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AUSTROADS TECHNICAL REPORT

Review of Relationship to Predict Subgrade Modulus from CBR (California Bearing Ratio)



Austroads

promoting improved road transport outcomes

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Review of Relationship to Predict Subgrade Modulus from CBR (California Bearing Ratio)

Austroads

Sydney 2009

Austroads profile

Austroads' purpose is to contribute to improved Australian and New Zealand transport outcomes by:

- providing expert advice to SCOT and ATC on road and road transport issues
- facilitating collaboration between road agencies
- promoting harmonisation, consistency and uniformity in road and related operations
- undertaking strategic research on behalf of road agencies and communicating outcomes
- promoting improved and consistent practice by road agencies.

Austroads membership

Austroads membership comprises the six state and two territory road transport and traffic authorities, the Commonwealth Department of Infrastructure, Transport, Regional Development and Local Government, the Australian Local Government Association, and NZ Transport Agency. Austroads is governed by a council consisting of the chief executive officer (or an alternative senior executive officer) of each of its eleven member organisations:

- Roads and Traffic Authority New South Wales
- Roads Corporation Victoria
- Department of Main Roads Queensland
- Main Roads Western Australia
- Department for Transport, Energy and Infrastructure South Australia
- Department of Infrastructure, Energy and Resources Tasmania
- Department of Planning and Infrastructure Northern Territory
- Department of Territory and Municipal Services Australian Capital Territory
- Department of Infrastructure, Transport, Regional Development and Local Government
- Australian Local Government Association
- New Zealand Transport Agency.

The success of Austroads is derived from the collaboration of member organisations and others in the road industry. It aims to be the Australasian leader in providing high quality information, advice and fostering research in the road sector.

SUMMARY

The Austroads *Guide to the Structural Design of Road Pavements: Pavement Design* (now the *Guide to Pavement Technology: Part 2 – Pavement Structural Design*) has been used throughout Australia for over 20 years. Progressive development of the Guide is required to take advantage of improved knowledge and technology and hence improve pavement design procedures.

Against this background, Austroads commissioned ARRB Group to:

- summarise recent research findings, including those on dynamic loading of pavements
- summarise recent developments in overseas design practices, particularly United States of America and South Africa
- review design procedures chapter by chapter
- identify a strategy to develop a new Austroads response to load model
- identify areas where the Guide should be improved.

Future Development of Austroads Pavement Design Guidelines (Austroads 2008a) detailed the findings and recommended a strategy for the development of the Guide over the next five years. The report recommended a number of key areas to improve the Guide. One recommendation was that procedures for estimating subgrade modulus from subgrade CBR (California Bearing Ratio) need to be reviewed as for high CBR values the modulus calculated are significantly higher than used in USA, Britain and South Africa.

This report details development and limitations of the current Austroads relationship for estimating subgrade modulus from subgrade CBR and compares the current Austroads relationship with relationships used overseas.

From data available it appears likely that, for relatively high stress levels, the Heukelom & Klomp (1962) relationship currently used by Austroads (2008b) is non-conservative when compared with overseas relationships for CBR values greater than 7. This apparent over-prediction of subgrade modulus is primarily due to the low stress/strain levels utilised in the wave propagation technique used to develop the relationship.

In addition, most subgrade modulus from subgrade CBR data has been found to have variation in the order to 2:1 to 4:1, meaning for a given the CBR the modulus may be 100% to 300% higher or lower than expected. Given that modulus is a measure if elastic response to load whereas CBR is a measure of the resistance to penetration, it is not surprising that these two parameters are not highly correlated over a range of subgrade material types.

However, research overseas and in Australia has shown that non-stress dependent relationships between CBR and resilient modulus, such as the current Austroads relationship, are not reliable as a result of the non-linear stress-strain relationship. The subgrade modulus has been found to vary significantly depending on the subgrade stress condition with increasing stress levels significantly reducing subgrade modulus.

Any change to the subgrade modulus from subgrade CBR relationship to address stress dependency of the subgrade modulus would also necessitate a change to the subgrade strain relationship to introduce a subgrade modulus dependency variable. For a given subgrade strain, the higher the subgrade modulus the higher the allowable loading. Intuitively this makes more sense as it would be anticipated that the amount of plastic strain deformation for a given elastic strain would be less for a higher CBR subgrade than a lower material. However, any changes to reflect the stress dependency of the subgrade modulus and the subgrade modulus dependency of the subgrade strain relationship would significantly complicate routine pavement design procedures.

It appears likely that, due to the stress dependency of subgrade modulus, the current Austroads subgrade modulus from subgrade CBR relationship is conservative for heavy duty structures (cemented and thick asphalt). In addition, the design of granular pavements with thin bituminous surfacings is based on an empirical relationship and therefore is not influenced by the modulus-CBR relationship.

Given the lack of detailed information about the stress dependency of subgrade modulus across the range of subgrade materials encountered in Australia and the likelihood the current relationship is conservative for the majority of pavement designs this report recommends that the current Austroads subgrade modulus from subgrade CBR relationship is retained in the short-term.

This report also recommends that laboratory testing is undertaken to allow a general relationship between subgrade CBR, subgrade stress and subgrade modulus to be developed and incorporated into development of the non-linear finite element model for pavement design currently being undertaken as part of Austroads project TT1452: *Development of Pavement Design Models*.

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1 INTRODUCTION

The *Guide to Pavement Technology: Part 2 – Pavement Structural Design* (Austroads 2008b), previously Austroads *Guide to the Structural Design of Road Pavements: Pavement Design*, has been used throughout Australia for over 20 years. Progressive development of the Guide is required to take advantage of improved knowledge and technology and hence improve pavement design procedures.

Against this background, Austroads commissioned ARRB Group to:

- summarise recent research findings, including those on dynamic loading of pavements
- summarise recent developments in overseas design practices, particularly United States of America and South Africa
- review design procedures chapter by chapter
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- identify areas where the Guide should be improved.

Future Development of Austroads Pavement Design Guidelines (Austroads 2008a) detailed the findings and recommended a strategy for the development of the Guide over the next five years. The report recommended a number of key areas to improve the Guide. One recommendation of this report was that procedures for estimating subgrade design modulus from subgrade design CBR (California Bearing Ratio) need to be reviewed particularly for high CBR values where the modulus calculated by the current Austroads relationship estimates significantly higher modulus when compared with many relationships used overseas.

This report:

- details the origins of the current Austroads E-CBR (subgrade design modulus from subgrade design CBR) equation
- summarises E-CBR equations used overseas
- compares the current Austroads E-CBR equation with equations used overseas
- discusses limitations with the current Austroads E-CBR equation
- details the need for laboratory testing to determine the stress dependency of subgrade modulus for a range of subgrade materials and subgrade CBR values
- recommends incorporating the stress dependency of subgrade modulus in the development of the non-linear finite element model for pavement design being undertaken as part of Austroads project TT1452: *Development of Pavement Design Models*.

