ANNUAL SUMMARY REPORT

P123: Improved Subgrade Characterisation for Pavement Design Purposes (Year 1 – 2020–21)

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SUMMARY

NACOE Project P123 *Improved Subgrade Characterisation for Pavement Design Purposes* aims to review the current methodology used for subgrade characterisation, current practices used internationally and identify opportunities for improvements.

In the first year of the project (2020–21), the project team considered potential research issues that could be investigated to improve subgrade characterisation. These issues were categorised as:

- improvements to laboratory test methods and test conditions
- improvements to the methods of determining subgrade design California Bearing Ratio (CBR) and modulus
- improvements to the elastic characterisation of subgrade materials used in structural design.

This report describes these issues and summarises the findings and recommendation of the following three technical report completed in 2020–21:

- Review of Queensland Department of Transport and Main Roads (TMR) laboratory CRB test conditions for subgrade soils. It was recommended that the density of CBR test specimens be increased from 95% to 97% Standard Proctor maximum dry density.
- The use of the Japan Road Association equation to determine the depths to which soft subgrade areas identified during construction needs to be removed and replaced. It was concluded that this method is not suitable for use as it does not allow for the influence of pavement layers on the required treatment depths.
- Review of TMR pavement structural design methods for subgrades with a design CBR less than 3%. It was recommended that TMR design procedures be improved by applying the design models to subgrade CBR values of 2% or more. New soft subgrade treatment thicknesses are proposed to increase the CBR to an effective strength of 2%.

There are number of structural design issues yet to addressed. These issues require a method of predicting the variation in select fill and subgrade moduli with depth. Such predictions require the development a new relationship to predict select fill/subgrade modulus from CBR with allowance for the variation in stresses with depth. It is proposed to commence research in 2021–22 to develop this new relationship.

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1 INTRODUCTION

The structural design of pavements requires the quantification of the support provided by the underlying support and subgrade layers. The Austroads *Guide to Pavement Technology Part 2: Pavement Structural Design* (Austroads 2017) includes a method for characterising the subgrade materials for use in pavement design. Additional guidance is provided in the Queensland Department of Transport and Main Roads (TMR) *Pavement Design Supplement* (TMR 2018).

NACoE Project P123 *Improved Subgrade Characterisation for Pavement Design Purposes* aims to review the current methodology used for subgrade characterisation and identify opportunities for improvements.

The potential benefits of this project include:

- reduced cost of pavements and/or subgrade treatments
- sustainability benefits from the reduced use of scarce resources
- reduced likelihood for contract disputes in project delivery.

It envisaged that this project will comprise multiple phases over a number of years, with the first year (2020–21) comprising four tasks:

- Identify and prioritise issues, and scope the project tasks for 2021–23.
- Review the use of the Japan Road Association (JRA) equation to determine treatments for soft subgrade areas identified during construction.
- Review the TMR laboratory California Bearing Ratio (CBR) test conditions.
- Review TMR pavement structural design methods for subgrades with a design CBR less than 3%.

Section 2 of this report describes the priority issues, whilst Section 3 summarises the findings of above-mentioned reviews. Section 4 includes the recommended research task for 2021–22.

2 RESEARCH ISSUES

2.1 INTRODUCTION

Early after the commencement of the project in June 2020 advice was sought from TMR regarding issues related to subgrade characterisation that could be investigated in the project. The list of issues included the following:

Laboratory testing

- Laboratory California Bearing Ratio (CBR) test conditions. TMR currently determines CBR and swell at Standard Proctor optimum moisture content (OMC) and 95% Standard maximum dry density (MDD), with either unsoaked or 4 or 10 day soaking and a 4.5 kg surcharge. The use of 95% MDD aligns with the minimum characteristic value for earthworks construction in TMR specification MRTS04 *General Earthworks* (TMR 2020). A review of test conditions is required as they may not always be appropriate.
- Austroads classification of expansive soils is based on 98% Standard MDD. This creates a practical issue for TMR as it does not align with 95% of MDD used for CBR testing. If TMR continue to test swell at 95% MDD, then equivalent Austroads criteria at this compaction level need to be developed.
- Given the limitations of the laboratory CBR test, alternative methods to characterise subgrade support such as resilient modulus, Californian Resistance Value, and field tests need to be reviewed.

Interpretation of laboratory results

- Currently TMR determines the subgrade design CBR and swell based on the 10th percentile value of test results for all road classes. There is a need to consider if the use of the 10th percentile is appropriate, or whether higher percentiles should be used for lower-order roads. Related to this, there is often a very limited number of subgrade samples obtained and hence a need to consider if percentile values are appropriate.

