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A Mechanistic Empirical Approach Utilizing Controlled Tolerable Deflection for the Design of Thin Surfaced Asphalt Pavements

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Abstract: Thin surfaced asphalts are designed in a similar manner to spray sealed asphalts considering only rutting as the major mode of failure while there is no consideration for fatigue in the current mechanistic empirical pavement design method adopted by Austroads. However, sprayed seal surfacing are less sensitive to vertical deflection compared to thin surfaced asphalts. Thin surfaced asphalts are commonly prematurely failed by fatigue before any major rutting failure. In this research, the Austroads tolerable deflection criteria was investigated utilizing deflection and cumulative traffic data from 30 thin asphalt pavement sections from Queensland. The data showed that the current Austroads tolerable deflection criterion is largely overestimating the design life of these pavement sections. A new calibrated tolerable deflection criterion was developed. The calibrated tolerable deflection criterion was used with synthetic deflection data and pavement responses generated by multilayer elastic analysis using Circly software for 200 pavement sections to develop a new subgrade criterion. The new subgrade criterion is designed to limit the maximum pavement deflection to be within the calibrated tolerable deflection. By limiting the maximum deflection of the thin asphalt pavements to the new calibrated tolerable deflection, it is expected that surface curvature will be reduced and therefore the fatigue life of these pavements will be significantly improved and it will limit the premature failures of these surfaces. The new criterion produces a stiffer pavement structure compared to the current method. The high stiffness can be achieved by using thicker base course or stabilized bases and subbases structures.

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***Key words**: Deflection; Pavements; Thin surfaced; Tolerable deflection.*

Background

The Australian guidelines (Austroads) use an empirical design chart to design unbound granular pavements with spray seals or thin surfaced asphalts; however, this chart does not differentiate between thin surfaced asphalts or sprayed seals pavements [1]. In the current Austroads Mechanistic Empirical pavement design method, thin surfaced asphalts are designed only for permanent deformation mode of failure with no consideration of fatigue. However, field experience and visual observation showed that significant premature fatigue failure always happen with thin surfaced asphalts. A thorough investigation into the possible causes of this problem reveals that the current Austraods method allows high tolerable deflection values for the design traffic. Thin asphalt surfaces are very sensitive to large deflection values as this will cause the pavement to fail by fatigue after short service life while spray seal treatments such as chip seals surfacing can tolerate larger deflections without major problems. Jameson [2] provided a thorough review of the history and origin of the current Austroads design procedure for granular materials. It was clear from his review that the current tolerable deflection criterion was driven from research undertaken by Scala in the early 1960 [3]. It was also obvious that the tolerable deflection criterion was mainly derived to control pavement rutting with no consideration for fatigue in asphalt layer. Thus, both the current Austroads Mechanistic Empirical design and the empirical method ignore the fatigue mode of failure of the thin asphalt surfacing; therefore, permanent deformation is the only mode of failure that is considered in the design of pavement structure. The main reason for this practice is the difficulty of using the current multilayer analysis to predict tensile strains in the thin surfacing and in fact the analysis might provide compressive strains at the bottom of these layers. In addition, thin surfacing asphalts are more prone to top down fatigue cracking which is not currently considered in the mechanistic analysis. Such complications make the calculations of fatigue in thin surface asphalt using conventional methods impractical. In this research, data from actual thin surfaced asphalts were used to calibrate the current Austroads tolerable deflection criterion. Synthetic data for deflection, compressive strains at the top of the subgrade form 200 pavement sections were analyzed by Circly and used to develop a new subgrade compressive strain criterion.