2 CURRENT AUSTROADS RELATIONSHIP FOR ESTIMATING SUBGRADE MODULUS FROM SUBGRADE CBR

2.1 Development of the Current Austroads Relationship

Austroads *Guide to Pavement Technology: Part 2 - Pavement Structural Design* includes a procedure to calculate the vertical modulus of subgrade materials from the subgrade design California Bearing Ratio (CBR) value. Despite it being well known that the relationship between the CBR strength test and material modulus varies between materials (discussed later), reliance on the CBR test is likely to continue until such time as improved methods are developed to predict moisture in pavements.

The Austroads relationship between subgrade modulus and subgrade CBR currently in use was adopted by the National Association of Australian State Road Authorities (NAASRA) in 1987 and is expressed as:

$$E = 10 \times CBR$$

Prior to 1987 the NAASRA *Interim Guide to Pavement Thickness Design* (1979) adopted the following relationship between subgrade modulus and subgrade CBR:

$$E = 22.4 \times CBR^{0.5} \text{ CBR} > 5 \text{ and } E = 16.2 \times CBR^{0.7} \text{ CBR} < 5$$

As shown in Figure 2.1 the 1979 NAASRA relationship, when compared with the current Austroads relationship, resulted in significantly more conservative modulus values for subgrades with CBR greater than 5 and slightly less conservative modulus values for subgrades with CBR less than 5.

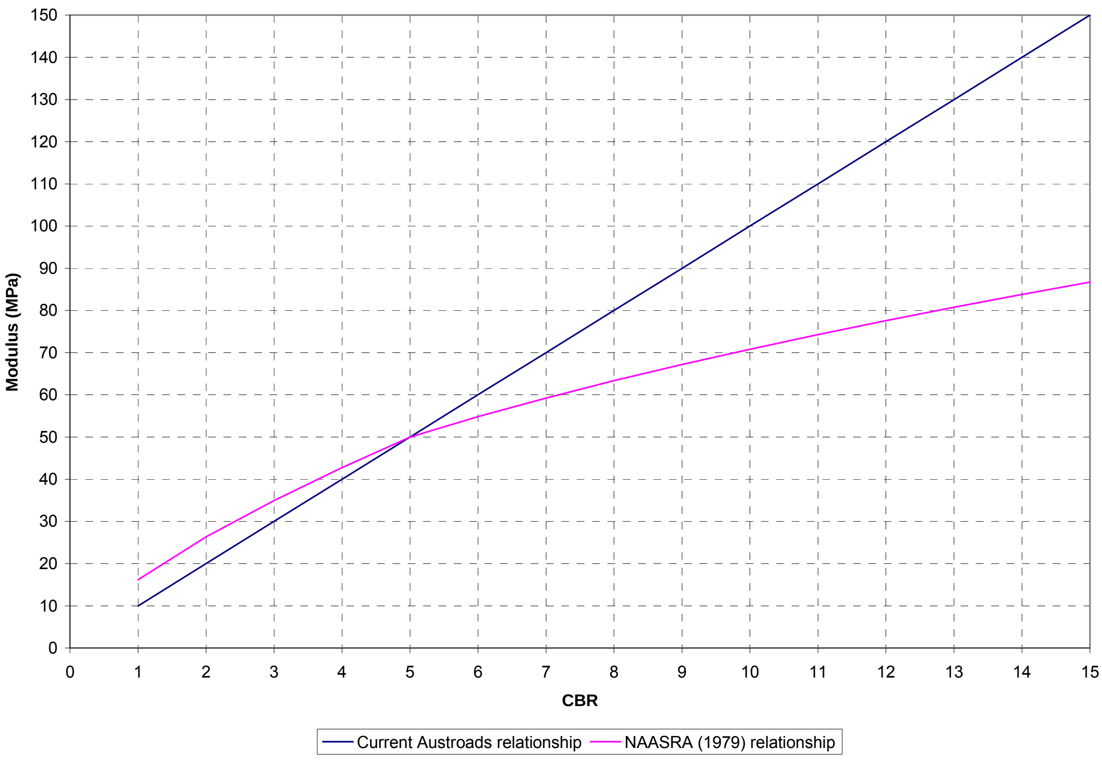

Figure 2.1: Austroads and NAASRA (1979) subgrade modulus from CBR relationships

Part 1 Section 4.2.3 of *Technical Basis of Austroads Pavement Design Guide* (Austroads 2004b) describes the origins of the relationship adopted in the 1987 NAASRA *Interim Guide to Pavement Thickness Design*:

> The establishment of a relationship between modulus and CBR is intrinsically fraught with difficulty. In the first instance, the two properties are markedly different. Resilient modulus is determined under stress-strain conditions wherein the permanent strain in the material (after removal of the applied stress) is but a small proportion of the total strain induced by the applied stress. In contrast to this, the CBR value is associated with the peak resistance developed to a progressive shearing failure of the material. Hence, the two properties are associated with the opposite ends of the stress-strain plot for the material. There is the further complication that the value of resilient modulus depends on the values of stresses applied.
>
> While the above difficulties pertain to one material in one condition (specified by, say, dry density and moisture content), a relationship was sought which was relevant for all naturally-occurring fine-grained materials and, for each material, over a wide range of conditions (even this is a considerable oversimplification, as it leaves aside the effects of how the material arrived at the specified condition).
>
> However, because the CBR test (or some surrogate for it) was (and essentially still is) the only test commonly used to characterise subgrade materials, a relationship between CBR and modulus was an essential component of the mechanistic design procedure.
>
> The WG started with consideration of the information presented in Sparks and Potter (1982). The report contained a review and comparison of relationships then in use (or proposed); together with relationships for two Melbourne clays developed from results of in-house testing.
>
> The test results reported, together with relationships developed, well illustrated the intrinsic variability in subgrade material and the effect of the stress-dependency of the modulus (more significantly, the strain dependency).
>
> After reviewing the information in this report, the WG tentatively adopted the relationship in the report for the two Melbourne clays ($E = 40.7\ CBR^{0.37}$) on the grounds that "at least it is for Australian soils and it is in amongst other relationships in use".
>
> However, upon later reflection, the WG opted for the relationship E = 10 CBR (developed by Heukelom and Klomp (1962) from results of Rayleigh Wave and Dynamic Impedance testing in the Netherlands and Rayleigh Wave testing in the UK) on the following grounds:
>
> - the relationship encompassed more soil types
> - it improved the fit of the subgrade strain relationship derived from mechanistic analysis of granular pavements
> - it had a simpler form, and
> - it had been widely adopted.
>
> The comment in the Guide that "a maximum value of 150 MPa is normally used" is in reference to cohesive soils.

