Selection and Design of Flexible Pavements

2002

AUSTRALIAN ASPHALT PAVEMENT ASSOCIATION
Cover photographs
Main photo: an asphalt highway carves a flexible pathway through scenic countryside.
Small photos: asphalt arterials carry a punishing load (left) and local pavements cater for a mix of private and light commercial vehicles. Photos courtesy of VicRoads.

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While the information given in the Guide is considered to represent best practice at the time of publication, as pavement technology is in a state of continuous improvement, it will no doubt be improved upon in the future.
Selection and Design of Flexible Pavements

2002
PREFACE

This Guide provides assistance in the selection, specification and design of flexible road pavements for a variety of applications. It brings together information on design, construction, performance and maintenance on a wide range of flexible road pavements with the aim of promoting selection, design and construction of pavements that will provide sound long-term performance and low whole-of-life costs.

The guide contains a number of charts that provide typical design thicknesses and compositions for a number of different types of flexible pavements. These charts have been prepared using the Austroads mechanistic analysis procedure for a specific set of input parameters and performance relationships and these designs should be used as preliminary designs only. Detailed designs, utilising job-specific input parameters and performance relationships and tempered by local experience should be prepared by an experienced pavement designer.
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1. INTRODUCTION

The purpose of this Guide is to assist in the selection, specification and design of flexible road pavements for a variety of applications.

It provides guidance on layering, composition, and construction and maintenance issues relating to a range of flexible pavements, as well as typical pavement thickness and compositions for specific situations.

The pavements covered by this Guide are those which are subject to trafficking by heavy commercial vehicles and which have load associated distress as the primary distress mode. For the design of light-duty pavements such as those subjected to pedestrian traffic, local access roads, residential driveways, car parks, cycleways etc., the AAPA Guide to the Design, Construction and Specification of Light-Duty Hot-Mix Asphalt Pavements (2002) may be used. Further information may also be found in APRG Report 21 (1998) – A guide to the design of new pavements for light traffic – A Supplement to Austroads Pavement Design.

The information contained in this Guide is intended to supplement and assist in the effective use of the Austroads Guide to the Structural Design of Road Pavements by providing information on current developments and good practice which will lead to pavements with sound long-term performance and low whole-of-life costs.

It is intended that the typical thicknesses and compositions provided in this Guide should be used at the conceptual, or preliminary, design stages. It is not to be used in lieu of detailed pavement design procedures that require consideration of site-specific traffic, climate and materials data. Detailed design should be undertaken using guidelines such as the Austroads Guide to the Structural Design of Road Pavements.

It should also be noted that the issues discussed in this guide primarily relate to conventional pavements carrying normal road traffic. Although the principles discussed may relate to a broader range of pavements, extrapolation should be made with caution.
2. TYPES OF FLEXIBLE PAVEMENT STRUCTURES

Flexible pavements used in the Australian road network fall into six structural types, as shown in Figure 1. A description of the characteristics and application of each pavement type is provided in Section 4, together with particular factors relating to construction and maintenance that may influence choice of pavement type, layer thickness, materials specifications and whole-of-life costs.

Each of these pavement structures has its own specific characteristics and its own pattern of associated distress. Deterioration of these different types of pavement under the repeated loading of heavy vehicles is due to one or other (and sometimes both) of the following criteria:

- **Permanent deformation of unbound materials and asphalt.** This is due to an accumulation of plastic deformations in these materials.

- **Cracking of bound materials.** Cracking is caused either by fatigue induced by repeated flexure under load or materials-related phenomena such as shrinkage cracking or reflection cracking.

In addition, local environmental effects can cause deterioration such as cracking resulting from thermal changes and oxidation of bituminous materials.

A further flexible pavement type, which is not shown in Figure 1, is a cemented granular pavement with a sprayed seal or thin asphalt surfacing. Such pavements are not generally used for construction of new pavements, largely due to the difficulty in controlling reflection cracking in surfacing materials arising from cracking in cemented base materials. They are more usually associated with pavement rehabilitation using in situ stabilisation techniques. Guidance to rehabilitation using stabilisation is provided in the Austroads Guide to Stabilisation in Roadworks (1998).
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Granular pavement with sprayed seal (see Section 4.2)

- Sprayed seal
- Unbound granular base layer(s)
- Unbound granular sub-base layer(s)
- Working platform
- Subgrade

Granular pavement with thick asphalt
(40 mm < asphalt < 75 mm – see Section 4.4)

- Asphalt wearing and intermediate and base course(s)
- Unbound granular base layer(s)
- Unbound granular sub-base layer(s)
- Working platform
- Subgrade

Granular pavement with thin asphalt
(≤ 40 mm)

- Thin asphalt
- Unbound granular base layer(s)
- Unbound granular sub-base layer(s)
- Working platform
- Subgrade

Deep strength asphalt pavement with granular sub-base (see Section 4.5)

- Asphalt wearing, intermediate and base courses
- Unbound granular sub-base layer(s)
- Working platform
- Subgrade

Deep strength asphalt pavement with cemented sub-base (composite pavement – see Section 4.7)

- Asphalt wearing, intermediate and base courses
- Cemented layer(s)
- Working platform
- Subgrade

Figure 1 - Flexible Pavement Types (see notes overleaf)
Notes for Figure 1:

1. Asphalt wearing course could be dense graded asphalt, open graded asphalt, stone mastic asphalt or fine gap graded asphalt depending on individual job requirements. (Open graded asphalt will require a waterproof membrane or layer beneath it.)

2. Unbound sub-base layers and working platform material may coincide as long as the requirements for the working platform are also met by the sub-base.

3. All pavement types with asphalt on granular materials are part of a continuum of a single pavement type. However, for the purpose of this guide they have been somewhat arbitrarily subdivided into 4 classes to distinguish between their different behaviour, usage, design, construction and maintenance requirements.
3. PAVEMENT SELECTION AND DESIGN

3.1 General

The selection of the type, or types, of flexible pavement to be considered for any particular situation requires due consideration of the operating parameters for the pavement. The variables that require consideration include traffic, pavement materials, subgrade soil conditions, climatic conditions and construction and maintenance practices and constraints. The influence of operating parameters on different pavement types is discussed in Section 4.

The design of a new pavement begins with a decision on the type of surfacing to be employed. The design process should distinguish between the functions fulfilled by the surfacing and those fulfilled by the underlying courses. The choice of surfacing should be based on local experience and objectives related to the use of the roadway, for example, noise, water spray, surface texture and skid resistance, ride quality and service level. A guide to performance characteristics and choice of surfacing types is provided in the Austroads Guide to the Selection of Road Surfacing (2000) and the Austroads/AAPA Asphalt Guide (2002).

The structural design of pavements involves a number of major variables: the subgrade, pavement layer properties, traffic characteristics, environmental conditions and level of acceptable risk (project reliability). Control of moisture through pavement drainage and consideration of the effect of permeability and the moisture sensitivity of materials, are further factors in the structural design of pavements.

The final step in the design process is a check of whole-of-life costs. In addition to construction and maintenance costs, whole-of-life costs may consider delay costs associated with traffic disruption during maintenance and rehabilitation work. A guide to whole-of-life costing is provided in the Austroads Guide to the Structural Design of Road Pavements. AAPA is also in the process of preparing a guide to whole-of-life costing. More guidance on whole-of-life costing is provided in Section 7. The principal steps involved in determining a pavement structure are shown in Figure 2.

![Figure 2: Determining a Pavement Structure](image-url)
3.2 Road Class

The road categories or classes used in Australia are detailed in the Austroads Guide to the Structural Design of Road Pavements. The classes are grouped into the broad categories of rural and urban and are summarised in Table 1.

As the importance of the road increases, the desired project reliability usually rises (i.e., the acceptable level of risk reduces) to reflect the increase in road user costs associated with traffic disruption. The increased road user costs may negate any material and construction savings that may have been obtained by adopting a lesser project reliability. Project reliability needs to be considered when assessing risk as part of the whole-of-life cost analysis.

Table 1. Austroads Road Classes

<table>
<thead>
<tr>
<th>Road Class</th>
<th>Description of Function</th>
<th>Perceived Importance</th>
<th>Project Reliability</th>
<th>Design ESAs Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural Classes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Principal links between major regions and capital cities</td>
<td>Very important</td>
<td>Very high</td>
<td>$10^7 - 10^6$</td>
</tr>
<tr>
<td>2</td>
<td>Linking capitals and key towns, capitals and major regions</td>
<td>Important</td>
<td>High</td>
<td>$10^5 - 10^7$</td>
</tr>
<tr>
<td>3</td>
<td>Linking important centres, Class 1 &amp; 2 roads and rural arterials</td>
<td>Less important</td>
<td>Medium</td>
<td>$10^5 - 10^7$</td>
</tr>
<tr>
<td>4</td>
<td>Provides access to abutting property</td>
<td>Low importance</td>
<td>Low</td>
<td>$10^4 - 10^5$</td>
</tr>
<tr>
<td>5</td>
<td>One type of activity and not Class 1, 2, 3 or 4</td>
<td>Not important</td>
<td>Very low</td>
<td>$&lt; 10^4$</td>
</tr>
<tr>
<td>Urban Classes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Main link that performs massive traffic movements</td>
<td>Very important</td>
<td>Very high</td>
<td>$10^7 - 10^5$</td>
</tr>
<tr>
<td>7</td>
<td>Supplements Class 6 by distributing to local streets</td>
<td>Important</td>
<td>High</td>
<td>$10^5 - 10^7$</td>
</tr>
<tr>
<td>8</td>
<td>Provides access to abutting property</td>
<td>Low importance</td>
<td>Medium</td>
<td>$10^5 - 10^8$</td>
</tr>
<tr>
<td>9</td>
<td>One type of activity and not Class 1, 2, 3 or 4</td>
<td>Low importance</td>
<td>Low</td>
<td>$&lt; 10^8$</td>
</tr>
</tbody>
</table>

Notes:
1. The desired project reliability is the chance that the pavement being considered will carry its design traffic before reaching a terminal level of serviceability, given that:
   - The pavement is designed in accordance with the procedures in this Guide. The pavement is constructed and maintained in accordance with industry standard specifications.
   - Materials used meet the industry standard specification requirements.
   - The desired project reliability is chosen by the designer.
The classifications provided in Table 1 are indicative only. By rationally assessing the risks associated with any type of pavement type and road class, the level of project reliability can be varied to suit individual needs (see Section 7).

### 3.3 Traffic

Traffic loading factors include traffic volume, composition, axle loads, tyre pressures, configuration, speed and road geometry.

The traffic loading used for the designs presented in Section 6 of this Guide are based on Equivalent Standard Axles (ESAs) using a half axle load and a uniform vertical circular contact stress of 750 KPa. This essentially represents traffic travelling at a uniform speed. Also, the design performance criteria used relate primarily to highways and so the implicit traffic wander inherent in these criteria relate to lane widths of about 3.2 m to 3.5 m.

There are a number of situations where other loading conditions may exist, including:

- Shear forces where braking, acceleration, hill climbing and tight cornering occur
- Centrifugal forces on roundabouts and tight corners which can significantly increase the loading on one side of vehicles
- Dynamic loading as a result of pavement surface roughness
- Increased concentration of vertical loads where channelisation occurs such as with some traffic calming measures.

Where one or more of these situations occur, some adjustment may be required in the designs presented in Section 6 to reflect the additional loadings imposed on the pavement.

Traffic loading and conditions at the site will also determine the characteristics of the wearing surface as referred to in Section 3.4.

### 3.4 Subgrade and Working Platform

The subgrade is the trimmed or prepared portion of the formation on which the pavement is constructed. It is often of a poor and variable quality and can consist of a variety of materials from heavy clay, to sand, weathered rock or even imported fill. Variable subgrade strength and condition can cause significant problems in the construction of the overlying pavement. It is widely recognised that capping the subgrade with a uniform platform of select material is critical to good long-term pavement performance. The provision of a uniform, high strength platform over the exposed subgrade is recommended for all pavements subject to trafficking by heavy commercial vehicles. This enables:

- Access for pavement construction equipment and minimises loss of construction time resulting from wet weather
- Facilitates compaction of pavement layers (particularly stabilised materials or asphalt)
- Uniform pavement conditions to be achieved during construction and subsequent use.

(For light-duty pavements the working platform is sometimes omitted. In these circumstances guidance for design may be found in the AAPA Guide to the Design, Construction and Specification of Light-Duty Hot-Mix Asphalt Pavements (2002) and in APRG Report 21 (1998) – A Guide to the design of new pavements for light traffic – A Supplement to Austroads Pavement Design.

