

FINAL REPORT

P123: Improved Subgrade Characterisation for Pavement Design Purposes: Use of the Japan Road Association Equation (2020–21)

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SUMMARY

During the construction of new pavements, testing of the in situ subgrade may indicate that at some locations the subgrade design strength is lower than that used in the original pavement structural design. In addressing the structural deficiency of such low subgrade strength areas, the most commonly used approach is not to change the pavement layers but rather to treat the subgrade. A common treatment is the removal of the low strength subgrade to the required depth and replacement with selected subgrade material with a design strength exceeding the original subgrade design strength.

Currently for flexible pavements with bound pavement layers, the mechanistic-empirical (ME) design method is used to calculate the removal and replacement (R&R) depths. However, as such R&R determinations are undertaken during construction, there is interest in using an alternative simpler method to determining R&R depths.

The Austroads structural design method for concrete pavements includes a simplified method of considering the structural contribution of subgrade materials where more than one type of material is present. An equation is provided to determine the equivalent subgrade California Bearing Ratio (CBR) strength considering the thickness of each material and its design CBR. The method uses a stiffness parameter ($h_i \text{CBR}_i^{0.333}$), which is based on the stiffness parameter ($h_i E_i^{0.333}$) used in Odemark's method of equivalent layer thickness. This Austroads method was developed from a method used by the Japan Road Association (JRA) for the design of asphalt pavements.

This report describes the method and why in the design of concrete pavements it was necessary to provide a simplified method of characterising multiple subgrade layers.

The Queensland Department of Transport and Main Roads sought advice on whether the JRA method could be adapted to determine the R&R depths for flexible pavements.

Several methods of calculating an equivalent subgrade modulus (ESM) were selected and evaluated. The R&R depths were compared to the values calculated using the ME design method. It was concluded that ESM is not suitable for use as it does not allow for the influence of pavement layers on the required R&R depths.

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1 INTRODUCTION

The mechanistic-empirical (ME) design procedures for new pavements (Austroads 2017, TMR 2018) provide processes for the elastic characterisation of subgrades, primarily based on the California Bearing Ratio (CBR) test. During the construction of new pavements, testing of the existing subgrade material may indicate that at some locations the subgrade design strength is lower than that used in the original pavement structural design. Whilst subgrade design strength is commonly determined such that at least 90% of the project exceeds the design value, it is common Queensland Department of Transport and Main Roads (TMR) practice to treat any areas below the design values found during construction regardless of the extent. Other road agencies also appear to follow this practice.

In addressing the structural deficiency of such low subgrade strength areas, the most commonly used approach is not to change the pavement layers but rather to treat the subgrade. Such treatments include:

- removal of the low CBR subgrade and replacement with selected subgrade material with a CBR equal to or exceeding the design CBR used to determine the design modulus
- in situ stabilisation of the subgrade (e.g. lime stabilisation).

To assess the suitability of different treatments, the ME design procedures are currently used to evaluate:

- whether the tensile strains at the bottom of bound materials (e.g. asphalt) do not exceed the values required to provide the required fatigue life
- whether the vertical compressive strains on top of selected subgrade materials and subgrade do not exceed the value required to provide the required life in terms of permanent deformation.

As such treatment evaluations are undertaken during construction, there is interest in using an alternative simpler method to determining removal and replacement (R&R) depths consistent with the ME method.

For the design of concrete pavements, Austroads (2017) includes a simplified process for the calculation of an equivalent CBR strength, considering the design CBR and thicknesses of each subgrade materials (see Section 3). This report investigates the applicability of this method in the design of flexible pavements.

2 OVERVIEW OF THE DESIGN METHOD FOR CONCRETE PAVEMENTS

Section 9 of Austroads (2017) provides guidance on the structural design of concrete pavements. In relation to the thickness design of concrete bases, the following two distress types are considered:

- flexural fatigue cracking of the concrete base
- subgrade/subbase erosion arising from repeated deflections at joints and planned cracks.

In the development of the prediction procedure for concrete fatigue cracking, the traffic-induced tensile stresses at the bottom of the concrete base was adopted as the critical response to load parameter. The allowable traffic loading for erosion is predicted from the load-induced joint vertical deflections.

The Austroads (2017) design method was developed from the method previously developed by the Portland Cement Association (PCA 1984). The PCA method included nomographs to calculate the allowable loading of a proposed pavement configuration for two distress types (i.e. flexural fatigue and erosion) using the following inputs:

- concrete pavement type (jointed or continuously reinforced), whether dowels are provided at joints and whether or not concrete shoulders are provided
- concrete base thickness
- concrete flexural strength
- the support provided to the concrete base and subbase, expressed in terms of Westergaard's modulus of subgrade reaction, k
- the expected number of repetitions of each axle group type and load, considering the load safety factor selected according to the desired project reliability level.

The design nomographs were developed from the stresses and displacements calculated using finite element modelling. From the PCA method, tables for equivalent stress and erosion factors were provided in Austroads (1992). Later Austroads developed equations to predict equivalent stresses and erosion factors (Jameson 2013) consistent with the PCA tables.

Note that unlike the design of flexible pavements, the Austroads concrete design method does not include a response to load model to enable calculation of stresses and deflections due to multilayer subgrades, including the use of selected subgrade materials. As a consequence, a simplified method was adopted by Austroads to characterise the support provided by multiple subgrade layers (see Section 3).

3 USE OF EFFECTIVE SUBGRADE STRENGTH IN CONCRETE PAVEMENT DESIGN

3.1 INTRODUCTION

As mentioned in Section 2, unlike in the design of flexible pavements, the Austroads (2017) concrete base thickness design method does not include a response to load model to enable prediction of the slab support provided by more complex subgrades, including the use of selected subgrade materials. As a consequence, the simplified method described below was adopted by Austroads for pavements with multiple subgrade layers including selected subgrade materials.