Tolerable Deflection

In the 1992 Austroads guidelines, two tolerable deflection curves were provided as shown in Fig. 1, Curve 1 was to model rut depth for all types of pavements and curve 2 was intended for asphalt pavements to control fatigue in asphalts overlays [4]. However, in the 2004 and subsequent guidelines, curve 2 was removed while keeping curve 1. Fatigue was controlled in the new guidelines for asphalt overlays by controlling the value of asphalt surface curvature which is defined as difference between the measured deflection under the center of the FWD load and deflection measured at 200mm from the center of the load (D_0-D_{200}). The tolerable deflection given by curve 1 is quite large for thin asphalt

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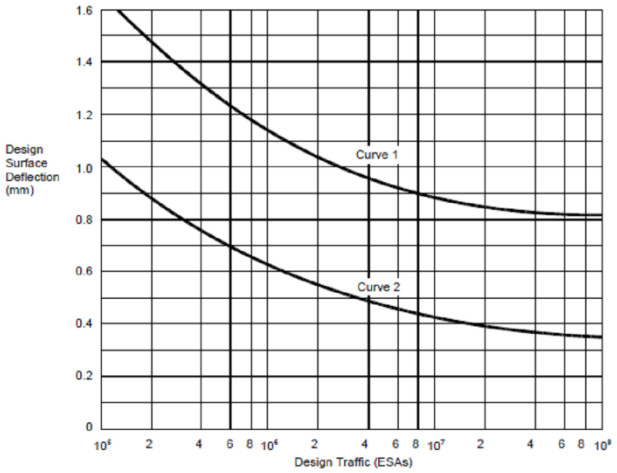

Fig. 1. Austroads Design Deflection Criteria (Austroads, 1992).

surfacing and this explains the reason why thin surfaced asphalts are most commonly prematurely failed by fatigue before any significant rutting is observed.

Calibration of the Austroads Tolerable Deflection Criteria

Field data collected from 30 pavement sections from the North Coast region of Queensland designed with thin asphalt surfacing were investigated. Table 1 shows the data for four thin surfaced asphalt sections from Caloundra road, Queensland, Australia. The collected data included the surface deflection data at the start of pavement life, percentage of heavy vehicles, traffic growth rate, the year of the first rehabilitation since construction, and design age of pavement sections as shown in Table 1. The deflection data was measured by the Department of Transport and Main Roads deflectograph device. For each section, the cumulative traffic expressed in terms of the equivalent standard axle loads (DESA) calculated from the start of construction year or from the year when the first major rehabilitation occurred until the year when fatigue cracking started to manifest in the thin surfaced asphalts. The digital video recording (DVR) images of the pavement surface collected over several years were analyzed to determine the age of the thin surfaced asphalts. The maximum surface defection at the start of pavement life and the cumulative design traffic expressed in equivalent standard axles (ESA) were plotted against Austroads tolerable deflection criterion provided by curve 1 as shown in Fig. 2. The Austroads tolerable deflection shown in curve 1 is significantly overestimated the tolerable deflection of the thin surfaced asphalt pavement and therefore overestimating the design life as shown in Fig. 2. This is expected because this curve was designed to control rutting not fatigue in asphalt pavements. The deflection data of the 30 pavement sections was used to calibrate the current tolerable deflection curve using Eq. (1). Eq. (1) was derived based on minimizing the total error function between measured and predicted tolerable deflection [5]. The calibrated tolerable deflection curve is somehow reasonably close to Curve 2 in Fig. 1.

$$k = \frac{\sum_{i=1}^{n=30} d_i * d_m}{\sum_{i=1}^{n=30} d_i^{\,2}} \quad (1)$$

k = calibration factor
d_i = Austroads tolerable deflection for pavement section i
d_m = field measured deflection for pavement section i
n = number of pavement sections (30 pavement sections in total)

The calibrated tolerable deflection was correlated with cumulative design traffic (DESA) expressed in Equivalent Standard axles as shown by Eq. (2):

$$D_0 = 3.1833 * DESA^{-0.107} \quad (2)$$

D_0= maximum surface deflection in mm
DESA= Design traffic in Equivalent Standard Axles.

New Compressive Strain Criterion

The deflection data for 200 pavement sections were generated using Circly analysis. Circly is a multilayer linear elastic program that can analyze any number of pavements layers, in addition; it also can model isotropic or cross anisotropic properties for rough or smooth

Table 1. Sample of the Thin Surfaced Asphalt Pavement Sections Used in the Calibration Process.