It is noted that the E = 10 x CBR relationship was originally developed by Heukelom and Klomp (1962) and was derived from wave propagation testing conducted at very low strain levels and dynamic deflection testing. The results, adjusted for the material's Poisson ratio, were used to determine the dynamic moduli of elasticity and correlated to measured CBR values. In essence wave velocity was determined in the horizontal plane but the reported modulus was calculated for the vertical plane (i.e. Ev). The relationship was originally established for CBR strength 2 to 200 and as such its accuracy for CBR 2 to 15, as applied in the Austroads *Guide to Pavement Technology: Part 2 - Pavement Structural Design*, is unclear. In addition, E = 10 x CBR is a mean relationship and has a reported accuracy of E = 5 - 20 x CBR.

In 1990 the Main Roads Department, Queensland (QDMR) decided that the Heukelom and Klomp relationship was not the most appropriate as 'test data seem to indicate a modulus greater than 10xCBR for CBR less than about 5 and less than 10xCBR for CBR greater than 5' (Angell 1988). Instead it adopted the following relationship:

$$E = 21.2 \times CBR^{0.64} \quad CBR < 15 \text{ and } E = 19 \times CBR^{0.68} \quad CBR > 15$$

The reasons stated for this selection included: good conformance with Transport and Road Research Laboratory (TRL) in the UK and Council for Scientific and Industrial Research (CSIR) in South Africa experience, relationship lies within ranges established by Sparks and Potter and also Heukelom and Klomp, consistent with pavement material modulus of 350 MPa considered an appropriate maximum for CBR 80 material compacted to 95% modified maximum dry density and represents a reasonably smooth relationship across the range of subgrade and paving materials. However, in 2004 QDMR adopted the Austroads pavement design guide including the Heukelom and Klomp relationship.

2.2 Lack of Conservatism of the Current Austroads Relationship

Concerns have been raised as to whether the current relationship overestimates the subgrade modulus, particularly for CBR values greater than 5. A number of researchers both overseas and in Australia have found measured subgrade modulus values significantly lower than predicted by the Heukelom and Klomp relationship.

The Heukelom and Klomp relationship is based on wave propagation and dynamic deflection testing conducted at very low strain rates. Many authors including Croney (1977) and Powell et al. (1984) have noted that when wave propagation data is either compared with repeated loading triaxial testing data at realistic stress levels or adjusted for more realistic stress levels the estimated modulus values are significantly lower than the original relationship proposed by Heukelom and Klomp, particularly for high CBR materials. This revelation has seen the majority of overseas organisations change to new relationships using adjusted wave propagation data often supplemented by additional repeated loading triaxial (RLT) test data.

In an evaluation of nonlinear resilient modulus results on granular materials using RLT testing and correlated with soaked moulded laboratory CBR testing Rada and Witczak (1981) found measured subgrade modulus in the order of 1/6th to 1/2 lower than Heukelom and Klomp. They hypothesised that this discrepancy may be attributed to shear strain differences caused by the dynamic wave propagation field tests of Heukelom and Klomp and those found in laboratory specimens that undergo resilient modulus testing.

The laboratory CBR and RLT testing results of Sparks and Potter of two Australian clays at various moisture contents also showed that the Heukelom and Klomp relationship predicted higher modulus values for a given CBR for CBR values greater than 5 than was found experimentally.

Sukumaran et al. (2002) in a study of materials with CBR 11 to 40 used a finite element model to investigate the relationship between CBR and resilient modulus and found that the resilient modulus of the subgrade materials studied could not be suitably predicted using the Heukelom and Klomp relationship. They observed that the Heukelom and Klomp relationship over-predicted subgrade modulus. Sukumaran et al. found that a more accurate estimate of resilient modulus can be obtained knowing the unconfined compressive strength of the soil.

Erlingsson (2007) in a study of 20 granular materials with laboratory CBR between 40 and 140 undertook repeated load triaxial testing, where both the CBR and repeated load triaxial (RLT) testing was conducted at consistent moisture content and compacted according to the Proctor compaction method. Erlingsson found that the CSIR relationship gave the best prediction of measured resilient modulus. From the data presented it can be inferred that the TRL relationships was more conservative than the measured results and that the Heukelom and Klomp relationship was not an accurate predictor of modulus for the granular materials in this study.

3 OVERSEAS PRACTICE

3.1 Relationships between Subgrade Modulus and Subgrade CBR

Many relationships for estimating subgrade modulus from subgrade CBR have been proposed by numerous researchers over the past 50 years. A summary of some of the most important of these relationships is shown in Table 3.1.

Table 3.1: Relationships proposed for estimating subgrade modulus from subgrade CBR

Author(s)	Relationship
Jeuffroy and Bachelez (1962)	$E = 6.5 \times CBR^{0.65}$
Heukelom and Klomp (1962)	$E = 10 \times CBR$
Gschwendt and Poliacek (1972)	$E = 11 \times CBR^{0.8}$
Thrower, Lister and Potter (1972)	$E = 17.5 \times CBR$
Croney (1977)	$E = 6.6 \times CBR$
Sparks and Potter (1982)	$E = 40.7 \times CBR^{0.37}$
Paterson (1978); Freeme, Maree and Viljoen (1982) – NITRR (CSIR)	Categorised to $E = k \times CBR$ CBR k 3 15 7 10 10 9 15 8
Powell et al. (1984) – TRL	$E = 17.6 \times CBR^{0.64}$
Livneh (1991)	$E = 14.8 \times CBR^{0.71}$

It is noted that the majority of the relationships presented in Table 3.1 are primarily derived from data collected by Jones (1958) or Heukelom and Klomp (1962) using wave propagation techniques. The differences between the relationships can be attributed to the degree to which the base data has been adjusted to account for the low stresses/strain values used in wave propagation techniques, supplemented by additional data, either additional wave propagation or repeated loading triaxial and/or manipulated to achieve a desired level of confidence.

The relationships outlined in Table 3.2 have been, or currently are, used for pavement design purposes by road or airport authorities to estimate subgrade modulus from subgrade CBR.

Table 3.2: Relationships used to estimate subgrade modulus from subgrade CBR

Country	Organisation	Relationship
Australia	NAASRA (1979)	$E = 16.2 \times CBR^{0.7}$ CBR < 5 $E = 22.4 \times CBR^{0.5}$ CBR > 5
Australia	Main Roads Department, Queensland (Angell 1988)	$E = 21.2 \times CBR^{0.64}$ CBR < 15 $E = 19 \times CBR^{0.68}$ CBR > 15
Australia	NAASRA (1987) then Austroads (1992, 2004a and 2008b)	$E = 10 \times CBR$
India	Rao (2008)	$E = 10 \times CBR$, CBR < 5 $E = 17.6 \times CBR^{0.64}$, CBR > 5
Israel	Livneh (2007)	$E = 20 \times CBR^{0.71}$
South Africa	CSIR / National Institute for Transport and Road Research (Paterson 1978)	Categorised to $E = k \times CBR$ CBR k E 3 15 45 7 10 70 10 9 90 15 8 120
UK and USA	TRL / American Association of State Highway and Transportation Officials (Powell et al. 1984)	$E = 17.6 \times CBR^{0.64}$
USA	Federal Aviation Administration (McQueen et al. 2001)	$E = 23.2 \times CBR^{0.68}$
USA	Georgia Department of Transport (Webb & Campbell 1986)	$E = 21.5 \times CBR^{0.48}$
USA	US Army Corp (Green & Hall 1975)	$E = 37.3 \times CBR^{0.71}$
USA	Virginia Department of Transportation (2003)	$E = 10 \times CBR$, CBR 5-10 $E = 20 \times CBR^{0.65}$, CBR >10

It is noted that some of the relationships presented in Table 3.2, such as the Indian relationship, are a direct combination of the Heukelom and Klomp (1962) and Powell et al. (1984) relationships while others, such the QDMR, Israeli and South African relationships are manipulations of the original data for a given level of confidence, to address local factors or to account for additional laboratory testing.