3.2 AUSTROADS METHOD FOR CONCRETE PAVEMENTS

Section 9.3.2 of Austroads (2017) describes the method of determining the effective subgrade strength for use in the design of concrete pavements as follows:

Where the subgrade within 1 m of the underside of the subbase shows (or is likely to show) vertical stratification, the determination of the design CBR must be based on a multi-layered subgrade system. The formula given in equation 1 provides a model that may be used to determine this equivalent subgrade design strength (CBR_e) based on the strength of the supporting soil depth (Japan Road Association 1989).

$$CBR_e = \left[\frac{\sum_i h_i CBR_i^{0.333}}{\sum_i h_i^{0.333}} \right]^3 \quad 1$$

where

CBR_e = equivalent subgrade design strength (%)

CBR_i = the CBR of subgrade layer i (%)

h_i = thickness of layer i (m)

$\sum_i h_i$ = sum of subgrade layer thicknesses taken to a depth of 1 m (m)

The following conditions apply to the use of equation 1:

- Layers of thickness less than 200 mm must be combined with an adjacent layer. The lower CBR value must be adopted for the combined layer.
- It is assumed that higher CBR materials will be used in the upper layers. The formula is not applicable where weaker layers are located in the upper part of the subgrade.
- Filter layers must not be included in the calculation.
- The maximum equivalent subgrade CBR from the use of equation 1 is 15%.

The use of Equation 1 generally does not impact on the design of heavily trafficked concrete pavements which include thick select subgrade materials and the provision of 150 mm thickness of lean-mix concrete subbase (Roads and Maritime Services 2018). As seen from Figure 9.1 of Austroads (2017), for such situations the effective subgrade CBR for determination of the concrete base thickness would be 75% (the maximum permitted value). However, for pavements without such lean-mix concrete subbases and/or without substantial thicknesses of selected subgrade materials, Equation 1 may influence the concrete base thickness.

3.3 ODEMARK'S STIFFNESS PARAMETER

Details of the origin of the Japan Road Association (JRA) Equation (1) used in the design of Japanese asphalt pavements could not be found. However, Odemark (1949) used a layer stiffness parameter ($h E^{0.333}$)

to enable the use of Boussinesq's equation to predict the stresses on top of the subgrade beneath one or more pavement layers.

According to Odemark, the stiffness of a layer is proportional to the following term (Equation 2):

$$\left[\frac{h^3 E}{1 - \nu^2} \right]^3 \quad 2$$

where

- h = thickness of layer
- E = layer modulus
- ν = Poisson's ratio of the layer

Odemark used this parameter to transform a multilayer pavement system into an equivalent one-layer system with equivalent thickness and a single modulus. This concept is known as the method of equivalent thickness (MET). The MET assumes that the vertical stresses **below** a layer depend only on the stiffness parameter shown in Equation 2. If the thickness, modulus and Poisson's ratio of a layer is changed, but the stiffness parameter remains unchanged, the stresses below the layer are assumed to remain relatively unchanged.

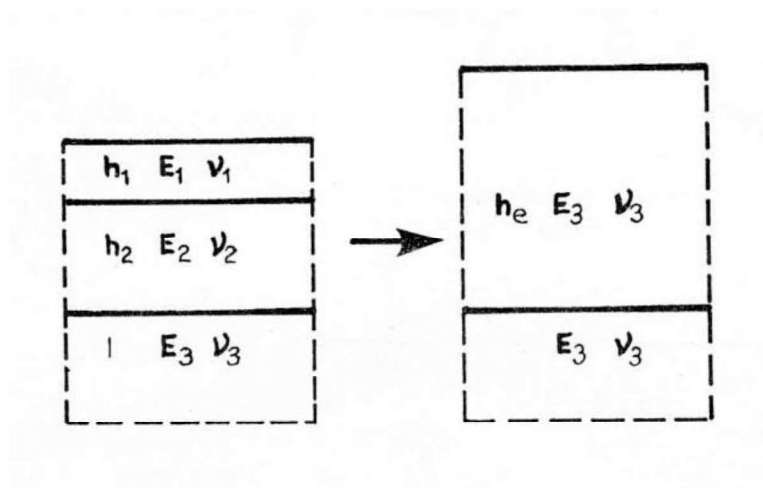
Figure 3.1 illustrates an example for a three-layer pavement system where each of the layers has the same Poisson's ratio. The equivalent layer thickness (h_e) to the top of subgrade is calculated as follows:

$$h_e = a \left[h_1 \left(\frac{E_1}{E_3} \right)^{0.333} + h_2 \left(\frac{E_2}{E_3} \right)^{0.333} \right] \quad 3$$

where

- h_e = equivalent layer thickness
- h_i = thickness of layer i
- E_i = modulus of layer i
- a = correction factor to provide similar stresses to multilayer linear elastic modelling, 0.8 to 0.9 for flexible pavements

Figure 3.1: Example of the application of the MET



3.4 USE OF THE STIFFNESS PARAMETER TO ESTIMATE EFFECTIVE SUBGRADE STRENGTH

The Austroads (2017) use of Equation 2 in the design of concrete pavements differs from Odemark's MET. Odemark's method calculates an equivalent thickness (depth) at which to calculate the response to load. In contrast, the Austroads Equation 1 uses the similar stiffness parameter as an index of support to assess the performance of an overlying concrete slab. So an equivalent thickness (depth) is not calculated, rather it is an equivalent modulus/CBR. The assumption in using Equation 1 is that the responses to load of pavement structures using the equivalent CBR are similar to the values if a finite element model be used to more rigorously predict the structural contribution of the individual subgrade layer thicknesses and moduli. As discussed in Section 2, the critical responses to load are:

- the traffic-induced tensile stresses at the bottom of the concrete base
- the vertical deflections on the top of the supporting layer.

As such, the most appropriate method to assess the suitability of Equation 1 for use in the design of concrete pavements would be through the use of finite element modelling. The development of such a model is however beyond the scope of this NACOE project.

It was considered that some insight would be obtained by using linear elastic modelling as used for the design of flexible pavements. The major limitation of such modelling is its inability to predict the slab edge and corner responses, these being the location of the maximum responses to load. In using linear elastic modelling, the concrete slab is of infinite horizontal extent. Nevertheless, linear elastic modelling was considered suitable to investigate the predicted **relative** responses due to changes in the properties of the support layer.

The linear elastic model CIRCLY was used to calculate the following responses to load under an 80 kN single axle with dual tyres:

- the maximum tensile stress and strain at the bottom of the concrete base
- the maximum vertical deflections and strains on top of the supporting layer.

The concrete base was characterised as follows:

- base thickness of 250 mm
- base modulus of 40 000 MPa and Poisson's ratio of 0.2.