Structural design

- During construction soft areas of subgrade may need treatment. Currently the Austroads (2017) mechanistic-empirical (ME) method is used to design such a treatment, but a simpler method would be desirable. A number of design consultants have suggested the Japan Road Association (JRA) equation be used to determine a treatment based on the calculation of an equivalent subgrade modulus.
- Many Queensland heavily trafficked pavements have a subgrade design CBR less than 3%. In the design of these pavements TMR provides a table of subgrade treatments to improve them to a subgrade with a design CBR of 3% before designing the overlying layers using the Austroads ME method. The origins of these subgrade treatments needs to be investigated and consideration given to the use of the ME method to design pavements with subgrade CBRs less than 3%.
- TMR considers that the Austroads (2017) sub-layering and characterisation procedures for select fill is overly conservative and may not reflect actual modulus variation with depth. The method leads to conservative pavement depths and/or excessive treatments of soft subgrade areas identified during construction. TMR (2018) has added an additional design step to the sub-layering (i.e. only the bottom portion of select fill is sub-layered). This new method needs to be reviewed to identify whether further improvements can be made.
- Guidance is required regarding the appropriate depth below the top of the subgrade that needs to be characterised for pavement design. Austroads (2017) suggests 1 m for weak layers below the subgrade (Section 5.3.7) but also suggests 2 m for embankments (Section 8.2.2). For rigid pavements Austroads (2017) suggests 1 m (Section 9.3.2). TMR MRTS04 was recently amended to specify 1.5 m for both cut and fill. Confirmation of the decision to adopt the 1.5 m depth is required.

- Separate processes for pavement foundation and pavement design are adopted in the United Kingdom and similar methods are in use in Germany and France. The benefits of developing a TMR pavement foundation design method needs to be investigated.

These issues were discussed in project meetings in June and July 2020 and the outcomes are reported below. It was agreed that in 2020–21 Project P123 should investigate an improved method of laboratory testing (Section 2.2.1, Section 3.1), the use of the JRA equation (Section 2.4.2, Section 3.2) and structural design methods for pavements with subgrade CBRs less than 3% (Section 2.4.3, Section 3.3).

2.2 IMPROVING LABORATORY CHARACTERISATION

2.2.1 CBR TEST CONDITIONS

In 2020–21, the project investigated the following issues related to the laboratory CBR test method used by TMR compared to other national road agencies and international best practice:

- the relative moisture content to which soils are mixed prior to compaction and the conditioning period
- the relative dry density to which CBR test specimens are compacted compared to minimum construction standards
- periods of soaking in water
- surcharge weights during soaking and testing and whether the weight used should vary with the self-weight stresses.

Differences in road agencies construction specifications for compaction will be considered in this evaluation.

The findings are summarised in Section 3.1.

2.2.2 MEASUREMENT OF MODULUS INSTEAD OF CBR

The Austroads ME method requires the use of a subgrade design modulus. In Australia for the last 30 years or more, subgrade vertical design moduli have been estimated from laboratory CBR results using the relationship E = 10 x CBR.

This subgrade elastic characterisation method has two significant limitations:

- As stated in Austroads (2017), the use of the relationship E = 10 x CBR for a particular soil may result in the modulus being in error by a factor of 2.
- The moduli of subgrade soils vary with applied and self-weight stresses, yet the E = 10 x CBR relationship makes no allowance for variation in modulus with stress. For instance, it does not provide for the variation in subgrade modulus with the pavement composition as previously reported (Austroads 2009).

As a consequence, there are benefits in TMR changing to measuring subgrade modulus rather than measuring CBR. Whilst there are Austroads and TMR test methods for the measurement of resilient modulus of unbound granular materials, test methods for soils have yet to be developed.

As part of Project P123 a TMR test method could be developed to measure the resilient modulus of soils. Of particular importance is the development of a method to prepare test specimens at likely in-service moisture conditions, which for cohesive subgrades may well be above Standard Proctor OMC. In the CBR test, specimens are commonly soaked in water prior to testing. As it is unlikely that modulus test specimens can be compacted well above OMC, a sample preparation method will need to be developed or a process to adjust the measured moduli at OMC to a design moisture content.

As discussed in Section 2.4.1, research to develop a TMR test method and a new E-CBR with stress-dependency is proposed for commencement under Project P123 in 2021–22.

2.3 INTERPRETATION OF LABORATORY CBR RESULTS

2.3.1 DETERMINATION OF DESIGN CBR OF THE IN SITU SUBGRADE

To undertake pavement structural design, a key task is to determine the support provided by the subgrade to the overlying pavement layers. In Austroads (2017), the support is primarily determined from the subgrade CBR. Conceptually, a subgrade design CBR is determined for each homogeneous sub-section of a project based on topography, drainage and soil type. There is an absence of detailed guidance in the Austroads (2017) and TMR (2018) design methods about how these sub-sections are determined apart from the following from Austroads (2017):

> If the testing interval and data are unbiased, and the variability of test results is low, then statistical analysis can be used to determine a design CBR at an appropriate percentile level. To ensure homogeneous sub-sections of subgrade, the CBR values should have a coefficient of variation (i.e. standard deviation divided by the mean) of 0.25 or less. The 10th percentile level (i.e. 90% of results exceed this level) is commonly adopted for the design of highway pavements. For roads in arid climates, or roads of lesser importance, higher percentile values may be appropriate (VicRoads 2013, 2017).