Thin Surfaced Asphalt Pavement Sections from Caloundra Road, Queensland				
Segment Number	1	2	3	4
Station /Chainage (km)	5.4	5.8	6	6.1
Maximum Deflection - 1998	0.34	0.31	0.31	0.35
Maximum Deflection - 2012	0.39	0.43	0.59	0.73
Asphalt Surface Mix Type	DGA (1996)	DGA (1996)	DGA (1996)	DGA (1996)
Surface Age	17.6	17.6	17.6	17.6
Surface Thickness (mm)	40	40	40	40
Pavement Type	Granular	Granular	Granular	Granular
Pavement Construction Year	1996	1996	1996	1996
Grade (Up or Down Hill, or on Flat)	Uphill	Slight Downhill	Downhill	Downhill
Average annual daily traffic (AADT)	29000	28000	28000	28000
% Traffic Growth	1	2	2	2
% Heavy Vehicles	6	4	4	4
Year Cracks First Evident	2010	2010	2009	2009

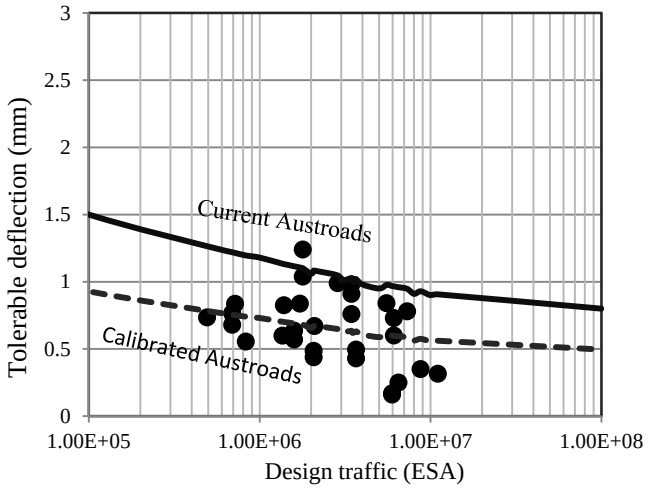

Fig. 2. Austroads Tolerable Deflection Criteria before and after Calibration Utilising Data from 30 thin Asphalt Pavement Sections in Queensland.

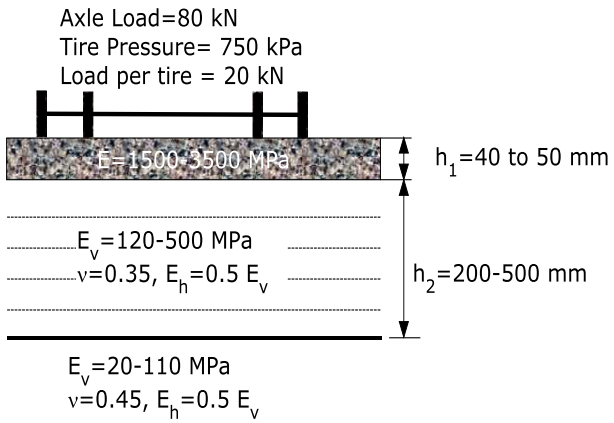

Fig. 3. Circly Modeling for Pavement Structure and Deflectograph Loading

interface [6]. Circly also allows for granular materials to be sublayered accounting for the nonlinear behavior of these materials. The granular base and the subgrade layers were modelled as cross anisotropic while the asphalt layer was modelled as isotropic layer according to the Australian guideline [6]. Asphalt was modeled as an isotropic material with a modulus ranges from 1500 MPa to 3500 MPa. The subgrade and base were modeled as cross anisotropic materials with a range of moduli and thicknesses as shown in Fig. 3. The ratio of the vertical modulus to horizontal modulus which is known as the degree of anisotropy was assumed 2.0 as per Austroads guidelines [1]. The asphalt thickness ranges from 40 to 50 mm to model the common thin surfaced asphalt pavement structures in New Zealand and Australia. The compressive strain at the top of the subgrade and maximum surface deflection were calculated for the 50 pavement sections.