3.1.1 UK and USA

The UK Transport and Road Research Laboratory (TRL) relationship, also adopted by American Association of State Highway and Transportation Officials (AASHTO), was developed by Powell et al. in 1984 and was established from modulus measured by wave propagation (Jones 1958) to in situ CBR tests. In developing the TRL relationship account was taken of the likely effect of the unrealistically low stress/strain levels generated in the wave propagation technique and of other information obtained from repeated loading triaxial testing carried out at realistic strain levels and in situ measurements of transient stress and strain in experimental pavements (Powell et al. 1984).

3.1.2 South Africa

The Scientific and Industrial Research (CSIR) relationship that has been used in South Africa for the past 20 years (Paterson 1978; Paterson and Maree 1978; Freeme, Maree and Viljoen 1982) was adapted from the Rhodesian Ministry of Transportation and derived from much earlier data in the UK, however it, appears to have been adjusted in applying the relationship to southern Africa.

The South African relationship categorises the subgrade modulus relationship and a number of mathematical approximations for the relationship are possible depending on which points are selected and the degree of freedom allowed for the various points.

3.1.3 Comparison of Australian, UK/USA and South African Relationships

The 1990 QDMR, TRL and CSIR relationships estimate significantly lower subgrade modulus values for CBR values greater than 7, 5 and 7 respectively when compared with the current Austroads relationship as shown in Table 3.3 and Figure 3.1. It is also apparent from Table 3.3 and Figure 3.1 that the QDMR, TRL and CSIR relationships estimate slightly higher subgrade moduli for CBR values less than 7, 5 and 7 respectively indicating that the current Austroads relationship is more conservative across this range of CBR values.

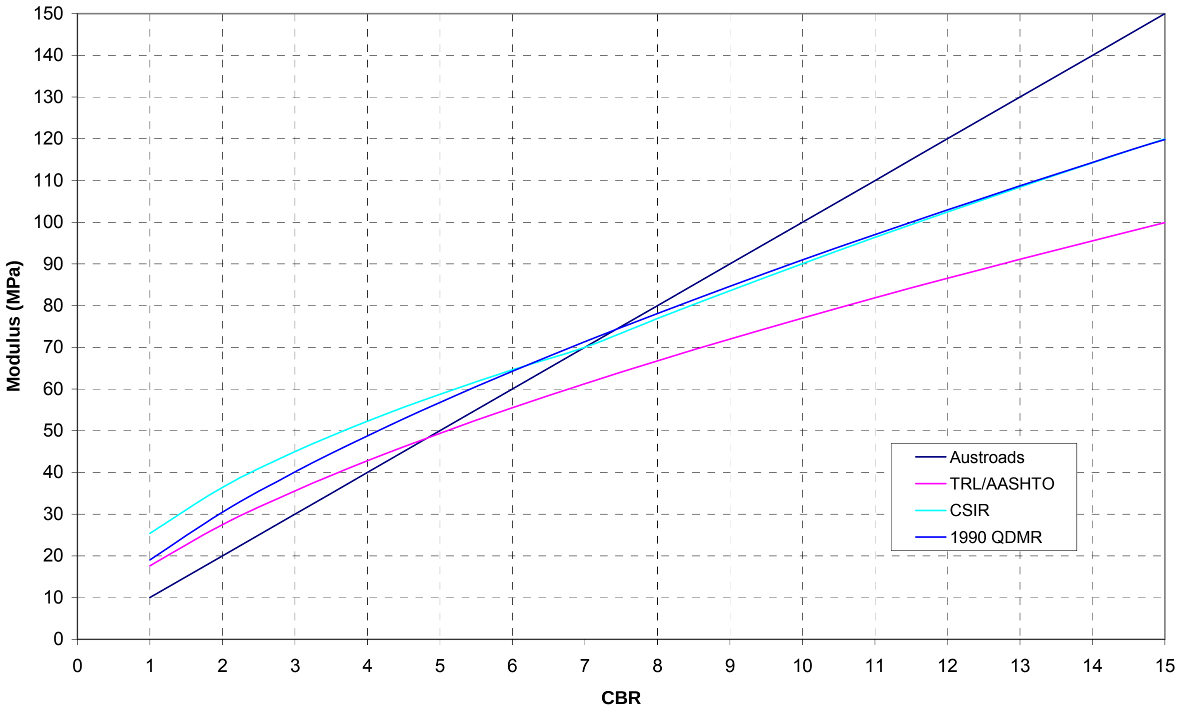

Figure 3.1: Austroads, 1990 QDMR, TRL and CSIR subgrade modulus from subgrade CBR relationships

Table 3.3: Austroads, 1990 QDMR, TRL and CSIR estimates of subgrade modulus from subgrade CBR

Subgrade CBR	Subgrade modulus (Austroads relationship) (MPa)	Subgrade modulus (1990 QDMR relationship) (MPa)	Subgrade modulus (TRL relationship) (MPa)	Subgrade modulus (CSIR relationship) (MPa)
1	10	19	18	25
2	20	30	27	36
3	30	40	36	45
4	40	49	43	52
5	50	57	49	59
6	60	64	56	65
7	70	71	61	70
8	80	78	67	77
9	90	85	72	84
10	100	91	77	90
12	120	103	87	102
15	150 (max value)	120	100	120
30	150 (max value)	187	155	190

4 LIMITATIONS OF SUBGRADE MODULUS FROM SUBGRADE CBR RELATIONSHIPS

Many researchers have commented that CBR is not an accurate predictor of modulus (Rada & Witczak 1981; Sparks & Potter 1982; NCHRP 2004; Brown et al. 2006).

National Cooperative Highway Research Program (NCHRP 2004) states 'Users are cautioned that the resilient modulus value selected has a very significant effect on the resulting structural number determined. Therefore, users should be very cautious about using high resilient modulus values, or their overlay thickness values will be very thin.'