For many new constructions, the amount of subgrade sampling and testing does not enable reliable estimates of the coefficient of variation. Hence there is a need for more guidance on design unit selection. Accordingly, it is proposed that the national and international design methods be reviewed, and appropriate TMR guidance developed.

Within each homogeneous sub-section, the in situ subgrade soil varies but commonly to a lesser extent than the overall project. For each sub-section, a characteristic CBR value needs to be determined considering the variability of CBR results. As seen from the above extract from Austroads (2017), the Austroads design method uses the characteristic value that reflects the lower CBR values within a unit similar to the use of characteristic deflection. In both cases, the percentiles to use in the determination of characteristics values are intended to reflect the extent of distress at the end of structural life, that is when the pavement is rehabilitated. Austroads (2017) is deficient in not specifying the severity and extent of this structural distress. For highway pavements, a 10th percentile value would be not be unreasonable. Guidance for other road classes will be developed in consultation with TMR and consideration of national and international practices.

The use of percentiles requires sufficient number of CBR test results within each design unit. It is understood that TMR has investigated alternative methods to determine a characteristic CBR when there is a low number of CBR results.

This task will need to include a definition of the severity and extent of this structural distress at the end of structural life. Given the challenge in developing these definitions it is proposed to defer this research task until later in Project P123.

2.4 IMPROVED PAVEMENT STRUCTURAL DESIGN METHODS

2.4.1 INTRODUCTION

TMR (2018) design methods for new pavements are based on the *Guide to Pavement Technology Part 2: Pavement Structural Design* (Austroads 2017).

Like most overseas design methods, the Austroads ME design method for flexible pavements involves the calculation of critical responses to load (e.g. strains) using linear elastic modelling. In such modelling, each pavement layer/sublayer and the semi-infinitely thick subgrade is assigned a single modulus value. For unbound granular materials, select fills and subgrades this can be a gross simplification as their moduli are stress-dependent and therefore vary vertically and horizontally with load-induced and self-weight stresses. The Austroads method of characterisation provides sub-layering methods for granular and selected subgrade materials which in part have the objective of considering the vertical variation in modulus with depth below the surface. However, variation in modulus with horizontal distance from the load is not considered. Moreover, the Austroads method does not allow for variation in subgrade modulus with stress.

The use of non-linear finite element (FE) modelling using the measured stress-dependency of materials has the potential to provide more appropriate predictions of response to load as the moduli used vary vertically and horizontally. A FE model that could be utilised to predict the subgrade modulus variation depth due to stress variations was developed (Austroads 2012). As part of this Austroads research, presumptive modulus stress-dependencies were selected for various subgrade soil types and design CBRs.

However, the laboratory repeated load triaxial modulus data used to develop these presumptive values did not include an adequate range of confining stresses consistent with the increase in self-weight stresses with depth below the top of the subgrade. As a consequence, the presumptive subgrade modulus characterisation used (Austroads 2012) does not adequately consider the effect of increasing self-weight stresses with depth.

As described below, TMR has identified a number of significant issues with current methods of characterising selected subgrade and subgrade moduli. Whilst two of these issues have been investigated and reported to date (Section 3.2 and Section 3.3), the following key tasks for Project P123 require the development of a method of allowing for the variation of subgrade moduli with depth:

- improved sub-layering of selected subgrade materials (Section 2.4.4)
- sub-layering of subgrades (Section 2.4.5).
- depth of subgrade considered in response to load calculations (Section 2.4.6)
- the method to estimate soil modulus from CBR (Section 2.4.7).

In this respect, in 2021–22 it is proposed to commence research to develop a new method for estimating modulus from CBR and stress. As such, the above-mentioned project tasks, whilst described below, will need to be deferred until later in Project P123.

2.4.2 USE OF JAPAN ROAD ASSOCIATION EQUATION DURING CONSTRUCTION TO DETERMINE REMOVAL AND REPLACEMENT DEPTHS

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 to remove the low-strength subgrade to the required depth and replace it with selected subgrade material with a design strength exceeding the original subgrade design strength.

Currently for flexible pavements with bound pavement layers, the 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 CBR strength considering the thickness of each material and its design CBR. The method uses a stiffness parameter ($h_iCBR_i^{0.333}$), which is based on the stiffness parameter ($h_iE_i^{0.333}$) used in Odemark's method of equivalent layer (MET) thickness. This Austroads method was developed from a method used by the JRA for the design of asphalt pavements (JRA 1989).