If suitable select material is not readily available, the subgrade can be improved by stabilisation or modification to provide the working platform. Chapter 5 of the Austroads
Guide to the Structural Design of Road Pavements provides guidance in this regard. Many road agencies have preferences for different treatments for the improvement of subgrade and provision of select fill or capping layers as working platforms.

For the purpose of the pavement thicknesses presented in this Guide, subgrade support values of California Bearing Ratio (CBR) of 2, 5 and 10 have been utilised as representative values. In practice, other values of subgrade support values may apply, which will require pavement thickness to be adjusted accordingly.

Subgrades with strength lower than CBR 2 usually require improvement to increase their bearing capacity, especially for pavements intended to carry significant traffic volumes. Table 2 provides suggested treatments for subgrades to provide uniform support.

### Table 2. Treatments to Provide Uniform Support

<table>
<thead>
<tr>
<th>Existing design subgrade conditions</th>
<th>CBR &lt; 2*</th>
<th>2 ≤ CBR ≤ 5*</th>
<th>CBR &gt; 5*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment for subgrade</td>
<td>Special treatment required, e.g. lime stabilisation</td>
<td>Rip and compact minimum 150 mm to ensure CBR 2 exists</td>
<td>Rip and compact minimum 150 mm to ensure CBR 5 exists</td>
</tr>
<tr>
<td>Select layer</td>
<td>Special treatment required</td>
<td>Add 300 mm CBR 15**</td>
<td>Add 150 mm CBR 15**</td>
</tr>
</tbody>
</table>

Notes:
* CBR values are design values (long term). CBR values at construction are usually substantially higher.
** CBR values based on soaked values.

It should also be noted that the adopted supporting subgrade conditions should be verified to an adequate depth to ensure that support does exist. Typically the level of investigation of the subgrade should be around 700 mm to 1200 mm below subgrade level depending on the importance and level of service required of the road.

Clay subgrade materials should be compacted close to their long term equilibrium moisture content to avoid shrinkage and volume change. Subgrade materials must also be protected against moisture change (see section 3.7).

### 3.5 Material Types

The nomenclature for flexible pavement materials is provided in Chapter 6 of the Austroads Guide to the Structural Design of Road Pavements.

In broad terms the materials used for the structural design of pavements are as follows:

- **Subgrade**
  - Existing in situ soil
- **Unbound granular materials, including**:
  - Crushed rock
  - Gravel (including capping or select layer)
- **Mechanically stabilised materials**
- **Chemically modified materials**
- **Lightly modified materials, including cementitious and bituminous binders**.
Selection and Design of Flexible Pavements

- Cemented materials, including those stabilised with:
  - Lime
  - Cement
  - Lime/fly ash
  - Slag
  - Other binders that develop significant tensile strength (e.g., those bound with a combination of bituminous and cementitious binders).

- Asphalt including:
  - Dense graded asphalt (DGA), also referred to as asphaltic concrete (AC)
  - Open graded asphalt (OGA)
  - Stone mastic asphalt (SMA)
  - Fine gap graded asphalt (FGGA).

The selection of binder type can play a significant role in the properties and performance of all of the above asphalt types.

In addition to the above materials, there are a number of thin surfacing types that, while they do not play a part in the structural design of pavements, play an important role in helping to meet the serviceability requirements of pavements as well as aiding pavements in maintaining structural integrity by preventing moisture ingress through the wearing surface. These may include:

- Asphalt
  - Ultra thin asphalt (UTA).

- Sprayed surfacings
  - Prime
  - Primsseal
  - Sprayed seal (SS)
    - Single application seal
    - Multiple application seal
    - Strain Alleviating Membrane (SAM)
    - Strain Alleviating Membrane Interlayer (SAMi)
    - High Stress Seal (HSS)
    - Surface enrichment seal
    - Fibre Reinforced Seal (FRS)
    - Gaxtextile Reinforced Seal (GRS).

- Bituminous slurry seals
  - Slurry seals
  - Cape seals
  - Microsurfacing.

Details of surfacing treatments can be found elsewhere, e.g., Austroads Guide to Selection of Road Surfacings.

3.6 Design Thickness

The design process involves verification that the structure of the road is sufficient to carry the traffic loads over the design period.

The performance of pavement structures is dependent on:

- Limiting the vertical strain at the top of the subgrade to limit subgrade deformation and subsequent roughness in the pavement to acceptable levels.
Selection and Design of Flexible Pavements

- Limiting the horizontal tensile strains at the bottom of asphalt layers and other bound materials layers to control fatigue cracking within these layers.
- Selecting pavement materials that may not suffer significant permanent deformation.
- Achieving a uniform, high quality of pavement construction to ensure that the materials' design parameters assumed in design are realised in the field.

The aim is to determine the minimum thickness that will meet the structural performance criteria while ensuring that the result is compatible with the minimum and maximum thicknesses appropriate to the technical application of the materials comprising each layer of the structure.

3.7 Pavement Drainage

Moisture access by the pavement can be through the pavement surfacing, from the sides or verge or by capillary suction from the pavement foundations.

Moisture ingress into pavements can cause serious damage in terms of:

- Loss of strength and stiffness in subgrade and granular materials
- Pumicing and erosion in cemented materials
- Loss of stiffness and adhesion in asphalt
- Debonding between layers.

When designing a pavement, careful attention should be given to ensure that any permeability reversals between pavement layers are identified and that they are taken into account during the structural design and materials assessment phases. The effects of permeability reversals can be minimised by:

- Provision of pavement drains with free draining outlets within the pavement structure.
- Decreasing the moisture sensitivity of granular materials by either using a better quality material or modifying the material using a cementitious or bituminous binder.
- Ensuring adequate binder is used in cemented materials to ensure durability and minimise erosion at layer boundaries.
- Ensuring asphalt compaction is adequate to minimise interconnecting voids and ingress of moisture.

Pavement drainage is a critical element for the long-term performance of pavements in cuttings or in boxed pavement structures.

Pavement drains can also act as conduits for water infiltration into the pavement as well as for its removal. The interaction of the various layers in the pavement cross section, with any internal drains and drainage outlets, should be reviewed prior to approval for construction.

3.8 Ride Quality

The initial ride quality of a road immediately after construction plays a significant role in determining the life of the pavement and the time before structural rehabilitation occurs. Smooth pavements which do not generate high dynamic loads, minimise the cumulative loading on the pavement over time and hence maximise the serviceable life of the pavement, all other factors being equal.

To achieve a smooth wearing surface it is necessary to control the ride quality of all the pavement layers. As the cost of pavement materials usually increases from the bottom of the pavement up, control of ride quality and levels for all pavement layers makes economic sense and saves expensive corrections near the wearing surface.
4. PAVEMENT TYPES

4.1 General

The general suitability of the various flexible pavement types (illustrated in Figure 1) with respect to road class and typical design traffic loading (in ESAs), is shown in Table 3, where [I] regions are the best perceived application for the pavement type and the [x] regions indicate adequate performance, * regions indicate applications for which the particular pavement type is generally not recommended. In this general overview, there is no discernment based on environmental or other regional factors.

Table 3. Suitability of Pavement Types

<table>
<thead>
<tr>
<th>Situation</th>
<th>Rural*</th>
<th>Urban*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Road Class</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design Traffic (ESAs)</td>
<td>$10^4$</td>
<td>$10^5$</td>
</tr>
<tr>
<td>Granular/sprayed seal</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>Granular/thin asphalt</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>Granular/thick asphalt</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>Deep strength asphalt/aggregate</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>Full depth asphalt</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>Deep strength asphalt/composites</td>
<td>I</td>
<td>I</td>
</tr>
</tbody>
</table>

Notes:
- Pavement types recommended are based on design for free-flowing traffic. For high stress conditions such as turning traffic, accelerating and braking traffic and on steep grades, other considerations may govern.
- This type of pavement can be used successfully in this road class but very good quality control of materials and construction processes, together with good maintenance, are required.
- Generally require high maintenance.
- Usually uneconomic when considered on whole-of-life cost basis.
- May be difficult to achieve satisfactory structural design.

Legend:
- [I] Most suitable
- [I] Adequate performance
- [x] Not recommended
4.2 Granular Pavements with Sprayed Seal Surfacing

General

Granular pavements with sprayed seal surfacing are the major pavement type of rural Australia and are also used in some urban locations. They comprise some 90% of the length of all surfaced roads. In rural situations, they encompass the majority of Class 3, 4 and 5 roads and are even successfully used on roads of Classes 1 and 2 subject to suitable materials and construction and maintenance standards. In urban situations they are used in Classes 8 and 9.

The wearing surface on light and medium trafficked roads usually comprises a single application spray seal, while double application seals are used for heavier traffic applications and areas of greater traffic stress such as intersections and roundabouts.

Light and medium traffic can be defined as follows (from Austroads 1997 Selection and Design of Asphalt Mixes):

- Light traffic: <100 commercial vehicles/lane/day and design traffic <5 x 10^3 ESAs
- Medium traffic: 100 to 500 commercial vehicles/lane/day and design traffic between 5 x 10^3 and 5 x 10^5 ESAs.

The limitations of this pavement type are loss of surface aggregate from sprayed seals in situations involving stopping and turning traffic and inability of unbound granular materials to withstand high traffic loads. Relatively high noise levels may also limit the use of this pavement type.

Design Issues

The mode of structural distress exhibited by these types of pavements is normally deformation or surface rutting, caused by a combination of plastic deformation within the pavement layers and the subgrade.

While the charts for granular pavements in this Guide have been prepared using mechanistic design procedures, the determination of layer thickness is also frequently undertaken using empirical charts based on the CBR of the subgrade and granular layers, and the anticipated design traffic load (AAPA 2002, APRNG 1998, VicRoads 1993 Fig.8.5).

Typical thickness and compositions are given in Section 6, Chart 1(a) and (b).

Construction Issues

A wide variety of granular materials are used depending on availability, traffic requirements and climate. Generally the quality should meet the requirements set down for various traffic levels by the various state authorities (e.g. Queensland Transport 1990, Austroads 1992, VicRoads 1993). Primary measures are grading, durability, hardness of the coarse aggregate and plasticity of the fine fraction.

The stiffness within the pavement structure developed by granular materials at a given level in the pavement is dependent upon the level of compaction, moisture content, support provided by the underlying material and the applied load. The influence of the applied load...
and the distance of the pavement layer from the surface is termed stress dependency. It is important that the layer beneath that being compacted has sufficient density to enable compaction of the overlying layer and sufficient bearing capacity to provide support during service and in higher trafficked situations (Classes 1 to 3) it is essential that an adequate depth of high quality granular base material be used.

Moisture control in granular pavement layers is of prime importance. Premature failure of granular pavements is often the result of high moisture content and saturation of granular layers leading to development of positive pore pressures and reduction in load bearing capacity. It is recommended that crushed rock pavements be dried back to a maximum saturation level of 65%, and gravel pavements to a maximum level of 70%, prior to trafficking. This avoids the possibility of the granular layers becoming unstable as a result of positive pore pressures developing during initial trafficking.

A method for assessing whether this situation is likely to occur is provided in Appendix A. It should be noted that higher compaction standards result in lower void levels within the pavement and higher degrees of saturation for a given moisture content. Drying back is particularly important on heavily trafficked pavements, where a combination of high standards of compaction, low air voids and high traffic loading apply.

Greenfield sites, where the seal is applied some time before opening to traffic, require careful monitoring on opening to traffic.

**Maintenance and Rehabilitation Issues**

Performance of sprayed seal pavements requires regular routine and periodic maintenance to protect the pavement from surface ingress of moisture. Routine maintenance includes crack sealing, repair of surface damage, edge breaks and localized pavement failures, and periodic resurfacing with sprayed seals or other suitable thin surfacing types to maintain the integrity of the surfacing.

Serviceability of the pavement will be affected by increasing surface roughness due to deformation in the supporting layers and subgrade. The life of the surfacing will depend on the traffic levels, the quality of the base layers and the effectiveness of routine maintenance.

Rehabilitation of granular pavements to correct roughness or structural deficiencies, in rural areas where there are no level constraints, is generally undertaken by resheeting with granular material followed by a sprayed seal or using in situ recycling techniques where there is a need to strengthen the pavement or by ripping, recompaclling and rescaling where there is no structural deficiency.
4.3 Granular Pavements with Thin Asphalt Surfacing (Asphalt < 40 mm)

**General**

Granular pavements with thin asphalt surfacing are structurally similar to sprayed seal pavements except that asphalt wearing course is used in place of, or in addition to, the sprayed seal. In this case the asphalt wearing course makes little contribution to the overall strength of the pavement, but provides greater resistance to minor traffic damage as well as a smoother and more durable surface. These attributes make it particularly suited to residential streets and other light traffic urban applications (urban road Classes 8 and 9).