However, as discussed in Austroads (2008a) it is noted that reliance on the CBR test is likely to continue until such time as improved methods are developed to predict moisture in pavements. As such conservatism in estimating subgrade modulus from subgrade CBR is prudent.

4.1 Dependency of Subgrade Modulus on Subgrade Stress

Rada and Witczak (1981) found, in a study of 271 test results obtained from 10 different research agencies, that subgrade modulus is stress dependent and that there cannot be a unique relationship between modulus and CBR. However, they also concluded that for a given stress level a general correlation between modulus and CBR does exist, albeit that a wide range of scatter exists for the relationship. Though the data studied by Rada and Witczak appears to have been primarily granular materials with CBR between 20 and 200 the findings, that subgrade modulus is stress dependent, are equally applicable to subgrade CBR values less than 15 as typically used in Australian pavement designs.

Brown et al. 2006 reported that research has shown the relationship between CBR and resilient modulus is not reliable and that this unreliability results from the non-linear stress-strain relationship involved.

Figure 4.1 shows the variation in subgrade modulus with deviator stress as measured by repeated load triaxial testing of a CBR7 clay material used in the 1990/91 Mulgrave ALF trial (Jameson et al. 1992). It can be seen that the subgrade modulus varies significantly depending on the stress condition with increasing stress levels significantly reducing subgrade modulus.

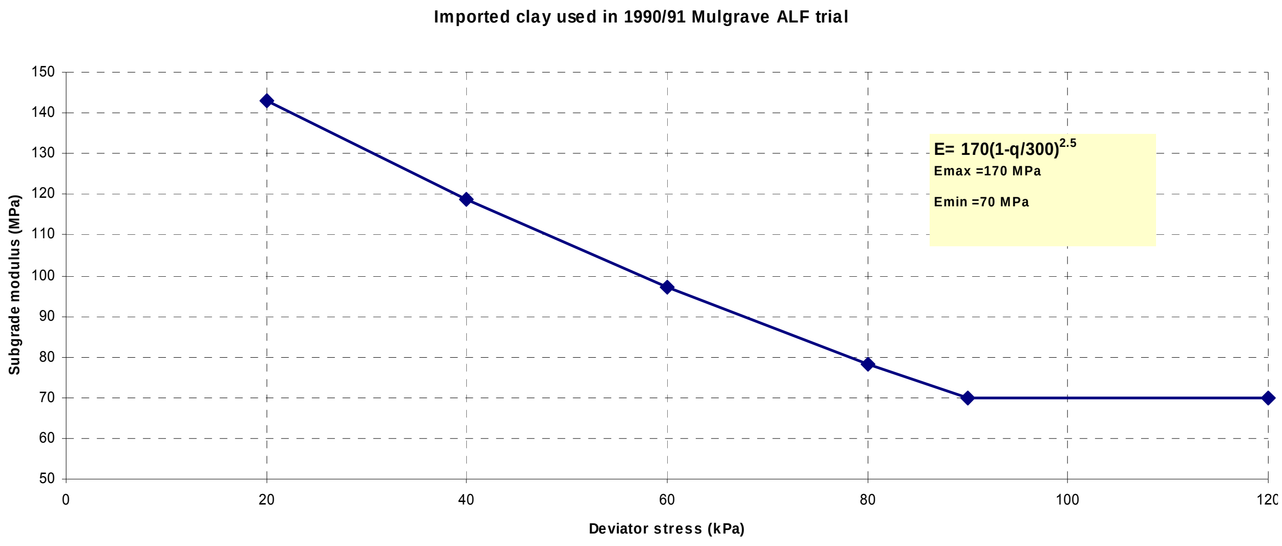

Figure 4.1: Variation in subgrade modulus with deviator stress

For this material, E = 10 x CBR may be suitable for light structures where stresses are high, but conservative for heavy duty structures where stresses are low.

The stress dependency of the subgrade modulus is not well understood and a general relationship for a range of subgrade CBR values is not available. The stress dependency for some CBR values is available, such as that shown in Figure 4.1, but the data available does not cover the wide range of materials encountered by Australian pavement designers.

Figure 4.2 shows the impact that variation in the thickness of unbound granular and full depth asphalt pavement has on the subgrade modulus for a given in situ CBR 7 material. It can be seen that the subgrade modulus is significantly influenced by pavement thickness for both the unbound granular and full depth asphalt pavements.

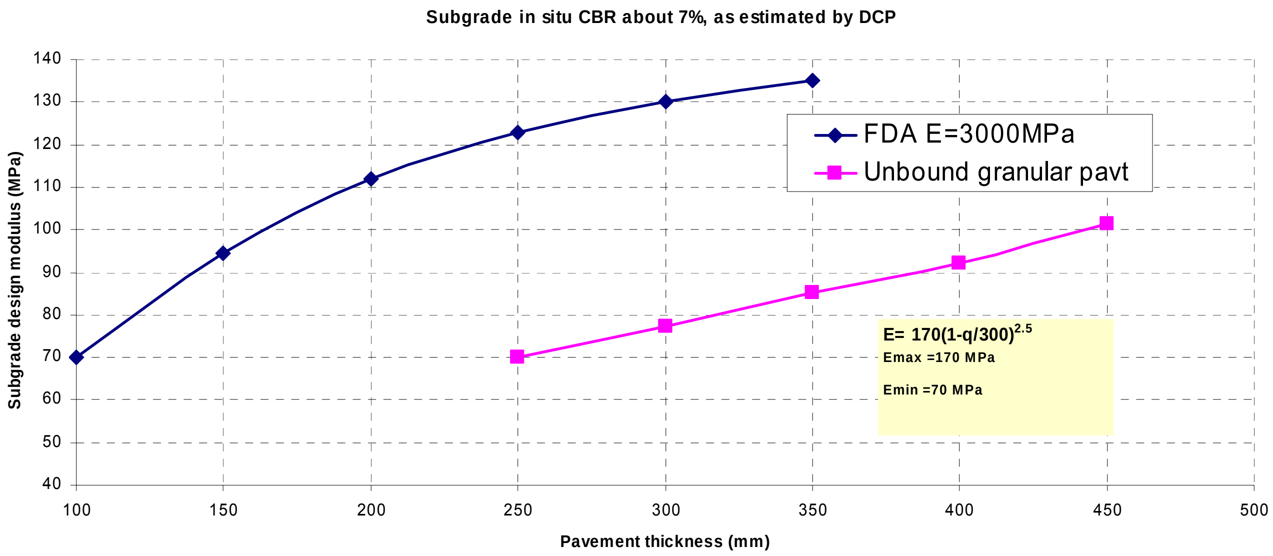

Figure 4.2: Variation in subgrade modulus with pavement thickness

The dependence of subgrade modulus on the stress condition is critically important for pavement design as changes to the subgrade modulus value used in design significantly influence the resultant design life.

Given the lack of information about the stress dependency of subgrade modulus across the range of subgrade materials encountered in Australia additional laboratory testing is necessary to allow a general relationship between subgrade CBR, subgrade stress and subgrade modulus to be developed.