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

This task was undertaken in 2020–21 and the findings summarised in Section 3.2.

2.4.3 PAVEMENT DESIGN FOR SUBGRADE DESIGN CBR LESS THAN 3%

In contrast to Austroads (2017), the TMR (2018) ME design method only applies to the design of pavements on subgrades with a design CBR of 3% or more. For subgrades with a design CBR less than 3%, TMR provides soft subgrade treatments to increase the subgrade support to the pavement layers to a level equivalent to a subgrade with a design CBR of 3% before using the ME design method for the overlaying layers.

Concerning these soft subgrade treatments, TMR (2018) states:

> A presumptive subgrade design CBR of 3% for the assumed semi-infinite layer (that is, from the top of the treatment and extending infinitely below) is typically adopted for the following treatments:
>
> – Geotextile wrapped granular material, comprising either coarse unbound granular material (for example, Type 2.5 materials with B or C grading envelope in dry conditions, or Type 2.4 material with B or C grading envelop in wet conditions), recycled material blend (for example RM004 or RM005 material) or rock fill (MRTS04), with thickness determined using Table 2.1.
>
> – A minimum 200 mm of Category 1 or 2 heavily-bound (cemented) material over subgrade material with a design CBR of 2 or 3%.
>
> – A minimum 150 mm of mass concrete (either lean-mix concrete or no fines concrete with geotextile) or sand/cement (12:1) mix over subgrade material with a design CBR of 2 or 3%.

Table 2.1: Minimum thickness of coarse granular or rock fill required for the adoption of a presumptive design CBR of 3%

Subgrade CBR (%) at design density and moisture conditions	Minimum thickness (mm) of coarse granular or rock fill required for the adoption of a presumptive design CBR of 3%
1.0	400
1.5	300
2.0	200
2.5	150
3.0	0

Source: TMR (2018).

The TMR decision to not use the Austroads ME method to design pavements with subgrade design CBRs less than 3% was likely due to concerns that such low-strength materials are less likely to behave elastically than higher-strength materials. Hence there would possibly have been concerns about the use of linear elastic theory which is part of the Austroads ME method.

The TMR method was reviewed in 2020–21 and the findings and recommendations are summarised in Section 3.3.

2.4.4 REVIEW TMR METHOD OF SUB-LAYING SELECTED FILL

TMR has concluded that the Austroads (2017) sublayering and characterisation procedures for select fill are overly conservative and may not reflect actual modulus variation with depth. Based on engineering judgement TMR considers the Austroads method leads to conservative pavement thicknesses and/or excessive subgrade treatments.

Accordingly, TMR (2018) has added an additional step to the Austroads sub-layering process (i.e. only the bottom portion of select fill is sub-layered); however, TMR considers the method needs to be evaluated.

Select fill and subgrade moduli vary with load-induced and self-weight stresses. Both the TMR and Austroads method are deficient in that moduli assigned to select fill materials are not determined considering stress. Without such consideration it is not possible to evaluate whether or not the TMR method is more appropriate than the Austroads method.

As described in Section 2.4.1, it is proposed to defer this evaluation until a new relationship for estimating modulus from CBR and stress is developed in Project P123. Using this relationship, the select fill moduli assigned using the TMR and Austroads method can be compared to the variation in moduli with depth considering the stress states.

2.4.5 IMPROVED DESIGN MODEL TO PROVIDE SUB-LAYERING OF IN SITU SUBGRADE

In the Austroads ME design of flexible pavements, the in situ subgrade is considered to be a homogeneous semi-infinite layer with a single design modulus. This simplification does not consider the variation in subgrade modulus with depth due to:

- changes in soil type
- changes in moisture content, soil suction
- changes in density
- changes in load-induced and self-weight stress.

The results of both Dynamic Cone Penetrometer testing of subgrades and the back-calculation of moduli from measured deflections undertaken as part of rehabilitation design commonly conclude that the level of the support provided by cohesive subgrade materials increases with depth. There is potential to reduce whole-of-life pavement costs by allowing for the variation in subgrade support with depth in the ME method.

In relation to changes in soil type with depth such as duplex soils, structural design processes could be developed based on laboratory CBR testing and subgrade sub-layering. However, reliable methods to predict subgrade in-service moisture content and soil suction have yet to developed. As such, laboratory CBR testing would not allow for moisture variation with depth. This is a significant limitation in implementing subgrade sub-layering.

Despite these challenges, pavement structural analysis would be improved by allowing for the variation in subgrade moduli with depth due to the variation in load-induced and self-weight stresses.

As described in Section 2.4.1, it is proposed to defer the development of a subgrade sub-layering method until a new relationship for estimating modulus from CBR and stress is developed in Project P123. Consideration will be given to iterating moduli with depth from stresses calculated using a linear elastic model (CIRCLY) as the development of a finite element model is beyond the scope of Project P123.

