in a standard clay flocculating solution. The suspension is allowed to stand in a sand equivalent cylinder filled to the 380 mL mark for 20 minutes after which the height of flocculate (H mm) is measured. The degradation factor is given by the expression in Equation A4:

$$\frac{380 - H}{380 + 1.75 * H} * 100 \qquad \text{A4}$$

In the wet/dry strength variation test, the forces required to produce 10% fines for an aggregate in dry and saturated surface-dry conditions are measured. The variation is the decrease in force required to produce 10% fines for wet aggregate expressed as a percentage of the force required for dry aggregate.

The secondary mineral content determination involves petrological examination of a thin section of rock and the use of a point counting procedure of the identified secondary minerals.

## A.3 Fillers

The tests to assess fillers for use in asphalt mixes are usually specified in road authority specifications. Typical filler requirements are also included in AS 2150.

The percentage by mass passing the 75 μm sieve is determined by dry sieving in accordance with Australian Standard AS 1141.0, *Methods for sampling and testing aggregates: list of methods*. The grading of the filler could be determined by hydrometer analysis but, more commonly, the procedure of determining the ‘surface’ area by measuring the air permeability of the compacted filler is used.

The packing behaviour of the filler particles, which determines the porosity or air voids of the compacted filler is determined in accordance with AS 1141.17 (Figure A 4).

The water soluble fraction is determined in accordance with AS 1141.8, while the active lime content is determined using AS 4489.6.1.

Moisture content of all fillers and the plasticity index of crusher dust or ground limestone are determined in accordance with AS 1289, *Testing soils for engineering purposes*.

**Figure A 4: Rigden device used in AS 1141.17 to assess packing behaviour of fillers**

## A.4 Binders

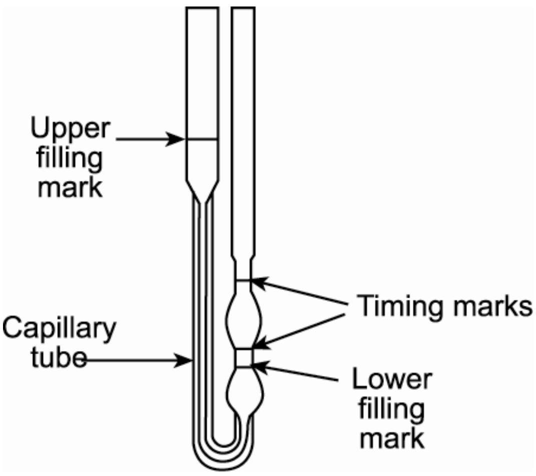
### A.4.1 Bitumen

In Australia, bitumens are classified on the basis of the mid-point of their viscosity range at 60 °C measured in Pascal seconds (Pa.s) as shown in increasing order of stiffness:

- Class 170 140 to 200 Pa.s (pre-RTFO treatment)
- Class 240 190 to 280 Pa.s (pre-RTFO treatment)
- Class 320 280 to 360 Pa.s (pre-RTFO treatment)
- Class 450 750 to 1150 Pa.s (post-RTFO treatment)
- Class 600 500 to 700 Pa.s (pre-RTFO treatment).

In general, the heavier the loading that the asphalt mix is to be subjected to, the stiffer, or more viscous the bitumen should be in the mix. A schematic of a viscometer is shown in Figure A 5.

**Figure A 5: Viscometer used to classify bitumens**



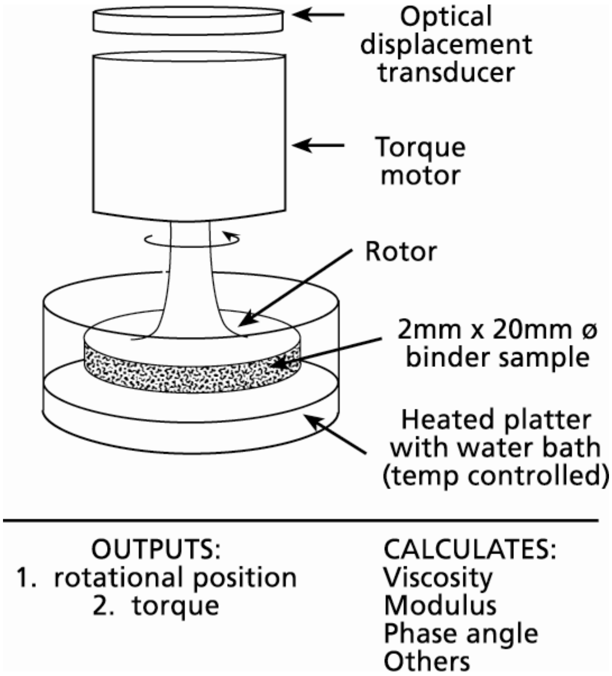
### A.4.2 Modified Binders

The test equipment and procedures used to measure the properties of modified binders are available as Austroads Test Methods on the Austroads web site (www.austroads.com.au).

A recent development is the more widespread use of the dynamic shear rheometer (Figure A 6) which has been introduced as part of the Strategic Highway Research Program (SHRP) Binder Specification in the U.S. This equipment is used to characterise the temperature and loading time effects on binder flow properties by measuring the complex shear modulus, or stiffness and the phase angle, or visco-elasticity of a binder sample. These instruments have been in use for over 20 years by road research groups.

Due to the complex behaviour of polymer modified binders their evaluation requires careful selection of the test apparatus and conditions. In particular, when measuring the mechanical properties it is important to control the temperature, strain rate and the level of strain.

**Figure A 6: Principle of a dynamic shear rheometer**



# Appendix B Mixing, Conditioning and Compaction of Samples for Density Testing

## B.1 General

The following description refers principally to the preparation of laboratory mixed samples of dense graded asphalt for compaction in a gyratory compactor. Similar procedures also apply to other mix types and to laboratory mixed materials for Marshall compaction, as well as samples taken from asphalt production, with some differences as noted below.

The major difference introduced in conjunction with the design of asphalt mixes using gyratory compaction was the emphasis on controlling oxidation of the binder. Exposure of thin films of binder at high temperature (as occurs during mixing, and storage of mixed material) can lead to comparatively rapid increases in viscosity due to oxidation.

The resilient modulus test is sensitive to binder (viscosity) hardness, whereas Marshall flow and stability are relatively insensitive. The sensitivity of modulus to binder viscosity resulted in the adoption of a conditioning process (Alderson 1994). This standardises the degree of binder oxidation that occurs during asphalt sample preparation.

Manufactured samples taken from asphalt production should be sampled in accordance with AS 2891.1.1.

Procedures for the mixing, quartering and conditioning of samples are described in AS 2891.2.1.

## B.2 Prior to Mixing

Prior to commencing the manufacture of any asphalt specimens it is necessary to have all documentation ready. The mix composition should be known and the source of the raw components identified. Oven temperatures for heating the aggregates and binders should be decided upon, as should whether the mixing, conditioning and compaction procedures are standard or whether special conditions need to be applied.

Incorrect storage and handling of aggregate fractions can lead to serious errors in reproducing mix composition. It is most important that the instructions in AS 1141.3 be followed when sampling aggregates. Aggregates are also vulnerable to absorption of moisture from the atmosphere. In most cases the moisture contents will be low but, particularly in tropical areas, the absorption can be noticeably higher and should be known. It is advised that continuous records be maintained on aggregate moisture contents.

Proper handling of the aggregates will also reduce systematic errors in mix preparation. Large samples of aggregate should be divided into manageable, representative portions using the procedures outlined in AS 1141.3. When sampling a bin fraction for a mix, a complete, representative sample should be put through splitter boxes (Figure B 1) until approximately the right amount is split out. This will ensure that no systematic errors occur by sampling the coarse aggregates and allowing the fines to remain and accumulate in the bottom of the container.

**Figure B 1: Splitter box to divide samples evenly**

**Figure B 2: Laboratory planetary mixer**

## B.3 Mixing

### B.3.1 General

The emphasis in mixing of the aggregates and binder is on achieving an even coating of the binder over all the aggregate particles. The mixing times suggested in the standards are those that have been found in practice to achieve an even coating using a planetary-style mixer (Figure B 2), though the standard does not preclude the use of other mixers.

Mixers that require longer than the three minute maximum mixing time to achieve an even binder coating on the aggregate will cause additional oxidation of the binders above that considered normal in laboratory practice and steps should be taken to speed up the mixing process or a new, more efficient mixer obtained. The rate of oxidation of binders is greatest during mixing as fresh binder is constantly exposed to air and any extra time above the three minute maximum may cause measurable changes in the properties of the mixes.

Some breakdown of the aggregate will occur during the mixing process. The amount of extra fines produced will depend upon the size of the asphalt mix, quality of the aggregate and on the type of mixer bowl and paddle. It is not necessary to measure the mixed grading for every mix produced but records should be kept for generic mix types and aggregate sources.

The procedure known as ‘wetting of the mixing bowl and splitting equipment’ is mandatory. This means that a dummy mix is put through the mixing process before normal mixing is undertaken. The mixing bowl and equipment are scraped to remove the bulk of the dummy mix, leaving a thin coating of binder and fine particles on the bowl and mixing equipment. This will ensure that fines and binders from subsequent mixes will not adhere to the mixing equipment. It is important that the binder used in the dummy mix is the same as the binder used in subsequent mixes. This is particularly important when using modified binders.

### B.3.2 Raw Materials

Sufficient aggregate for one batch is split from the various bin fractions (to the nearest 5 g) according to the mix design. Allowances should be made for moisture content when determining quantities for a mix design. The aim is to produce a design grading based on dry aggregate masses.

The quantity of binder should be sufficient for one asphalt batch. If a sub-sample of binder needs to be split from a large quantity of binder then care should be taken to limit oxidation. Most binders become fluid at less than 100 °C (some PMBs may require a higher temperature) and a large sample of binder should be warmed gently until it becomes fluid. Once the binder is fluid it should be stirred for about one or two minutes to ensure that the mass is homogeneous. Sub-samples should be decanted and stored in closed tins with a capacity that is not much greater than the volume required for a single mix. AS/NZS 2341.21 *Methods of testing bitumen and related roadmaking product: sample preparation*, should be consulted as to the correct sampling procedures.

In practice, sub-samples of around one litre in volume are often used. This will provide sufficient binder for two dense graded asphalt mixes with a maximum particle size less than 20 mm, or one mix of a larger stone mix or a binder-rich mix. Binders should be heated to the required mixing temperature only once and any binder remaining after completion of all mixing should be discarded (and not reheated and used at a later date).

PMBs may need to be heated to higher temperatures before becoming fluid. The supplier's recommendations should be consulted and should be noted on the report form.

