Interim guide for the design of high modulus asphalt mixes and pavements in South Africa

Restricted

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### Abstract:
This interim guideline contains a performance related method for the design of High Modulus Asphalt (HiMA) mixes in South Africa. An approach for the design of pavement structures containing HiMA layers is also presented. The interim guide was developed as part of the HiMA Technology Transfer (T²) project funded by the South African bitumen association (Sabita). The interim design guide is based on the final report on Phase II of the HiMA T² project (Denneman et al, 2011).

*Note: the design methods presented in this document were developed based on a laboratory study of limited scope. Validation of the design methods through Accelerated Pavement Testing (APT) and Long Term Pavement Performance testing is pending.*

### Keywords:
High modulus asphalt, mix design, structural design

### Proposals for implementation:
As an interim guide for the design of HiMA mixes and structures in South Africa

### Related documents:
Denneman et al (2011)
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1. INTRODUCTION

1.1 Background

This interim guideline contains a performance related method for the design of High Modulus Asphalt (HiMA) mixes in South Africa. An approach for the design of pavement structures containing HiMA layers is also presented. The interim guide was developed as part of the HiMA Technology Transfer ($T^2$) project funded by the South African bitumen association (Sabita). The interim design guide is based on the final report on Phase II of the HiMA $T^2$ project (Denneman et al, 2011). The overall HiMA technology transfer project consists of four phases:

- Phase 1: Preliminary assessment of viability;
- Phase 2: Preliminary guidelines on mix design and structural design;
- Phase 3: Validation of the HiMA mix and structural design methods through Accelerated Pavement Testing (APT), Long Term Pavement Performance (LTPP) testing and laboratory studies;
- Phase 4: Drafting of final guidelines and specifications for HiMA

Note: the design methods presented in this document were developed based on a laboratory study of limited scope. Validation of the design methods through Accelerated Pavement Testing (APT) and Long Term Pavement Performance testing is pending.

1.2 Structure of the preliminary design guide

The report is divided into two parts: (a) a section on HiMA mix design, and (b) a section on the structural design of road pavements containing HiMA layers.
2. **HiMA MIX DESIGN**

The proposed performance related design process for HiMA mixes is shown in Figure 1. The first step is to select appropriate mix components in terms of aggregate and binder. A suitable grading is developed from the different aggregate fractions. The binder content is set based on a minimum richness factor, similar to the film thickness conventionally used in South Africa. Using this trial mix design gyratory specimens are compacted. A maximum air void content after a set number of gyrations has to be achieved. This is the first of the performance criteria, aimed at creating a workable mix. If the workability criterion is met specimens are subjected to a durability test. The remaining performance criteria relate to a minimum dynamic modulus requirement, a minimum level of resistance to permanent deformation and finally a minimum fatigue life. The difference steps in the process are discussed in the following sections.

![Figure 1: HiMA mix design process](image-url)
2.1 Material selection

The characteristics that define a HiMA mixture are a high binder content of low penetration grade bitumen combined with good quality, fully crushed aggregate, graded in a way that ensures good workability and produces a mix with sufficient durability and low permeability.

2.1.1 Binder selection

In Europe, typically either a 10/20 or a 15/25 Pen grade binder, conforming to EN 13924, is used in HiMA. Most of the work under the Sabita study (Denneman et al 2011) was performed using 20/30 pen grade binder, which at the time was the only HiMA binder available in South Africa. A summary of EN requirements for hard pavement grade binders is shown in Table 1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Test method</th>
<th>Unit</th>
<th>Penetration grade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>10/20</td>
</tr>
<tr>
<td>Penetration at 25 °C</td>
<td>EN 1426</td>
<td>0.1 mm</td>
<td>10-20</td>
</tr>
<tr>
<td>Softening point</td>
<td>EN 1427</td>
<td>°C</td>
<td>58-78</td>
</tr>
<tr>
<td>Viscosity at 60 °C</td>
<td>EN 12596</td>
<td>Pa.s</td>
<td>&gt;700</td>
</tr>
</tbody>
</table>