With suitable quality of materials and construction standards, these pavements are sometimes used for urban Class 7 pavements, although they may not provide the same serviceability as more heavily bound pavements (see also construction and maintenance issues, below). They are not generally recommended for urban Class 6 applications.

Thin asphalt surfacing can also be used on rural road pavements (Classes 1-5), where sprayed seals do not provide adequate serviceability, e.g. intersections and other areas of turning traffic, or to provide improved ride quality.

**Design Issues**

The structural design of granular pavements with thin asphalt surfacing is the same as pavements designed for sprayed seal (Section 6, Charts 1(a) and (b)).

While the design procedure is based on limiting vertical compressive strain in the subgrade, there is a possibility for fatigue failure in the asphalt, particularly for higher traffic loadings (more than about $5 \times 10^6$ ESAs). As it is difficult to accurately predict strain levels in thin surfacing layers using existing design models, it is not possible to predict fatigue life. Fatigue life on heavily trafficked roads can, however, be improved by the use of polymer modified binders in dense graded asphalt or the use of stone mastics asphalt mixtures. Such mix types are recommended for thin asphalt surfacing on heavily trafficked pavements (more than about $5 \times 10^6$ ESAs).

**Construction Issues**

Issues relating to construction of granular pavements with sprayed seal surfacing also apply to asphalt surfaced pavements.

Prior to placing asphalt on lightly trafficked pavements (residential streets, carparks etc.) a prime or primercem should be applied to the granular base to ensure asphalt adhesion.

For more heavily trafficked pavements, a sprayed seal (usually 1 mm) should be applied to the granular base prior to the placement of the asphalt layer so as to reduce the chance of moisture ingress into the pavement through the asphalt. Unless compacted to high standards of density, thin layers of asphalt are more permeable than sprayed seals and so provide less moisture protection to the underlying granular base material. Preferably, the sprayed seal should be trafficked for a period of time before placing the asphalt. This assists in confirming that drying back and compaction at the surface of the granular layer has been effective and...
that there are no localised areas of weaker materials that could affect the performance of the asphalt surfacing.

**Maintenance Issues**

On lightly trafficked roads, and provided that there is no deterioration or deformation of the supporting base, pavements with asphalt wearing courses require low levels of routine and periodic maintenance. Asphalt wearing courses will eventually deteriorate due to oxidation and ravelling, at which point it may be restored using another layer of asphalt or any other suitable surfacing treatment such as sprayed seals, asphalt surfacing or slurry surfacing.

On heavily trafficked roads, maintenance may include repair of localised base failures and correction of shape due to deformation or increased roughness. The addition of any further asphalt layers must take account of the influence of pavement deflection and curvature on the potential performance of the asphalt.
Granular Pavements with Thick Asphalt Surfacing
(40 mm < Asphalt ≤ 75 mm)

General

A “thick asphalt surfacing” is defined as an asphalt layer greater than 40 mm, but generally not more than 75 mm, in thickness, placed on a granular base and sub-base. In these pavements the primary purpose of the asphalt is to provide a wearing course and make a small contribution to the structural capacity of the pavement. The granular base layer(s) provide a substantial proportion of the load-carrying capacity and both a deformation and fatigue failure mechanism is possible and therefore both the asphalt and granular base material must be of high quality.

The main application for asphalt on granular pavement is for medium to high traffic urban roads (Class 7). It may also be suitable for rural Classes 1 and 2 depending on actual traffic loads.

Design Issues

Deformation may be due to a combination of asphalt distress or granular and subgrade layer plastic deformation, or a combination of all three distress modes. For high stress situations it may be necessary to incorporate a modified binder in the asphalt to aid in the control of deformation in the asphalt layer or to review the type and nominal size of asphalt mix.

Fatigue cracking failure may occur in the asphalt layer if the underlying pavement deflections are high.

In this type of pavement the traffic load is resisted by both the asphalt and the granular materials, with the amount of load sharing dependent on the specific composition and material characteristics of the pavement.

The balance of asphalt depth versus depth of supporting base material will depend on local cost ratios for the materials and preferred future maintenance regimes. This type of pavement is somewhat difficult to design because of the stress-dependent nature of the granular material. Increases in the thickness of the asphalt layer result in a decrease in the stresses in the granular material. This leads to a decrease in the stiffness of the granular material so the balance between these effects must be considered to optimise the design.

Typical layer thickness and compositions for thick asphalt on granular pavements are given in Section 6, Charts 2(a) & 2(b).

At high stress areas, such as intersections and roundabouts where there are heavy vehicles turning on sharp radii curves, there will be high shear and tension stresses, and increased vertical loads due to centrifugal forces, exerted on the wearing surfaces. Current design methods do not take these forces into account. Such forces can make it difficult to gain adequate performance from thin asphalt wearing courses and a minimum asphalt wearing course thickness of about 70 mm is recommended in such circumstances.
Construction Issues

Since the fatigue life of asphalt is dependent on the support provided by the underlying layers it is important to ensure that granular supporting layers have high stiffness. This is aided by using high quality crushed rock, compacted to modified compaction standards. If crushed rock is used, care must be taken not to place asphalt until the level of moisture saturation in the granular base is less than about 65% (see Appendix A).

Achievement of high standards of ride quality in asphalt layers is assisted where the granular layers are also finished to high standards of shape that allow the asphalt to be placed in layers of uniform thickness. High standards of compaction assist durability and minimise moisture infiltration in asphalt layers.

Depending on the thickness of the asphalt it may be placed in one or more layers composed of one or more asphalt mix types. If an open graded asphalt wearing course is used, the asphalt layer on which it is placed should have a low permeability or otherwise be sealed with a sprayed seal (usually 7 mm).

Maintenance Issues

Deterioration of these pavements is often a combination of deformation and wear of the surfacing materials, deformation of granular base materials, or fatigue cracking of the asphalt layers. Deterioration of surfacing can be corrected with thin, non-structural overlays or by mill and resheet. Where deterioration includes asphalt fatigue cracking or deformation of base layers, rehabilitation may involve a structural overlay or selective strengthening of the pavement using deep patching.

An Austroads Class 7 Road
4.5 Deep Strength Asphalt Pavements (Asphalt > 75 mm)

General

In this case asphalt is used in both the wearing course and base layers to provide a significant proportion of the load carrying capacity, supported by the unbound granular sub-base layer.

These pavements are suited to moderate to heavily trafficked roads including urban Classes 6 and 7, and rural Classes 1 and 2. Advantages include rapid construction, reduced overall pavement thickness, and low maintenance.

Design Issues

In this type of pavement the asphalt provides most of the structural capacity. The term deep strength asphalt is generally used to describe pavements where the total thickness of asphalt is greater than 75 mm. In design terms, thick asphalt, deep strength asphalt and full depth asphalt are part of a continuum where the asphalt is used to provide a greater proportion of the load capacity, and the significance of the granular layer is decreased. The extent to which granular layers are used will depend on the relative cost of asphalt and granular materials, and the need to provide granular capping and sub-base layers to improve bearing capacity of a weak subgrade prior to placing the asphalt.

Failure mechanisms to be addressed in the design process are the same as for thick asphalt pavements, above, and include vertical strain at the surface of the subgrade and tensile strain at the base of the asphalt layer. High strains on the subgrade lead to premature wheel path deformation, while high strains at the base of the asphalt layer leads to fatigue cracking. Design is usually a matter of optimising the thickness of the asphalt and granular layer to avoid both situations and meet the required design life.

The asphalt base may consist of one or more structural layers with or without a specialised wearing course such as open graded asphalt or stone mastic asphalt, depending on the serviceability requirements.

Typical thickness and compositions for thick asphalt on granular pavements are given in Section 6, Charts 2(c) and 2(d).

Construction Issues

Compaction of the asphalt must be such that voids in the asphalt mix and the granular layer are reduced to minimise water penetration and subsequent moisture damage of the pavement structure.

Depending on the thickness of the asphalt, it may be placed in a number of layers composed of one or more asphalt mix types. If an open graded asphalt wearing course is used, the asphalt layer on which it is placed should be a dense mix with low permeability. In some cases it may desirable to seal the surface with a sprayed seal (usually 5 mm or 7 mm).

Larger size asphalt mixes (20 mm and 28 mm, and sometimes 40 mm) are generally used in lower layers but care must be taken to ensure segregation does not occur during transport and placing of the larger mixes. Usually binder content decreases with maximum aggregate...
size and this can make larger stone mixes attractive from a cost point of view. However, these advantages need to be balanced against the difficulty in transporting and laying large stone mixes which are sometimes prone to segregation.

Table 4 provides guidelines for maximum and minimum layer thickness for achieving adequate density and uniformity in the field.

As a general rule, the compacted thickness of asphalt layers should be at least three times the nominal size of the asphalt mix. (The recommended minimum layer thickness has been increased from 2.5 times the nominal mix size as a result of higher density standards and coarser mixes and binders now being regularly used in practice.)

In practical terms, placing is generally limited to a compacted thickness of four or five times the nominal mix size. For a greater layer thickness, it is generally more economical to use a larger size of mix than placing very thin layers, or multiple layers, of smaller nominal sizes. Thicker layers of asphalt assist in achieving high density in asphalt due to the increased workability resulting from retaining heat in asphalt layers. They also provide greater structural capacity through the increased mix stiffness arising from the use of a higher volume of aggregate.

Limiting factors on maximum layer thickness include increased difficulty in maintaining accurate control of surface shape. The number of layers may be influenced by the practicality in achieving the required standards of surface shape and ride quality.

**Maintenance issues**

This type of pavement requires very little routine maintenance and rehabilitation within the pavement design period. Deterioration usually occurs by ageing of the wearing course, or rutting that is restricted to the upper 70 mm or so of the pavement. Thin, non-structural overlays to correct wearing course deficiencies, or replacement of the surfacing materials by milling and resheeting can be performed periodically with minimal disturbance to the road user.

**Table 4: Recommended Asphalt Layer Thicknesses**

<table>
<thead>
<tr>
<th>Nominal Mix Size (mm)</th>
<th>Compacted Layer Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>15 to 20</td>
</tr>
<tr>
<td>7</td>
<td>20 to 30</td>
</tr>
<tr>
<td>10</td>
<td>25 to 40</td>
</tr>
<tr>
<td>14</td>
<td>35 to 55</td>
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<tr>
<td>20</td>
<td>50 to 60</td>
</tr>
<tr>
<td>28</td>
<td>65 to 120</td>
</tr>
<tr>
<td>40</td>
<td>100 to 160</td>
</tr>
</tbody>
</table>

*Note: 1. Segregation in large stone mixes can lead to pockets of higher air voids with increased permeability and reduced asphalt stiffness.*
4.6 Full Depth Asphalt Pavements

General

In a full depth asphalt pavement, asphalt base and sub-base layers provide the total structural capacity of the pavement. Full depth asphalt pavements are relatively quick to build and provide low maintenance and long life in both heavy duty and light duty situations.

Applications are typically urban Class 6 or 7 roads, or rural Class 1 or 2 roads where extremely high traffic loads can be expected.

Full depth asphalt may also be used effectively for some light duty applications (urban Classes 3 and 9) where durability and low maintenance are required. They are particularly effective in commercial applications such as major car parks and industrial premises where minimal disruption due to maintenance is desirable or where rapid construction is required to minimise traffic delays.

Design Issues

Full depth asphalt pavements traditionally consist of a number of layers of structural grade asphalt, with or without a specialised wearing course, depending on the serviceability needs of the pavement.

A more sophisticated approach to designing full depth asphalt pavements has been developed which seeks to design each of the layers within the pavement to fill a specific purpose and so improve the whole-of-life costs. This type of pavement is called the Modified Full Depth Asphalt pavement (MFDA).

A MFDA pavement typically consists of asphalt surfacing and base overlying an asphalt fatigue layer. The asphalt wearing course may be open graded, stone mastic or dense graded asphalt dependent upon the operating requirements. If a rough rugose surface with good noise reduction properties were required then stone mastic asphalt would be selected. Open graded would be used to attenuate noise and spray where this is important and dense graded used for other cases.