### B.3.3 Pre-mixing and Material Preparation

Individual aggregate fractions should be added to the mixer bowl and mixed for 15 seconds to ensure that the dry mineral components are thoroughly blended. The aggregate need not be heated prior to pre-mixing. The aggregate is then placed in an oven and heated (a temperature of about 15 to 25 °C greater than the binder temperature is usually required to achieve a final mix temperature about the same as the binder temperature).

A sample of binder is also placed in an oven and heated to the required mixing temperature. The quantity of a binder sample should be sufficient for one or two asphalt batches that are to be made at the same time.

PMBs may require higher temperatures to allow mixing to take place. The supplier's instructions should be consulted. The practice of over-heating these binders should be avoided. The binder temperature and the length of time that the binder is kept at an elevated temperature must be controlled to ensure that the binder is not oxidised beyond normal expectations. AS 2891.2.1 stipulates the maximum time that binders can be held at elevated temperatures.

### B.3.4 Mixing of Binder and Aggregates

A planetary-style mixer is recommended, with the emphasis during mixing being to ensure adequate coating of the aggregate whilst maintaining the mix temperature. Provision of heating to the bowl during mixing is not required and operators should not mix longer than is necessary. If the mix cools too much it will be difficult for the mix to achieve a stable temperature equilibrium during the subsequent conditioning process. The time required to complete the mixing process should be carefully controlled and the operator should work quickly whilst maintaining safe and accurate work practices.

If a number of batches are to be prepared, then it is useful to have a separate mixing bowl for each mix. This will ensure that the temperature of the mixing bowl is the same for each mix and will help to control the heat loss (see previous comments on wetting of the mixing bowl in Section B.3.1).

The mixing bowls should have a thin film of binder and fine aggregate before wet mixing. This thin film is the residual after mixing and scraping clean a dummy mix the same as the test mix. This is particularly important when using 'sticky' binders such as some of the PMBs or when compacting open graded mixes that are mixed at lower temperatures.

It is preferable to adopt a set mixing time for all mixes (ensuring that an homogenous binder coating is attained) rather than using different mixing times for different mixes. This ensures that all mixes produced by the mixer will have the same relative properties (same binder oxidation). For planetary mixes, a mixing time of three minutes has proven sufficient to ensure an even binder coating. However, the binder coating should be checked periodically and the mixing time adjusted (for all mixes) as necessary.

## B.4 Splitting of the Mix

### B.4.1 General

The emphasis in the splitting process is to divide the mix into roughly equal amounts, avoid segregation and conserve mix temperature. Alternative procedures for splitting of mix are described in AS 2891.1.1 and include cone and quartering and sample divider (riffle box).

### B.4.2 Cone and Quartering

After mixing, the mix is placed onto a splitting tray (Figure B 3). If the mixing bowl can be up-ended on to the tray so as to leave the mix in a conical shape then no further mixing of the mix is required. If the mix is transferred from the mixer to the splitting tray by scoops then the whole mix needs to be quickly formed into a cone (avoiding segregation).

**Figure B 3: Tools for splitting mix into sub-samples**

Splitting of the mix is done using a flat steel plate. The mix is divided into ‘roughly’ four equal portions.

Having split out the four portions, these are then scooped (using a square-mouthed high-sided scoop) into trays for conditioning. The conditioning trays should be between 100 and 200 mm in diameter and the use of a lid is optional.

It is important to split the mixes and place the portions back in the oven quickly in order to conserve the temperature of the asphalt mix.

If additional samples are required for other purposes then three of the samples should be marked as the standard quality indicator samples. These samples should be monitored closely to ensure compliance with the standards. Additional samples may be manufactured for other purposes and it is the responsibility of the supervising authority to determine what practices need to be adopted.

### B.4.3 Sample Divider

A sample divider as an alternative to cone and quarter is particularly applicable to obtaining test portions from larger samples such as obtained from sampling of plant manufactured materials. The sample divider is the same equipment as that described for splitting of aggregate samples in Section B.2 except that a release agent is required to be applied to all surfaces of the sample divider. Heating of the sample divider and receiving boxes is also desirable particularly for stone mastic asphalt and open graded asphalt types. Rotating the receiving boxes during the division operation assists in minimising segregation in larger-size mixes.

## B.5 Conditioning

The mix is returned to the oven and conditioned at the required compaction temperature for a period of one hour.

The oxidation that takes place during laboratory mixing and conditioning in the oven simulates the oxidation that takes place in the mixing plant, during transport to the site and during the first year or two of pavement service, from work previously undertaken by ARRB (Alderson 1994). This conditioning process will ensure that binder properties of laboratory prepared mixes are, on average, similar to binder properties of mixes placed in the field.

The size of the oven containers used to condition the loose asphalt samples has been found not to significantly affect the oxidation process. However, it is not advisable to use oven containers that permit the loose asphalt to be spread in a layer less than 30 mm thick. (It is recommended that containers be less than 200 mm in diameter.) The use of lids on the oven containers also does not significantly affect the oxidation process and their use is optional. From limited studies it appears that there is sufficient air present in the voids of the loose asphalt to allow oxidation to proceed independent of the depth of the mix in the oven container.

## B.6 Compaction

### B.6.1 Principles of Gyratory Compaction

***Equipment***
The equipment needed to produce gyratory compacted specimens must conform to AS 2891.2.2.

During gyratory compaction, the asphalt mix is subjected to shearing forces. This is achieved by the application of a constant vertical compressive force to the asphalt confined in a cylindrical mould while the mould is simultaneously rotated about its longitudinal axis through a small angle, inducing shearing and rearrangement of the aggregate particles. The small angle is maintained throughout the compaction process which is terminated when either a set height or a set number of cycles is achieved.

The Gyropac (Figure B 4), which is manufactured by Industrial Process Controls Ltd (IPC), is the type of gyratory compactor most commonly used in Australia. The Servopac (Figure B 5) is also manufactured by IPC Global. It is a more advanced version of gyratory compactor that includes more options and control over the compaction process making it suited to both routine design and research applications. It is also the type of gyratory compactor more commonly used in New Zealand.

Procedures described below refer specifically to the Gyropac although general principles also apply to the Servopac.

**Figure B 4: Gyropac and ancillary equipment with computer attached to a PC to automatically record the compaction process**


**Figure B 5: Servopac connected to a PC**


### B.6.2 Gyratory Compaction to a Set Density or to a Set Number of Gyratory Cycles

Gyratory compactors can be used to compact to a set number of cycles or compact until a set height (set density) is achieved. Most mix design methods have sample preparation requirements for specimens to be manufactured with a set energy input. Design procedures described here use this approach by setting the number of gyratory cycles for each level of service.

The gyratory compaction mix design method has three different levels of compaction: 50, 80 and 120 cycles, for light, medium and heavy traffic respectively, as well as a maximum of 250 or 350 cycles representing the compaction level at which no further compaction can occur without crushing of aggregate. Compaction levels of 50, 80 and 120 cycles are analogous to Marshall compaction levels of 35, 50 and 75 blows although the correlation between gyratory compaction and Marshall is not equal for all mixes as each method will result in minor differences in density arising from different material characteristics.

The wearing disks and the bottom plate should be clean before starting any compaction. Small particles can build up on the edges of these and bind them to the wall of the gyratory mould. This of course reduces the compactive effort applied to the asphalt.

When the gyratory compactor is switched on it is not unusual for the pressure at the regulator to drop. However, the pressure should recover within a few cycles. If the pressure requires more than five cycles to recover then the manufacturer should be consulted.

***Gyratory compaction to set number of cycles***

The compaction procedure is to place sufficient mass of conditioned asphalt (at the correct temperature) in a heated mould. Paper disks are placed on the top and bottom of the asphalt mix to stop the compacted specimen adhering to the wearing disks. The mould (with asphalt mix) is placed between the loading platens in the gyratory compactor and the settings on the device are adjusted to conform to AS 2891.2.2. The required number of cycles is set and the compactor is switched on.

At the completion of compaction the mould is removed from the compactor and the compacted specimen extracted from the mould. Most mixes are sufficiently stiff that compacted specimens can be removed from the mould whilst still hot. However, should there be a possibility of the compacted specimen being damaged during extraction or slumping while hot then the specimen should be cooled in the mould and extracted later.

Extracted specimens need to be labelled with a unique code when cool enough to handle so that the compaction order can be identified.

Gyratory compacted specimens for resilient modulus and moisture sensitivity testing should have a height of between 65 and 70 mm (for 100 mm diameter specimens) and between 85 and 90 mm (for 150 mm diameter specimens). When compacting unusual mixes it is difficult to determine the mass to be added to the mould to achieve this height. A simple way to overcome this is to compact a dummy specimen first using the fourth quarter sample (to be used for maximum bulk density determination). This specimen should be compacted after about 45 minutes of conditioning. The mass added to the mould is noted and the final height of the compacted specimen is determined to the nearest millimetre.

***Gyratory compaction to a set height***

The mass required to give a specimen height of about 65 mm can be determined using Equation A5.

$$M_{65} = M\left(\frac{65}{H}\right) \qquad \text{A5}$$

where

$M_{65}$ = mass required to compact a specimen to about 65 mm in height

$M$ = actual mass placed in the mould for the dummy specimen

$H$ = measured height of the dummy specimen (in millimetres)

***Gyratory compaction to set density***

It is more difficult to compact a specimen to a set density than to a set number of compaction cycles. This is because a number of assumptions have to be made regarding the mix. The procedure is as follows:

- determine the desired bulk density or the maximum density of the mix, MD ($t/m^3$), and the desired air voids content, AV (%)
- determine the desired height of the compacted specimen, H (mm)
- determine the average diameter of the compaction mould, d (mm)
- estimate the surface voids of the compacted specimen, SV (%)
- calculate the mass (g) using Equation A6.

$$\text{Required mass} = \frac{MD * \pi * d^2 * H}{4000} * \left(1 - \frac{AV + SV}{100}\right) \quad \text{A6}$$

The maximum density of the mix is measured using test method AS 2891.7.1.

Specimens can be compacted until the height cut-off switch is activated and this should give a specimen height of 65 mm. The actual cut-off height should be determined for each machine and after any adjustments are made to the gyratory compactor. There will be small variations in the finished height of specimens due to random variability in the machine operation. Variations in the thickness of the wearing disks will affect the finished height of the specimens. If a displacement transducer has been fitted to the gyratory compactor then specimens of other heights can be produced by manually stopping the gyratory compaction at the desired height.

The gyratory moulds need to be individually identified and measured to determine internal diameters. They will also require checking from time to time as the moulds wear.

Estimation of the surface voids of the compacted specimen has the greatest uncertainty of any of the parameters in Equation A6. In general, the surface voids are greatest at the beginning of compaction diminishing to almost zero at 350 cycles. The actual values will vary, depending upon the coarseness of the grading, the amount of binder present and the number of compaction cycles.