2.1.2 Binder content requirements

Table 2 shows the minimum binder contents for different HiMA mix types, expressed as a percentage by mass of total mix P_b. The French specifications allow for two classes of HiMA mixes: Class 1 for ‘light’ traffic, and Class 2 for ‘heavy’ traffic. The difference between the classes lies in the fatigue requirement for the mix, which explains the higher binder content for Class 2. The table is intended as a point of departure for selection of optimum binder content.
The richness modulus $K$ shown in Table 2 is a proportional value related to the thickness of the binder film coating the aggregate. It is akin to the film thickness calculation in the South African TRH 8. The richness modulus $K$ is a key design parameter used in the French asphalt mix design method. The values in Table 2 should be adhered to. $K$ is obtained from:

$$T_{est} = K \cdot \alpha \sqrt[\Sigma]{\text{est}}$$  \hspace{1cm} (1)

Where:

$T_{est}$: is the binder content by mass of total aggregate. $T_{est}$ can be converted to the binder content by mass of total mix ($P_b$) generally used in South Africa using Equation 2

$$T_{est} = \frac{100P_b}{(100 - P_b)}$$  \hspace{1cm} (2)

$\alpha$: is a correction coefficient for the relative density of the aggregate (RDA)

$\alpha = \frac{2.65}{\text{RDA}}$

$\Sigma$: is the specific surface area calculated from: $100\Sigma = 0.25G + 2.3S + 12s + 150f$

Where:

$G$: is the proportion of aggregate retained on and above the 6.3 mm sieve,
$S$: is the proportion of aggregate retained between the 0.25 mm and 6.3 mm sieves,
$s$: is the proportion of aggregate retained between the 0.063 mm and 0.25 mm sieves,
$f$: is the percentage passing the 0.063 mm sieve

### 2.1.3 Aggregate selection

HiMA is typically produced using fully crushed fractured aggregate. In the selection of an aggregate source, both angularity and surface texture are important. High aggregate angularity and sufficient surface texture assist in the creation of voids in the mineral aggregate (VMA). The VMA has to be such that it can accommodate the fairly high binder content. The proposed aggregate selection criteria

---

**Table 2: Typical values for minimum binder content and target richness modulus**

<table>
<thead>
<tr>
<th>D (mm)</th>
<th>HiMA base course</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Class 1</td>
<td>Class 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10,14,20</td>
<td>10,14</td>
<td>20</td>
</tr>
<tr>
<td>$P_{b\text{min}}$ $\rho = 2.65 \text{ g/cm}^3$</td>
<td>3.8</td>
<td>5.1</td>
<td>5.0</td>
</tr>
<tr>
<td>$P_{b\text{min}}$ $\rho = 2.75 \text{ g/cm}^3$</td>
<td>3.8</td>
<td>4.9</td>
<td>4.9</td>
</tr>
<tr>
<td>Richness modulus $K$</td>
<td>2.5</td>
<td>3.4</td>
<td>3.4</td>
</tr>
</tbody>
</table>

The richness modulus $K$ shown in Table 2 is a proportional value related to the thickness of the binder film coating the aggregate. It is akin to the film thickness calculation in the South African TRH 8. The richness modulus $K$ is a key design parameter used in the French asphalt mix design method. The values in Table 2 should be adhered to. $K$ is obtained from:

$$T_{est} = K \cdot \alpha \sqrt[\Sigma]{\text{est}}$$  \hspace{1cm} (1)

Where:

$T_{est}$: is the binder content by mass of total aggregate. $T_{est}$ can be converted to the binder content by mass of total mix ($P_b$) generally used in South Africa using Equation 2

$$T_{est} = \frac{100P_b}{(100 - P_b)}$$  \hspace{1cm} (2)

$\alpha$: is a correction coefficient for the relative density of the aggregate (RDA)

$\alpha = \frac{2.65}{\text{RDA}}$

$\Sigma$: is the specific surface area calculated from: $100\Sigma = 0.25G + 2.3S + 12s + 150f$

Where:

$G$: is the proportion of aggregate retained on and above the 6.3 mm sieve,
$S$: is the proportion of aggregate retained between the 0.25 mm and 6.3 mm sieves,
$s$: is the proportion of aggregate retained between the 0.063 mm and 0.25 mm sieves,
$f$: is the percentage passing the 0.063 mm sieve