If open graded asphalt is used as the wearing surface it is important to provide any underlying asphalt with water proofing by means of use of an appropriate impermeable dense graded mix and/or by application of a spray seal as mentioned above. This will greatly reduce the ingress of moisture into the structural layers of the pavement and hence any possibility of stripping and other moisture related damage occurring in the dense graded material supporting the open graded asphalt.

If open graded asphalt is used as a wearing course it is usually considered as a non-structural layer, i.e. it does not contribute significantly to the structural capacity of the pavement. However, as a result of its finite layer thickness, it does have the effect of distancing the applied wheel loads from the critical pavement design interface (usually the bottom of the fatigue layer) and hence it should not be ignored during the structural design process. It is suggested that the open graded asphalt layer be included in the design but be assigned a low stiffness value.
Selection and Design of Flexible Pavements

The layer directly below the wearing course is generally a dense graded mix, not exceeding 14 mm in size. On heavily trafficked pavements, multigrade or modified binder may be incorporated to reduce the tendency to rut under heavy traffic.

The next layer may consist of a larger stone mix (generally 20 mm) which provides a relatively stiff load bearing layer. Class 600 binder can be used in this layer to help develop stiffness. Guidance for the selection of suitable binders for wearing courses, intermediate and base layers can be found in Table 2.3 and Table 2.4 of APRG 18 (1997).

The bottom asphalt layer is usually termed a fatigue layer and consists of a conventional dense graded mix in which the binder content is increased from 0.5% to 4% by mass. This increases the fatigue resistance of the mix and means that a reduction in total pavement thickness of about 10% to 15% can be realised when compared to standard mixes.

As this mix has higher permanent deformation characteristics than conventional mixes, it is important that its layer thickness be limited to no more than 25%–30% of the total pavement thickness or not exceed 70 mm in thickness to control any propensity for rutting within the pavement. A minimum cover of 125 mm of structural asphalt is also required over the fatigue layer.

Where a fatigue layer is utilised and overlaid by a large stone mix, consideration should be given to incorporating drains in the pavement structure, to enable any moisture trapped at the top of the fatigue layer to be removed.

Typical thickness and compositions for modified full depth asphalt pavements are given in Section 6, Chart 3.

Construction issues

An important issue in construction of full depth asphalt pavements is getting the paving plant onto the site to place the first layer of asphalt. The subgrade must be capable of supporting the paver and spreading trucks as well as providing sufficient support to enable effective compaction of the first layer of asphalt. Modification of the subgrade layer, or provision of a capping layer may be required to be incorporated in the pavement design to provide the necessary working platform.

It must be restated that if open graded asphalt is used as the wearing course it is important to provide any underlying asphalt with water proofing as this will greatly reduce any possibility of moisture damage occurring in the dense graded material supporting the open graded asphalt.

The minimum practical thickness of the fatigue layer is of the order of 60 mm.

Choice of layer thickness is important to ensure there is adequate thickness in each layer to achieve adequate compaction and that there is a balance between minimising the number of layers to optimise construction costs and having a sufficient number of layers to achieve shape and ride quality requirements.

Full depth asphalt pavements are relatively quick to construct and are therefore suited to situations where trafficking is required as soon as possible.

Maintenance issues

Adequately designed, full depth pavements have an exceptionally long life. Recent studies have shown that pavements that exceed a certain threshold thickness value do not fail
structurally and can achieve a very long life with periodic maintenance to correct texture, shape, or cracking deficiencies occurring in the surfacing layers. Appendix C illustrates the likely structural benefits of asphalt ageing.
4.7 Composite Pavements – Deep Strength Asphalt with Cemented Sub-base

General

Deep strength composite pavements consist of deep strength asphalt placed on cemented material. They are primarily used for heavily trafficked situations, especially where low strength subgrade exists.

This type of pavement combines the stiffness and support of cemented granular materials with the flexibility and durability of asphalt surfacing. In many cases they provide the most cost effective flexible pavement option for all forms of heavy duty pavements including urban Classes 5 and 6 and rural Classes 1 and 2. They are also suitable for heavy duty industrial pavements such as freight handling terminals.

Design Issues

The limiting design criterion for these types of pavements is predominantly the horizontal tensile strain at the base of the cemented layer. The consequences of this should be carefully considered as the premature failure of the cemented layer may lead to expensive rehabilitation that is also disruptive to traffic. The fact that the strength and performance of cemented layers is sensitive to lack of thickness and/or lack of compaction is also worthy of careful consideration. A conservative approach to the design of the cemented layer is usually warranted.

This type of pavement structure helps to minimise the chance of asphalt fatigue failure.

The cemented material is usually designed to achieve a stiffness in the range 2000 MPa to 10000 MPa with a typical value of 5000 MPa and may consist of plant manufactured material, in situ stabilised material or lean mix or roller compacted concrete. Plant mix materials are preferred, where possible, as more uniform material is produced. In most cases, by designing for a stiffness of at least 5000 MPa, the necessary binder contents to achieve this stiffness (typically 3%) will provide adequate protection against pumping and erosion should moisture ingress occur.

For this type of pavement a second phase life may be considered after the predicted fatigue failure of the cemented layer. The cemented layer can then be considered as a still unbound layer and the limiting design criterion for the second phase of life then becomes the tensile strain in the asphalt. To do this, the percentage of the fatigue life of the asphalt consumed during the initial life of the cemented layer needs to be taken into account using the following equation (VicRoads 1993, RTA 1996):

\[
N_{2} = \left(1 - \frac{N_{fatigue}}{N_{fatigue(1)}}\right) \times N_{fatigue(2)}
\]

where

- \(N_{2}\) = second post cracking phase life (ESAs)
- \(N_{fatigue}\) = number of load repetitions (ESAs) to cemented subbase (CTS) failure (1st life)
- \(N_{fatigue(1)}\) = number of load repetitions (ESAs) for asphalt based on critical strains during CTS 1st life
- \(N_{fatigue(2)}\) = number of load repetitions (ESAs) for asphalt fatigue after CTS failure (2nd phase life).
The asphalt is similar in function as described previously under deep strength and full depth asphalt pavements and can be layered accordingly. In addition, the possibility of the reflection of either shrinkage cracks and/or fatigue cracks from the cemented layer through the asphalt requires consideration.

The following minimum thicknesses of structural asphalt are recommended over the cemented layer to minimise problems due to reflection of shrinkage cracking during the design life:

- For cemented layers with design modulus values of 5000 MPa or less and all roller compacted layers – 150 mm for design traffic of < 5 x 10^7 ESAs. For design traffic > 5 x 10^7 ESAs, 175 mm of asphalt should be used.
- For cemented layers with design modulus values ≥ 10000 MPa and all wet mix material – 175 mm of asphalt should be used, except for subgrade CBR 2 and design traffic ≥ 10^8 ESAs when 200 mm of asphalt should be used.

While experience has shown that these recommended values have provided reasonable performance in a broad range of circumstances in the past, the unique circumstances of each job with regard to traffic, environment and material may not mean this is the situation in all cases.

These guidelines are reflected in the design thicknesses given in Section 6.

Modern equipment allows the construction of cemented layers in depths up to and sometimes exceeding 300 mm in depth in a single layer, although a 250 mm thickness limit helps ensure a consistent quality profile with respect to compaction. The cemented layer thickness should not be less than 150 mm so that it provides a substantial level of structural support for the asphalt. Multiple layers of cemented materials should be avoided, wherever possible, to minimise the risk of debonding between the layers. Debonding results in a very large loss of structural capacity.

Typical layer thickness and compositions for full depth composite pavements are given in Section 6, Charts 4(a), (b) and (c).

**Construction Issues**

For the asphalt layers, the construction issues are similar to those of full depth asphalt pavements.

For the cemented layers the construction issues are primarily related to ensuring there are adequate construction tolerances to ensure that:

- the design layer thickness is achieved throughout the layer
- binder contents are adequate throughout the layer
- compaction requirements are met throughout the layer
- the material has sufficient working time to allow compaction and trimming to shape to be achieved
- provision is made for adequate curing of the layer to ensure the design stiffness values are achieved.

It is also important that the cemented material has adequate support during construction so that adequate compaction and strength/stiffness can be achieved.
Maintenance issues

Maintenance issues are generally similar to deep strength and full depth asphalt pavements. The pavement must be structurally adequate to avoid cracking in the asphalt layer arising from reflective cracking due to either shrinkage or fatigue cracking of the cemented layer, or cracking due to fatigue in the asphalt layer arising from a reduction in support provided by the cemented layer.

Measures required to minimise the effect of cracking include crack sealing, thin non-structural overlays and surfacing incorporating strain alleviating layers, or thick structural overlays.
5. MAXIMISING THE LIFE OF HEAVY DUTY ASPHALT PAVEMENTS

The current AUSTROADS pavement design procedures do not contain a shift factor to allow for the differences between asphalt fatigue performance as measured in the laboratory and that measured in the field, but are proposed in future revisions.

The asphalt fatigue curves used in design were developed using fairly severe laboratory loading conditions that are not reflected in the field performance of many asphalt pavements. In particular, the fatigue criteria do not make due allowance for support offered by other pavement layers, the possibility of some healing occurring between load applications and ageing of the asphalt mix with time. As a consequence, conservative values of the life of pavements containing asphalt as a major structural component are often produced using the AUSTROADS pavement design procedures.

Studies carried out by Nunn (1996) on long-life flexible roads and by Parry et al. (1996) on the UK design of full depth asphalt and composite pavements have shown pavement fatigue lives substantially in excess of those predicted. Readers are encouraged to peruse the Nunn and Parry et al. papers due to the importance and relevance of the research to Australia. A paper by Bullen and Mangan (1998) will also provide some useful information.

Nunn carried out an extensive review of thick flexible asphalt pavement in the UK and found during his review of performance of roads built since 1984 that "... deterioration of thick, well-constructed fully flexible pavements is not structural, and that deterioration generally occurs at the surface in terms of cracking and rutting". One reason hypothesised for lack of failure by asphalt fatigue was that an increase in viscosity of binder with time could result in a continual increase in pavement strength. Data from the UK has shown that many heavy-duty flexible pavements have shown a reduction in deflection with time and increasing traffic.

It was found that if less than about 180 mm of asphalt existed, then rutting occurred in the subgrade and the asphalt (combined). The small amount of rutting in pavements with more than 180 mm of asphalt appeared to be due to rutting in the asphalt. Rutting was also found to be a function of the subgrade with a threshold value of CBR 5 being identified. It appears that if a subgrade with less than CBR 5 exists, then the thickness of asphalt cannot economically compensate for the low support provided. A capping layer is then required over the low strength subgrade to ensure that a robust material exists to allow good compaction of the asphalt.

Nunn hypothesised that if fatigue was occurring then there would be a reduced fatigue life for heavily trafficked pavements compared with lightly trafficked pavements and for bottom of road base, ignoring tyre induced fatigue tensile stresses and differential ageing effects. The Transport Research Laboratory extracted samples from four road pavements with 230 mm–300 mm of asphalt, with loadings of 22–71 x 10^6 standard axles, but found no difference in fatigue performance. This indicated that fatigue damage was not a prime factor in long life pavement performance and appears to explain anecdotal Australian evidence.

Increased hardness due to binder ageing gives increased stiffness, which can influence laboratory fatigue life. Increased stiffness in the field in thick structures gives reduced strains, which could compensate for the increased stiffness and lead to an increased life, as represented in Figure 3.
Figure 3: Schematic representation of variation in pavement performance characteristics resulting from asphalt ageing

For instance, Nunn indicated that recovered binder penetration (pen) values reduced from 100 nominal to 70 at laying, and down to 20 after 10 years indicating a substantial hardening of the binder and increased mix stiffness. Nunn also indicated that virtually all original, reconstructed, and overlaid pavements showed a reduction in deflection with time.

Research in the Netherlands by Schmorak and Van Dommelen (1995) supported Nunn’s belief that fatigue is not a governing criterion in thick asphalt flexible pavement. It was found in a study of 176 flexible pavements that in all pavements with greater than 100 mm of asphalt, distress was restricted to cracking from the surface down to depths of up to 100 mm. There was no exhibition of classical fatigue failure. It may be surmised that surface distress is the prevailing mode due to non-uniform radial stresses induced by tyres, these being at a level greater than the tensile stresses induced at the bottom of the asphalt.

Potter and Youdale (1998) investigated the implications of Nunn’s work in the Australian context and suggested ways that the ageing of asphalt may be taken into account using the Austroads pavement design model.

Appendix B presents a methodology of how asphalt ageing may be taken into account in the design process. Appendix C provides design examples.