2.4.6 DEPTH OF SUBGRADE EVALUATION

As mentioned in Section 2.1, clarity is required regarding the appropriate depth of material in the subgrade that needs to be characterised for pavement design.

The current Austroads linear elastic model is not well suited to determining the influence of deep (> 1 m) subgrade materials on pavement performance as it does not allow for modulus variation with stress.

As described in Section 2.4.1, it is proposed to defer this evaluation until a new method for estimating modulus from CBR and stress is developed in Project P123. Using this method, the variation in subgrade moduli with depth will be predicted to enable an assessment of the influence of deep subgrades (> 500 mm) to pavement performance.

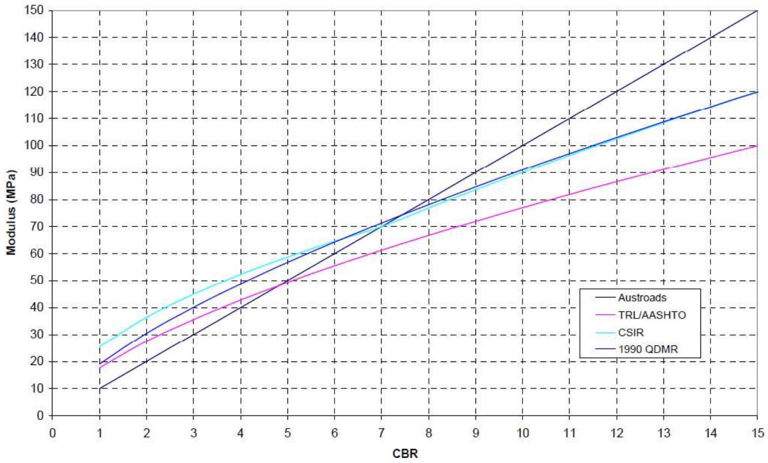
Consequently, this research task will be deferred until later in Project P123.

2.4.7 IMPROVED ESTIMATION OF SUBGRADE MODULUS FROM CBR

As already discussed, the Austroads (2017) and TMR (2018) design methods, the subgrade vertical design modulus is determined by multiplying the subgrade design CBR by 10 (i.e. E = 10 x CBR).

The origins of this subgrade modulus/ CBR relationship, together with comparisons with alternative relationships in the UK (Powell et al. 1984), South Africa (e.g. Paterson 1978) (Figure 2.1), is reported in Austroads (2009).

Figure 2.1: Austroads, 1990 QDMR, TRL and CSIR subgrade modulus from subgrade CBR relationships



Source: Austroads (2009).

The wide variation in modulus values determined by the various relationships brings into question whether the E = 10 x CBR relationship, selected for use by Austroads more than 30 years ago, is still the most appropriate.

A preliminary review (Section 3.3) concluded that, due to the variation in soil modulus with stress, there is no single relationship applicable for all pavement configurations. In addition, the stress states at which the moduli were determined are not known. Due to both these factors, it is not possible to determine which existing E-CBR relationship is more appropriate to use.

To improve subgrade modulus characterisation, the relationship used to estimate modulus from CBR needs to include a dependence on stress.

The following steps are required to determine such a stress-dependent relationship:

- Collate existing published data on the variation in subgrade modulus with CBR and stress.
- Select a range of 5–20 select fill and subgrade materials with 4-day soaked CBRs between 2% and 15%.
- Draft a TMR test method for measuring resilient modulus using the repeated load triaxial test based on AASHTO T307: 1999, *Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials*.
- Measure resilient modulus of each soil over a range of confining and axial stresses.
- Determine a E-CBR relationship with stress-dependency.

As discussed in Section 2.4.1, it is recommended that this research commence in 2021–22 as it is critical to the completion of many project tasks.

2.4.8 SEPARATE PROCESS FOR FOUNDATION DESIGN

In the United Kingdom (UK) the design of pavement foundations (Highways England 2020a) and the design of pavement layers (Highways England 2020b) are separate processes. Note that in the UK, the pavement foundation includes 'all materials up to and including the subbase'.

The concept of separating the pavement foundation design from the pavement design appears to have been first proposed by Brown and Dawson (1992). The benefits of providing a separate process for the foundation was that the foundation on which the pavement is constructed is firstly designed to carry the construction traffic and act as a construction platform. German and French design methods also include a process for foundation design.

There is no Australian design process that addresses the adequacy of the pavement foundation to carry the construction traffic and act as a construction platform. However, for heavily trafficked roads, road agencies have developed minimum pavement layer support requirements, for example minimum selected materials qualities and thickness and minimum thickness of lightly bound or unbound granular materials. TMR (2018) requires that, for asphalt and heavily bound (cemented) pavements with a design traffic of 1000 ESA/day or more at opening, the improved layer (and any underlying layers) is typically designed to achieve a vertical design modulus at the top of the improved layer of at least 150 MPa.