### 2.1.3 Aggregate selection

HiMA is typically produced using fully crushed fractured aggregate. In the selection of an aggregate source, both angularity and surface texture are important. High aggregate angularity and sufficient surface texture assist in the creation of voids in the mineral aggregate (VMA). The VMA has to be such that it can accommodate the fairly high binder content. The proposed aggregate selection criteria
for HiMA are shown in Table 3. The criteria are similar to those recommended for HMA as contained in Taute et al. (2001). The particle index test provides a measure of aggregate angularity and surface texture. The value for particle index is tentative. Generally aggregates with a high particle index test result have a higher VMA. The flakiness index for HiMA aggregate should preferably lie between 10 and 15 (Delorme et al, 2007).

### Table 3: Aggregate selection criteria

<table>
<thead>
<tr>
<th>Property</th>
<th>Test</th>
<th>Active standard</th>
<th>Planned SANS</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness</td>
<td>Fines aggregate crushing test: 10 %FACT</td>
<td>TMH1, B1</td>
<td>3001-AG10</td>
<td>≥ 160 kN</td>
</tr>
<tr>
<td></td>
<td>Aggregate crushing value ACV</td>
<td>TMH1, B1</td>
<td>3001-AG10</td>
<td>≤ 25%</td>
</tr>
<tr>
<td>Particle shape &amp; texture</td>
<td>Flakiness Index test</td>
<td>SANS 3001-AG4</td>
<td></td>
<td>≤ 25</td>
</tr>
<tr>
<td></td>
<td>Percentage of fully crushed (&gt; 5 mm)</td>
<td></td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Particle index test</td>
<td>ASTM D3398</td>
<td></td>
<td>&gt; 15</td>
</tr>
<tr>
<td>Water absorption</td>
<td>Water absorption coarse (&gt;5 mm) aggregate</td>
<td>SANS 3001-AG20</td>
<td></td>
<td>≤ 1.0 %</td>
</tr>
<tr>
<td></td>
<td>Water absorption fine aggregate</td>
<td>SANS 3001-AG21</td>
<td></td>
<td>≤ 1.5 %</td>
</tr>
<tr>
<td>Cleanliness</td>
<td>Sand equivalency test fine aggregate</td>
<td>SANS 5838</td>
<td></td>
<td>≥ 50</td>
</tr>
</tbody>
</table>

#### 2.2 Design grading

The LPC bituminous mixtures design guide provides target grading curves and envelopes for HiMA mixes (Delorme et al, 2007). It should be noted that these only provide a point of departure for the mix design process and that they should not be used to impose a restriction on the grading as per the current South African COLTO specifications.

The French guideline for grading curves cannot readily be translated into general South African practice. This is due to the definition of the maximum particle size and the use of European sieve sizes. In South Africa (SA), the nominal maximum particle size (NMPS) is defined as one sieve size larger than the first sieve to retain at least 10% of aggregate. The French use the maximum stone size $D$, with the requirement that 100% of aggregate passes the sieve at $2D$, 98-100% passes at $1.4D$ and 85-98% passes at $1.2D$. In this document, the French definition of maximum aggregate size has been maintained and the grading curves are plotted for both European and SA standard sieve sizes. It is recommended that the customization of the LCPC grading guidelines be conducted once more local experience with HiMA grading has been gained. The grading guidelines for HiMA base courses according to the LCPC design method are shown in Table 4 for French sieve sizes. These have been converted in Table 5 for TMH 1 standard sieve sizes and to the new SANS 3001-AG1:2009 sieve sizes in Table 6. For key sieve sizes, the table provides a target grading that can be used as a point of departure in developing trial gradings. The values for the 13.2 mm maximum size aggregate are plotted in Figure 2 for illustration purposes. Also shown is the maximum density line (assuming a 5%
binder content). The suggested target grading is fairly close to the maximum density line for the smaller sieves. The grading includes a kink due to the relatively large percentage retained on and above the 6.7 mm sieve.