***Example of calculation of the mass for a set density***

The maximum density of the mix was found to be 2.45 $t/m^3$ and it was desired to produce specimens with an air voids content of 5%.

It is known that the gyratory compactor will cut off when the sample height is 65.5 mm.

The average diameter of the mould was determined at 99.8 mm.

The surface voids allowance for this 14 mm dense graded asphaltic concrete was estimated to be 2%.

The mass required to be added to the mould to achieve 5% air voids is calculated in Equation A7.

$$\frac{2.45 * \pi * 99.8^2 * 65.5}{4000} * \left(1 - \frac{5 + 2}{100}\right) = 1167 \text{ g} \quad \text{A7}$$

# Appendix C Measurement of Volumetric Properties

## C.1 Introduction

The measurement and calculation of volumetric properties is vital to the understanding and design of asphalt. Selecting a suitable aggregate grading and binder content for a specific application is the crux of asphalt mix design. The Australian Standards and Austroads Test Methods used for determining volumetric properties are as follows:

- Austroads AGPT/T234 Asphalt binder content (ignition oven method).
- Austroads AGPT/T220 Sample preparation: compaction of asphalt slabs.
- Standards Australia Method 3.1: Bitumen content and aggregate grading: reflux method. AS 2891.3.1.
- Standards Australia Method 3.2: Bitumen content and aggregate grading: centrifugal extraction method. AS 2891.3.2.
- Standards Australia Method 3.3: Bitumen content and aggregate grading: pressure filter method. AS 2891.3.3.
- Standards Australia Method 7.1: Determination of maximum density of asphalt: water displacement method. AS 2891.7.1.
- Standards Australia Method 8: Voids and density relationships for compacted asphalt mixes. AS 2891.8.
- Standards Australia Method 9.1: Determination of bulk density of compacted asphalt – waxing procedure. AS 2891.9.1
- Standards Australia Method 9.2: Determination of bulk density of compacted asphalt: presaturation method. AS 2891.9.2.
- Standards Australia Method 9.3: Determination of bulk density of compacted asphalt: mensuration method. AS 2891.9.3.

In addition to these asphalt test methods, the following aggregate and binder test methods are also required:

- Standards Australia Method 5: Particle density and water absorption of fine aggregate. AS 1141.5
- Standards Australia Method 6: Particle density and water absorption of coarse aggregate-weighing-in-water method. AS 1141.6.1
- Standards Australia Method 7: *Apparent particle density of filler.* AS 1141.7
- Standards Australia Method 11: *Particle size distribution: sieving method*. AS 1141.11.1
- Standards Australia Method 6: Determination of density using a hydrometer. AS 2341.6
- Standards Australia Method 7: Determination of density using a density bottle. AS 2341.7.

## C.2 Specimen Requirements

The air voids content of a mix is expressed as the difference between the bulk density of the compacted specimens and the maximum density as a percentage of the maximum density of the loose mix. This usually means that when preparing aggregate and binder for a mix, sufficient materials are split out so that both compacted specimens and loose mix for a maximum density determination can be obtained from a single batch. The amount of material batched will depend upon the compacted specimen size and upon the nominal size of the mix.

The loose asphalt used in determining the maximum density to AS 2891.7.1 can also be used to determine the binder content as the material is not compromised.

## C.3 Equipment

The equipment required will depend upon the test methods adopted. Each of the test methods for binder content determination, maximum density or bulk density uses different apparatus. If the more commonly preferred tests are used than the equipment list is as follows:

- balance
- ovens
- water bath
- pycnometers
- vacuum pump (or aspirator)
- desiccator
- pressure filtration cell
- thermometers
- suspension device for determining buoyant mass
- timer
- fume cupboard
- flasks
- sieves.

## C.4 Calculation of Volumetric Properties

### C.4.1 Bulk Density

***Waxing method***

The waxing method, AS 2891.9.1, eliminates the effect of water permeable voids by sealing the surface with a layer of wax. It is used for dense mixes where it is desirable to avoid the influence of water permeable voids on the measurement of bulk density.

***Saturated surface dry method***

The saturated surface dry method for bulk density is described in AS 2891.9.2. This requires that specimens are weighed to determine their dry mass in the air and then soaked for five minutes in water. The buoyant mass is determined and then the sample is taken from the bath and quickly blotted to a surface dry condition on a damp cloth and the saturated surface dry mass is recorded. Using these three masses and the density of the water, the bulk density can be calculated.

***Mensuration method***

The mensuration density method, AS 2891.9.3, is based on direct measurement of the volume of the specimen. The height is measured at eight points, the diameter is measured at four points (all to 0.1 mm) and the mean recorded and used to determine the volume of the specimen. The dry mass is measured to 0.1 g and divided by the volume of the specimen to give the mensuration density. This is the preferred density determination method for open graded asphalts.

### C.4.2 Maximum Density

The maximum density method, AS 2891.7.1, is based on placing a mass of loose asphalt in a volumetric flask and covering it with water. Entrapped air is removed by the application of a vacuum. This method is in common use at present and does not require any solvents or specialised equipment.

### C.4.3 Voids and Density Relationships

The relationships for air voids content, bulk density of combined aggregates, percentage of mass of absorbed binder, mass of effective binder, maximum theoretical density, VMA and VFB are included in AS 2891.8.

Mix designers both in Australia and overseas place differing emphasis on each of the volumetric parameters. Air voids content is the most often quoted but the other properties are significant to varying degrees. The formulae for the most common volumetric parameters are listed in Equation A8 to A12.

Air voids content:

$$AV = \frac{(\rho_{max} - \rho_{bulk})}{\rho_{max}} * 100 \qquad \text{A8}$$

Voids in mineral aggregate:

$$VMA = 100 - \frac{\rho_{bulk} * B_e}{\rho_a} * (100 - B) \qquad \text{A9}$$

or

$$VMA = AV + \frac{\rho_{bulk} * B_e}{\rho_b} \qquad \text{A10}$$

Voids filled with binder:

$$VFB = \frac{100 * B_e}{VMA} * \frac{\rho_{bulk}}{\rho_b} \qquad \text{A11}$$

or

$$VFB = \frac{VMA - AV}{VMA} \qquad \text{A12}$$

where

$\rho_{max}$ = maximum density of asphalt (t/m$^3$) as per AS 2891.7.1

$\rho_{bulk}$ = bulk density of asphalt (t/m$^3$) as per AS 2891.9.1, AS 2891.9.2 or AS 2891.9.3

$\rho_a$ = bulk density of combined mineral aggregates (t/m$^3$) as per AS 2891.8

$\rho_b$ = density of binder (t/m$^3$) as per AS 2341.6 or AS 2341.7

$B$ = proportion by mass of binder in the total mix (%) as per AS/NZS 2891.3.1, AS/NZS 2891.3.2 or AS/NZS 2891.3.3

$B_e$ = proportion by mass of effective binder (%) as per AS 2891.8

## C.5 Interpretation of Results

In the following sections relating to the mechanical and performance-related properties it is noted that the level of compaction (as measured by air voids content) is extremely important. In most mix design procedures, a number of trial mixes are tested at varying binder contents to determine an 'optimum' binder content. This involves plotting a number of mix variables, such as air voids content, against binder content.

VMA can be considered the potential for voids due to the aggregate grading, which is reduced by an amount equal to the volume of effective binder added to the mix.

VFB is the proportion of voids in the aggregate skeleton that are filled with bitumen and is affected by the porosity of the stone, the grading and the binder quantity.

## C.6 Effect of Variables on Volumetric Properties

Air voids content is affected primarily by the total compactive effort that the specimen is subjected to during compaction. Other variables such as binder type, binder content aggregate grading and temperature of compaction also affect the air voids content and these are briefly discussed below and summarised in Table C 1.

***Binder***

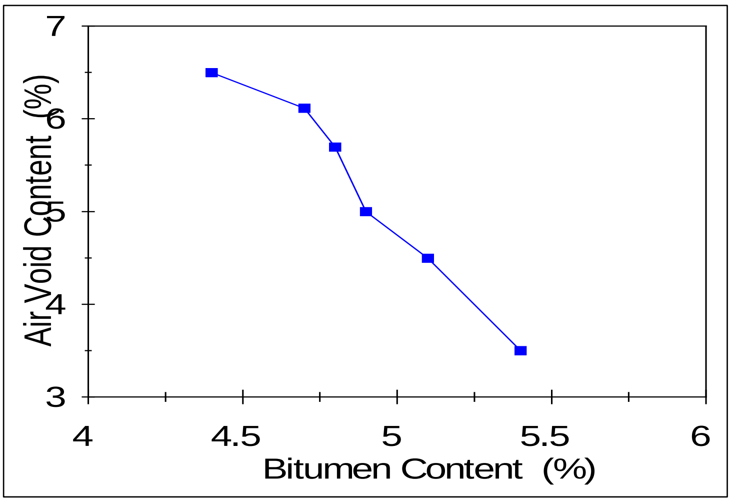
In Figure C 1 it can be seen that increasing the binder content decreases the air voids content. This is due to two effects, the first of which is that additional binder occupies a greater volume thus reducing the voids. The second effect is due to the extra lubrication supplied by the hot binder during compaction permitting the specimen to compact quicker and thus expelling more air for the same compactive effort.

The viscosity of a binder used in a mix will affect the air voids by promoting or hindering compaction. Binders with a high viscosity will tend to hinder compaction thus increasing voids for a set compactive effort.

**Table C 1: Effect on air voids content**

| Variable | Air voids content |
|---|---|
| Increased binder content | Reduce |
| Grading (coarse to fine) | |
| Increased compaction level | |
| Increased compaction temperature | |

**Figure C 1: Relationship between air voids content and bitumen content for fixed compactive effort**



***Aggregate***

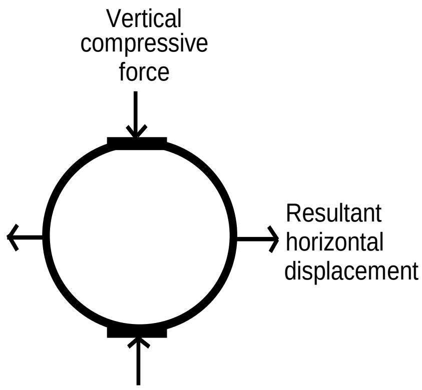
The gradation of the aggregate strongly affects the air voids content. Mixes with larger maximum particles will have greater VMA than mixes with small nominal size particles. Dense graded mixes with a larger percentage of coarse aggregate will have greater voids than those with less coarse aggregate. Gap graded mixes, including SMA and fine gap graded asphalt, also have larger VMA than continuously graded mixes.