The subgrade layers under the base comprised the following four configurations, all with the same equivalent subgrade CBR of 7% as determined using Equation 1:

- Support 1: 1000 mm thickness of subgrade with a single CBR value of 7%
- Support 2: 460 mm of select fill with CBR of 10% on 540 mm in situ subgrade CBR of 5%
- Support 3: 460 mm of select fill with CBR of 15% on 540 mm in situ subgrade CBR of 3%
- Support 4: 543 mm of select fill with CBR of 15% on 457 mm in situ subgrade CBR of 2%.

The results shown in Table 3.1 indicate that the Austroads procedures for determining the equivalent subgrade CBR do not result in equivalent responses to load in this case. As such, there is a case for developing a new method for characterising subgrade layers underneath concrete pavements. However, for heavy-duty concrete pavements which include lean-mix concrete subbases or thick selected subgrade materials, the equivalent subgrade support values do not influence concrete base thicknesses. Given this and the limited use of concrete pavements by TMR, the issue is not proposed to be addressed in this NACOE research project.

Note that in Section 4, it was similarly concluded that full-depth asphalt pavements with the same equivalent subgrade modulus do not necessarily have the same critical asphalt strains.

Table 3.1: Variations in responses to load of configuration with equivalent subgrade CBR

Configuration	Concrete base tensile stress (kPa)	Concrete base tensile strain (microstrain)	Vertical deflection top of supporting layer (mm)	Vertical compressive strain top of supporting layer (microstrain)
1	793	17.2	0.082	95.3
2	797	17.3	0.086	72.2
3	825	17.9	0.104	60.5
4	847	18.3	0.119	59.3

4 CURRENT USE OF A STIFFNESS PARAMETER IN FLEXIBLE PAVEMENT DESIGN

4.1 INTRODUCTION

Given the current use of the equivalent subgrade strength in the design of concrete pavements (Section 3), it has been suggested to TMR by a number of design consultants that this method could be used in the design of flexible pavements.

As described in Section 3.3, the equivalent subgrade strength method in Austroads (2017) uses an approximation to Odemark's stiffness parameter (i.e. $hE^{0.333}$).

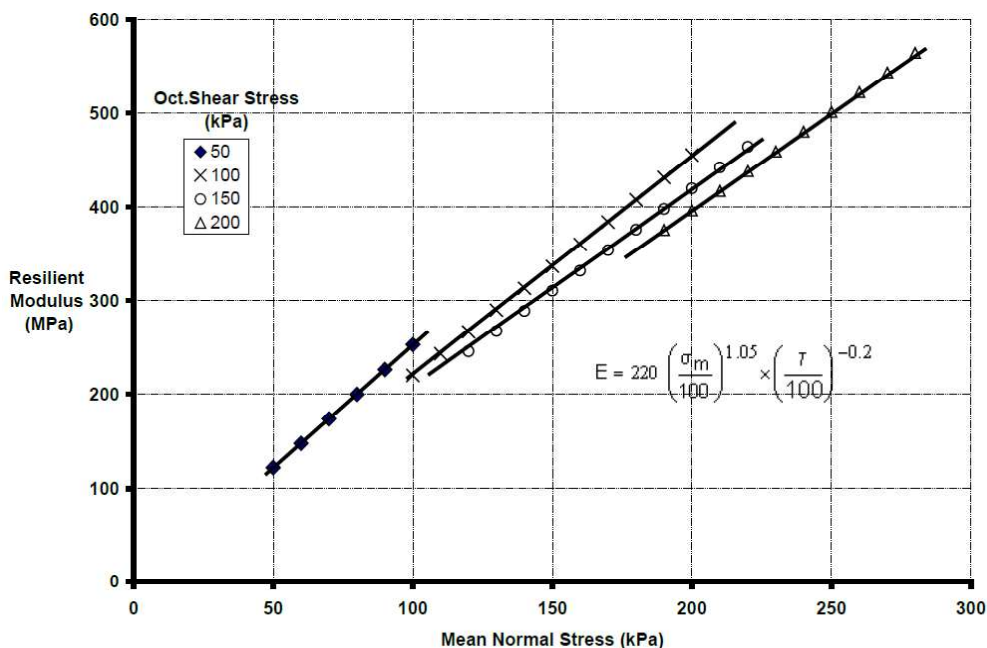
This section describes the current Austroads (2017) method's use of this stiffness parameter to determine an equivalent bound material modulus for use in estimating the design modulus of underlying granular materials. In this case, the calculated equivalent modulus of the overlying bound material is appropriate as it is correlated with the stresses applied to the underlying unbound granular materials.

Section 5 investigates whether or not an equivalent subgrade modulus is appropriate for the design of flexible pavements.

4.2 DETERMINATION OF GRANULAR MODULUS

The moduli of unbound granular materials vary with the applied stress, increasing with an increase in the mean normal stress and decreasing with increasing shear stress (Figure 4.1).

Figure 4.1: Example of variation of granular modulus with stress



Source: Austroads (2017).

The stress applied to granular materials varies with the thickness and modulus of any overlying bound materials (e.g. asphalt). Accordingly, Section 6.2.3 of Austroads (2017) describes a method for determining the influence of the thickness and modulus of overlying bound materials on the design modulus of granular materials. When the overlying materials comprise layers of different bound materials, with different moduli, Equation 4 provides a method of calculating an equivalent modulus of the same total thickness.

$$E_e = \left[\frac{\sum_i h_i E_i^{0.333}}{T} \right]^3$$

where

- E_e = equivalent modulus of the total thickness of bound materials (MPa)
- E_i = modulus of bound layer i (MPa)
- h_i = thickness of bound layer i (mm)
- T = total thickness of bound layers (mm)

Equation 4 was derived from Odemark's stiffness parameter (Section 3.3) assuming all bound materials have the same Poisson's ratio. However, unlike Odemark's method of equivalent thickness, this method calculates an equivalent modulus of overlaying bound materials for a given total thickness rather than an equivalent thickness.

The underlying assumption of this method is that for a given total thickness of bound materials and equivalent modulus, the stresses applied to the top sublayer of granular material are similar regardless of the thicknesses and moduli of the individual bound material layers.

To evaluate this assumption, the stresses applied to the top granular sublayer due to an 80 kN single axle with dual tyres were calculated for a range of pavement configurations. Using these calculated stresses and an assumed modulus stress-dependency relationship, the top sublayer granular modulus for each configuration was calculated.