4.2 Variability of the Subgrade Modulus Relationship with Material Type

Most subgrade modulus from subgrade CBR data has been found to have variation in the order of 2:1 to 4:1, meaning for a given the CBR the modulus may be 100% to 300% higher or lower than expected.

Croney (1977) found accuracy of approximately 2:1. Rada and Witczak (1981) found scatter bands in the order of 50%. Work undertaken by Sparks and Potter (1982) on two Australian clays found that CBR is not a reliable predictor of modulus and that a low value of correlation was obtained. This work reported modulus values for a given CBR varied in the order of 3:1 between the maximum and minimum values on the 95% confidence limits.

The E = 10 x CBR relationship originally developed by Heukelom and Klomp (1962) is a mean relationship and has a reported accuracy of E = 5-20 x CBR. Some other relationships in use worldwide (refer Section 3) are for a given level of confidence giving inherently higher levels of conservatism than the current Austroads relationship.

Given that modulus is a measure if elastic response to load whereas CBR is a measure of the subgrades resistance to penetration, it is not surprising that these two parameters are not highly correlated over a range of subgrade material types.

4.3 Dependency of the Subgrade Strain Relationship on Subgrade Modulus

The subgrade strain relationship (equation 5.3 of Austroads 2008b) expressed as $N = [9300/\mu\varepsilon]^7$ was derived by applying mechanistic procedures to a range of pavements selected from the Austroads (2008b) Figure 8.4 and represents a ‘best fit’ relationship.

Figure 4.3 plots the subgrade strain relationship across a range of CBR values utilising the current Austroads subgrade modulus relationship.

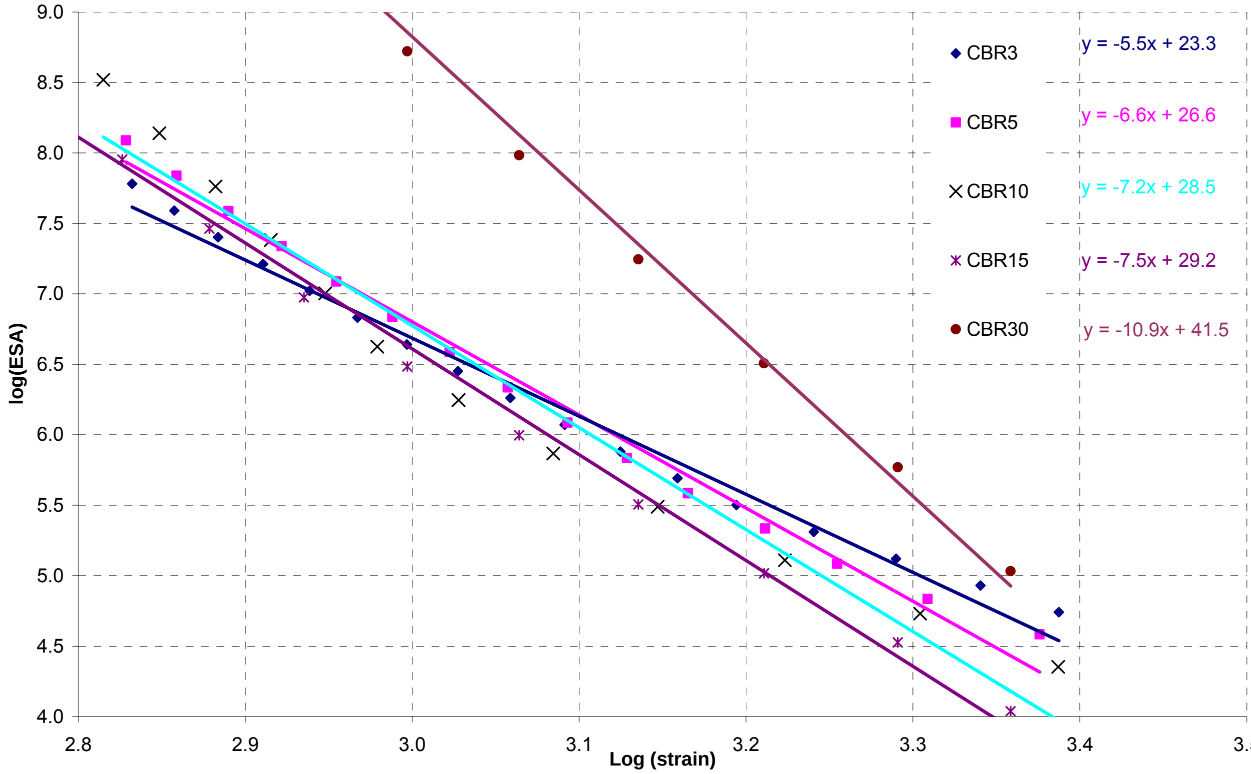

Figure 4.3: Subgrade strain relationship for various CBR values – current Austroads subgrade modulus relationship

It is apparent from Figure 4.3 that for the current Austroads subgrade modulus relationship the subgrade strain relationship is not significantly affected by subgrade modulus. However, it is also noted that CBR greater than 15 was not considered when determining the current Austroads subgrade strain relationship. As such the current Austroads subgrade strain relationship (equation 5.3 of Austroads 2008b) is independent of subgrade modulus.

As a comparison, applying the same mechanistic principles to the TRL subgrade modulus relationship indicates that the subgrade strain relationship is affected by changes to the subgrade modulus.

Figure 4.4 plots the subgrade strain relationship across a range of CBR values utilising the TRL relationship. The full set of calculations is included as Appendix A.