# Appendix D Measurement of Modulus

## D.1 Introduction

The Australian Standard test for the determination of the resilient modulus of asphalt (AS 2891.13.1) is based upon an indirect tensile measurement. A repeated vertical compressive force is applied acting parallel to and along the vertical diametrical plane and the horizontal displacements are measured mid-height through the horizontal diameter (Figure D 1).

**Figure D 1: Indirect tensile test**




The resilient modulus is calculated using the relationship shown in Equation A13.

$$E = \frac{P * (\vartheta + 0.27)}{h_c * H} \qquad \text{A13}$$

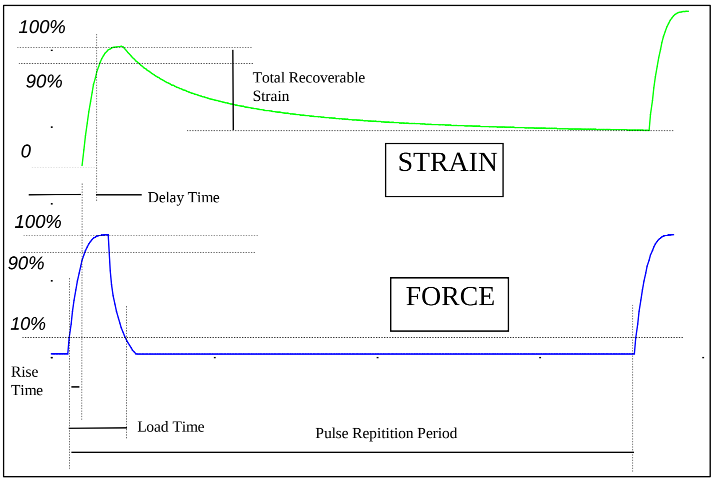
where

| | | |
|---|---|---|
| $E$ | = | estimated resilient modulus (MPa) |
| $P$ | = | peak load (N) |
| $\vartheta$ | = | Poisson's ratio (0.4, unless more precise information is available) |
| $h_c$ | = | average height of specimen (mm) |
| $H$ | = | recovered horizontal deformation (mm) |

The standard requires that a total horizontal strain of between 30 and 70 microstrain be achieved in the sample to ensure that there is sufficient deformation for the linear variable displacement transducers (LVDTs) to measure accurately and that the response of the specimen remains elastic. The load capacity of the testing device specified in AS 2891.13.1 (approximately 4.5 kN) allows specimens with resilient moduli between 600 to 28 500 MPa to be tested, but in practice the pneumatic loading response limits the upper resilient modulus to around 16 000 and 5500 MPa for 100 and 150 mm diameter specimens respectively. (These values are calculated on a sample thickness range of between 35 to 90 mm and a rise time of 40 ms.)

The loading and response of a specimen is shown in Figure D 2. A pulsed load, essentially triangular in shape, is applied to the specimen. The strain (deformation divided by thickness) is measured on the unloading portion of the curve. The total recoverable (defined here as the resilient) strain is calculated as the peak strain minus the strain immediately prior to the application of the next load pulse.

**Figure D 2: Force pulse and displacement timing diagram for resilient modulus test**




The rise time is defined as the time required to increase the load from 10% of the peak load to 90% of the peak load.

To compare the resilient modulus determined using the Australian Standard with a modulus determined by another method, it is necessary to understand the definitions related to the stresses and strains of the resilient modulus test.

## D.2 Specimen Requirements

The resilient modulus test requires that triplicate specimens be tested and they should be essentially right cylinders with a height between 35 and 70 mm for 100 (± 2) mm diameter specimens and a height between 60 to 90 mm for 150 (± 2) mm diameter specimens. Specimens with a maximum particle size greater than 20 mm and less than 40 mm have to be nominally 150 mm diameter. Specimens with a maximum particle size less than or equal to 20 mm can be either 100 or 150 mm in diameter, with 100 mm diameter preferred.

The faces of the specimens should be flat and not depart from squareness by more than 7.5 mm for 150 mm diameter samples and 5.0 mm for 100 mm diameter samples. Departure from squareness is normally determined using a right-square and a measuring scale. The body of the scale is placed against the curved surface of the cylinder and the blade moved into contact with the end face. The gap at either end is measured and then the right-square is positioned at right-angles to the previous measurement and the gaps measured. The procedure is repeated on the other end face. If any of the gaps are greater than allowed then the specimen should be cut and/or polished to produce a flat right specimen.

Specimens of other diameters may be tested but the height-to-diameter ratio should be maintained at around 0.5. If other diameters are to be tested then special loading platens will be required. The size of the loading platens should cater for the maximum thickness permitted and the radius of curvature should match the diameter of the specimens. The contact width of the loading platens should be 12.5% of the specimen diameter.

Resilient modulus specimens should be carefully prepared in order to get reproducible results. As-moulded gyratory specimens are suitable for testing without any further preparation. Should the specimens need some preparation (e.g. cores from pavements) then a jig to hold the specimen for cutting with a power saw is invaluable because it will enable operators to produce specimens to the required geometry without further preparation. Time spent making and installing a jig will be quickly repaid by the saving in time in correcting poorly cut specimens.

Bulk density is usually determined after resilient modulus testing so that the test result is not influenced by water penetration. If the cylinders need to be prepared before resilient modulus testing (i.e. cores) then this should be noted on the results sheet. All resilient modulus specimens should be thoroughly dried to constant mass before commencing testing.

Cores taken from a pavement should consist of a single layer of asphalt. Frequently, cores will have an undulating surface due to instability of the coring device. A group of cores with this defect often have a large scatter in resilient modulus due to 'noise' in the LVDT signal. This noise is related to movement of the cores during loading and unloading. Operators should take care when positioning cores to achieve the maximum stability on the loading platens and take extra care in fitting the LVDT yoke.

## D.3 Equipment

In Australia a materials testing apparatus (MATTA) device is the preferred device used for the determination of the resilient modulus of asphalt. However, the Australian Standard permits other loading devices to be used and the standards should be consulted to ensure that they conform.

Essentially the test equipment consists of a load frame that enables forces up to 4.5 kN to be applied to cylindrical specimens. The resultant displacements are measured at two points on the specimen and are required to measure up to 100 microns of movement. Control systems are needed to apply pulsed loads at a period of three seconds with a load duration of 40 milliseconds. A data acquisition system is needed to monitor the test and record the measurements.

If a computer-assisted measuring apparatus is used then a value will be displayed regardless of the validity of the test. The operator must exercise some judgement in accepting or rejecting a test.

***Checking indirect tensile jig***

The indirect tensile test induces complex stresses in test specimens and the algorithms used to determine the resilient modulus are sensitive to the location of the displacement measurements. For this reason it is necessary to check the alignment of the indirect tensile jig from time to time.

Check first that the loading platens are aligned in the same plane. The other check is to ensure that displacement measurements are at mid-diameter. This should be done when differing batches of specimens are to be tested (e.g. when testing cores after testing gyratory specimens). It is also wise to do this check before beginning a new project.

***Positioning a specimen for resilient modulus testing***

The resilient modulus test requires that operators follow a rigorous procedure in arranging a test specimen in the indirect tensile jig. It is recommended that the sample be marked with diametral lines at right-angles to one another. The marked specimen is placed centrally on the lower platen with one of the lines vertical. Place the upper platen on the specimen so that the vertical line bisects the width of the upper loading platen. The specimen should now be checked to determine if it is seated correctly. If the specimen is stable then the test can proceed.

## D.4 Monitoring of Test Temperature

Temperature is one of the most significant factors affecting the resilient modulus of asphalt. It is critical that the temperature of the test specimen be monitored and controlled to within 0.5 °C. The Australian Standard AS 2891.13.1 stipulates a temperature of 25 °C for the determination of a standard quality indicator value. Other temperatures may be used as required by research needs but the temperature must be accurately controlled. It has been shown (Sharp & Alderson 1992) that the effect of temperature was the single greatest contributor to the resilient modulus of asphalt.

Monitoring of the test temperature is done using a pair of thermometers embedded in a dummy specimen rather than the temperature cabinet display. The temperature cabinet should be adjusted so that the temperature of the dummy specimen (adjacent to the test specimens) is controlled to within the prescribed tolerances.

If shelves are installed then the temperature gradient within the temperature cabinet should be examined. The installation of baffles may create a more homogeneous temperature environment within the cabinet.

## D.5 Load Duration

The duration of the load applied to an asphalt specimen is controlled within the standard by stipulating a rise time when determining the standard quality indicator value. Due to the rheologically complex nature of asphalt, the resilient modulus is dependent on the rate of loading and this test parameter needs to be precisely controlled.

AS 2891.13.1 requires that test devices control the load repetition period to within 50 milliseconds and the rise time to within five milliseconds. Loading duration has been shown (Sharp & Alderson 1992) to be more significant than mix design variables such as bitumen content or maximum particle size.

## D.6 Poisson's Ratio

In Australia, Poisson's ratio is assumed to be 0.4 for all asphalt types at all temperatures, load durations and resilient moduli. Overseas experience suggests that this may not be the case but at this time in the development of the Australian Standards, a Poisson's ratio of 0.4 should be used in all cases.

## D.7 Interpretation of Results

Resilient modulus is a measure of the 'stiffness' of a material and is related to the load-spreading capacity. A material with a high resilient modulus, that is a high stiffness, will distribute load over a wider area. The stiffness of a material is of great importance to pavement designers as it is used to calculate the required pavement thickness (Austroads 2012).

Resilient modulus is normally found to be indirectly proportional to air voids content for a given mix. For laboratory-manufactured specimens this will not present a problem as the design procedures stipulate an air voids content of 5%. The change in resilient modulus due to air voids is of the order of a decrease of 350 MPa per 1% increase in air voids (less than this for soft grade binders such as SBS polymer modified binders). For cores from a pavement, a range of air voids contents may need to be tested so that a characteristic value can be interpolated.

Typical values of resilient modulus for dense graded asphalt are shown in Table D 1. These are from Chapter 6 of Austroads (2012).

**Table D 1: Modulus (MPa) of typical Australian dense-graded asphalts determined on laboratory-manufactured samples using the indirect tensile test procedure and standard test conditions and 5% air voids**

| Binder Type | Mix size (maximum particle size) (mm) | | | | | |
|---|---|---|---|---|---|---|
| | 10 | | 14 | | 20 | |
| | Range | Typical | Range | Typical | Range | Typical |
| Class 170 | 2000–6000 | 3500 | 2500–4000 | 3700 | 2000–4500 | 4000 |
| Class 320 | 3000–6000 | 4500 | 2000–7000 | 5000 | 3000–7500 | 5500 |
| Class 600 | 3000–6000 | 6000 | 4000–9000 | 6500 | 4000–9500 | 7000 |
| Multigrade | 3300–5000 | 4500 | 3000–7000 | 5000 | 4000–7000 | 5500 |
| A10E | 1500–4000 | 2200 | 2000–4500 | 2500 | 3000–7000 | 3000 |

Note: Standard test conditions are 40 ms rise time and 25 °C test temperature (AS 2391.13.1).