The following two pavement types were investigated:

- Pavement A: comprising two asphalt layers with a total asphalt thickness of 100 mm and an effective modulus of 3000 MPa, over 450 mm unbound granular material on a subgrade with a vertical design modulus of 50 MPa.
- Pavement B: comprising two asphalt layers with a total asphalt thickness of 150 mm and an effective modulus of 3000 MPa, over 240 mm unbound granular material on a subgrade with a vertical design modulus of 50 MPa.

For each pavement type, a range of asphalt layer thicknesses and moduli were considered with the same equivalent modulus of 3000 MPa calculated using Equation 4.

Using the linear elastic model CIRCLY, the top granular sublayer stresses due to an 80 kN single axle with dual tyres were predicted. These stresses were calculated mid-way between one set of dual wheels and 50 mm below the top of the layer. As the predicted stresses in the horizontal plane were tensile and granular materials have nil or very low tensile strength, it was decided to assign a residual compaction compressive stress of 40 kPa (Austroads 2012) for both the XX and YY directions.

Table 4.1 and Table 4.2 list the calculated stresses and the estimated granular moduli for the top granular sublayer. These moduli were calculated from the middle stresses in the granular sublayer and Equation 5.

$$E = K_1 \times \left(\frac{\sigma_m}{\sigma_{ref}} \right)^{K_2} \times \left(\frac{\tau}{\sigma_{ref}} \right)^{K_3} \quad 5$$

where

- E = granular modulus (MPa)
- σ_m = mean normal stress (kPa)
- τ = octahedral shear stress (kPa)

- σ_{ref} = reference stress, 100 MPa
- constant, for 100 mm and 150 mm asphalt thicknesses, values of 352 and 266
- K_1 = respectively were used as these resulted in granular moduli similar to Table 6.4 of Austroads (2017)
- K_2 = 1.05 from Figure 4.1
- K_3 = -0.2 from Figure 4.1

Table 4.1: Pavement type A configurations with an equivalent modulus of 3000 MPa

Configuration	Asphalt layer 1 thickness (mm)	Asphalt layer 1 modulus (MPa)	Asphalt layer 2 thickness (mm)	Asphalt layer 2 modulus (MPa)	Vertical stress (kPa)	Horizontal stress ⁽¹⁾ XX (kPa)	Horizontal stress ⁽¹⁾ YY (kPa)	Top granular sublayer modulus ⁽²⁾ (MPa)
A1	50	3000	50	3000	133.0	40	40	290.0
A2	50	2220	50	4000	134.4	40	40	291.1
A3	40	1157	60	5000	139.6	40	40	295.3
A4	30	1000	70	4390	138.2	40	40	294.2
A5	70	4390	30	1000	134.6	40	40	291.3

1. Set to the value of the residual compaction stress (Austroads 2012).

2. The granular modulus stress-dependency relationship was the same as shown in Figure 4.1 except that the K1 value of 352 was used instead of 220 so that the granular modulus of 290 MPa was calculated under 100 mm asphalt thickness with a modulus of 3000 MPa for pavement A1 consistent with the value in Table 6.4 (Austroads 2017).

Table 4.2: Pavement type B configurations with an equivalent modulus of 3000 MPa

Configuration	Asphalt layer 1 thickness (mm)	Asphalt layer 1 modulus (MPa)	Asphalt layer 2 thickness (mm)	Asphalt layer 2 modulus (MPa)	Vertical stress (kPa)	Horizontal stress ⁽¹⁾ XX (kPa)	Horizontal stress ⁽¹⁾ YY (kPa)	Top granular sublayer modulus ⁽²⁾ (MPa)
B1	75	3000	75	3000	64.6	40	40	190.0
B2	40	2000	110	3469	66.0	40	40	189.8
B3	75	2000	75	4350	65.9	40	40	189.8
B4	100	4650	50	1000	67.9	40	40	189.7

1. Set to the value of the residual compaction stress (Austroads 2012).

2. The granular modulus stress-dependency relationship was the same as shown in Figure 4.1 except that the K1 value of 266 was used instead of 220 so that the granular modulus of 190 MPa was calculated under 150 mm asphalt thickness with a modulus of 3000 MPa for pavement B1 consistent with the value in Table 6.4 (Austroads 2017).

For pavement type A, using the Austroads (2017) method a top granular modulus of 290 MPa would be used for all configurations (A1 to A5) whereas the granular moduli calculated using Equation 5 and the modulus stress-dependency varied up to a maximum of 295 MPa. This slight increase in granular modulus was predicted to result in a 0.7% reduction of the tensile asphalt strain applied to the bottom of a 100 mm thick asphalt. The resulting difference in asphalt fatigue life was 3-4% or about a 1 mm error in asphalt thickness. Similarly for pavement type B, the use of Equation 4 resulted in less than a 1% error in predicted fatigue life compared to a more rigorous approach of using the calculated stresses and an assumed modulus stress-dependency.

4.3 CONCLUSIONS

It was concluded that the use of an equivalent modulus for bound layers results in less than a 5% error in asphalt fatigue life for the pavements evaluated compared to a more rigorous approach of predicting the stresses in the granular moduli and determining the top granular modulus from its modulus stress-dependency. Such errors are considered acceptable considering the complexities of the rigorous approach. It was concluded that this use of Odemark's stiffness parameter is appropriate and should continue.

The use of an equivalent modulus for overlying bound materials is therefore considered as an appropriate approximation for the stresses applied to the underlying layers. Note that unlike the equivalent subgrade modulus investigated in Section 5, this equivalent bound material modulus is not used as a measure of the support provided to overlying layers but the stresses applied to underlying layers.

5 EVALUATION OF THE USE OF AN EQUIVALENT SUBGRADE MODULUS IN FLEXIBLE PAVEMENT DESIGN

5.1 INTRODUCTION

In Section 3.4, the use of the equivalent subgrade CBR in the design of concrete pavements was reviewed. A design example illustrated that the use of the Austroads (2017) method of equivalent CBR did not result in similar pavement responses to load compared to a multilayer subgrade characterisation.

In this section, a similar type of analysis was undertaken to investigate whether or not an equivalent subgrade modulus (ESM) concept could be developed for the design of flexible pavements such that the predicted responses to load are similar to those calculated using the Austroads (2017) ME design method.

Section 5.2 describes four methods of ESM calculation that were evaluated.

Section 5.3 describes the subgrade R&R scenarios used in the evaluation.

For each scenario, the R&R thickness predicted using the Austroads (2017) ME method (Section 5.4) and using the four ESM methods (Section 5.5) were compared.