Fig. 4 shows the relationship between the maximum surface deflection and the maximum compressive strain at the top of the subgrade. Eq. (3) shows the relationship between the maximum surface deflection under tire for the standard axle and the maximum compressive strain at the top of the subgrade. Utilizing Eq. (3) and the calibrated tolerable deflection shown in Fig. 2 and presented by Eq. (2), the compressive strain criterion shown in Eq. (4) was derived. Eq. (4) relates the number of equivalent standard axles (ESA) with the compressive strain at the top of the subgrade. By controlling the compressive strain at the top of the subgrade, the maximum surface deflection will be controlled and the total rut depth will also controlled. Fig. 5 shows the relationship between the cumulative design traffic (DESA) and the compressive strain on the top of subgrade. In order to express Eq. (3) in terms of the number of standard axle applications to cause rutting damage, traffic load distributions shown in Fig. 6 was used.

$$D_o = 12751 * \varepsilon_{zz} \quad (3)$$

ε_{zz}= Compressive strain on the top of subgrade
D_0 = maximum surface deflection under the standard axle load

$$N_{ESA} = \left(\frac{24965}{\varepsilon_{zz}} \right)^{9.3469} \quad (4)$$

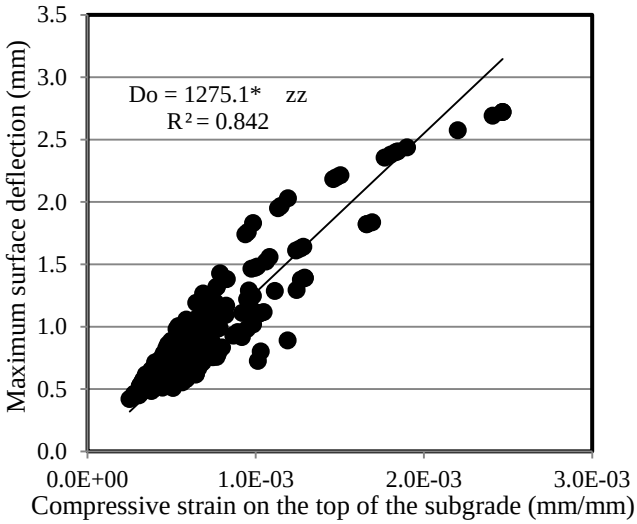

Fig. 4. Relationship between Maximum Surface Deflection and Maximum Compressive Strain on the Top of the Subgrade.

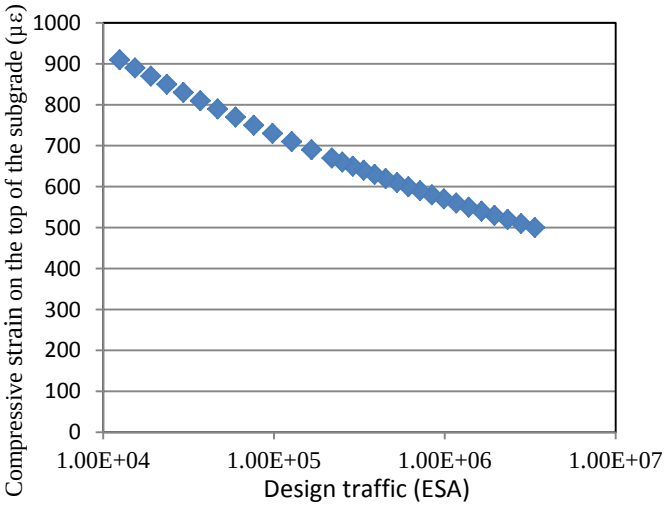

Fig. 5. Relationship between Compressive Strain on the Top of the Subgrade and Cumulative Design Traffic in Terms of Equivalent Standard Axles.

where,
N_{ESA} = Number of equivalent standard axle loads based on pavement overall damage
ε_{zz} = Compressive strain on the top of the subgrade.