In the UK method four foundations classes are defined (Table 2.2). The long-term foundation support is quantified using the foundation surface modulus calculated from the predicted deflection on the top of the foundation and Boussinesq's equation to predict the surface modulus.

Table 2.2: UK foundation classes

Foundation class	Assumed long-term confined foundation surface modulus (MPa)	Maximum predicted deflection under a standard wheel load 40 kN load over a 151 mm radius load area (mm)
1	≥ 50	2.96
2	≥ 100	1.48
3	≥ 200	0.74
4	≥ 400	0.37

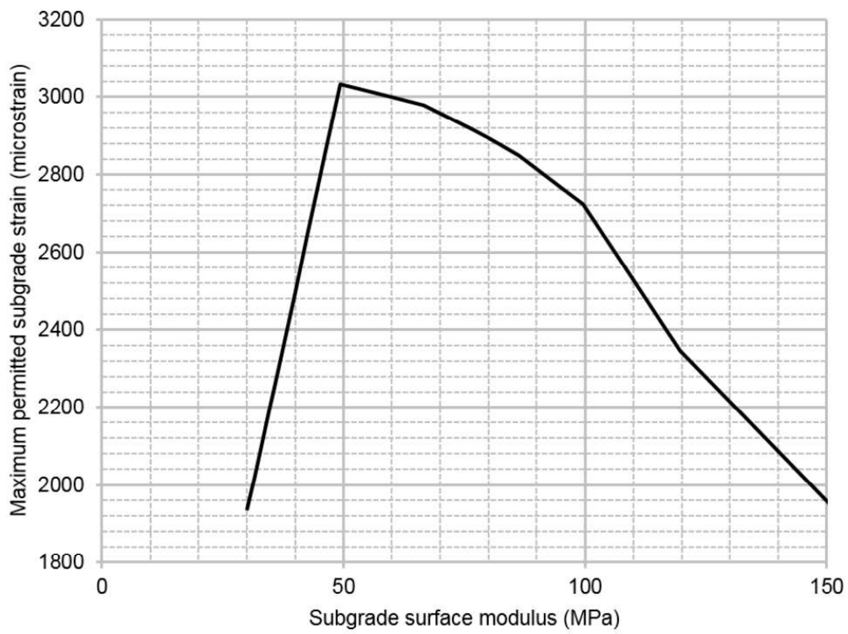
Source: Adapted from Highways England (2020a).

In relation to the minimum foundation support levels, Highways England (2020b) varies the requirements with the design traffic as follows:

- Foundation Class 1 is only used for projects with a design traffic up to 2 x 10^7 ESA.
- Where a pavement is being designed for a new carriageway, Foundation Class 2 shall only be used for design traffic of 8 x 10^7 ESA or less.
- Where a flexible pavement with an asphalt base using EME2 is being designed for a new carriageway, Class 3 or 4 foundation is required, unless Class 2 can be demonstrated to achieve a minimum equivalent modulus of 120 MPa.

To inhibit excessive deformation due to construction traffic (short-term performance), the predicted vertical compressive strain on the top of the subgrade due to a standard wheel load on the top of the foundation is limited. Figure 2.2 shows the maximum strain values to limit the deformation on the top of the subbase to no more than 40 mm assuming the foundation carries up to 1000 standard axles of traffic during construction.

Figure 2.2: UK subgrade strain limits to inhibit deformation during construction



Source: Highways England (2020b).

In the UK pavement design method the calculated foundation support modulus is used to evaluate the effect of granular subbase, selected subgrade materials and in situ subgrade on the tensile strains at the base of bound pavement layers (e.g. asphalt). Similar to the discussion in Section 3.2, this approach is not consistent with the Austroads ME method predictions. Hence if TMR decide to develop a pavement foundation design method, it is recommended that no changes be made to the pavement design method. It is noted that a major challenge in developing a pavement foundation design method is the uncertainty of granular and subgrade moisture contents during construction.

An alternative project task to developing a TMR pavement foundation design method would be to use the UK design principles to validate, modify or enhance current TMR requirements for supporting layers. For example, requirements could be developed for pavements with 10 to 1000 ESA/day on opening mirroring the minimum 50 MPa foundation support modulus used in the UK.

This issue was discussed with the TMR Project Manager. TMR advised that the use of separate design methods for the foundation and pavement would be unnecessarily restrictive. In relation to subgrade stability during construction TMR address this issue in specification MRST04 *Earthworks*. TMR advised no further investigation of a foundation design method would be undertaken under this project.