Note that as Odemark's stiffness parameter (Equation 2) is for the elastic characterisation of isotropic materials, it was decided not to complicate the assessment by using anisotropic characterisation in the ME method and isotropic for the determination of the ESM. Isotropic moduli were therefore used in both methods.

5.2 EQUIVALENT SUBGRADE MODULUS CALCULATION METHODS

Section 3.2 describes the use of an equivalent subgrade strength in the design of concrete pavements.

In adapting this method for the design of flexible pavements, the following aspects were considered:

- The Austroads (2017) ME method requires the determination of the design moduli of selected subgrade materials and the in situ subgrade. Consequently, the methods used in the evaluation were all based on ESM rather than equivalent subgrade strength.
- A consideration for quantifying the modulus of selected subgrade materials was whether to use a layer modulus of $10 \times \text{CBR}$ (consistent with the recommendations in Austroads (2017) for a semi-infinite subgrade) or to sublayer the material consistent with the ME method. It was decided to evaluate both options.
- Another issue relates to the depth of subgrade used to calculate the equivalent value. The Austroads (2017) concrete design method uses a depth of 1000 mm below the top of subgrade or top of selected subgrade material where such material is provided. In another element of this NACOE project, detailed consideration will be given to providing consistent advice about the depth to which subgrade support needs to be characterised. Based on a preliminary investigation, a depth of 1500 mm appears likely to be recommended. Hence two depths (1000 mm and 1500 mm) were investigated in this study.

The following four ESM methods were investigated:

- Method A: use the concrete design method (Section 3) but using a layer modulus ($E = 10 \times \text{CBR}$) rather than a layer strength (CBR). In this case, the equivalent modulus was calculated to a depth of 1000 mm.
- Method A1500: the same as Method A except that the depth of subgrade over which the equivalent modulus was calculated was extended to 1500 mm.
- Method B: the same as Method A except that selected subgrade materials were sublayered using the TMR (2018) method and the moduli assigned to each sublayer.

- Method B1500: the same as Method B except that the depth of subgrade over which the equivalent modulus was calculated was extended to 1500 mm.

For pavements with 150 mm thickness of granular subbase, the stiffness (i.e. $hE^{0.333}$) of this layer was included in the ESM calculation and its thickness was considered as part of the assessment depth (1000 mm or 1500 mm).

Note that the thickness and modulus of the pavement layers does not affect the ESM calculated using the four methods.

5.3 SUBGRADE R&R SCENARIOS

To evaluate the suitability of the ESM concept for flexible pavement design, eight full-depth asphalt pavement configurations were considered covering a range of asphalt thicknesses, with and without 150 mm thick granular subbase and for a range of subgrade design moduli (Table 5.1).

Table 5.1: Pavement configurations

Pavement number	Asphalt thickness (mm)	Asphalt design modulus (MPa)	Granular subbase thickness (mm)	Maximum granular subbase modulus (MPa)	Original subgrade design modulus (MPa)
Pavements without granular subbase					
1	350	3000	—	—	40, 50, 60, 70, 80 and 90
2	300	3000	—	—	
3	250	3000	—	—	
4	200	3000	—	—	
Pavements with 150 mm thick granular subbase					
5	350	3000	150	150	40, 50, 60, 70, 80 and 90
6	300	3000	150	150	
7	250	3000	150	150	
8	200	3000	150	150	

During the assessment of each pavement configuration it was assumed that areas with subgrade CBRs below the original design values were identified and treated, namely:

- For original designs based on subgrade design moduli of 40 MPa, 50 MPa, 60 MPa and 70 MPa, areas with subgrade design modulus of 30 MPa to a depth of at least 1500 mm were identified.
- For original designs based on subgrade design moduli of 60 MPa, 70 MPa, 80 MPa and 90 MPa, areas with subgrade design modulus of 50 MPa to a depth of at least 1500 mm were identified.

(Note that the depth of 1500 mm was selected as below this depth the subgrade modulus value is assumed not to influence design thicknesses. This issue may be addressed in a separate report to be prepared for this NACOE project).

To address the structural inadequacy of the original designs in these areas of low subgrade, the favoured treatment was to make no changes to the pavement layers but to remove the low-strength subgrade and replace it with selected subgrade material with a maximum vertical design modulus of 100 MPa. The objective of these subgrade treatments was to reduce asphalt tensile strains to the original design strains.

5.4 SUBGRADE R&R THICKNESSES USING ME PROCEDURES

Currently the Austroads (2017) ME design method is used to design the R&R treatments where the actual subgrade strength on site is less than the design strength, hence these R&R thicknesses provided the benchmark results to assess the ESM methods (Section 5.5).

In this evaluation, the Austroads (2017) ME method was simplified to only consider the critical strains at the bottom of the asphalt layer induced by an 80 kN single axle fitted with dual tyres. The subgrade R&R depths were calculated such that the asphalt strains reduced to the design values.

These depths are shown in Figure 5.1 to Figure 5.4, plotted against asphalt thickness.

Figure 5.1: Treatment depths for full-depth asphalt pavements without granular subbase for areas with subgrade modulus of 30 MPa