Source: Austroads (2012).

## D.8 Effect of Variables on Resilient Modulus

The effects of temperature and load duration on resilient modulus were discussed earlier as these variables are stipulated in the Australian Standard. Other variables also affect the resilient modulus and these are briefly discussed below.

***Binder***

The viscosity of a binder used in a mix design will affect the resilient modulus of asphalt. Soft-grade binders such as those modified with SBS polymer will have a very low resilient modulus of about 2000 MPa or less. Straight-grade bitumens such as Class 170 and Class 320 will have resilient moduli in the range 2500 to 5000 MPa for typical dense graded asphalt. If a binder is modified with a hard polymer such as the EVA type then the resilient modulus could be as high as 7000 MPa. (Note: these are indicative values only.)

In addition to the viscosity of the binder, the quantity of binder will also affect the resilient modulus. Within the normal range of binder contents (say 3 to 10% by mass) the greater the binder content the softer (lower resilient modulus) the mix will behave.

***Aggregate***

Aggregate quality will affect the resilient modulus. Aggregates that are roughly cubical and rough textured will produced a mix with greater resilient modulus than the same mix with rounded, smooth textured aggregates.

The gradation of the aggregate also affects the resilient modulus. Mixes with larger maximum particles will tend to have greater resilient moduli than mixes with small particles. Mixes with a large percentage of coarse aggregate will have greater resilient moduli than mixes with a large percentage of fine aggregates.

The effect of oxidation on most binders is to increase binder viscosity and hence result in an increase in resilient modulus. For some PMBs, excessive oxidation results in degradation of the binder with resulting reduction in viscosity and hence a reduction in modulus.

A summary of the above discussion on the factors affecting resilient modulus is given in Table D 2.

**Table D 2: Effect on resilient modulus**

| Variable | Resilient modulus |
|---|---|
| Increased binder content | Reduce |
| Increased binder viscosity | Increase |
| Grading (coarse to fine) | Reduce |
| Increased load duration | Reduce |
| Increased compaction level | Increase<br>(though some mixes can have a reduction in resilient modulus if the compaction level passes a critical level) |
| Increased temperature | Reduce |

# Appendix E Wheel Tracking Test

## E.1 Introduction

Wheel tracking is used in Level 2 mix designs to indicate the resistance of the candidate mix to deformation under traffic. Wheel tracking has been found to correlate well with road performance and typical wheel tracking values (Table E 2) have been developed for various performance levels.

The wheel tracking test procedure is available as Austroads test method AGPT/T231.

## E.2 Specimen Requirements

Wheel tracking specimens are normally prismatic with a plan area of 300 x 300 mm. The depth of the specimens in the Australian test will probably be in the range 50 to 100 mm. Procedures for the manufacture of slabs suitable for wheel tracking are described in Austroads test method AGPT/T220. Specimens cut from a pavement can also be wheel tracked, although a method of taking into account the effect of the (uncontrolled) thickness of these specimens still has to be developed. It has also been agreed that cylindrical specimens can be accommodated in the test method but these should be at least 200 mm in diameter.

The wheel tracking rate is dependent upon the air voids content of the specimens (although not to the same extent as dynamic creep) and, for standardised testing, an air voids content of 5% is usually specified. Specimens need to be brought up to the testing temperature and conditioned for a period at the test temperature to disperse any stresses due to handling.

## E.3 Equipment

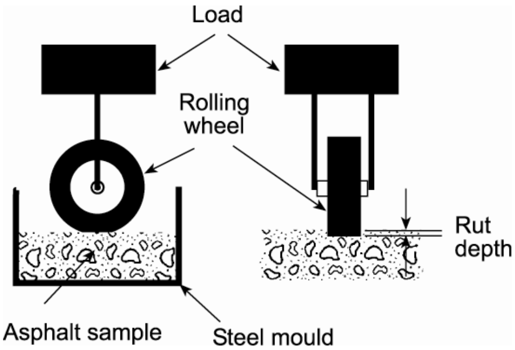
The important test parameters are listed below and some indicative values are given:

- wheel size: 200 mm outside diameter wheel with 10 mm of rubber tread by 50 mm wide
- tread: smooth with an international rubber hardness degrees (IRHD) hardness of about 80–90
- table travel: 250 mm at a frequency of 22 back and forth motions per minute
- vertical load: 700 N
- test temperature: 60 °C
- termination conditions: 10 000 cycles or 15 mm rut depth.

The values are based on the adaptation of a European draft standard to Australian conditions. A diagram of the equipment is shown in Figure E 1.

Measurement of tracking depth is normally recorded automatically using a computer-based data acquisition system. The test procedure is available as Austroads test method AGPT/T231.

**Figure E 1: Diagram of wheel tracking equipment**




## E.4 Test Procedure

A specimen is prepared according to Austroads test method AGPT/T220 and the bulk and maximum densities are measured to enable calculation of air voids content.

The specimen is placed in a test frame and adjustments are made to ensure that each side and bottom are fully supported with no free play and that there are no spaces into which the specimen can flow under loading. The specimen is conditioned at the test temperature for a set period (likely to be a range of times dependent on specimen dimensions).

An initial reading is taken and testing is commenced. The tracking depth (defined for each point along the tracked path as the vertical distance between the position of the wheel at the commencement of testing and its position at the time of measurement) is recorded as a function of the number of passes. The test temperature is monitored as a function of the number of passes.

The test is usually stopped when a set number of 10 000 passes have been completed, or when the tracking depth is greater than 15 mm although increased numbers of passes may be applied for heavy duty applications. The tracking rate is calculated as the change in tracking depth with the number of passes over the range 4000 to 10 000 passes. The test result is commonly expressed as final tracking depth (in mm after 10 000 passes).

## E.5 Monitoring of Test Temperature

Temperature is one of the most significant factors affecting the wheel tracking properties of asphalt. It is critical that the temperature of the test specimen be monitored and controlled to within 0.5 °C. A temperature of 60 °C for the determination of a standard quality indicator value has been adopted. Other temperatures may be used as required by research needs but the temperature must be accurately controlled.

Monitoring of the test temperature is done using a temperature measuring device embedded in a dummy specimen rather than the environment chamber air temperature. The environment chamber should be adjusted so that the temperature of the dummy specimen (adjacent to the test specimens) is controlled to within the prescribed tolerances.

## E.6 Specimen Examination

At the completion of testing, the upper surface of the specimen will have bulged due to the displacement of material from the wheel path, as occurs with rutting in the field. This is normal and may be used to provide an indication of the relative amounts of deformation due to consolidation of the specimen and to shear of the asphalt. At present the volume of the displaced material is not measured but it has been measured in some overseas studies by taking transverse measurements at intervals during testing.

## E.7 Effect of Variables on the Tracking Rate

As indicated previously, the wheel tracking rate is dependent upon the air voids content of the specimen (as is rutting due to traffic). Specimens with high air voids contents will develop ruts more quickly under wheel tracking than will specimens compacted to lower voids. Research has indicated that binder viscosity affects the wheel tracking rate. Generally, the higher the binder viscosity the lower the wheel tracking rate (and the lower the final tracking depth). For polymer modified binders (PMBs) the analogous property to viscosity is consistency.

***Binder***

The rheological properties of a binder used in a mix design will affect the wheel tracking rate of asphalt. In general, polymer modified binders have a better (lower) wheel tracking rate than Class 170 and Class 320 bitumens. The binder property or properties that determine rutting behaviour are under study and no data are available at this time.

In addition to the rheological properties of the binder, the quantity of binder will also affect the wheel tracking rate. Within the normal range of binder contents (say 3 to 10% by mass) the greater the binder content, the more likely that the mix will behave to plastic flow (higher wheel tracking rate).

***Aggregate***

Aggregate quality will affect the wheel tracking rate. Aggregates that are roughly cubical and rough textured will produce a mix with a better (lower) wheel tracking rate than the same mix with rounded, smooth textured aggregates.

The gradation of the aggregate also affects the wheel tracking rate. Mixes with larger maximum-sized particles will tend to have a better wheel tracking rate than mixes with small particles. Mixes with a large percentage of coarse aggregate will have a better wheel tracking rate than mixes with a large percentage of fine aggregates.

Mixes with fine aggregates produced by crushing will have a better wheel tracking rate than mixes manufactured using natural rounded (sands) fine aggregates. The effects of the parameters are summarised in Table E 1.

**Table E 1: Effect on wheel tracking rate**

| Variable | Resistance to permanent deformation |
|---|---|
| Increased binder content | Reduce |
| Increased binder viscosity | Increase |
| Grading (coarse to fine) | Reduce |
| Increased load duration | Reduce |
| Increased compaction level | Increase |
| Increased temperature | Reduce |

## E.8 Interpretation of Results

The tracking rate is determined from the tracking depth versus passes data. The calculation procedure is described in Austroads test method AGPT/T231. It is now considered that tracking depth (after 10 000 passes) is a more appropriate parameter than tracking rate, although the latter is still used overseas.

Some typical tracking depths for laboratory prepared specimens are shown in Table E 2. These values are indicative only and reference should be made to appropriate specifications for specific performance requirements.

**Table E 2: Typical tracking depths for laboratory specimens (mm)**

| Superior performance | Good performance | Medium performance | Low performance |
|---|---|---|---|
| < 3.5 | 3.5–8 | 8–13 | > 13 |

# Appendix F Measurement of Moisture Sensitivity

## F.1 General

Moisture damage to asphalt is caused either by loss of cohesive strength of the binder, or by a loss of adhesion or bond between the binder and the aggregate surface, in the presence of moisture and is commonly referred to as stripping. Stripping of asphalt requires the presence of water or moisture in the pavement and is normally highly load and temperature associated. It can occur in a number of ways and the three main mechanisms of disbonding are referred to as displacement, detachment and film rupture.

| | |
|---|---|
| Displacement | Displacement is when binder adhering to the aggregate surface is removed by water. In this type of stripping, free water moves to the aggregate surface through a break in the binder coating. The break may be from incomplete coating during mixing or from binder film rupture. |
| Detachment | Detachment is the separation of the binder from the aggregate surface by a thin film of water with no obvious break in the binder film. The binder film can be peeled away cleanly from the aggregate. |
| Film rupture | Film rupture actually initiates stripping. Rupture of the binder film on the aggregate particles is likely to occur under load such as generated by traffic, and has the greatest chance of occurring at sharp edges and corners on the aggregate particles where the binder film is thinnest. |

Although stripping is not a primary distress, it can significantly accelerate the occurrence of the primary distress modes of rutting, fatigue and cracking. It therefore is a factor that should be accounted for in mix design when the primary distress modes are important considerations for the pavement design, particularly where environments of high temperature and heavy traffic loadings are likely to exist.