3 SUMMARY OF PROJECT FINDINGS IN 2020–21

3.1 REVIEW OF LABORATORY CBR TEST CONDITIONS

As described in Section 2.2.1, in 2020–21 the TMR laboratory test procedures for the measurement of CBR of subgrade materials were reviewed, including comparison with the methods used by other Australian road agencies. The findings are summarised below based on a detailed description of research provided in Project P123 report *Improved Subgrade Characterisation for Pavement Design Purposes: Review of Laboratory CBR Test Conditions* (Jameson 2021a).

TMR currently requires all CBR test specimens to be compacted to a density ratio of 95% with respect to Standard Proctor MDD. This is a conservative value, reflecting the minimum specified characteristic density ratio (CDR) for subgrade materials construction more than 300 mm below subgrade level. This 95% density ratio is well below the levels used in laboratory CBR testing by other road agencies.

One option is for TMR to change its procedure such that the designer decides the density ratio to be used for testing based on the specified minimum compacted standard for the material.

However, it is understood that TMR consider it more appropriate to continue to use a simpler approach to CBR testing whereby the same CDR is used for all subgrade materials irrespective of the variation in specified CDR between materials. In this respect it is recommended that TMR compact CBR test specimens to 97% Standard Proctor MDD. Such a 2% increase in specimen density ratio from the current value of 95% to 97% could well result in a 30% increase in CBR values. This increase will bring CBR test results in better agreement with the values used by other Australian road agencies.

Note that such CBR results are not necessarily applicable for subgrade layers more than 300 mm below the subgrade level due to the lower minimum compaction standards. However, the reduction in CBR due to the lower density ratio of such materials is likely to be offset by the higher confining stress at such depths. In a future stage of Project P123, a method to estimate the CBR of such materials could be developed considering their lower minimum compaction standards and greater confining stresses.

Another very important testing parameter is the moisture conditioning of the compacted specimens prior to testing. The review found no need to change the current guidance on the use of unsoaked, 4-day soaked and 10-day soaked testing. TMR guidance is arguably the best Australian practice.

The surcharge weight applied during soaking and testing has a major influence on CBR values, particularly for high Liquid Limit soils. Despite the original intent that the surcharge weight be varied to reflect the confining stresses applied to the top of the subgrade due to the overlying pavement, except for Main Roads Western Australia (MRWA), Australian road agencies for many years have used the minimum weight of 4.5 kg. Given the long-standing Australian use of a 4.5 kg weight, it is recommended that the TMR continue to use this weight.

It was concluded that CBR testing of subgrade materials compacted to 97% Standard Proctor MDD using a surcharge weight of 4.5 kg is suitable for materials at subgrade level. To assess the applicability of these CBR values for subgrade layers more than 300 mm below subgrade level, consideration needs to be given to the variation in density ratio and confining stress with depth. It is recommended that testing be undertaken to quantify the effect on CBR of density and surcharge weight variations. Based on the findings, a decision will be taken on whether density and confinement adjustment factors need to be provided in the TMR pavement design supplement.

3.2 USE OF JAPAN ROAD ASSOCIATION EQUATION

As described in Section 2.4.2, in 2020–21 the use of the JRA equation to calculate subgrade removal and replacement (R&R) depths during construction was evaluated. The findings are summarised below; they are based on a detailed description of the research provided in Project P123 report *Improved Subgrade*

Characterisation for Pavement Design Purposes: Use of the Japan Road Association Equation (Jameson 2021b).

During the construction of new pavements, testing of the in situ subgrade may identify areas where the subgrade design modulus is lower than that used in the original pavement structural design. Whilst subgrade design moduli are commonly determined such that at least 90% of the project exceeds the design value, it is common TMR practice to treat any areas below the design value found during construction regardless of the extent. Other road agencies also follow this practice.

In addressing the structural deficiency of such soft subgrade areas, the most commonly used approach is not to change the pavement layers but 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 a treatment, 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 the 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 evaluations are undertaken during construction, there is interest in using an alternative simpler method to determine removal and replacement (R&R) depths consistent with the ME method.

For the design of concrete pavements, Austroads (2017) includes a simple process for the calculation of an equivalent CBR strength, considering the design CBR and thicknesses of each subgrade materials. An equation is provided to determine the equivalent subgrade CBR strength considering the thickness of each soil type and its design CBR. The method uses a stiffness parameter ($h_i CBR_i^{0.333}$), 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 JRA for the design of asphalt pavement (JRA 1989).

The Austroads (2017) 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 over homogeneous subgrades. Unlike the design of flexible pavements, the Austroads 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 simplified method was adopted by Austroads for multiple subgrade layers as described above.

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

In essence, the use of the JRA equation results in an equivalent subgrade modulus (ESM) intended to reflect the structural contribution of all subgrade materials. Several methods of calculating an 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 the design strains of the approved pavement design. The ESM index does not consider the overlying pavement structure and as a consequence the R&R thicknesses are different. As such, the ESM index was concluded to be unsuitable for the purpose investigated.