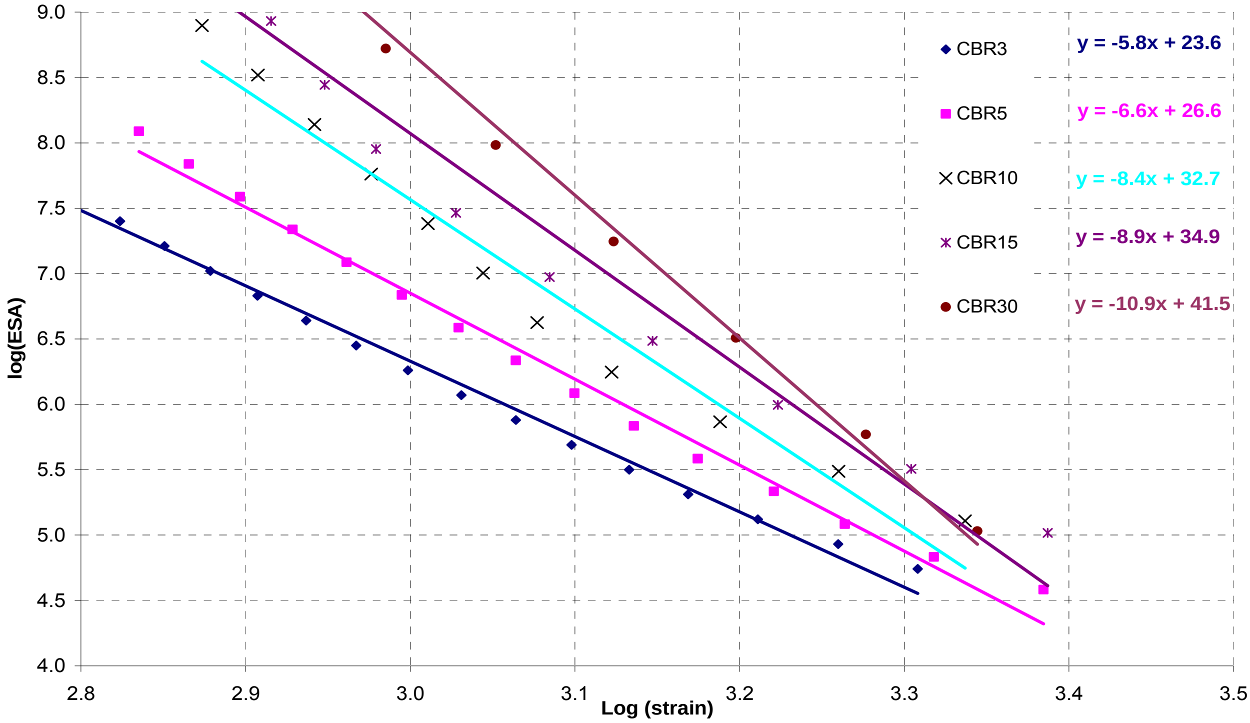

Figure 4.4: Subgrade strain relationship for various CBR values – TRL subgrade modulus relationship

As shown in Figure 4.4 it is apparent that a subgrade strain relationship for the TRL subgrade modulus from subgrade CBR relationship would need to include a dependence on the subgrade modulus and therefore would be significantly different to the current Austroads subgrade strain criteria. For a given subgrade strain, the higher the subgrade modulus the higher the allowable loading. Intuitively this makes more sense as it would be anticipated that the amount of plastic strain deformation for a given elastic strain would be less for a higher CBR subgrade than a lower material.

Therefore, was the current Austroads subgrade modulus from subgrade CBR relationship revised, for example to one of the overseas relationships or to include subgrade stress dependency, the subgrade strain relationship (equation 5.3 of Austroads 2008b) would need to be revised to introduce a subgrade modulus dependency variable. This would significantly increase the complexity of designing pavements where the subgrade strain is the limiting criteria, namely unbound granular pavements with thin bituminous surfacings.

5 CONCLUSIONS

From data available it appears likely that, for relatively high stress levels, the Heukelom & Klomp (1962) relationship adopted by NAASRA in 1987 and currently used by Austroads (2008b) is non-conservative when compared with overseas relationships for CBR values greater than 7. This apparent over-prediction is primarily due to the low stress/strain levels utilised in the wave propagation technique used to develop the Heukelom & Klomp relationship.

In addition, most subgrade modulus from subgrade CBR data has been found to have variation in the order to 2:1 to 4:1, meaning for a given the CBR the modulus may be 100% to 300% higher or lower than expected. Given that modulus is a measure if elastic response to load whereas CBR is a measure of the resistance to penetration, it is not surprising that these two parameters are not highly correlated over a range of subgrade material types.

However, research overseas and in Australia has shown that non-stress dependent relationships between CBR and resilient modulus, such as the current Austroads relationship, are not reliable as a result of the non-linear stress-strain relationship. The subgrade modulus has been found to vary significantly depending on the subgrade stress condition with increasing stress levels significantly reducing subgrade modulus.

Any change to the subgrade modulus from subgrade CBR relationship to address the stress dependency of the subgrade modulus would also necessitate a change to the subgrade strain relationship to introduce a subgrade modulus dependency variable. For a given subgrade strain, the higher the subgrade modulus the higher the allowable loading. Intuitively this makes more sense as it would be anticipated that the amount of plastic strain deformation for a given elastic strain would be less for a higher CBR subgrade than a lower material.

It appears likely that, due to the stress dependency of subgrade modulus, the current Austroads subgrade modulus from subgrade CBR relationship is conservative for heavy duty structures (cemented and thick asphalt). In addition, the design of granular pavements with thin bituminous surfacings is based on an empirical relationship and therefore is not influenced by the modulus-CBR relationship.

Given the lack of information about the stress dependency of subgrade modulus across the range of subgrade materials encountered in Australia and the impact this stress dependency might have on pavement design additional laboratory testing is necessary to allow a general relationship between subgrade CBR, subgrade stress and subgrade modulus to be developed. This testing, similar to the work completed by Sparks and Potter in 1982 on two Australian clays, would involve testing a range of materials of varying CBR values to determine resilient modulus at varying stress levels.

It is noted that a general relationship between subgrade CBR, subgrade stress and subgrade modulus would require significantly altering the subgrade strain relationship so that it too reflected the stress dependency of subgrade materials.

Changes to introduce stress dependence into the subgrade modulus and subgrade strain relationships are likely to add a significant additional level of complexity and difficultly to pavement designs and would necessitate changes to the example pavement design charts included in the Austroads Pavement Design Guide.

6 RECOMMENDATIONS

It is recommended that the current Austroads subgrade modulus from subgrade CBR relationship is retained in the short-term given the lack of information about the stress dependency of subgrade modulus across the range of subgrade materials encountered in Australia, the likelihood the current relationship is conservative for the majority of pavement designs and the use of a non-linear finite element model in the medium to long-term.

It is recommended that additional laboratory testing is undertaken to allow a general relationship between subgrade CBR, subgrade stress and subgrade modulus to be developed. This testing, similar to the work completed by Sparks and Potter in 1982 on two Australian clays, would involve testing a range of materials of varying CBR values to determine resilient modulus at varying stress levels.

Due to the additional complexities involved in designing pavements utilising a general relationship between subgrade CBR, subgrade stress and subgrade modulus and a new subgrade strain relationship reflecting subgrade modulus dependence it is recommended that the findings of the recommended testing be incorporated into development of the non-linear finite element model for pavement design currently being undertaken as part of Austroads project TT1452: *Development of Pavement Design Models*.