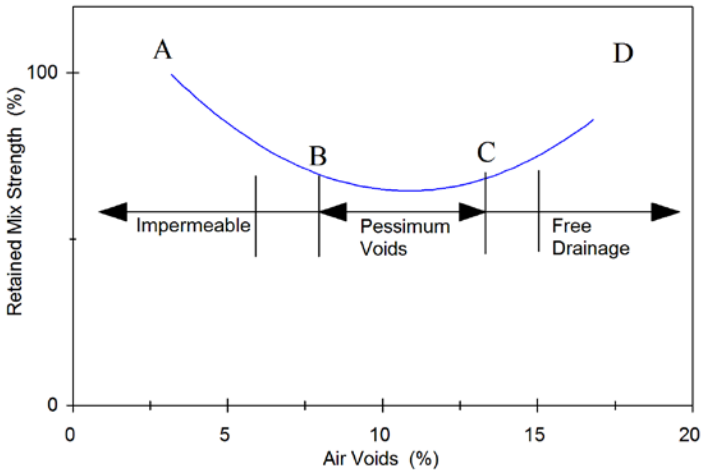
The mechanism of bonding the binder to the aggregate is extremely complex and is affected by aggregate surface chemistry. Substantial differences affecting bonding chemistry or adhesion can occur between aggregates.

If there are a number of sources of aggregate available, then a screening test is desirable to select the aggregate having the best compatibility with the binder for adhesion stability. The American Strategic Highway Research Program (SHRP) research work has developed the net adsorption test for this purpose but further development and validation work is required before general acceptance of this test is expected.

Terrel and Shute (1989) advanced the concept of 'pessimum' void content for stripping. Figure F 1 shows the general relationship between air voids and relative strength of hot mix asphalt following water conditioning. The amount of strength loss depends upon the amount and nature of the voids. As shown in the figure, at less than 4% voids, the mixture is virtually impermeable to water, becoming virtually unaffected.

Unfortunately region B to C is where many pavements are constructed. As the voids increase to D and beyond, the mix strength becomes less affected by water because the mixture is now free draining. The region B to C can be called pessimum void content because it represents the opposite of optimum for most properties. The objective in proper mix design and compaction control procedures is to stay out of the pessimum void range to minimise stripping problems.

**Figure F 1: Concept of 'pessimum' voids**




The asphalt stripping test (AASHTO T 283-07), commonly known as the modified Lottman test, is the basis for the preparation of the Austroads moisture sensitivity test AGPT/T232. Though not totally successful in the prediction of stripping in asphalt pavements, the test is regarded by many as the best test currently available and is the preferred test resulting from SHRP.

## F.2 Specimen Requirements

Moisture sensitivity evaluation requires that two sets of triplicate specimens be tested and they should be essentially right cylinders with a height of 65 ± 1 mm for 100 (± 2) mm diameter specimens and a height of 85 ± 1 mm for 150 (± 2) mm diameter specimens. Specimens with a maximum particle size greater than 20 mm and less than 40 mm have to be nominally 150 mm diameter. Specimens with a maximum particle size less than or equal to 20 mm can be either 100 or 150 mm in diameter, with 100 mm diameter preferred.

Specimens of other diameters may be tested but the height-to-diameter ratio should be maintained at around 0.5. If other diameters are to be tested then special loading platens will be required. The size of the loading platens should cater for the maximum thickness permitted and the radius of curvature should match the diameter of the specimens. The contact width of the loading platens should be 12.5% of the specimen diameter. It should be noted on the test report that the specimens were not of a standard configuration.

Moisture sensitivity specimens should be carefully prepared in order to get reproducible results. As-moulded gyratory specimens are suitable for testing without any further preparation. Should the specimens need some preparation (e.g. cores from pavements) then a jig to hold the specimen for cutting with a power saw is invaluable because it will enable operators to produce specimens to the required geometry without further preparation. Time spent making and installing a jig will be quickly repaid by the saving in time in correcting poorly cut specimens.

Cores taken from a pavement should consist of a single layer of asphalt. Frequently, cores will have an undulating surface due to instability of the coring device. A group of cores with this defect often have a large scatter in moisture sensitivity due to 'noise' in the LVDT signal. This noise is related to movement of the cores during loading and unloading. Operators should take care when positioning cores to achieve the maximum stability on the loading platens and take extra care in fitting the LVDT yoke.

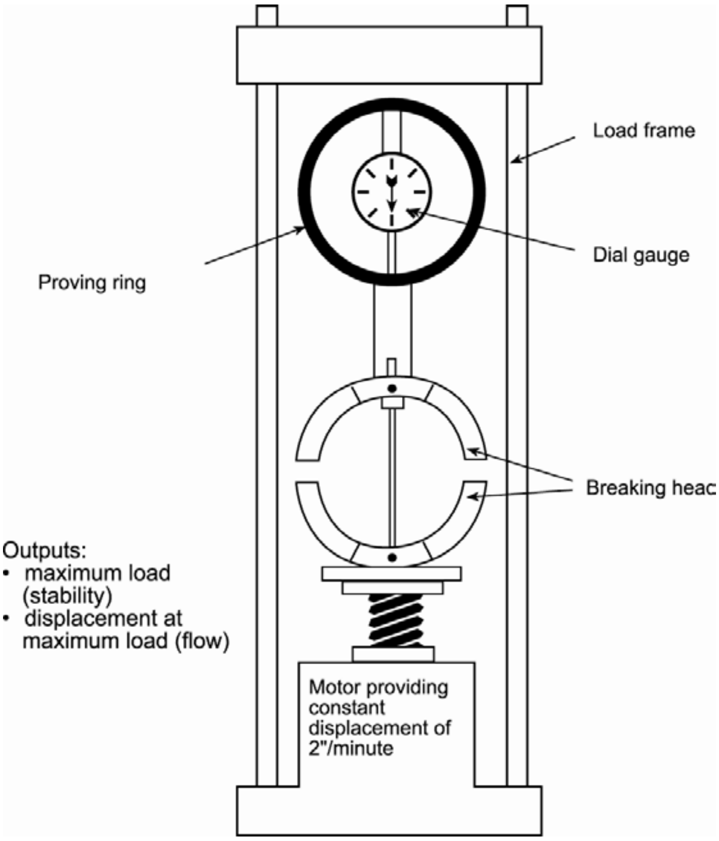
## F.3 Equipment

The test equipment consists of a load frame that enables forces up to 22 kN (a Marshall test machine is suitable, Figure F 2) to be applied to cylindrical specimens at a rate of travel of 51 mm per minute. The maximum load is measured and the specimen is loaded until failure.

Vacuum pumps and vacuum vessels are required to obtain the required degree of partial saturation. The vacuum pump normally used for determining the maximum density of an asphalt mix will suffice for this aspect of the test.

The optional freeze-thaw cycle was designed to utilise a domestic freezer unit.

**Figure F 2: Marshall test rig**




## F.4 Standard Procedure

The Austroads S*tripping potential of asphalt: tensile strength ratio* (AGPT/T232) test is a standardised procedure for evaluating stripping potential. It should be noted that the Austroads procedure has an optional freeze-thaw component.

Tensile strength ratio (TSR) is the test parameter reported for the test. The broken faces are inspected after testing to determine the percentage of stripped aggregate.

Briefly, the test is performed as follows:

- Specimens are prepared from the mix design formula to an air voids content in the range of 7 to 9%. This air voids content is within the pessimum range as described previously. This will require compaction to set density as explained in Section B.6.2.

- The specimens are divided into two subsets of approximately equal voids content. One subset is conditioned by being partially saturated with water in the range of 80 to 85%, while the other subset is conditioned in a dry state. A further two specimens may be required in order to establish the partial saturation conditions that need to be applied to ensure that the correct degree of saturation is attained. There is an optional freeze-thaw cycle permitted that will in some instances decrease the tensile strength of the conditioned subset.
- The tensile strength of each specimen within a subset is determined by the tensile strength test. The potential for damage by moisture is indicated by the ratio of the tensile strength of the moisture-conditioned subset divided by that of the dry subset expressed as a percentage.
- The broken faces of all specimens are visually assessed to determine if the coarse and fine aggregates show evidence of minimal, moderate or severe stripping.

A minimum TSR value of 80% is used in a number of specifications for the acceptance of an asphalt mix having a satisfactory resistance to stripping.

## F.5 Use of Additives

When alternative aggregates are not available that can produce an asphalt mix with TSRs above the specification limit, additives can be added to the asphalt mix to reduce the potential for stripping. The mix design procedure is the same and the TSR values need to exceed the specification limits with the additive included. Optimum values are normally obtained by varying the percentage additive and performing the asphalt stripping test.

Overseas and Australian experience shows that the addition of hydrated lime can be the most effective method. Typical amounts are 1 to 2% of the total mix by mass.

# Appendix G Measurement of Fatigue

## G.1 Introduction

Fatigue of an asphalt mix is a very important property since it relates to the ability of a mix to withstand cracking under traffic loading. Whilst the importance of fatigue has been recognised for a long time, suitable and affordable equipment to measure fatigue has only recently become widely available. In the absence of this equipment, for a given mix type, a minimum binder content or film index has normally been specified to ensure adequate fatigue resistance. Film index calculations will be retained as a quick check to avoid producing mixes likely to fatigue prematurely under the action of traffic.

The procedure described here is available as Austroads test method AGPT/T233.

## G.2 Developments in Measurement of the Fatigue of Asphalt Mixes

Fatigue characterisation of asphaltic mixes has historically been restricted to the research arena for two reasons:

- equipment unavailable/unaffordable
- lengthy test duration.

Development of an Australian manufactured pneumatic test device has enabled fatigue characterisation to be carried out on a more routine basis than was possible in the past. The Austroads test method has been limited to one million cycles (approximately one-day duration) when determining the characteristic fatigue value. The test duration can be longer if required for research studies.

The Austroads procedure was based on the SHRP M-009 (Strategic Highway Research Program 1994) test procedure. Testing is carried out under controlled strain at 20 °C with continuous haversine loading at 10 Hz. When determining the characteristic fatigue performance, the strain level is fixed at 400 $\mu\varepsilon$. Testing is normally continued until the mix stiffness is reduced to half its initial value. This is denoted as the fatigue life of the mix. This measure of fatigue life can be used to rank fatigue performance of candidate mixes.