Table 4: Target grading curves and envelopes for HiMA base course (after Delorme et al, 2007)

<table>
<thead>
<tr>
<th>Percent passing sieve size</th>
<th>D = 10 mm</th>
<th>D = 14 mm</th>
<th>D = 20 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>min.</td>
<td>target</td>
<td>max.</td>
</tr>
<tr>
<td>6.3 mm</td>
<td>45</td>
<td>55</td>
<td>65</td>
</tr>
<tr>
<td>4.0 mm</td>
<td>52</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>2.0 mm</td>
<td>25</td>
<td>33</td>
<td>38</td>
</tr>
<tr>
<td>0.063 mm</td>
<td>6.3</td>
<td>6.7</td>
<td>7.2</td>
</tr>
</tbody>
</table>

Table 5: Target grading curves and envelopes for HiMA base course (TMH1 sieve sizes)

<table>
<thead>
<tr>
<th>Percent passing sieve size</th>
<th>NMPS = 9.5 mm</th>
<th>NMPS = 13.2 mm</th>
<th>NMPS = 19 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>min.</td>
<td>target</td>
<td>max.</td>
</tr>
<tr>
<td>6.7 mm</td>
<td>47</td>
<td>56</td>
<td>68</td>
</tr>
<tr>
<td>4.75 mm</td>
<td>52</td>
<td>43</td>
<td>49</td>
</tr>
<tr>
<td>2.36 mm</td>
<td>31</td>
<td>36</td>
<td>43</td>
</tr>
<tr>
<td>0.075 mm</td>
<td>6.4</td>
<td>6.9</td>
<td>7.4</td>
</tr>
</tbody>
</table>

Table 6: Target grading curves and envelopes for HiMA base course (SANS3001 sieve sizes)

<table>
<thead>
<tr>
<th>Percent passing sieve size</th>
<th>NMPS = 10 mm</th>
<th>NMPS = 14 mm</th>
<th>NMPS = 20 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>min.</td>
<td>target</td>
<td>max.</td>
</tr>
<tr>
<td>7.1 mm</td>
<td>48</td>
<td>56</td>
<td>68</td>
</tr>
<tr>
<td>5 mm</td>
<td>53</td>
<td>44</td>
<td>50</td>
</tr>
<tr>
<td>2 mm</td>
<td>28</td>
<td>33</td>
<td>38</td>
</tr>
<tr>
<td>0.075 mm</td>
<td>6.4</td>
<td>6.9</td>
<td>7.4</td>
</tr>
</tbody>
</table>

Figure 2: Recommended initial grading and typical envelope for NMPS=13.2 mm
2.3 Layer thickness
The average and minimum specified layer thicknesses of HiMA are provided in Table 7. It should be noted that the average layer thicknesses of HiMA are generally thinner than those specified for bitumen-treated base courses (BTBs) or large-aggregate mixes for bases (LAMBs). This is due to the smaller stone size used in HiMA. Structurally, a thin HiMA layer may yield the same performance as a thicker BTB because of the higher stiffness of HiMA. HiMA is also richer in binder which, compared to conventional base courses, offers similar if not better resistant to fatigue cracking.

<table>
<thead>
<tr>
<th>D [mm]</th>
<th>Average thickness [mm]</th>
<th>Minimum thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>60 to 80 (base course)</td>
<td>50</td>
</tr>
<tr>
<td>14</td>
<td>70 to 130 (base course)</td>
<td>60</td>
</tr>
<tr>
<td>20</td>
<td>90 to 150 (base course)</td>
<td>80</td>
</tr>
</tbody>
</table>

2.4 Production of test specimens
The mixing temperature for the binder can be determined using the method in TMH1 C2. The aggregates and binder are to be prepared in accordance with the protocols in TMH1. Mixes are prepared using a heated mechanical mixer. The materials are to be mixed until a uniform mixture is obtained, i.e. all aggregate particles were coated with binder.

After mixing, the material is placed in an oven set at compaction temperature for four hours to induce short-term ageing. The purpose of short-term ageing is to simulate the ageing of the binder during manufacturing and placement/paving of the mix. After the four hour aging period the mix is compacted.

Slabs and gyratory specimens are compacted to a density of between 94 and 97 percent of Maximum Theoretical Relative Density (MTRD). The gyratory specimens are used for dynamic modulus and workability testing. Fracture, durability, fatigue and permanent deformation tests are performed on specimens cut from slabs. Alternatively durability specimens can be prepared using the Marshall compactor.