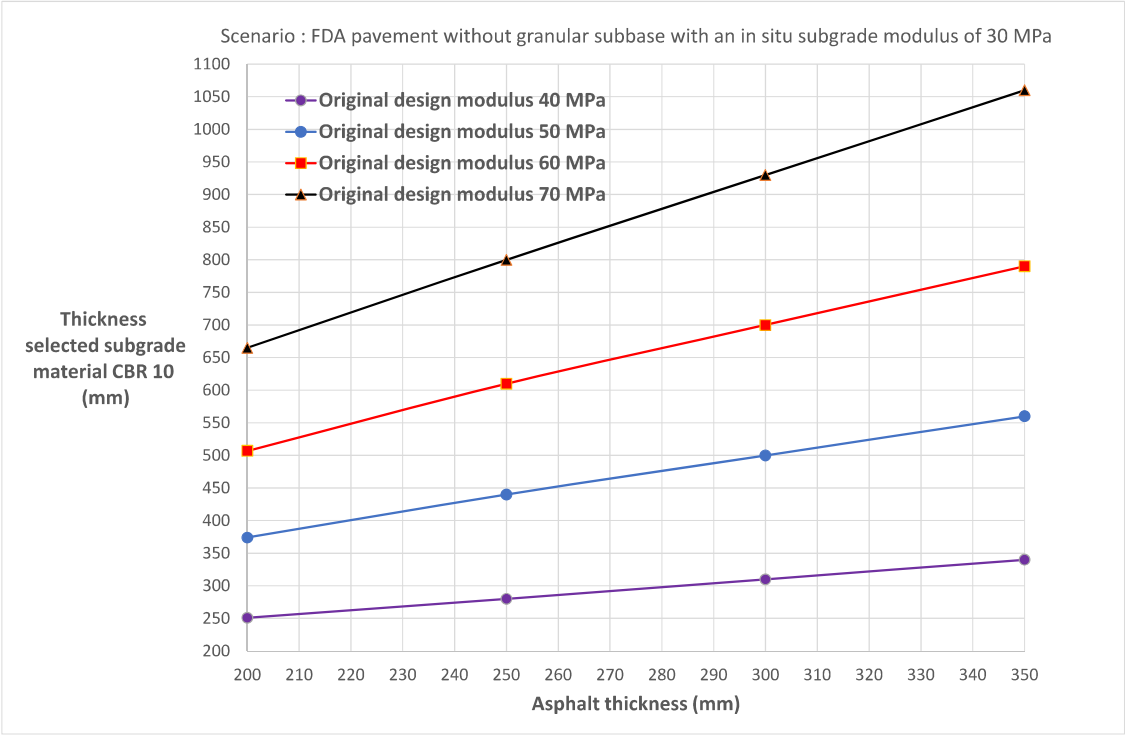


Figure 5.2: Treatment depths for full-depth asphalt pavements without granular subbase for areas with subgrade modulus of 50 MPa

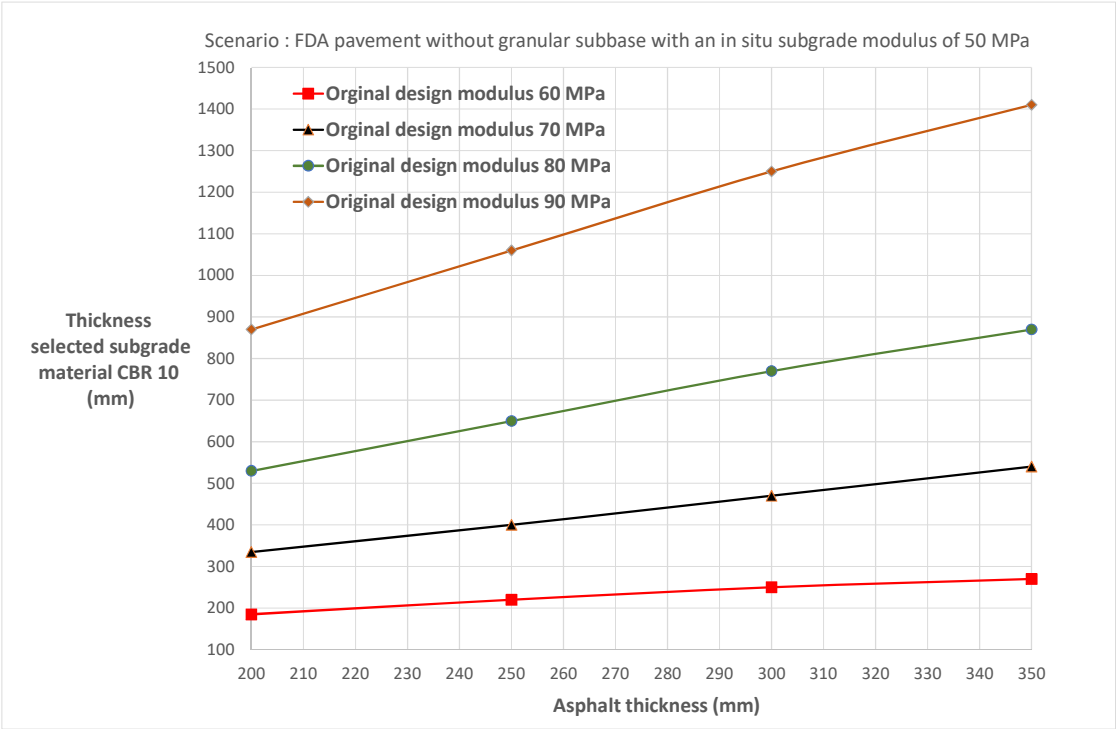


Figure 5.3: Treatment depths for full-depth asphalt pavements with granular subbase for areas with subgrade modulus of 30 MPa