AAPA is currently conducting a pilot study of a number of heavy duty flexible pavements which have been in service for a considerable period of time to determine if the behaviour reported by Nunn can be observed in Australia. Although the data for the pilot study was limited and scattered as in the Nunn study, it showed that the modulus increase from the lower asphalt layers ranged from a factor of 2 to 4 over the 15 to 25 years since the pavements were constructed. The important issue is that asphalt strength and stiffness increases over time, and is not taken into account in current design methodology. The visual assessment and non-destructive testing in the pilot study indicated that the deterioration since construction about 20 years ago was barely discernible and the pavements are structurally sound and clearly performing better than expectations.

If this methodology is adopted for design, the effect on design reliability will also need to be considered. Currently design reliability issues are covered by the use of a traffic multiplier, which is applied to the design traffic. Under the circumstances described above, this will result in an increase in asphalt design thickness, which in many cases will give a conservative estimate of pavement performance. If this conservatism is reduced by considering asphalt ageing in the design process, the effect of this on the reliability traffic multiplier will require careful consideration.
6. CATALOGUE OF PAVEMENT DESIGNS

6.1 General

This section of the Guide provides typical examples of a range of pavement types, indicating suitable material layer thicknesses for different applications. The layer thicknesses have been determined on the basis of the input values given in Section 6.2. These values should be considered as indicative only and designers should be aware of the influence of variations in quality of local materials, construction standards, traffic composition and environmental conditions on criteria used for the determination of pavement design thickness. The designs presented in Section 6.3 are meant to be used as preliminary designs only and should be refined for specific operating conditions.

Construction tolerances are not included in the layer thicknesses provided and appropriate margins should be included by the designer as required. Interpolation between the various traffic ranges can be used to obtain an estimate of pavement profiles for other values of design traffic and CBR.

Designers are encouraged to develop their own catalogue of pavement designs for application in a particular region, taking into account local materials and operating environment.

It should also be noted that the issues discussed in this Guide primarily relate to pavements carrying conventional road traffic and whose primary mode of distress is load-associated distress. Although the principles discussed may relate to a broader range of pavements, the extrapolation of these principles outside the scope of this guide should be done with considerable caution. (For guidance on the design of light-duty pavements, the AAPA Guide to the Design, Construction and Specification of Light-Duty Hot-Mix Asphalt Pavements [2002] and APRG Report 21 [1998]—A guide to the design of new pavements for light traffic: A Supplement to Austroads Pavement Design may be used.)

6.2 Bases for Design

Subgrade

Design subgrade strengths of CBR 2, 5 and 10 (E₀ = 20, 50 and 100 MPa). E₀/E₅ = 2 and Poisson’s Ratio = 0.45 have been used.

The following subgrade performance relationship has been used:

\[ N_{50} = \left( \frac{9.300}{\mu \varepsilon_s} \right) \]

Where \( N_{50} \) = allowable number of strain repetitions;
\( \mu \varepsilon_s \) = subgrade vertical compressive strain (microstrain).

Granular Materials

Granular materials have been modelled using both standard and modified compaction levels with maximum upper sublayer modulus values of 350 and 500 MPa respectively and a Poisson’s ratio of 0.35 for unbound granular pavements with a sprayed seal wearing surface. For asphalt on granular pavements only, modified compaction levels are used to minimise the risk of premature failure or poor performance. High compaction levels for granular
Selection and Design of Flexible Pavements

Materials where they support asphalt is critical to ensure a high stiffness in the granular material and so provide good support for the asphalt.

Cemented materials

Cemented materials with modulus values of 3500, 5000 and 10000 MPa have been used with a Poisson's ratio of 0.2.

The following performance relationships for the cemented materials have been used:

\[
N_c = \left[ \frac{(113,000/E_m + 191)}{E_t} \right]^{12}
\]

Where \(N_c\) is the number of strain repetitions,

\(E_m\) = modulus of the cemented materials (MPa),

\(E_t\) = Horizontal tensile strain in the cemented material.

Asphalt

Asphalt modulus values were chosen from Table 6.18 of VicRoads Technical Bulletin 37 (Sept 1993) and are considered to be typical design values. These are shown in Table 5. The basic values were corrected for the four temperatures shown. The modulus values used are representative of a traffic speed for heavy vehicles of 60 kph. Poisson's ratio has been taken as 0.40.

Table 5 – Asphalt Design Parameters

<table>
<thead>
<tr>
<th>Mix Type</th>
<th>Typical Modulus (MPa)</th>
<th>Corrected for temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>22°C</td>
</tr>
<tr>
<td>AC10</td>
<td>3300</td>
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</tr>
<tr>
<td>AC20 Hbit</td>
<td>3500</td>
<td>4380</td>
</tr>
</tbody>
</table>

Note: While the charts have been developed using AC20 as the largest size mix, in some situations it may be desirable to use a larger stone mix in its place.

Designs have been generated for values of Weighted Mean Annual Pavement Temperature (WMAPT) of 22°C, 25°C, 28°C and 32°C. WMAPTs for many places in Australia are given in Appendix C of the Austroads Guide to the Structural Design of Road Pavements.

WMAPTs for capital cities are given in Table 6.
Table 6 - WMAPTs for Australian Capital Cities

<table>
<thead>
<tr>
<th>City</th>
<th>WMAPT (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adelaide</td>
<td>27</td>
</tr>
<tr>
<td>Brisbane</td>
<td>32</td>
</tr>
<tr>
<td>Canberra</td>
<td>22</td>
</tr>
<tr>
<td>Hobart</td>
<td>20</td>
</tr>
<tr>
<td>Melbourne</td>
<td>24</td>
</tr>
<tr>
<td>Perth</td>
<td>30</td>
</tr>
<tr>
<td>Sydney</td>
<td>28</td>
</tr>
</tbody>
</table>

The asphalt fatigue performance criterion is:

\[ N_a = \left( \frac{6.918(0.856V_v + 1.08)}{S_{\text{mix}}^{0.635}} \right)^5 \]

Where \( N_a \) is the number of strain repetitions
\( V_v \) = Volume of bitumen (%)
\( S_{\text{mix}} \) = Modulus of the asphalt mix (MPa)
\( e_v \) = Horizontal tensile strain in the asphalt.

**Design Traffic**

Design traffic has been assessed in terms of Equivalent Standard Axles (ESAs) for a half axle load and a contact pressure of 750 kPa. Vertical loading only has been considered.

Where high stress conditions occur with complex loading conditions, such as braking and acceleration zones, turning areas and steep inclines, wearing surfaces may be subjected to considerable horizontal stresses as well. In such cases specialist advice should be sought.

Multipliers of 10 for cemented materials and 1.1 for asphalt and subgrade were used in the designs to convert ESAs to Standard Axles (ref. Section 7, Austroads 1992).

**6.3 Design Examples**

The following charts show design thicknesses for each of the six pavement types presented in Figure 1. The thicknesses for granular pavements with thin asphalt, thick asphalt and deep strength asphalt have been incorporated into a single table.

For asphalt on granular pavements, there is difficulty in realising a design in many situations as a result of the sensitivity of the stress dependency of the granular material on both the thickness and stiffness of the asphalt. For this reason, it is difficult to get a low risk design with this type of pavement in many situations. To reduce the risk in this type of pavement, only modified compaction of the granular material is considered in both the following tables and charts.

For composite and full depth asphalt pavements, fatigue layers have been used whenever the provisions in Section 4.6 can be met. The use of the fatigue layer has the advantages of reducing design thickness and also providing a layer over cemented material that should be more resistant to reflection cracking than conventional dense graded asphalt.

For composite pavements the design thicknesses of the asphalt layers are governed by the minimum asphalt thicknesses required to minimise reflection cracking. These requirements are set out in Section 4.7.
### LIST OF DESIGN CHARTS

**Pavement Type 1** - Thin Bituminous Surfacing (<40 mm) on Granular for Standard and Modified Compaction
- Chart 1(a) - Standard Compaction of Granular Material
- Chart 1(b) - Modified Compaction of Granular Material

**Pavement Type 2** - Asphalt on Granular Pavements (for Modified Compaction only)
- Chart 2(a) - Design traffic $10^5$ ESAs - 50 mm AC
- Chart 2(b) - Design traffic $10^6$ ESAs - 75 mm AC
- Chart 2(c) - Design traffic $10^6$ ESAs - 100 mm AC
- Chart 2(c) - Design traffic $10^6$ ESAs - 150 mm AC

**Pavement Type 3** - Full Depth Asphalt
- Chart 3(a) - WMA P 22°C
- Chart 3(b) - WMA P 25°C
- Chart 3(c) - WMA P 28°C

**Pavement Type 4.1** - Composite Pavement, Cemented Layer 3500 MPa
- Chart 4.1(a) - WMA P 22°C, 150 mm cemented layer
- Chart 4.1(b) - WMA P 22°C, 200 mm cemented layer
- Chart 4.1(c) - WMA P 25°C, 150 mm cemented layer
- Chart 4.1(d) - WMA P 25°C, 200 mm cemented layer
- Chart 4.1(e) - WMA P 28°C, 150 mm cemented layer
- Chart 4.1(f) - WMA P 28°C, 200 mm cemented layer
- Chart 4.1(g) - WMA P 32°C, 150 mm cemented layer
- Chart 4.1(h) - WMA P 32°C, 200 mm cemented layer

**Pavement Type 4.2** - Composite Pavement, Cemented Layer 5000 MPa
- Chart 4.2(a) - WMA P 22°C, 150 mm cemented layer
- Chart 4.2(b) - WMA P 22°C, 200 mm cemented layer
- Chart 4.2(c) - WMA P 25°C, 150 mm cemented layer
- Chart 4.2(d) - WMA P 25°C, 200 mm cemented layer
- Chart 4.2(e) - WMA P 28°C, 150 mm cemented layer
- Chart 4.2(f) - WMA P 28°C, 200 mm cemented layer
- Chart 4.2(g) - WMA P 32°C, 150 mm cemented layer
- Chart 4.2(h) - WMA P 32°C, 200 mm cemented layer

**Pavement Type 4.3** - Composite Pavement, Cemented Layer 10,000 MPa
- Chart 4.3(a) - WMA P 22°C, 150 mm cemented layer
- Chart 4.3(b) - WMA Pts 22°C, 25°C, 28°C and 32°C, 200 mm cemented layer
- Chart 4.3(c) - WMA P 25°C, 150 mm cemented layer
- Chart 4.3(d) - WMA P 25°C, 150 mm cemented layer
- Chart 4.3(e) - WMA P 32°C, 200 mm cemented layer
Selection and Design of Flexible Pavements

Pavement Type 1 - Thin Bituminous Surfacing (<40 mm) on Granular for Standard and Modified Compaction

Notes:
- Minimum granular base layer thickness for 10^5 ESA's is 125 mm
- Minimum granular base layer thickness for 10^6 ESA's is 175 mm
- Minimum granular subbase layer thickness is 100 mm

For light duty pavements, other empirical design procedures may also be applicable (see Section 4.2)
Pavement Type 2 – Asphalt on Granular Pavements
(for Modified Compaction only)

<table>
<thead>
<tr>
<th>Granular Layer Thicknesses (mm)</th>
<th>Design Traffic (ESAs)</th>
<th>Asphalt Thickness (mm)</th>
<th>Subgrade CBR 2°C</th>
<th>Subgrade CBR 5°C</th>
<th>Subgrade CBR 10°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>75[^1]</td>
<td>130</td>
<td>155</td>
<td>145</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 mm AC10 + 70 mm AC20</td>
<td>100[^1]</td>
<td>100[^1]</td>
<td>100[^1]</td>
</tr>
</tbody>
</table>

Notes:
- Working platform 300 mm of CBR 15 material
- 50 mm AC14
- 30 mm AC10 + 70 mm AC20

Granular materials, design parameters and are taken as a broad guide only and job specific, detail design analyses should be carried out for any specific circumstances. It may be possible to get feasible design thicknesses for some of the shaded sections using other sets of design inputs.