However, some mixes may not reach the point where the mix stiffness is half the initial value within one million cycles. In these cases, the fatigue performance is expressed as the percentage drop in mix stiffness from the initial mix stiffness.

A more extensive fatigue characterisation method involves testing triplicate beams at three strain levels, typically in the range 300 to 900 $\mu\varepsilon$. Tests are usually continued until the mix stiffness reduces to half the initial mix stiffness (i.e. some tests will be expected to require more than one million cycles). Testing of nine beams under these conditions can be quite lengthy. The mean fatigue lives are then plotted on a log strain versus log cycles graph and the line of best fit drawn. The strain corresponding to one million cycles is determined by interpolation (or by extrapolation from some extremely fatigue resistant mixes). The data can be used as a more reliable ranking procedure for candidate mixes or can be used in pavement design, and to make predictions about the life of pavement structures if suitable fatigue life prediction models are available.

The fatigue of an asphalt layer in a pavement is influenced by both the composition of the mix and the pavement configuration. To gather sufficient information to make predictions of the fatigue performance of a mix in a pavement, the mix must be tested at a minimum of three strain levels. It is recommended that a strain level of 400 $\mu\varepsilon$ is used for one set of triplicates and the strain level for the second and third set of triplicates should be such that failure at one million cycles can be interpolated.

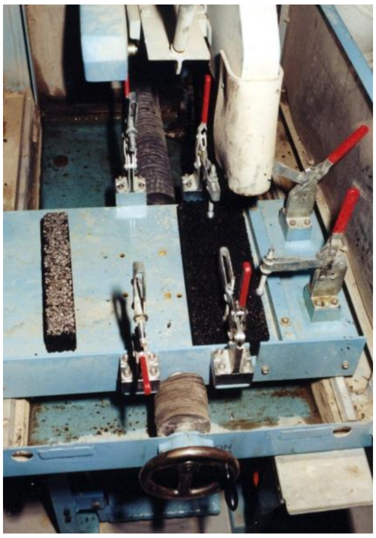
## G.3 Specimen Requirements

Test specimens of two sizes can be used in the test. The larger size (length 390 ± 10 mm) is the preferred geometry for reasons of improved precision. A minimum of three test specimens should be prepared at any one time to enable a reliable test result to be derived. Test specimens should be uniform in appearance and free of any notches on the surface as this can affect results. Specimens may be laboratory prepared or cut from the pavement, provided that there is sufficient depth of asphalt in a single layer.

In laboratory preparation of specimens, a slab of asphalt mix is compacted using a suitable device which ensures uniform compaction throughout the length of the slab and preferably simulates field compaction. Currently, specimens are manufactured using either a small ‘footpath’ style self-propelled roller or a laboratory compactor with a rolling curved foot (simulating the effect of a segment of a steel-wheel roller). The size of the compacted slab should be large enough to ensure that at least three specimens can be prepared from it, after material at the edges is discarded. The slab is sawn with a diamond saw (Figure G 1) to produce cut surfaces on all four sides.

Fatigue resistance is dependent upon the air voids content of a specimen and, for standardised testing, it is recommended that an air voids content of 5% be used. Specimens need to be brought up to the testing temperature and conditioned for a period at the test temperature to disperse any stresses due to handling. Fatigue testing can be greatly influenced by micro-cracks induced in the specimens due to careless handling. It is important that fatigue specimens are stored on a flat, rigid surface until they are placed in the test frame.

**Figure G 1: Preparation of fatigue beam – cutting of beam to size with saw**



## G.4 Equipment

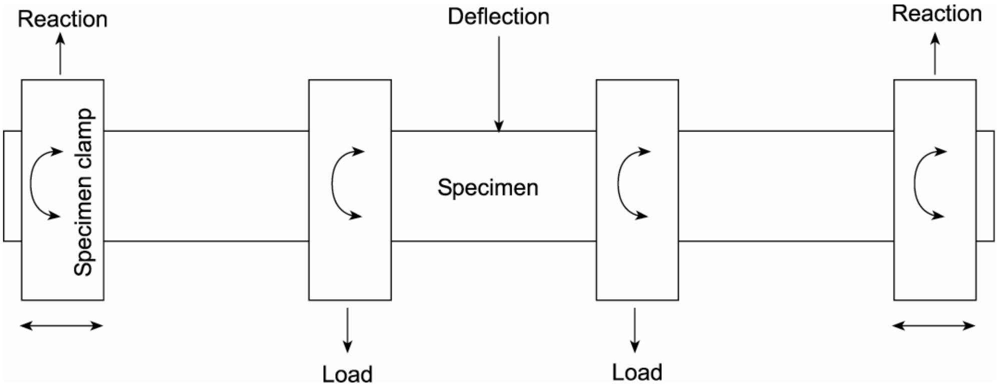
The Austroads fatigue test is commonly referred to as a third-point loading test or a four-point bending beam test. This confusing terminology arises since the test beam is held at four points along its length while it can also be described as being divided into thirds by the loading clamps. This is shown diagrammatically in Figure G 2. The ends are held to prevent vertical or horizontal movement while permitting rotation and the load is applied through the two mid-supports. The principle of the test is to induce a uniform bending moment and hence constant stress regime in the mid-third portion of the beam. Deflection of the beam is measured in the middle of the beam relative to the end restraints.

Equipment required for measurement of fatigue is as follows:

- test system comprising closed loop digital control testing machine, complete with beam cradle, load cell, displacement transducers, control and data acquisition system, and personal computer
- temperature-controlled cabinet for enclosing beam cradle
- dry, clean air supply with minimum of at least 700 kPa pressure

- temperature measuring device embedded in a dummy asphalt sample at the same level in the cabinet as the sample being tested
- callipers and ruler for measuring beam dimensions to nearest 0.1 mm.

**Figure G 2: Diagram of four-point beam bending test**




***Test procedure***

The following instructions relate specifically to a MATTA fatigue tester (Figure G 3) but the general principles apply to all fatigue testing:

- Allow specimens to dry to constant mass on a flat, rigid surface. Plywood of 10 mm thickness has been found suitable for this. Drying can be accelerated by placing in a fan-forced oven at a temperature not exceeding 40 °C.
- Adjust temperature of the cabinet to ensure that the temperature of a conditioned dummy asphalt sample reads 20 °C. It is important that the dummy sample should be positioned in the cabinet close to the beam cradle to eliminate any problems with uneven temperature distribution within the cabinet.

  (Note: A temperature of 20 °C is for standard test conditions; other test temperatures (5 to 20 °C) can be used if the effect of test temperature on fatigue is to be investigated.)
- Measure specimen dimensions and record them.
- Condition the test sample for a minimum of two hours at test temperature. Ensure the sample rests on a flat surface during this conditioning period.
- Follow manufacturer's instructions for enabling the air supply and software.
- Insert the sample into beam cradle by following manufacturer's instructions.
- Enter set-up parameters on the computer screen. For both pulse width and pulse repetition, select 100 ms for both as this will give continuous loading at 10 Hz. The strain level can be set in the range 100 to 900 $\mu\varepsilon$ if no other information is available. Set conditioning pulses to 50. Enter other information as required.

  (Note: At least three strain levels are needed to characterise the fatigue properties of a mix.)
- Allow the specimen to condition in the cradle for at least 10 minutes before commencing the test.
- Run the test. The test will stop after the 50 conditioning pulses. Press 'Enter' to accept the nominated termination stiffness.
- Print the test report at the end of testing.
- Test the other specimens and report results as per the test method.

**Figure G 3: MATTA beam fatigue jig**


***Test outputs***

Test outputs include:

- initial strain
- flexural stiffness
- fatigue life
- phase angle
- dissipated energy per loading cycle
- cumulative dissipated energy at fatigue failure.

The stresses and strains induced in the extreme fibres of the test specimen are given by Equations A14 and A15 and the flexural modulus is given by Equation A16.

Extreme fibre stress:

$$\sigma = \frac{3a * P}{w * h^2} \qquad \text{A14}$$

Extreme fibre strain:

$$\varepsilon = \frac{12b * \delta}{3l^2 - 4a^2} \qquad \text{A15}$$

Flexural stiffness:

$$S_{mix} = \frac{\sigma}{\epsilon} \qquad \text{A16}$$

where

P = applied force (in Newton)

h = beam thickness (in mm)

a = beam length between supports (in millimetres) (118.5 mm = $^{l}/_{3}$)

w = beam width (in mm)

l = length of beam between outside clamps (in mm)

$\delta$ = displacement of beam (in mm)

***Calibration of test equipment***

The first level of calibration involves calibrating the measuring devices. This includes load cell and displacement transducers.

A second level of calibration involves the use of a reference test beam (of certified static modulus) to be run on the test equipment. The aim is to compare the measured modulus with the certified level. This form of testing should be done at least once monthly when the machine is used regularly.

## G.5 Monitoring of Test Temperature

Temperature is one of the most significant factors affecting the fatigue of asphalt. It is essential that the temperature of the test specimen be monitored and controlled to within 0.5 °C. It is likely that testing for the determination of a standard quality indicator value will be performed at 20 °C. Other temperatures may be used as required but the temperature must be accurately controlled.

Monitoring of the test temperature is done using a pair of temperature probes embedded in a dummy specimen rather than the temperature cabinet display. The temperature cabinet should be adjusted so that the temperature of the dummy specimen (adjacent to the test specimens) is controlled to within the prescribed tolerances.

If shelves are installed then the temperature gradient within the temperature cabinet should be examined. The installation of baffles may create a more homogeneous temperature environment within the cabinet.

## G.6 Interpretation of Results

Test results should include at least one triplicate group at 400 $\mu\varepsilon$ and, if appropriate, additional triplicate groups at other strain levels so that the strain level necessary to cause failure at one million cycles can be interpolated as follows:

- number of cycles to failure for a strain level of 400 $\mu\varepsilon$
- strain level required to fail a beam in one million cycles and the slope of the line of best fit.

The most appropriate measure or measures will depend on whether the testing is used to simply rank candidate mixes or a prediction of pavement performance is required. Table G 1 gives typical values.

**Table G 1: Typical fatigue values (cycles to failure and % decrease in initial modulus)**

| Highly modified PMB asphalt | Moderately modified PMB asphalt | Lightly modified PMB asphalt and superior conventional bitumen asphalt | Conventional bitumen asphalt |
|---|---|---|---|
| $> 10^7$ | $10^6$–$10^7$ | $1 \times 10^5$–$10^6$ | $< 1 \times 10^5$ |
| > 35 | 35–50 | 50 | 50 |

## G.7 Factors Affecting Fatigue Performance

Major factors influencing fatigue performance in laboratory tests include:

- air voids content
- mode of loading
- mixture variables (particularly volume of binder).