Load Damage Factors

In order to relate the number of equivalent standard axles (ESAs) calculated based on overall damage which uses the fourth power law (i.e exponent 4) and the number of standard axle repetitions to cause certain type of damage, traffic load distributions data collected from weigh in motion located in Yandina station at Queensland was used. Fig. 6 shows the traffic load distributions collected in 2008 using Yandina Weigh in Motion station data. Similar data for 2008, 2009 and 2013 for different lanes on Bruce Highway, Queensland were used to develop damage factors. Fig. 6 show the axle load distributions for six heavy axle configurations: Single Axle Single Tire (SAST), Single Axle with Dual Tire (SADT), Tandem Axle with Single Tire (TAST), Tandem Axle with Dual Tire (TADT), Tridem Axle with Dual Tire (TRDT) and Quad Axle with Dual Tire (QADT). These six axle loads configurations are the most common heavy axles trafficking Australian highway network. Table 2 shows the average and 97.5% damage factors developed for rural areas in Queensland based on Weigh in Motion data. The exponent 9.35 as shown in Eq. (4) was used to determine the ratio between the number of standard axle repetition SARs and the number of equivalent standard axle as shown in table 2. The details of the damage factors calculations to convert traffic loading expressed in terms of Equivalent Standard Axles (DESA) to standard axle repetitions for specific type of failure (i.e. rutting or fatigue for asphalts or cement stabilized materials) are fully detailed in Austroads guidelines [1].

$$N_f = \frac{SAR_s}{ESA} * N_{ESA} \quad (5)$$

Using Eq. (5) and a damage factor for (SARs/ESA) of 6.8 as shown in Table 2, Eq. (6) was developed.

$$N_f = \left(\frac{3065}{\varepsilon_{zz}}\right)^{9.3469} \quad (6)$$

Fig. 7 shows the compressive strain criterion developed based on maximum tolerable surface deflection shown in Fig. 2. By using Eq. (6), the maximum surface deflection under the standard axle will be less than or equal the design calibrated tolerable deflection shown in Fig. 2. It should be noted that the main purpose is design the pavement structure that result in maximum surface deflection to be within the tolerable limit given by Eq. (2). Therefore, the designer might need to do some few trails and check the total surface deflection for each trail. Programming the new strain criterion in Circly software will help reducing the number of trails required to achieve the required tolerable deflection. By limiting the deflection of the asphalt surfaces, this will ensure that these surfaces will not prematurely fail by fatigue. Using subgrade strain criterion given by Eq. (6) will yield thicker and stiffer granular bases than that designed by the current Austroads. In this case, designers might need to use cement stabilized bases with stress absorbing membrane

Table 2. Damage Factors Based on Weigh in Motion Traffic Load Distributions.

Year	2008		2009			2013		Average	Standard Deviation	97.50%
Lane Number	L2	L3	L1	L2	L3	L1	L3			
SARs/HVAG	4.7	2.1	4	4.2	2.1	1.7	0.7	2.8	1.5	5.8
ESA/HVAG	0.9	0.6	0.8	0.9	0.6	0.7	0.5	0.7	0.2	1.1
SARs/ESA	5.1	3.6	4.9	4.7	3.7	2.5	1.5	4.1	1.3	6.8

SARs= Standard axle repetitions to cause rutting failure
HVAG= Heavy vehicle axle group.
ESA= Equivalent standard axle load based on overall damage

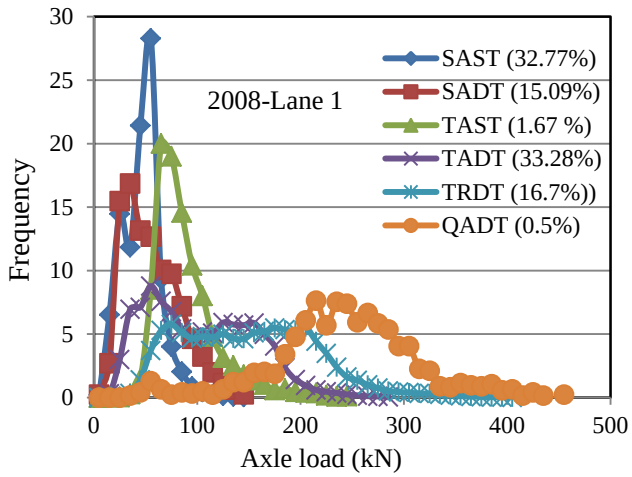

Fig. 6. Weigh in Motion Survey for Axle Load Distributions for Bruce Highway, Queensland, Australia.