* The granular thicknesses shown in the above table are for specific materials' design parameters and are sensitive to these parameters. They should therefore be taken as a broad guide only and job specific, detailed design analyses should be carried out for any specific circumstances. It may be possible to get feasible design thicknesses for some of the shaded sections using other sets of design inputs.
Selection and Design of Flexible Pavements

Asphalt on Granular Pavements for Modified Compaction in Granular Layer

Design Traffic $10^5$ ESAs
50mm AC

Chart 2(a)

<table>
<thead>
<tr>
<th>Wearing Course asphalt (AC10 or AC14)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Course Asphalt (AC14 or AC20)*</td>
</tr>
<tr>
<td>(where utilised)</td>
</tr>
<tr>
<td>Granular Layer</td>
</tr>
<tr>
<td>Working Platform (cBR ≥ 15)</td>
</tr>
<tr>
<td>Subgrade</td>
</tr>
</tbody>
</table>

Level: Relative to the top of the working platform

Design Traffic $10^5$ ESAs
75mm AC

Chart 2(b)

<table>
<thead>
<tr>
<th>Wearing Course asphalt (AC10 or AC14)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Course Asphalt (AC14 or AC20)*</td>
</tr>
<tr>
<td>(where utilised)</td>
</tr>
<tr>
<td>Granular Layer</td>
</tr>
<tr>
<td>Working Platform (cBR ≥ 15)</td>
</tr>
<tr>
<td>Subgrade</td>
</tr>
</tbody>
</table>
Selection and Design of Flexible Pavements

Chart 2(c)

<table>
<thead>
<tr>
<th>Wearing Course Asphalt (AC10 or AC14)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Course Asphalt (AC14 or AC20); (where utilized)</td>
</tr>
<tr>
<td>Granular Layers</td>
</tr>
<tr>
<td>Working Platform (CBR 15)</td>
</tr>
<tr>
<td>Subgrade</td>
</tr>
</tbody>
</table>

Design Traffic $10^5$ ESAs

100mm AC

Chart 2(d)

Design Traffic $10^6$ ESAs

150mm AC

Legend:
- Working Platform
- Granular Material
- Minimum Granular 30mm AC14+100mm AC20
- Minimum Granular 50mm AC14+100mm AC20
Selection and Design of Flexible Pavements

Chart 3(a)

Pavement Type 3 – Full Depth Asphalt

WMAPT 22°C

WMAPT 25°C

Chart 3(b)
Selection and Design of Flexible Pavements

Chart 3(c)

Chart 3(d)
Selection and Design of Flexible Pavements

Pavement Type 4.1 - Composite Pavement
Cemented Layer 3500 MPa

WMA PT 22°C
150mm Cemented Layer (3,500MPa)

Chart 4.1(a)

Levels relative to the top of the Wearing Course
-250 -200 -150 -100 0 50 100 150 200 250 300 350 400 450

Design Traffic (ESAs)

Wearing Course
Asphalt (AC14)
Base Course
Asphalt (AC20)
Fatigue Course
Asphalt (AC20HB)
Cemented Layer
Working Platform (cBR 15)
Subgrade

200mm Cemented Layer (3,500MPa)

Chart 4.1(b)

Levels relative to the top of the Working Platform
-250 -200 -150 -100 0 50 100 150 200 250 300 350 400

Design Traffic (ESAs)
Selection and Design of Flexible Pavements

WMAPT 25°C
150mm Cemented Layer (3,500MPa)

_chart 4.1(c)_

<table>
<thead>
<tr>
<th>Layer's Relative to the Top of the Working Platform (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBR 2</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>75</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>25</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>-25</td>
</tr>
<tr>
<td>-50</td>
</tr>
<tr>
<td>-75</td>
</tr>
<tr>
<td>-100</td>
</tr>
<tr>
<td>-125</td>
</tr>
<tr>
<td>-150</td>
</tr>
<tr>
<td>-175</td>
</tr>
<tr>
<td>-200</td>
</tr>
<tr>
<td>-225</td>
</tr>
<tr>
<td>-250</td>
</tr>
<tr>
<td>-275</td>
</tr>
<tr>
<td>-300</td>
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<td>-325</td>
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<tr>
<td>-350</td>
</tr>
<tr>
<td>-375</td>
</tr>
<tr>
<td>-400</td>
</tr>
<tr>
<td>-425</td>
</tr>
<tr>
<td>-450</td>
</tr>
</tbody>
</table>

Design Traffic (ESAs)

WMAPT 25°C
200mm Cemented Layer (3,500MPa)

_chart 4.1(d)_

<table>
<thead>
<tr>
<th>Layer's Relative to the Top of the Working Platform (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBR 2</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>-25</td>
</tr>
<tr>
<td>-50</td>
</tr>
<tr>
<td>-75</td>
</tr>
<tr>
<td>-100</td>
</tr>
<tr>
<td>-125</td>
</tr>
<tr>
<td>-150</td>
</tr>
</tbody>
</table>

Design Traffic (ESAs)
Selection and Design of Flexible Pavements

WMAPT 28°C
150mm Cemented Layer (3,500MPa)

Chart 4.1(e)

Levels relative to the top of the working platform (m/m)

Design Traffic (ESAs)

CBR 2  CBR 5  CBR 10

Wearing Course
Asphalt (AC'14)
Base Course
Asphalt (AC20)
Fatigue Course
Asphalt (AC20HB)
Cemented Layer
Working Platform
(cBR 15)
Subgrade

WMAPT 28°C
200mm Cemented Layer (3,500MPa)

Chart 4.1(f)

Levels relative to the top of the working platform (m/m)

Design Traffic (ESAs)

CBR 2  CBR 5  CBR 10

Wearing Course
Asphalt (AC'14)
Base Course
Asphalt (AC20)
Fatigue Course
Asphalt (AC20HB)
Cemented Layer
Working Platform
(cBR 15)
Subgrade
Selection and Design of Flexible Pavements

WMA P 32°C
150mm Cemented Layer (3,500MPa)

Chart 4.1(g)

Wearing Course
Asphalt (AC14)
Base Course
Asphalt (AC20)
Fatigue Course
Asphalt (AC20HB)
Cemented Layer
Working Platform (cBR 1s)
Subgrade

Levels relative to the top of the Working Platform (mm)

Design Traffic (ESAs)

CBR 2
CBR 5
CBR 10

WMA P 32°C
200mm Cemented Layer (3,500MPa)

Chart 4.1(h)

Levels relative to the top of the Working Platform (mm)

Design Traffic (ESAs)

CBR 2
CBR 5
CBR 10

Levels relative to the top of the Working Platform (mm)
Selection and Design of Flexible Pavements

Pavement Type 4.2 – Composite Pavement
Cemented Layer 5000 MPa

WMAPT 22°C
150mm Cemented Layer (5,000MPa)

Chart 4.2(a)

WMAPT 22°C
200mm Cemented Layer (5,000MPa)

Chart 4.2(b)
Selection and Design of Flexible Pavements

WMAPT 25°C
150mm Cemented Layer (5,000MPa)

Chart 4.2(c)

Wearing Course Asphalt (AC14)
Base Course Asphalt (AC20)
Fatigue Course Asphalt (AC20HB)
Cemented Layer
Working Platform (cBR 15)
Subgrade

Chart 4.2(d)

WMAPT 25°C
200mm Cemented Layer (5,000MPa)

Leaves relative to the top of the Working Platform:

<table>
<thead>
<tr>
<th>Wearing Course Asphalt (AC14)</th>
<th>Base Course Asphalt (AC20)</th>
<th>Fatigue Course Asphalt (AC20HB)</th>
<th>Cemented Layer</th>
<th>Working Platform (cBR 15)</th>
<th>Subgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBR 2</td>
<td>CBR 5</td>
<td>CBR 10</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Leaves relative to the top of the Working Platform:

Design Traffic (ESAs)
Selection and Design of Flexible Pavements

Chart 4.2(a)

WMAPT 28°C
150mm Cemented Layer (5,000MPa)

Chart 4.2(f)

WMAPT 28°C
200mm Cemented Layer (5,000MPa)
Selection and Design of Flexible Pavements

WMAPT 32°C
150mm Cemented Layer (5,000MPa)

Chart 4.2(g)

WMAPT 32°C
200mm Cemented Layer (5,000MPa)

Chart 4.2(h)
Selection and Design of Flexible Pavements

Pavement Type 4.3 - Composite Pavement
Cemented Layer 10,000 MPa

WMAPT 22°C
150mm Cemented Layer (10,000 MPa)

Chart 4.3(a)

WMAPT 22°C, 25°C, 28°C & 32°C
200mm Cemented Layer (10,000 MPa)

Chart 4.3(b)

- Levels relative to the top of the working platform
- Levels relative to the top of the fatigue layer

Wearing Course
Asphalt (AC14)

Base Course
Asphalt (AC20)

Fatigue Course
Asphalt (AC20HB)

Cemented Layer

Working Platform (cBR 15)

Subgrade
Selection and Design of Flexible Pavements

WMAPT 25°C
150mm Cemented Layer (10,000MPa)

Design Traffic (ESAs)

Levels relative to the top of the working platform (mm):

-300 -250 -200 -150 -100 -50 0 50 100 150 200 250 300 350 400

CBR 2 125 125 125 125 125 125 125 125 125
CBR 5 125 125 125 125 125 125 125 125 125
CBR 10 125 125 125 125 125 125 125 125 125

Chart 4.3(c)

WMAPT 28°C
150mm Cemented Layer (10,000MPa)

Design Traffic (ESAs)

Levels relative to the top of the working platform (mm):

-300 -250 -200 -150 -100 -50 0 50 100 150 200 250 300 350 400

CBR 2 125 125 125 125 125 125 125 125 125
CBR 5 125 125 125 125 125 125 125 125 125
CBR 10 125 125 125 125 125 125 125 125 125

Chart 4.3(d)
Selection and Design of Flexible Pavements

Chart 4.3(e)

WMA PT 32°C
150mm Cemented Layer (10,000MPa)
### Design Examples

<table>
<thead>
<tr>
<th>Example 1</th>
<th>Example 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Traffic 10^6 ESAs, Design CBR 5, WMAP 28°C</td>
<td>Design Traffic 10^6 ESAs, Design CBR 2, WMAP 32°C</td>
</tr>
</tbody>
</table>

#### Sprayed Seal or thin asphalt on Granular

**Chart 1(a):**
- 175 mm granular base (minimum recommended thickness)
- 300 mm working platform CBR 15

**Example 1**

**Example 2**

### Asphalt on Granular

**Chart 2(d):**
- 50 mm AC14
- 100 mm AC20
- 100 mm granular base (minimum recommended thickness)
- 300 mm working platform CBR 15

**Not feasible**
(See Sections 4.4 and 4.5 and notes on Chart 2)

### Full Depth Asphalt

**Chart 3(c):**
- 50 mm AC14
- 110 mm AC20
- 300 mm working platform CBR 15

**Chart 3(d):**
- 50 mm AC14
- 230 mm AC20
- 60 mm AC20 fatigue layer
- 300 mm working platform CBR 15

### Composite Pavement

**Chart 4.2(e):**
- 50 mm AC14
- 105 mm AC20
- 160 mm CTB 5000 MPa
- 300 mm working platform CBR 15

**Chart 4.2(f):**
- 50 mm AC14
- 100 mm AC20
- 60 mm AC20 Fatigue Layer
- 200 mm CTB 5000 MPa
- 300 mm working platform CBR 15

**Chart 4.2(g):**
- 50 mm AC14
- 195 mm AC20
- 150 mm CTB 5000 MPa
- 300 mm working platform CBR 15

**Chart 4.2(h):**
- 50 mm AC14
- 135 mm AC20
- 60 mm AC20 fatigue layer
- 200 mm CTB 5000 MPa
- 300 mm working platform CBR 15

**Chart 4.3(d):**
- 50 mm AC14
- 125 mm AC20
- 160 mm CTB 10000 MPa
- 300 mm working platform CBR 15

**Chart 4.3(c):**
- 50 mm AC14
- 140 mm AC20
- 60 mm AC20 fatigue layer
- 150 mm CTB 10000 MPa
- 300 mm working platform CBR 15

**Chart 4.3(b):**
- 50 mm AC14
- 125 mm AC20
- 80 mm AC20 Fatigue Layer
- 200 mm CTB 10000 MPa
- 300 mm working platform CBR 15

**Chart 4.3(b):**
- 50 mm AC14
- 125 mm AC20
- 80 mm AC20 Fatigue Layer
- 200 mm CTB 10000 MPa
- 300 mm working platform CBR 15
7. COMPARISON OF ALTERNATIVE PAVEMENT DESIGNS

7.1 Overview

As illustrated in Figure 2, when a number of feasible, alternative pavement designs have been determined, these are compared using a whole-of-life cost approach. This method of comparison takes into account not only the initial cost of construction of each alternative, but also all the maintenance and rehabilitation costs that occur during the life of the pavement, as well as an estimate of the salvage value of the pavement at the end of its design life.