2.5 Performance testing
Table 8 provides an overview of the interim design criteria for South African HiMA. The table also shows the recommended number of specimens per test required to validate a mix design. The recommended number of tests is based on the local experience with the design of HiMA mixes to date. The workability of a mix can usually be assessed based on three gyratory compactions. The modified Lottman method involves indirect tensile tests on six specimens, i.e. three conditioned and three unconditioned. The resistance against permanent deformation of a mix design can be reliably
assessed from three RSST-CH results. Generally three specimens are required to determine the dynamic modulus of a material. Fatigue testing is notorious for its inherent scatter in results. It is recommended that, as a minimum, tests are performed at three strain levels, with three specimens tested per strain level, in order to create a fatigue curve. The requirements in the table were derived from French performance specifications. A HiMA reference mix was first assessed against the French specifications in a French laboratory and then evaluated at the CSIR using South African test methods for a similar set of performance parameters (Denneman et al, 2011). The tentative performance related mix design criteria were developed based on a laboratory study of limited scope. The values require validation through further comparative laboratory testing as well as Long Term Pavement Performance (LTPP) monitoring and Accelerated Pavement Testing. APT and LTPP is planned as part of the next phase of the HiMA T² project.

Table 8: Tentative performance related specifications HiMA base mixes

<table>
<thead>
<tr>
<th>Property</th>
<th>Test</th>
<th>Number of specimens</th>
<th>Method</th>
<th>Performance requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workability</td>
<td>Gyratory compactor, air voids after 45 gyrations</td>
<td>3</td>
<td>ASTM D6926</td>
<td>≤ 10% ≤ 6%</td>
</tr>
<tr>
<td>Moisture sensitivity</td>
<td>Modified Lottman</td>
<td>6</td>
<td>ASTM D4867</td>
<td>Refer Table 9</td>
</tr>
<tr>
<td>Permanent deformation</td>
<td>RSST-CH, 55°C, 5 000 reps</td>
<td>3</td>
<td>AASHTO T 320</td>
<td>≤ 1.1% strain ≤ 1.1% strain</td>
</tr>
<tr>
<td>Dynamic modulus</td>
<td>Dynamic modulus test at 10 Hz, 15°C</td>
<td>3</td>
<td>AASHTO TP 62</td>
<td>≥ 14 GPa ≥ 14 GPa</td>
</tr>
<tr>
<td>Fatigue</td>
<td>Beam fatigue test at 10 Hz, 10°C, to 50% stiffness reduction</td>
<td>9</td>
<td>AASHTO T 321</td>
<td>≥ 10⁶ reps @300 µε ≥ 10⁶ reps @390 µε</td>
</tr>
</tbody>
</table>

Table 9: Minimum TSR criteria

<table>
<thead>
<tr>
<th>Climate</th>
<th>Permeability</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td></td>
<td>0.60</td>
<td>0.65</td>
<td>0.70</td>
</tr>
<tr>
<td>Medium</td>
<td></td>
<td>0.65</td>
<td>0.70</td>
<td>0.75</td>
</tr>
<tr>
<td>Wet</td>
<td></td>
<td>0.70</td>
<td>0.75</td>
<td>0.80</td>
</tr>
</tbody>
</table>
3. DESIGN OF HiMA PAVEMENT STRUCTURES

The laboratory study of the Sabita T² project was designed to feed into SANRAL project to revise the South African Pavement Design Method (SAPDM). Resilient response and damage models for HiMA will form an integral part of the new SAPDM once this is released. In the interim, the design of pavements containing HiMA will have to rely on existing models available to practitioners. This chapter provides a guideline on the design of pavements with HiMA layers using available methods.

3.1 Minimum layer thickness

Apart from structural requirements, the minimum layer thickness is determined by the aggregate size as described in Table 7.

3.2 Determining the elastic modulus of HiMA

Asphalt is a visco-elastic material and the modulus of asphalt is therefore sensitive to changes in temperature and loading speed. The revised SAPDM will include methods to develop dynamic modulus (E*) master curves for the material and predict the stiffness of an asphalt material at any combination of loading speed and temperature. The influence of aging of the binder on the modulus of the material will also be taken into consideration in the SAPDM models. Although the aging models are not yet available, it is already possible to use master curves in HiMA pavement design.