***Mode of loading***
Two modes of loading are generally used for laboratory characterisation of fatigue performance. One method uses controlled stress and the other uses controlled strain. The two methods may give different results. The controlled strain method is more applicable for thin asphalt layers (< 80 mm) where the addition of the asphalt layer will not appreciably affect the deflection of the pavement under traffic. The controlled stress mode is more applicable for thick asphalt layers (> 150 mm) where the stiffness of the asphalt layer will affect the pavement deflection. The controlled strain method of measurement is generally used in Australia since the majority of asphalt surfacings are relatively thin.

***Effect of mixture variables on fatigue performance***
The effect of mixture variables on fatigue performance depends on the mode of loading. Table G 2 shows indicative trends resulting from an increase in the mixture variable. The information is applicable to the controlled strain mode of testing as used in the Austroads method. Results may be different for some of the variables if a different mode of testing, e.g. controlled stress, is employed.

Flexural stiffness may be different to resilient modulus values even when measurements are made at the same temperature and loading time. In the flexural stiffness calculation there is no assumption made of Poisson's ratio, as is the case for the resilient modulus test, and also the mode of loading is different.

Laboratory fatigue life results can be used to rank materials or can be used in pavement design. For ranking purposes, comparison of fatigue life at the same strain level is a suitable means of comparing relative fatigue performance. When large differences exist in the stiffness of materials, this approach may be incorrect due to different strain levels which pavement structures may undergo.

Laboratory fatigue data may be used in pavement design. A shift factor is normally applied to laboratory data to account for the higher fatigue life encountered in the field. This increase in field fatigue life is attributed to factors such as rest periods, traffic wander and periodic healing. The magnitude of the shift factor has to be determined from comparison of laboratory data with field performance. Values in the range 10 to 100 times have been reported.

A summary of factors affecting the fatigue life is given in Table G 2.

**Table G 2: Effect of increasing mixture variable on fatigue life and flexural stiffness**

| Increasing mixture variable | Effect on fatigue life | Effect on flexural stiffness |
|---|---|---|
| Binder content | Increase | Decrease |
| Binder viscosity | Decrease | Increase |
| Compaction level | Increase | Increase |
| Grading coarse to fine | Increase | Decrease |
| Temperature | Increase | Decrease |

# Appendix H Measurement of Particle Loss

## H.1 Introduction

An abrasion loss test has been introduced into Australian mix design procedures to cater for those mixes that fail by loss of cohesion between the binder and the aggregate. Open graded asphalt is the main mix type that is susceptible to this type of failure and the particle loss test (AGPT/T236) is used to assess this property of candidate mixes.

The test measures the abrasion losses when cylindrical specimens are subjected to wear simulated by tumbling them in a Los Angeles abrasion device (Figure H 1). Testing is normally undertaken on dry samples although the test method also provides for testing of specimens conditioned by a similar procedure to that used in the moisture sensitivity test.

## H.2 Specimen Requirements

The particle loss test requires that triplicate specimens be tested and they should be essentially right cylinders with a height between 50 and 70 mm for 100 (± 2) mm diameter specimens and a height between 70 to 90 mm for 150 (± 2) mm diameter specimens. Specimens with a maximum particle size greater than 20 mm and less than 40 mm have to be nominally 150 mm diameter. Specimens with a maximum particle size less than or equal to 20 mm can be either 100 or 150 mm in diameter, with 100 mm diameter preferred. Specimens of other diameters may be tested but the height to diameter ratio should be maintained at around 0.5.

Test specimens should be carefully prepared in order to get reproducible results. As-moulded gyratory specimens are suitable for testing without any further preparation. Should the specimens need some preparation (e.g. cores from pavements) then a jig to hold the specimen for cutting with a power saw is invaluable because it will enable operators to produce specimens to the required geometry without further preparation. Time spent making and installing a jig will be quickly repaid by the saving in time in correcting poorly cut specimens. Cores taken from a pavement should consist of a single layer of asphalt.

Bulk density must be determined before particle loss testing as the specimens will be irreversibly damaged during testing. If the cylinders need to be prepared before testing (i.e. cores) then this should be noted on the results sheet. Specimens that are to be tested without conditioning should be dried back (in an oven set to a maximum of 40 °C) to constant mass before proceeding. Specimens that are to be conditioned can proceed with the conditioning protocol.

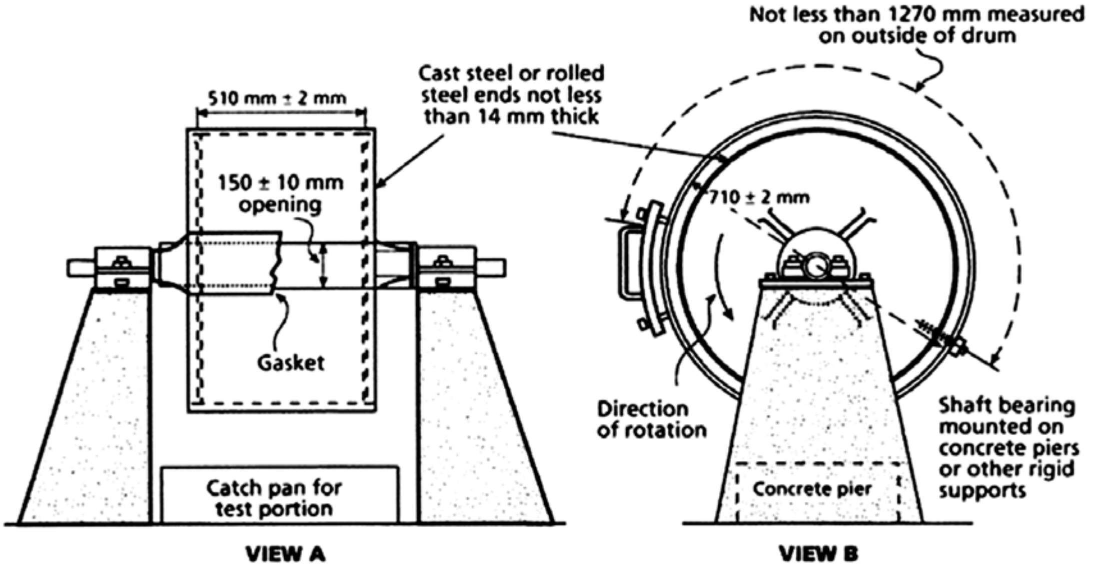
The air voids contents of the specimens for testing will depend upon the type of mix undergoing testing. Dense graded asphalt and stone mastic asphalt should be tested with an air voids content of 5% while open graded asphalt should be tested at the design voids (usually in excess of 20%). Fine gap graded asphalt is not normally subjected to the test.

## H.3 Equipment

In order to condition the specimens it is necessary to provide a vacuum and desiccator as well as water baths (see Appendix F on moisture sensitivity testing).

A Los Angeles abrasion device as specified in AS 1141.23 is required without the steel balls (Figure H 1).

**Figure H 1: Los Angeles abrasion device complying with AS 1141.23**




Test specimens are weighed prior to placing them in the Los Angeles abrasion device and this is known as the initial mass. In the case of conditioned specimens the dry mass is used as the initial mass. Single specimens are then placed in the tumble drum and tumbled for 300 cycles (without the steel balls) at 25 °C. The mass of the largest fragment is recorded as the final mass. Conditioned specimens will need the fragment to be dried back to constant mass before determining the final mass.

The abrasion loss is expressed as a percentage loss and is determined using Equation A17.

$$\text{Abrasion loss} = \frac{\text{initial mass} - \text{final mass}}{\text{initial mass}} * 100 \qquad \text{A17}$$

The mean abrasion loss of the triplicate specimens is determined and recorded as the abrasion loss for the candidate mix. Limits have been set for dense graded, stone mastic and open graded asphalt mixes and these are shown in Table H 1. No limits are available for fine gap graded asphalt.

## H.4 Monitoring of Test Temperature

Temperature is a significant factor affecting the particle loss test. It is critical that the temperature of the test specimen be monitored and controlled to 25 ± 0.5 °C. It is necessary to control the specimen temperature in either a water bath or a temperature cabinet and the Los Angeles abrasion device should be within 3 °C of the test temperature. Other temperatures may be used as required by research needs but temperature must be accurately controlled.

Monitoring of the test temperature is done using a pair of thermometers embedded in a dummy specimen rather than the temperature cabinet display or by the temperature of the water bath. The temperature cabinet should be adjusted so that the temperature of the dummy specimen (adjacent to the test specimens) is controlled to within the prescribed tolerances.

If shelves are installed then the temperature gradient within the temperature cabinet should be examined. The installation of baffles may create a more homogeneous temperature environment within the cabinet.

## H.5 Interpretation of Results

Typical limits for open graded asphalt are shown in Table H 1. The values in Table H 1 apply to the maximum losses for a triplicate group. If an individual specimen result is greater than the permitted mean for the mean of the triplicates by more than 15% then the results are deemed to be invalid and the testing repeated.

**Table H 1: Provisional information on abrasion loss**

| Mix type | Maximum abrasion loss (%) | |
|---|---|---|
| | **Unconditioned** | **Conditioned** |
| Open graded | 20 | 30 |

## H.6 Effect of Variables on Particle Loss

The effect of temperature on particle loss was considered in Section H.4. Other variables also affect particle loss and these are briefly discussed below.

***Binder***

The cohesive and adhesive properties of the binder have a marked influence on the test results. PMBs are likely to produce mixtures with improved resistance to loss of particles.

The quantity of binder used also affects particle loss. Within the normal range of binder contents (say 3 to 10% by mass) the greater the binder content the less particles will be lost.

***Aggregate***

Aggregate quality will affect the particle loss. Aggregates with a strong affinity for bitumen and rough surface texture will provide greater resistance to abrasion loss than mixes made using smooth aggregate or aggregates with weak affinity for bitumen.

The cleanliness of the aggregates affects the particle loss. Dusty aggregate or aggregate containing deleterious materials will lose more particles than a mix made from the same aggregate that had been cleaned and deleterious materials removed.

A summary of factors affecting particle loss are given in Table H 2.

**Table H 2: Effect on resistance to particle losses**

| Variable | Resistance to particle loss |
|---|---|
| Increased binder content | Increase |
| Increased binder cohesion | Increase |
| Increased compaction level | Increase |
| Increased temperature | Reduce |

Austroads' Guide to Pavement Technology Part 4B: Asphalt provides an introduction to the nature of asphalt as a material and its application in road pavements. Asphalt is widely used in the construction and surfacing of roads in Australia and New Zealand. The properties of asphalt are complex and its performance requirements vary considerably with its application. Further publications in the Guide to Pavement Technology provide supporting detail for the placing of asphalt as well as the selection of materials for particular applications.

**Guide to Pavement Technology Part 4B**

4B

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