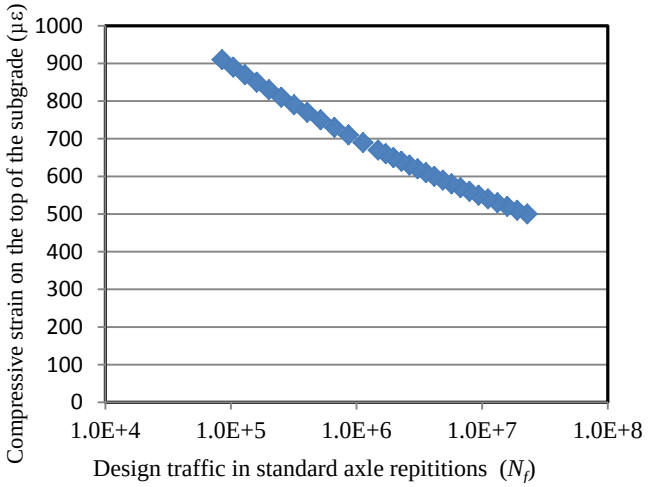

Fig. 7. Relationship between Compressive Strain on the Top of the Subgrade and Design Traffic in Terms of Standard Axle Repetitions.

interlayer or 100 to 150 mm granular base over the cement stabilized base to ease the reflection cracks that might develop in the cement stabilized base or use foam bitumen stabilized bases to provide the necessary stiffness to reduce the total surface deflection to be within the design tolerable deflection.

Case Study

In order to compare the modified design criteria and currently used Austroads design guidelines, this case study of thin surfaced asphalt pavement design is discussed here.

A thin asphalt pavement of thickness 50 mm made of dense graded asphalt of 10 mm maximum nominal size and stiffness modulus of 3000 MPa is required to be constructed on subgrade of resilient modulus of 50 MPa. For a base granular material with resilient modulus of 500 MPa, the thicknesses of the base is required to carry cumulative design traffic of 10^7 ESA.

Design According to the Current Austroads

Design Based on Austroads Empirical Chart

Using the current Austroads Empirical chart, a total depth of the unbound granular materials required is 500 mm which can be subdivided into 170 mm base and 330 mm subbase [1]. The empirical chart does not specify the mechanical properties of the base and subbase materials, however, it is expected that the materials are required to satisfy the minimum standard required by Austroads specifications.

Design Based on Austroads Mechanistic Empirical Design

According to the current Austroads Mechanistic Empirical design, the pavement will be designed for rutting mode only according to the subgrade compressive strain criterion shown in Eq. (7) [1]. The granular and subgrade materials will be modeled as cross anisotropic materials. Fig. 8 shows the proposed design. The compressive strain at the top of the subgrade, cumulative damage factor and the maximum surface deflection will be as follows.

$$N_f = \left(\frac{9300}{\varepsilon_{zz}}\right)^7 \tag{7}$$

Maximum surface deflection = 1128 µm

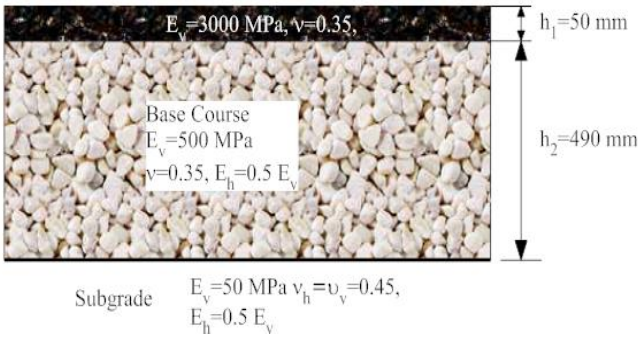

Fig. 8. The Design According to the Current Austroads M.E.