Master curves are generated using time-temperature superposition principle. This principle allows for test data collected at different temperatures and frequencies to be shifted along the frequency axis relative to a reference temperature to form a single characteristic master curve. Master curves can be developed based on dynamic modulus laboratory tests on cylindrical or, where less reliability is required using a predictive equation. There are various ways to develop master curves; in this interim guide the discussion is limited to two examples of simple approaches to develop a master curve from either laboratory data or using a predictive equation.

3.2.1 Development of E* master curves for HiMA using laboratory results

Figure 3 shows the average results of dynamic modulus tests performed on the HiMA reference mix at different temperatures. The figure also shows the master curve, which is obtained by shifting the results for different temperatures to form a smooth function with the results at the chosen reference temperature of 20ºC.
The shape of the master curve is defined by the sigmoidal function in Equation 1:

$$\log |E^*| = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \log f_r}}$$  \hspace{1cm} (1)

where:

- $|E^*|$ = dynamic modulus
- $f_r$ = reduced frequency [Hz]
- $\delta$ = minimum value of $|E^*|
- \delta + \alpha$ = maximum value of $|E^*|
- \beta, \gamma$ = parameters describing the shape of the sigmoidal function

The fitting parameters $\delta$ and $\alpha$ depend on aggregate grading, binder content, and air voids content whereas the parameters $\beta$ and $\gamma$ depend on the characteristics of the binder and the magnitude of $\delta$ and $\alpha$. 

**Figure 3: Master curve development based on $E^*$ tests (reference temperature 20°C)**
The results of the dynamic modulus tests are shifted with respect to time of loading until a single smooth curve emerges, by means of the reduced frequency parameter \( f_r \). The reduced frequency is defined as the actual loading frequency multiplied by the time-temperature shift factor, \( a(T) \).

\[
f_r = a(T) \times f
\]  

(2)

where:

\[f\] = frequency [Hz]

\[a(T)\] = shift factor as a function of temperature [°C]

\[T\] = temperature [°C]

The shift function is fitted using a second order polynomial equation:

\[
\log a(T) = aT^2 + bT + c
\]  

(3)

where:

\[a, b, c\] = fitting parameters

Microsoft Excel solver can be used to simultaneously determine the optimum values for the fitting parameters for Equations 1 and 3, by maximizing the coefficient of determination \( R^2 \) of the fit. The fitted curve parameters for the master curve of the reference mix in Figure 3 are shown in Table 10. The shift factor at different temperatures is shown in Figure 4. Equations 1, 2 and 3, in combination with the parameters in Table 10 can now be used to calculate the dynamic modulus of the HiMA reference mix at any combination of loading speed and temperature. If no other data are available, the results for the HiMA reference mix presented here could be used by practitioners as a point of departure in estimating the stiffness of HiMA material for structural analysis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( \delta )</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( \gamma )</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.49179</td>
<td>4.08124</td>
<td>-1.86826</td>
<td>-0.31569</td>
<td>9.9374E-4</td>
<td>-0.18260</td>
<td>3.14717</td>
</tr>
</tbody>
</table>
3.2.2 Prediction of $E^*$ using the Hirsch predictive equation

The Hirsch dynamic modulus predictive equation was proposed by Christensen et al. (2003). The Hirsch model uses a number of material parameters to determine the dynamic modulus of the mix. The dynamic modulus ($E^*$) of the asphalt mix is estimated from the complex shear modulus of binder ($G^*_{binder}$) determined in the laboratory using Dynamic Shear Rheometer (DSR) testing, the voids in mineral aggregate (VMA), and the voids filled with binder (VFB). The Hirsch model is shown in Equation 4.

$$\begin{align*}
E^*_{mix} &= P_c \left[ 4,200,000 \left( 1 - \frac{\text{VMA}}{100} \right) + 3 \left| G^*_{binder} \right| \left( \frac{\text{VFB} \times \text{VMA}}{10,000} \right) \right] + \frac{1 - P_c}{\left( \frac{1 - \text{VMA}}{100} + \frac{\text{VMA}}{4,200,000} \right) \left( \frac{3 \text{VFB} \left| G^*_{binder} \right|}{100} \right)} \\