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APPENDIX A SUBGRADE STRAIN RELATIONSHIP CALCULATIONS

Table A 1: Calculation of subgrade strain relationship: TRL subgrade modulus from subgrade CBR relationship

Granular thickness	Subgrade CBR	Subgrade modulus	Strain	Life
350	3	18	2033	5.50E+04
375	3	18	1819	8.52E+04
400	3	18	1626	1.32E+05
425	3	18	1475	2.04E+05
450	3	18	1358	3.17E+05
475	3	18	1253	4.90E+05
500	3	18	1159	7.60E+05
525	3	18	1074	1.18E+06
550	3	18	997	1.82E+06
575	3	18	927	2.82E+06
600	3	18	864	4.37E+06
625	3	18	808	6.78E+06
650	3	18	756	1.05E+07
675	3	18	709	1.63E+07
700	3	18	666	2.52E+07
725	3	18	627	3.90E+07
750	3	18	592	6.04E+07
250	5	49	2424	3.83E+04
275	5	49	2080	6.81E+04
300	5	49	1836	1.21E+05
325	5	49	1663	2.16E+05
350	5	49	1495	3.84E+05
375	5	49	1367	6.83E+05
400	5	49	1258	1.22E+06
425	5	49	1159	2.16E+06
450	5	49	1070	3.85E+06
475	5	49	988	6.86E+06
500	5	49	915	1.22E+07
525	5	49	848	2.17E+07
550	5	49	788	3.87E+07
575	5	49	734	6.88E+07
600	5	49	684	1.22E+08

Table A 1: Calculation of subgrade strain relationship: TRL subgrade modulus from subgrade CBR relationship (Continued)

Granular thickness	Subgrade CBR	Subgrade modulus	Strain	Life
200	10	77	2322	1.29E+05
225	10	77	1948	3.08E+05
250	10	77	1651	7.36E+05
275	10	77	1414	1.76E+06
300	10	77	1264	4.21E+06
325	10	77	1171	1.01E+07
350	10	77	1083	2.41E+07
375	10	77	1000	5.77E+07
400	10	77	923	1.38E+08
425	10	77	853	3.30E+08
450	10	77	788	7.90E+08
150	15	100	2800	1.04E+05
175	15	100	2313	3.21E+05
200	15	100	1921	9.89E+05
225	15	100	1610	3.05E+06
250	15	100	1365	9.43E+06
275	15	100	1197	2.91E+07
300	15	100	1075	8.98E+07
325	15	100	998	2.77E+08
350	15	100	925	8.56E+08
375	15	100	855	2.64E+09
400	15	100	791	8.16E+09
100	30	156	3425	1.07E+05
125	30	156	2930	5.88E+05
150	30	156	2438	3.21E+06
175	30	156	2015	1.76E+07
200	30	156	1672	9.61E+07
225	30	156	1403	5.26E+08
250	30	156	1215	2.88E+09
275	30	156	1066	1.57E+10
300	30	156	953	8.61E+10

Table A 2: Calculation of subgrade strain relationship: current Austroads subgrade modulus from subgrade CBR relationship (2008)

Cemented materials thickness	Subgrade CBR	Subgrade modulus	Strain	Life
350	3	30	2440	5.50E+04
375	3	30	2190	8.52E+04
400	3	30	1949	1.32E+05
425	3	30	1740	2.04E+05
450	3	30	1564	3.17E+05
475	3	30	1442	4.90E+05
500	3	30	1333	7.60E+05
525	3	30	1234	1.18E+06
550	3	30	1145	1.82E+06
575	3	30	1065	2.82E+06
600	3	30	993	4.37E+06
625	3	30	927	6.78E+06
650	3	30	868	1.05E+07
675	3	30	814	1.63E+07
700	3	30	765	2.52E+07
725	3	30	720	3.90E+07
750	3	30	680	6.04E+07
250	5	50	2376	3.83E+04
275	5	50	2036	6.81E+04
300	5	50	1797	1.21E+05
325	5	50	1627	2.16E+05
350	5	50	1463	3.84E+05
375	5	50	1345	6.83E+05
400	5	50	1239	1.22E+06
425	5	50	1141	2.16E+06
450	5	50	1053	3.85E+06
475	5	50	973	6.86E+06
500	5	50	901	1.22E+07
525	5	50	835	2.17E+07
550	5	50	776	3.87E+07
575	5	50	723	6.88E+07
600	5	50	674	1.22E+08

Table A 2: Calculation of subgrade strain relationship: current Austroads subgrade modulus from subgrade CBR relationship (2008) (Continued)

Cemented materials thickness	Subgrade CBR	Subgrade modulus	Strain	Life
150	10	100	2438	2.25E+04
175	10	100	2015	5.38E+04
200	10	100	1672	1.29E+05
225	10	100	1403	3.08E+05
250	10	100	1215	7.36E+05
275	10	100	1066	1.76E+06
300	10	100	953	4.21E+06
325	10	100	887	1.01E+07
350	10	100	823	2.41E+07
375	10	100	762	5.77E+07
400	10	100	706	1.38E+08
425	10	100	653	3.30E+08
100	15	150	2283	1.09E+04
125	15	150	1954	3.36E+04
150	15	150	1625	1.04E+05
175	15	150	1366	3.21E+05
200	15	150	1159	9.89E+05
225	15	150	993	3.05E+06
250	15	150	862	9.43E+06
275	15	150	756	2.91E+07
300	15	150	671	8.98E+07
325	15	150	624	2.77E+08
100	30	150	2283	1.07E+05
125	30	150	1954	5.88E+05
150	30	150	1625	3.21E+06
175	30	150	1366	1.76E+07
200	30	150	1159	9.61E+07
225	30	150	993	5.26E+08
250	30	150	862	2.88E+09
275	30	150	756	1.57E+10
300	30	150	671	8.61E+10

INFORMATION RETRIEVAL

Austroads, 2009, **Review of Relationship to Predict Subgrade Modulus from CBR (California Bearing Ratio)**, Sydney, A4, 32pp, AP-T130/09

Keywords:

Subgrade / CBR / Modulus

Abstract:

The Austroads *Guide to the Structural Design of Road Pavements: Pavement Design* (now the *Guide to Pavement Technology: Part 2 – Pavement Structural Design*) has been used throughout Australia for over 20 years. Progressive development of the Guide is required to take advantage of improved knowledge and technology and hence improve pavement design procedures.

Against this background, Austroads commissioned ARRB Group to:

- summarise recent research findings, including those on dynamic loading of pavements
- summarise recent developments in overseas design practices, particularly United States of America and South Africa
- review design procedures chapter by chapter
- identify a strategy to develop a new Austroads response to load model
- identify areas where the Guide should be improved.

Future Development of Austroads Pavement Design Guidelines (Austroads 2008a) detailed the findings and recommended a strategy for the development of the Guide over the next five years. The report recommended a number of key areas to improve the Guide including that procedures for estimating subgrade modulus from subgrade California Bearing Ratio (E-CBR equation) need to be reviewed as for high CBR values the modulus calculated are significantly higher than used in USA and Britain.

This report:

- details the origins of the current Austroads E-CBR equation
- summarises E-CBR equations used overseas
- compares the current Austroads E-CBR equation with equations used overseas
- discusses limitations with the current Austroads E-CBR equation
- details the need for laboratory testing to determine the stress dependency of subgrade modulus for a range of subgrade materials and subgrade CBR values
- details the need to incorporate the stress dependency of subgrade modulus in the development of a non-linear finite element model for pavement design.