While, in many cases, road user costs are not taken into account in this analysis, this needs careful consideration especially for heavily trafficked roads and other high usage roads such as through shopping centres where the cost of traffic disruption resulting during pavement maintenance and rehabilitation works may be costly and have considerable social implications associated with them. Care needs to be taken with heavily trafficked roads, to ensure that, wherever possible, structural rehabilitation can be carried out in an automated fashion on surface layers only to minimize traffic disruption.

In addition, the risks associated with each whole-of-life pavement scenario need careful consideration. Risk has been allowed for in the past by the application of a “design reliability factor”, which has been a multiplier for the calculated design traffic. This has been a “catch all” approach which has attempted to take into account a number of uncertainties such as:

- Uncertainty in estimating design traffic loading
- In-situ materials properties as constructed and over the life of the pavement
- Variations in pavement layer thicknesses
- Accuracy of the design method for various pavement types.

However, for a particular job, if these uncertainties are quantifiable and, to a certain extent, controllable, a more rational assessment of risk, project reliability and the likely whole-of-life cost estimation can be made.

7.2 Method of Comparison

The Present Worth of Cost Method is the preferred method for comparison of different design scenarios. Details can be found in Chapter 11 of the Austroads Guide to the Structural Design of Road Pavements.

In brief the Present Worth of costs is calculated as follows:

\[ PWOC = C + \sum_{i} M_i (1 + r)^{-x_i} - S(1 + r)^{-z} \]

The present worth of costs can be calculated as follows:

Where \( PWOC \) = present worth of costs,

- \( C \) = present cost of initial construction,
- \( M_i \) = cost of the \( i \)th maintenance and/or rehabilitation measure,
- \( r \) = real discount rate,
- \( x_i \) = number of years from the present to the \( i \)th maintenance and/or rehabilitation measure, within the analysis period,
- \( z \) = analysis period, and
- \( S \) = salvage value of pavement at the end of the analysis period expressed in terms of present values.
In estimating present worth the principal elements are:

- construction costs;
- maintenance and rehabilitation costs, including routine periodic maintenance and structural rehabilitation;
- salvage value of the pavement at the end of the analysis period;
- real discount rate; and
- analysis period.

**Construction Costs**

Construction costs can be estimated from first principles or by reference to past similar works. Due notice should be paid to the construction issues for the different pavement types that are discussed in Section 4.

**Maintenance Costs**

Guidance on maintenance costs is available (e.g. Porter & Tinni 1993, Bennett & Moffat 1995, VicRoads 1993). Typical lives for wearing surfaces are illustrated in Table 7.

In assessing the whole-of-life costs for pavements, it should be remembered that, in practice, many pavements are required to perform for very long periods of time, often well in excess of the nominal "design life". As a consequence of this, it is often prudent to ensure that, as far as possible, the distress mechanisms are limited to those that occur near the surface of the pavement so that rehabilitation, when it is required, can be performed in an efficient and automated manner so as to minimise traffic disruption.
Table 7: Typical Service Lives for Wearing Surfacing (from Austroads 2000)

<table>
<thead>
<tr>
<th>Surfacing type</th>
<th>Expected Average Service Life of Treatments (Years) ¹ ² ³</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprayed seals 5 and 7 mm ⁴</td>
<td>5 to 10</td>
<td>Traffic volumes are very important. Initial treatments may have lower lives while reseal treatments on low trafficked roads can have long lives.</td>
</tr>
<tr>
<td>Sprayed seals 10 mm and larger ⁵</td>
<td>8 to 15</td>
<td>Traffic volumes are very important, also climate</td>
</tr>
<tr>
<td>Double application seals ⁶</td>
<td>8 to 15</td>
<td>Traffic volumes are very important, also climate</td>
</tr>
<tr>
<td>Open Graded Asphalt ⁷</td>
<td>7 to 10 (standard binder) 10 to 15 (modified binder)</td>
<td>Traffic volumes are very important, also climate</td>
</tr>
<tr>
<td>Ultra Thin Asphalt ⁸</td>
<td>7 to 12 (modified binder)</td>
<td>Can be significantly influenced by turning traffic</td>
</tr>
<tr>
<td>Dense graded asphalt</td>
<td>10 to 20</td>
<td>Traffic volumes are important, also climate</td>
</tr>
<tr>
<td>Stone Mastic Asphalt, Coarse Gap Graded Asphalt</td>
<td>10 to 25</td>
<td>Traffic volumes are important, also climate</td>
</tr>
<tr>
<td>Fine Gap Graded Asphalt</td>
<td>15 to 25</td>
<td>Generally applicable to light traffic only</td>
</tr>
<tr>
<td>Slurry/Microsurfacing</td>
<td>5 to 10</td>
<td>Traffic volumes and climate are important</td>
</tr>
<tr>
<td>Cape Seal ⁹</td>
<td>8 to 15</td>
<td>Traffic volumes are important, also climate</td>
</tr>
<tr>
<td>Concrete</td>
<td>20 to 40</td>
<td>Maintenance issues in concrete are normally related to construction problems, joints and cracking.</td>
</tr>
</tbody>
</table>

Notes

1. The service lives in this table are for average conditions. Service conditions which affect the expected life include:
   - Traffic volumes. High traffic volumes and high stress areas where there is braking and turning traffic will tend to give service life near the lower end of the range whereas lesser traffic volumes will result in longer service life.
   - Climate. High service temperatures generally reduce service life. High rainfall may also reduce service life.

2. Clogging or reduction in voids of OGA and UTA may influence effective life.

3. Inspection of sprayed seal surfacings is particularly important as they may exhibit signs of early failure such as oxidation and cracking.

4. Figures are for structurally sound pavements.
Risk Assessment

In order to carry out a simple but informative risk assessment for a candidate pavement design based on the projected whole-of-life model, the designer needs to identify events/circumstances that are contrary to the design assumptions and consider the likelihood of that event occurring.

Routinely it is recommended that the designer consider up to about four significant events/circumstances to compare with the neutral circumstance whereby the pavement is constructed fully compliant with the design assumptions. Subsequently, whole-of-life analysis can compare the discounted cost of the neutral circumstance and a weighted whole-of-life cost based on the probability of the set of possible events/circumstances.

Consider for example:
There are four ways in which construction of a candidate pavement design can deliver circumstances that are detrimental to the neutral pavement performance based on the designer's reasonable assumptions. The likelihood of each circumstance is estimated by the designer based on the designer's experience and industry records and is represented by a probability. The likely probability of the four circumstances plus the neutral event must sum to 1.

\[
P_1 + P_2 + P_3 + P_{\text{neutral}} = 1
\]

\(P_1\) might be a 20% underestimate in design traffic loading
\(P_2\) might be a 20 mm under-thickness in a critical asphalt layer
\(P_3\) might be understrength granular material
\(P_4\) might be a weaker subgrade strength than estimated by geotechnical studies.

Whole-of-life costs are calculated by modelling behaviour for the four circumstances and the neutral event over the design period. The weighted present worth of cost (PWOC) for this candidate pavement is determined as:

\[
\text{PWOC} = [P_1 \times \text{LCC}_1] + [P_2 \times \text{LCC}_2] + [P_3 \times \text{LCC}_3] + [P_4 \times \text{LCC}_4] + [P_{\text{neutral}} \times \text{LCC}_{\text{neutral}}]
\]

This value can then be used for comparison with the PWOC for other candidate pavements. Such analysis replaces the "catch all" reliability approach and allows the designer to consider the warrant for particular controls to be specified for pavement materials and construction risks which can be specified to reduce the likelihood of a substandard performance result. For major designs, records of the whole-of-life analyses under the proposed procedure can assist in providing for effective design audits.
8. REFERENCES


RTA Technical Direction 96/16 (1997) – Pavements – Amendments to RTA Form 76 (June 1997).


APPENDIX A

CALCULATION OF THE DEGREE OF SATURATION OF UNBOUND GRANULAR MATERIALS

The degree of saturation $S$, of a compacted pavement material can be calculated from the equation:

$$ S = \frac{\text{w}}{\text{Pd} - \text{APD}} $$

Where
- $S$ = Degree of saturation (%)
- w = Moisture Content (%)
- Pd = Dry Density (t/m$^3$)
- APD = Apparent Particle Density (t/m$^3$ void free mass)

A typical basalt crushed rock may have an Apparent Particle Density of 2.60 t/m$^3$ and a Maximum Dry Density (Modified compaction) of about 2.40 t/m$^3$.

If the Optimum Moisture Content for modified compaction and compaction is specified at OMC $+0.2\%$ and compaction is achieved at 4.5% (i.e. within the specification requirements), by utilising the equation above the Degree of Saturation can be calculated at 76%.

RTA Technical Direction 98/15 – Early Failure in Unbound Granular Pavements due to High Initial Traffic Loading – dated 11 December 1998 recommends that the degree of saturation (% of voids filled with moisture) should be as shown in Table A1 for pavements subjected to high initial traffic loading.

<table>
<thead>
<tr>
<th>Degree of Saturation</th>
<th>Recommended Treatment of Moisture Content Prior to Sealing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushed Rock</td>
<td>Natural Gravel</td>
</tr>
<tr>
<td>&lt; 65%</td>
<td>&lt; 70%</td>
</tr>
<tr>
<td>65-75%</td>
<td>70-80%</td>
</tr>
<tr>
<td>&gt;75%</td>
<td>&gt; 80%</td>
</tr>
</tbody>
</table>

Nil. Stiffness of the pavement layer should be adequate.

Deflection testing with deflection bowl analysis.

Reduce moisture content prior to sealing or replace material.

Technical Direction 98/15 cites the possibility of early failure of unbound granular pavements subject to high traffic loadings, despite the fact they may meet materials and compaction requirements.
APPENDIX B

DESIGN METHODOLOGY FOR TAKING INTO ACCOUNT ASPHALT AGEING CHARACTERISTICS

To take into account asphalt ageing in the design procedure it is necessary to:

1. Decide on how much the asphalt will gain in stiffness over the design life. This is expressed as an asphalt ageing multiplier ($A_n$). $A_n$ is defined as the ratio of the asphalt modulus at the end of the design period ($S_{m,n}$) to the design asphalt modulus at year 1 ($S_{mixr}$).

$$A_n = \frac{S_{m,n}}{S_{mixr}}$$

2. Calculate the asphalt moduli value for each year of the design period using the equation:

$$S_{m,n} = S_{mixr} \left[ 1 + (A_n - 1) \frac{\log n}{\log N} \right]$$

Where $S_{mixr} =$ initial design asphalt modulus at year 1
$S_{m,n} =$ asphalt modulus at year $n$
$N =$ Design period in years
$A_n =$ as defined above.

3. Calculate the design traffic for each year of the design period. This should be calculated from the total design traffic $N_{ax}$ as follows. (The total design traffic should include appropriate consideration of project reliability – see Section 7 of Austroads 2000).

Select a cumulative growth factor from Table 1 below (Table 7.2 of Austroads 1992).

Table B1: Cumulative Growth Factors (GFs)

<table>
<thead>
<tr>
<th>Design Period (Years)</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5</td>
<td>5.2</td>
<td>5.4</td>
<td>5.6</td>
<td>5.9</td>
<td>6.1</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>10.9</td>
<td>12.0</td>
<td>13.2</td>
<td>14.5</td>
<td>15.9</td>
</tr>
<tr>
<td>15</td>
<td>15</td>
<td>17.3</td>
<td>20.0</td>
<td>23.3</td>
<td>27.2</td>
<td>31.8</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>24.3</td>
<td>28.8</td>
<td>36.8</td>
<td>45.8</td>
<td>57.3</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>32.0</td>
<td>41.6</td>
<td>54.9</td>
<td>73.1</td>
<td>98.3</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
<td>40.6</td>
<td>56.1</td>
<td>79.1</td>
<td>113.3</td>
<td>164.5</td>
</tr>
<tr>
<td>35</td>
<td>35</td>
<td>50.0</td>
<td>73.7</td>
<td>111.4</td>
<td>172.3</td>
<td>271.0</td>
</tr>
<tr>
<td>40</td>
<td>40</td>
<td>60.4</td>
<td>95.0</td>
<td>151.8</td>
<td>259.1</td>
<td>442.6</td>
</tr>
</tbody>
</table>
Determine the initial design traffic for the first year $N_0$:

$$N_0^* = \frac{N_0}{\gamma T}$$

The design traffic for any year $N_n$ can then be calculated using the following equation:

$$N_n^* = N_0^*(1 + r)^n$$

Where $n > 1$ and $r$ = annual traffic growth rate expressed as a proportion.