P_c &= \left( \frac{20 + \frac{\text{VFB} \times 3 \left| G^*_{binder} \right|}{\text{VMA}}}{650 + \left( \frac{\text{VFB} \times 3 \left| G^*_{binder} \right|}{\text{VMA}} \right)^{0.58}} \right)^{0.58}
\end{align*}$$

where:

$|E^*| = \text{dynamic modulus (psi)}$;

$|G^*_{binder}| = \text{shear complex modulus of binder (psi)}$;

VMA = percent voids in mineral aggregates

VFB = percent voids filled with binder

$P_c = \text{aggregate contact factor}$

Figure 4: Shift factors for reference mix.
Research as part of the SANRAL SAPDM project has shown that the Hirsch equation provides satisfactory results in predicting the $E^*$ of the mix. In order to use the Hirsch equation, DSR temperature and frequency sweep testing of the binder is required. The master curve developed for the binder (after RTFOT) can be translated into a master curve for the asphalt mix using the equation.

### 3.2.3 Loading time and pavement temperature

In order to make use of the master curves developed using the methodology in 3.2.1 and 3.2.2, the loading frequency and temperature of the asphalt pavement needs to be determined. The loading time and therefore load frequency to which the asphalt material in a pavement is subjected depend on a complex interaction of factors, including traffic speed, tyre contact area and shape, stiffness of supporting layers, load magnitude, depth in the pavement structure, etc. A frequently cited reference for the determination of the compressive stress pulse time in a flexible pavement is a paper by Barksdale (1971). A reasonable estimation of the loading frequency may be obtained by making assumptions on the average speed of heavy vehicles on the road, the typical shape of the tyre contact area and the shape of the stress cone in the pavement. The relationship introduced by Brown (1973) can be used to calculate the loading time:

$$\log(t) = 0.5d - 0.2 - 0.94\log(v) \tag{6}$$

where

- $t$ = loading time [s],
- $d$ = depth [m],
- $v$ = vehicle speed [km/h]

The temperature in the HiMA material in a pavement can be estimated using the predictive equations calibrated for South Africa (Viljoen, 2001, Denneman, 2007). The equations have been incorporated in the CSIR ThermalPADS temperature prediction software, available from www.prac.co.za. These models allow the prediction of the temperature at any time of day and at any depth in asphalt pavements.

### 3.3 Fatigue prediction

New fatigue prediction models are being developed under the SANRAL revision of SAPDM, which is planned to become available end 2013. It is proposed that in the interim the existing TRH4-1995 models for fatigue in thick asphalt bases be used for HiMA. These models are deemed conservative for HiMA base materials, because of the higher binder content used in HiMA mixes.
3.4 Permanent deformation modelling

The TRH4-1995 design method does not contain damage models for permanent deformation in asphalt layers. Models for permanent deformation are being developed as part of the new SAPDM.

To get an estimate of the permanent deformation in HiMA base layers use can be made of the models in the Mechanistic Empirical Design Guide (MEPDG) recently introduced in the USA (NCHRP, 2004). These models have not been validated for South Africa, but provisional results from the SAPDM development project indicate that they may be reasonably accurate.

The final calibrated model for laboratory and field data for the relation between elastic and plastic strain in MEPDG is given in Equation 7:

\[
\frac{\varepsilon_p}{\varepsilon_r} = k_1 \cdot 10^{-3.4488} \cdot T^{1.5606} \cdot N^{0.479244}
\]

Where:
- \( \varepsilon_p \) = the accumulated plastic strain,
- \( \varepsilon_r \) = the resilient strain in the middle of the layer calculated using linear elastic analysis,
- \( T \) = temperature (°F),
- \( N \) = the number of load repetitions
- \( k_1 \) = a function of the total asphalt thickness (\( h_{ac} \)) and depth (both in inches) to correct for confining pressure,

\[
k_1 = (C_1 + C_2 \cdot depth) \cdot 0.328196^{depth}
\]

\[
C_1 = -0.1039 \cdot h_{ac}^2 + 2.4868 \cdot h_{ac} - 17.342
\]

\[
C_2 = -0.172 \cdot h_{ac}^2 + 1.7331 \cdot h_{ac} + 27.428
\]
REFERENCES