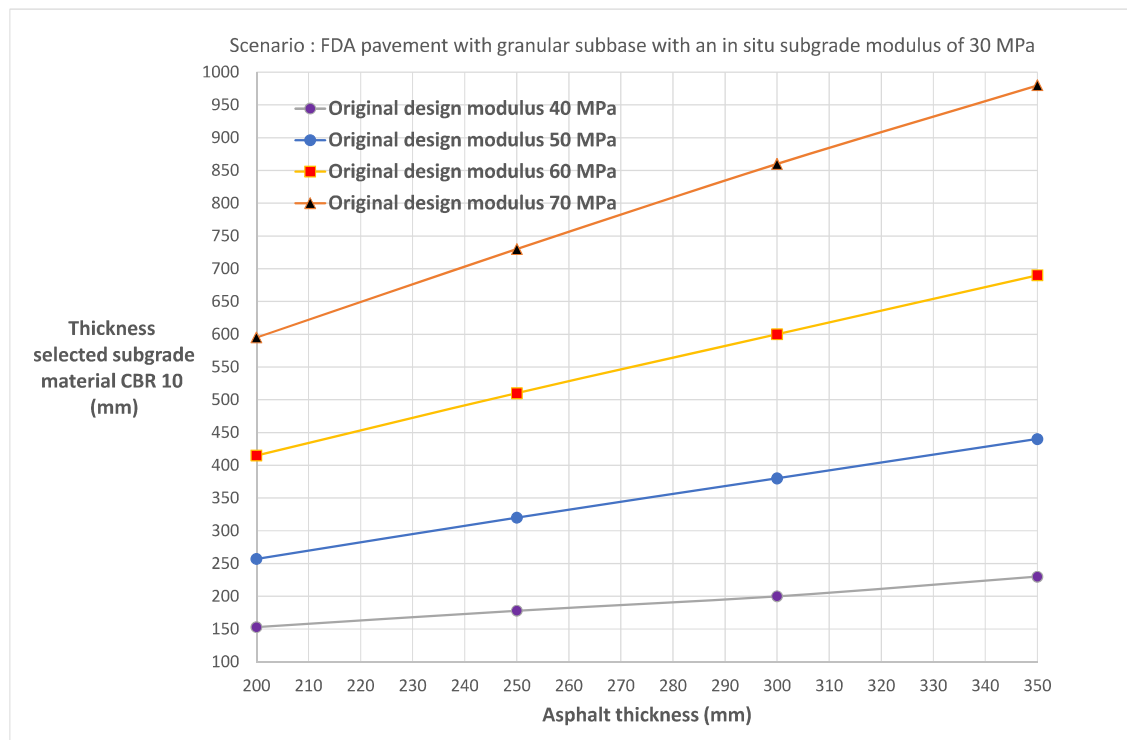
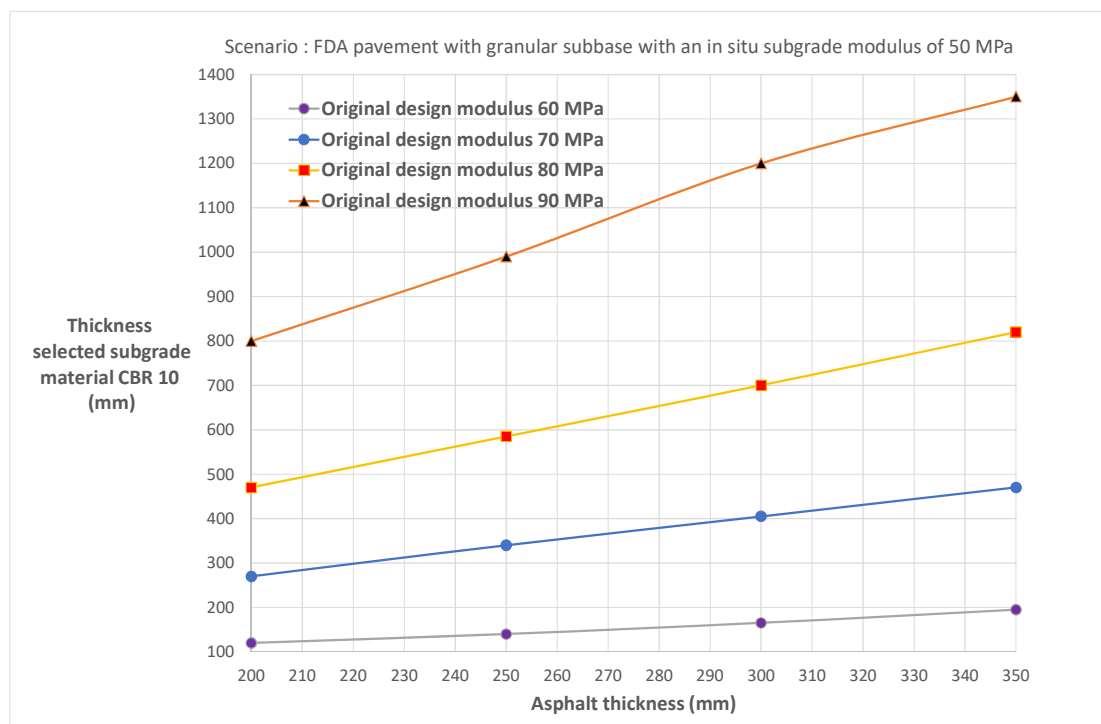


Figure 5.4: Treatment depths for full-depth asphalt pavements with granular subbase for areas with subgrade modulus of 50 MPa



Of particular interest was the variation in the required R&R thicknesses with the asphalt thickness. The greater the asphalt thickness, the greater the R&R depth. To gain a better appreciation of the reason for this variation, the asphalt strains were calculated for a range of full-depth asphalt thicknesses on two semi-infinite subgrade moduli (30 MPa and 100 MPa). For each asphalt thickness, the ratios of asphalt strains for subgrade moduli of 30 MPa to 100 MPa were calculated.

Figure 5.5 shows the calculated strain ratios plotted against asphalt thickness. The ratios decrease with asphalt thickness with the variation in semi-infinite subgrade modulus having more impact on strains (and

hence fatigue life) for thinner asphalt layers where the supporting layer moduli have a greater influence on the asphalt strains. This effect is consistent with the understanding that the load-induced asphalt strains of thin asphalt layers are largely influenced by the modulus of the supporting layers (controlled strain), whereas for the thick asphalt layers the modulus of asphalt is more influential (controlled stress).

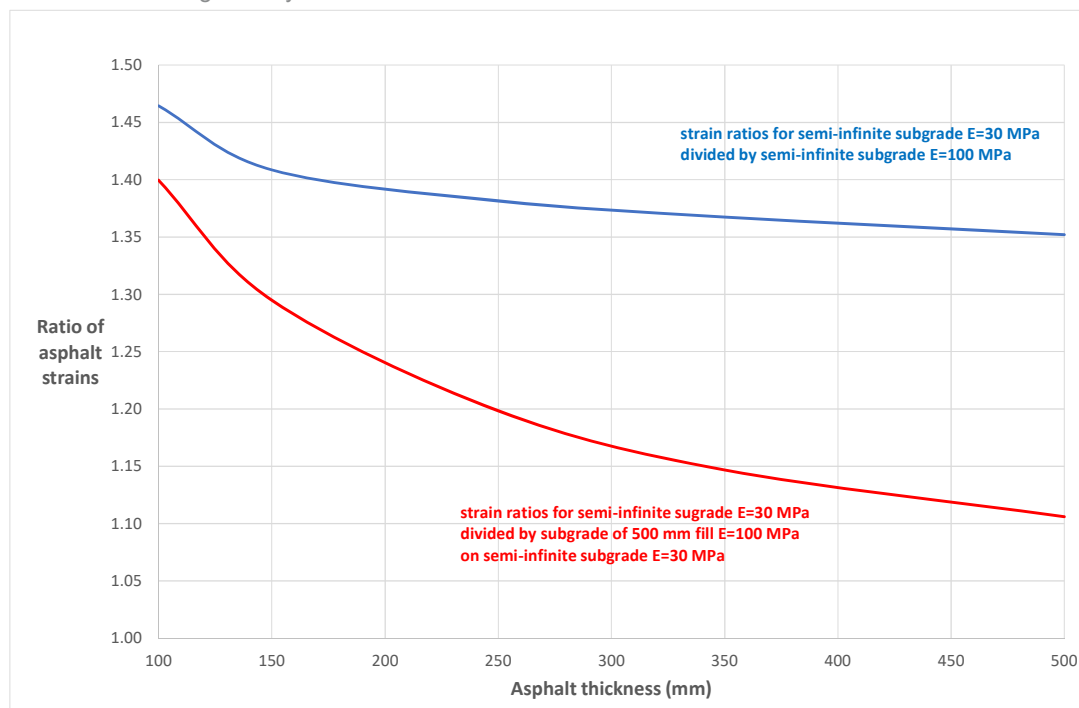
Next the asphalt strains were predicted where the asphalt layers were supported by 500 mm thick selected subgrade material ($E = 100$ MPa) placed on a semi-infinite subgrade with a modulus of 30 MPa. For each asphalt thickness, the ratio of the asphalt strains due to a semi-infinite subgrade ($E = 30$ MPa) to the strain when supported by a 500 mm thick selected subgrade material was calculated.