4. As the fatigue performance relationship for asphalt is dependent on the stiffness of the asphalt mix, and as the mix stiffness changes, the fatigue relationship for each asphalt layer must be determined for each year of the design period.

This is achieved by using the stiffness data calculated in Step 2 above and substituting it into the equation below (from Austroads 1992 Section 6.4.6):

$$\frac{N_n}{N_{1n}} = \left( \frac{6.918(0.856 V_b - 1.08)}{\mu E S_{asph}} \right)^m$$

Where $N_{1n}$ = Tolerable number of repetitions of load in year $n$.

$V_b$ = % by volume of bitumen in the asphalt.

$\mu E$ = maximum horizontal tensile strain in the asphalt in microstrain.

$S_{asph}$ = asphalt mix stiffness in MPa in year $n$.

For each asphalt layer the above equation will reduce to the form:

$$N_n^* = \left( \frac{K_b}{\mu E} \right)^5$$

Where $K_b$ is a constant depending on the volume of binder in the mix and the stiffness of the mix as calculated in Section 2 above.

5. To carry out a design a trial pavement configuration is chosen. Then, using the mix stiffness, design traffic and asphalt fatigue criteria calculated in Steps 2, 3 and 4 above the proportion of the fatigue life of the asphalt used for each year of the design period can be calculated using Miner's Law. These proportions can then be summed to ascertain if the trial pavement is adequate.

For the pavement to be adequate:

$$\sum_{n=1}^{N} \frac{N_n^*}{N_n^*_{total}} \leq 1$$

Where $N_n^*$ = design repetitions for year $n$ (from Step 3).

$N_n^*_{total}$ = tolerable repetitions from year $n$ (from Step 4).

An example of the use of this method is provided in Appendix C.
APPENDIX C

EXAMPLE DESIGN TAKING INTO ACCOUNT ASPHALT AGEING CHARACTERISTICS

The following simplified design examples will illustrate the design methodology presented in Appendix B.

Consider a simple full-depth asphalt pavement consisting of a single asphalt type. (In practice, the design of this type of pavement would involve considerably more computational complexity as the layering considerations described in Section 9.4 would be utilised. However, the design principles and calculations would be the same as for a single layer of asphalt.)

**Asphalt Properties**

Initial asphalt stiffness $S_{\text{max}} = 2800$ MPa

Asphalt ageing multiplier $A_a = 2.0$ (i.e. the asphalt stiffness at the end of the design life will be $5600$ MPa)

The volume of bitumen in the mix $V_b = 11\%$

The asphalt fatigue performance relationship is

$$N_{fa} = \left[ \frac{6,918 (0.856 V_b + 1.08)}{\mu \varepsilon S_{\text{max}}^{0.58}} \right]^5$$

or

$$N_{fa} = \left[ \frac{72,811}{\mu \varepsilon S_{\text{max}}^{0.58}} \right]^5$$

**Subgrade Properties**

Subgrade CBR = 5

Poisson's ratio = 0.45

Degree of anisotropy = 2

Subgrade performance relationship

$$N_{SG} = \left[ \frac{9,300}{\mu \varepsilon} \right]^7$$

Where $\mu \varepsilon = \text{maximum vertical compressive strain in microstrain at the top of the subgrade}$

$N_{SG} = \text{allowable number of strain repetitions}$
Design Period

Design Period - 20 years

Design Traffic

Initial traffic in design lane - 0.720 FSAs per day.
Traffic in first year = 0.720 x 365 - 2.15 x 10⁶ FSAs
Annual growth rate = 4%.

Growth factor (20 years, 4%) = 29.8
Total design traffic over 20-year design period = 2.926 x 10⁷ FSAs

ESA used for design calculation purposes - full axle, 1800 mm spacing between centres of dual tyre assemblies, contact stress = 750 KPa

Design Calculations

Consider firstly the design of the pavement if no asphalt ageing is considered. The design calculations for an asphalt thickness of 320 mm are presented in Table C1.

### Table C1 - Full Depth Asphalt Design - Asphalt Thickness 320 mm - No Asphalt Ageing

<table>
<thead>
<tr>
<th>Year</th>
<th>Traffic (ESAs)</th>
<th>Asphalt Stiffness</th>
<th>Asphalt K value</th>
<th>Fatigue Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.450E+06</td>
<td>2800</td>
<td>4169</td>
<td>0.0337</td>
</tr>
<tr>
<td>2</td>
<td>2.548E+06</td>
<td>2800</td>
<td>4169</td>
<td>0.0350</td>
</tr>
<tr>
<td>3</td>
<td>2.650E+06</td>
<td>2800</td>
<td>4169</td>
<td>0.0364</td>
</tr>
<tr>
<td>4</td>
<td>2.756E+06</td>
<td>2800</td>
<td>4169</td>
<td>0.0379</td>
</tr>
<tr>
<td>5</td>
<td>2.866E+06</td>
<td>2800</td>
<td>4169</td>
<td>0.0394</td>
</tr>
<tr>
<td>6</td>
<td>2.981E+06</td>
<td>2800</td>
<td>4169</td>
<td>0.0410</td>
</tr>
<tr>
<td>7</td>
<td>3.100E+06</td>
<td>2800</td>
<td>4169</td>
<td>0.0426</td>
</tr>
<tr>
<td>8</td>
<td>3.224E+06</td>
<td>2800</td>
<td>4169</td>
<td>0.0443</td>
</tr>
<tr>
<td>9</td>
<td>3.353E+06</td>
<td>2800</td>
<td>4169</td>
<td>0.0461</td>
</tr>
<tr>
<td>10</td>
<td>3.494E+06</td>
<td>2800</td>
<td>4169</td>
<td>0.0480</td>
</tr>
<tr>
<td>11</td>
<td>3.647E+06</td>
<td>2800</td>
<td>4169</td>
<td>0.0499</td>
</tr>
<tr>
<td>12</td>
<td>3.772E+06</td>
<td>2800</td>
<td>4169</td>
<td>0.0519</td>
</tr>
<tr>
<td>13</td>
<td>3.903E+06</td>
<td>2800</td>
<td>4169</td>
<td>0.0539</td>
</tr>
<tr>
<td>14</td>
<td>4.079E+06</td>
<td>2800</td>
<td>4169</td>
<td>0.0561</td>
</tr>
<tr>
<td>15</td>
<td>4.243E+06</td>
<td>2800</td>
<td>4169</td>
<td>0.0583</td>
</tr>
<tr>
<td>16</td>
<td>4.412E+06</td>
<td>2800</td>
<td>4169</td>
<td>0.0607</td>
</tr>
<tr>
<td>17</td>
<td>4.589E+06</td>
<td>2800</td>
<td>4169</td>
<td>0.0631</td>
</tr>
<tr>
<td>18</td>
<td>4.772E+06</td>
<td>2800</td>
<td>4169</td>
<td>0.0656</td>
</tr>
<tr>
<td>19</td>
<td>4.993E+06</td>
<td>2800</td>
<td>4169</td>
<td>0.0682</td>
</tr>
<tr>
<td>20</td>
<td>5.162E+06</td>
<td>2800</td>
<td>4169</td>
<td>0.0710</td>
</tr>
</tbody>
</table>

Notes on Table C1:
- The asphalt stiffness remains constant at 2800 MPa throughout the pavement life.
- The asphalt performance relationship remains constant throughout the pavement life.
- The proportion of the fatigue life consumed increases each year.
- The asphalt thickness of 320 mm is adequate (barely).
- The design could have been carried out in a single step by considering the total design traffic.
Secondly consider the same pavement configuration with an asphalt ageing multiplier of 2.0 being used.

The stiffness of the asphalt would change throughout the design life as illustrated in Figure C1 (from Appendix B, Section 2).

Asphalt Ageing

![Asphalt Ageing Graph](image)

**Figure C1 – Change in Asphalt Stiffness with Time**

As the asphalt stiffness changes with time the asphalt fatigue performance relationship also changes.

The design calculations taking into account an asphalt ageing multiplier of 2.0 for an asphalt thickness of 280 mm are presented in Table C2.
Table C2 – Full Depth Asphalt Design – Asphalt Thickness 280 mm – Asphalt Ageing Multiplier 2.0

<table>
<thead>
<tr>
<th>Year</th>
<th>Traffic (ESAs)</th>
<th>Asphalt Stiffness</th>
<th>Asphalt K value</th>
<th>Fatigue Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.450E+06</td>
<td>2800</td>
<td>4163</td>
<td>0.0880</td>
</tr>
<tr>
<td>2</td>
<td>2.548E+06</td>
<td>3448</td>
<td>3868</td>
<td>0.0614</td>
</tr>
<tr>
<td>3</td>
<td>2.650E+06</td>
<td>3827</td>
<td>3725</td>
<td>0.0419</td>
</tr>
<tr>
<td>4</td>
<td>2.755E+06</td>
<td>4096</td>
<td>3635</td>
<td>0.0411</td>
</tr>
<tr>
<td>5</td>
<td>2.865E+06</td>
<td>4304</td>
<td>3574</td>
<td>0.0443</td>
</tr>
<tr>
<td>6</td>
<td>2.991E+06</td>
<td>4475</td>
<td>3522</td>
<td>0.0426</td>
</tr>
<tr>
<td>7</td>
<td>3.100E+06</td>
<td>4619</td>
<td>3482</td>
<td>0.0415</td>
</tr>
<tr>
<td>8</td>
<td>3.224E+06</td>
<td>4744</td>
<td>3448</td>
<td>0.0409</td>
</tr>
<tr>
<td>9</td>
<td>3.353E+06</td>
<td>4854</td>
<td>3420</td>
<td>0.0406</td>
</tr>
<tr>
<td>10</td>
<td>3.487E+06</td>
<td>4952</td>
<td>3395</td>
<td>0.0406</td>
</tr>
<tr>
<td>11</td>
<td>3.627E+06</td>
<td>5041</td>
<td>3374</td>
<td>0.0407</td>
</tr>
<tr>
<td>12</td>
<td>3.772E+06</td>
<td>5123</td>
<td>3354</td>
<td>0.0409</td>
</tr>
<tr>
<td>13</td>
<td>3.923E+06</td>
<td>5197</td>
<td>3337</td>
<td>0.0413</td>
</tr>
<tr>
<td>14</td>
<td>4.079E+06</td>
<td>5267</td>
<td>3321</td>
<td>0.0418</td>
</tr>
<tr>
<td>15</td>
<td>4.243E+06</td>
<td>5331</td>
<td>3306</td>
<td>0.0426</td>
</tr>
<tr>
<td>16</td>
<td>4.412E+06</td>
<td>5391</td>
<td>3293</td>
<td>0.0437</td>
</tr>
<tr>
<td>17</td>
<td>4.593E+06</td>
<td>5448</td>
<td>3281</td>
<td>0.0439</td>
</tr>
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<td>5502</td>
<td>3260</td>
<td>0.0447</td>
</tr>
<tr>
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<td>4.963E+06</td>
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<td>0.0457</td>
</tr>
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<td>5.162E+06</td>
<td>5600</td>
<td>3246</td>
<td>0.0467</td>
</tr>
<tr>
<td></td>
<td>7.296E+07</td>
<td></td>
<td></td>
<td>0.0312</td>
</tr>
</tbody>
</table>

Notes on Table C2:
- The asphalt stiffness varies as illustrated in Figure C1 throughout the pavement life.
- The asphalt performance relationship varies throughout the pavement life.
- The proportion of the fatigue life consumed each year initially decreases each year as the asphalt stiffness increases. At year 10 it levels off and then increases each year as the increase in damage caused by growing traffic repetitions cannot be matched by the increasing stiffness of the asphalt.
- The asphalt thickness of 280 mm is adequate for the same design traffic as used in the first example.
- Unlike in Table C1, the design calculations must be carried out in 20 steps, 1 for each year of the design life.

Comparison of Designs
The two designs in Tables C1 and C2 are illustrated below and results in a 40 mm (13%) reduction in design asphalt thickness.

- Asphalt stiffness constant at 2600 MPa throughout design life.
  - Design Traffic: 7.3 x 10^7 ESAs
  - Asphalt Thickness: 280 mm
  - Subgrade CBR 5

- Asphalt stiffness increases from 2600 MPa at year 1 to 5800 MPa at year 20.
  - Design Traffic: 7.3 x 10^7 ESAs
  - Asphalt Thickness: 280 mm
  - Subgrade CBR 5