3.3 PAVEMENT DESIGN METHODS FOR SUBGRADES WITH A DESIGN CBR LESS THAN 3%

As described in Section 2.4.3, in 2020–21, the TMR pavement design procedures for subgrades with a design CBR less than 3% were reviewed. The findings are summarised below based on a detailed description of the research provided in Project P123 report *Improved Subgrade Characterisation for Pavement Design Purposes: Subgrade Design CBR Less Than 3%* (Jameson 2021c)

TMR currently limits the application of its rigid pavement procedures and ME method for the design of flexible pavements to subgrades with a design CBR of 3% or more. For the design of pavements with subgrades with CBR less than 3%, TMR provides subgrade treatments which are assumed to increase the subgrade design CBR to 3%.

Except for TfNSW, no other state road agency provides a minimum design CBR. TfNSW applies its design methods for subgrades with a design CBR of 2% or more. For the design of pavements on in situ subgrades of CBR less than 2%, TfNSW provides subgrade treatments which are assumed to increase the design CBR to an effective value of 3%.

It was concluded that a minimum subgrade design CBR of 2% is more appropriate than 3% for all pavement types as:

- it aligns with the Austroads minimum subgrade design CBR for rigid pavements
- it aligns with the minimum subgrade design CBR provided on the Austroads empirical design chart (Figure 8.4) for thin bituminous surfaced unbound granular pavements
- it aligns with the TfNSW method and no other Australian state road agency uses a value higher than 2%.

For the design of pavements on subgrades with design CBRs less than 2%, new minimum subgrade treatments are proposed to yield an effective subgrade design CBR of 2%. As expected, the proposed granular/rock fill thicknesses of these treatments are lower than the current values which yield an effective CBR of 3%. However, the overlying capping layer and pavement structure will be thicker.

As part of this project, the method of estimating subgrade modulus from CBR data was reviewed as it was relevant to the minimum design modulus to use in the ME design of flexible pavements. It was concluded that the current E = 10 x CBR was selected by Austroads more than 30 years due to its simplicity, including simplicity in the subgrade strain performance relationship. The modulus prediction equation used by TMR up until the adoption of the Austroads Guide in 2004 is in better agreement with the measured data and the relationships used in the United Kingdom and USA. It was concluded that, due to the variation in soil modulus with stress, there is no single relationship applicable for all pavement configurations. In addition, the stress states at which the existing E-CBR relationships were determined is not known. Due to both these factors, it is not possible to determine which existing E-CBR relationship model is more appropriate to use.

To improve subgrade modulus characterisation, the relationship used to estimate modulus from CBR needs a dependence on stress. As discussed in Section 2.4.7, consideration should be given to developing such a relationship under Project P123 in 2021–22.

4 SUMMARY AND RECOMMENDATIONS

The aim of NACoE Project P123 *Improved Subgrade Characterisation for Pavement Design Purposes* is to review the current methodology used for subgrade characterisation, current practices used internationally and identify opportunities for improvements.

In the first year of the project (2020–21), the project team considered potential research issues that could be investigated to improve subgrade characterisation. These issues were categorised as: 1) improvements to laboratory test methods and test conditions, 2) improvements to the methods of determining subgrade design California Bearing Ratio (CBR) and modulus, and 3) improvements to the elastic characterisation of subgrade materials used in structural design.

In discussions with TMR staff, the following three tasks were agreed for 2021–22:

- laboratory CBR test conditions (Section 2.2.1)
- use of the JRA equation (Section 2.4.2)
- pavement design for subgrade design CBRs less than 3% (Section 2.4.3).

This report also summarises the findings of the technical reports prepared for each task, including:

- Review of TMR laboratory CBR test conditions for subgrade soils: It was recommended that the density of CBR test specimens be increased from 95% to 97% Standard Proctor MDD. It was estimated that, due to this 2% increase in density, measured subgrade CBR values will increase by about 30%.
- The use of the JRA equation to determine the depths to which soft subgrade areas during construction be identified needs to be removed and replaced. It was concluded that this method is not suitable for use as it does not allow for the influence of pavement layers on the required treatment depths.
- Review of TMR pavement structural design methods for subgrades with a design CBR less than 3%: Current procedures limit the application of flexible and rigid pavement design models to subgrades CBRs of 3% or more. In the event that the design CBR is less than 3%, coarse granular and rock fill treatments are provided to increase the CBR to an effective strength of 3%. It was recommended that the TMR design procedures be improved by applying the design models to subgrade CBR values of 2% or more. New soft subgrade treatment thicknesses are proposed to increase the CBR to an effective strength of 2%.

There are a number of structural design issues yet to addressed, including a method of predicting the variation in select fill and subgrade moduli with depth. Such predictions require the development a new relationship to predict select fill/subgrade modulus from CBR with allowance for the variation in stresses with depth. It is proposed to commence research in 2021–22 to develop this new relationship.

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