Figure 5.5 shows that for a 100 mm asphalt thickness, the 500 mm thick selected subgrade material almost results in the same strain ratio as the ratio for semi-infinite subgrades. Expressed another way, for a 100 mm thick asphalt layer the provision of a 500 mm thick selected subgrade material ($E = 100$ MPa) on subgrade with a modulus 30 MPa, almost reduces the asphalt strain to the value for a semi-finite subgrade with $E = 100$ MPa. However, as the asphalt thicknesses increase, the provision of a 500 mm thickness of selected subgrade material has less influence on the asphalt strains.

It was concluded that as the thickness of the asphalt layer increases, the effect on asphalt strains of providing a selected subgrade material of finite thickness reduces and the asphalt layer has increasing influence on the asphalt strains. Consequently, as the asphalt thickness increases greater R&R thicknesses are required.

As discussed in Section 5.5, this influence of pavement structure on R&R depths is not addressed using the equivalent subgrade modulus methods.

Figure 5.5: Example of sensitivity of full-depth asphalt strains to changes to thicknesses and moduli of underlying subgrade layers



5.5 SUBGRADE R&R THICKNESSES USING ESM METHODS

For each pavement configuration (Table 5.1), the ESM of the original pavement design was calculated using the four methods (Section 5.2). These are the 'design ESM' used to determine the R&R depth, similar to the use of design strains in the ME method.

For each pavement configuration and low subgrade strength construction scenarios (Section 5.2), the required thickness of R&R with selected subgrade material (CBR = 10) was calculated such that the ESM equalled the design ESM. Table 5.2 lists the R&R thicknesses calculated using the four ESM methods.

Table 5.2: Removal and replacement thicknesses for full-depth asphalt pavements calculated using ESM methods

Thickness of subbase (mm)	In situ subgrade modulus (MPa)	Original subgrade design modulus (MPa)	Method A R&R thickness (mm)	Method A1500 R&R thickness (mm)	Method B R&R thickness (mm)	Method B1500 R&R thickness (mm)
0	30	40	205	307	318	421
		50	378	567	491	681
		60	529	793	642	907
		70	664	996	776	1109
	50	60	243	365	306	428
		70	460	690	524	753
		80	657	986	720	1050
		90	839	1258	903	1321
	150	40	172	273	285	386
		50	319	506	431	619
		60	446	709	560	823
		70	561	891	674	1005
	50	60	201	321	265	384
		70	386	613	449	676
		80	553	879	616	942
		90	706	1123	770	1186

The findings were:

- Including the granular subbase in the ESM calculation lowered the R&R thicknesses.
- As expected, the use of 1500 mm depth to calculate the ESM resulted in significantly higher R&R thicknesses than 1000 mm.
- When the ESM calculation uses the ME selected subgrade sublayering process and the associated sublayer moduli (Methods B, B1500), the R&R thickness increases by up to about 100 mm compared to the simpler method (Methods A, A1500).

The major deficiency in the use of ESM is that the method does not provide for the variation in R&R thicknesses with the overlying pavement structure as obtained using the ME method (Section 5.4). For this reason, the ESM is not recommended for use in the design of flexible pavements.

6 SUMMARY AND CONCLUSIONS

During the construction of new pavements, testing of the in situ subgrade may indicate that at some locations the subgrade design strength is lower than that used for the original pavement structural design. In addressing the structural deficiency of such low subgrade strength areas, the most commonly used approach is not to change the pavement layers but to treat the subgrade. One common treatment is the removal of the low strength subgrade and replacement with selected subgrade material with a design strength exceeding the original subgrade design strength.

Currently for flexible pavements with bound pavement layers, the mechanistic-empirical (ME) design method is used to calculate the removal and replacement (R&R) depths. However, as such R&R determinations are undertaken during construction, there is interest in using an alternative simpler method to determining R&R depths.

The Austroads structural design method for concrete pavements includes a simplified method of considering the structural contribution of subgrade materials where more than one type is used. An equation is provided to determine the equivalent subgrade CBR strength considering the thickness of each material and its design CBR. The method uses of a stiffness parameter ($h_i \text{CBR}_i^{0.333}$), which is based on the stiffness parameter ($h_i E_i^{0.333}$) used in Odemark's method of equivalent layer thickness. This method was developed from a method used by the Japan Road Association (JRA) for the design of asphalt pavement (JRA 1989).

The concrete thickness design method uses equations to predict concrete base stresses and erosion factors (related to joint displacements). These equations were derived from finite element modelling of concrete pavements with homogeneous subgrades. Unlike the design of flexible pavements, the Austroads (2017) concrete design method does not include a response to load model to enable prediction of the slab support provided by more complex subgrades, including the use of selected subgrade materials. As a consequence, the above simplified method was adopted by Austroads for multiple subgrade layers.

TMR sought advice on whether this JRA method can be adapted to determine the R&R depths of flexible pavements.

Several methods of calculating an equivalent subgrade modulus (ESM) were selected and evaluated. The R&R depths were compared to the values calculated using the ME design method.

It was concluded that the use of ESM does not provide R&R thicknesses consistent with those calculated using the ME method. In the ME design calculations, the R&R is determined such that the critical strains do not exceed of the design strains of the approved pavement design. The ESM index does not consider these strains and as a consequence the R&R thicknesses are different and do not vary with the overlaying pavement structure as required. As such the ESM index was concluded to be unsuitable for the purpose investigated.

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