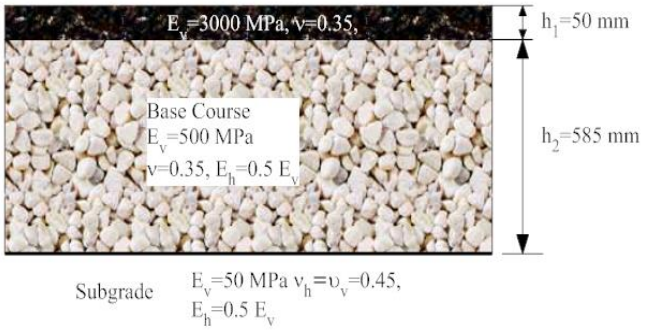

Fig. 9. Alternative Design According to Modified Subgrade Criterion.

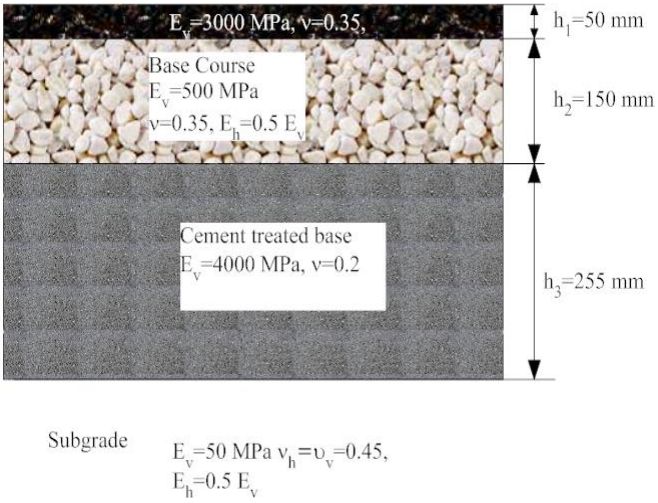

Fig. 10. Alternative Design Using Cement Treated Base According to Modified Subgrade Criterion.

Maximum compressive strain at the top of the subgrade (ε_{zz}) = 863.3 µε

$N_f = 1.6836*10^7$

Cumulative damage factor (CDF) = 0.95 < 1

According to Eq. (2), the maximum tolerable deflection should not exceed 567.4 µm. It is obvious that the current Austroads almost double the deflection which is likely to cause premature fatigue failure for the thin surfaced asphalt.

To compare the modified design according to the new subgrade criterion given by Eq. (6), two alternative designs are proposed as shown in Figs. 9 and 10 and detailed designs are discussed below.

Modified Design: Alternative 1

By programming the new subgrade design criterion given Eq. (6) in Circly software, the thickness for the base course will increase from 490 to 585 mm (an increase of 19.4%) as shown in Fig. 9. The pavement response to the standard axle (i.e maximum surface deflection and maximum compressive strain at the top of the subgrade) is as shown below.

Maximum surface deflection = 792.4 µm

Maximum compressive strain at the top of the subgrade (ε_{zz}) = 441.3 µε

Table 3. Summary of the Current Austroads Guidelinedesign and the New Modified Design Atemative.

Design Options	Asphalt Thickness (mm)	Base Thickness (mm)	CTB Base Thickness (mm)	Surface Deflection (μm)	Compressive Strain on top of the Subgrade (με)
Current Austroads Design	50	500	0	840.5	556
Modified Design 1	50	585	0	792.4	441.3
Modified Design 2	50	150	255	565.9	198.6

$$N_f = \left(\frac{3065}{441.3}\right)^{9.3469} = 7.3664*10^7$$

$$CDF = \frac{6.8*DESA}{N_f} = \frac{6.8*10^7}{7.3664*10^7} = 0.923<1$$

Modified Design: Alternative 2

In this design, cement treated base is used to reduce the surface deflection together with granular unbound base course as shown in Fig. 10.

Maximum surface deflection = 565.9 μm

Maximum tensile strain at the bottom of cement stabilized layer (ε_{yy}) = 70.21 με

Maximum compressive strain at the top of the subgrade (ε_{zz}) = 198.6 με

Cement stabilized layer is designed for fatigue according to the following model shown by Eq. (8)

$$N_f = \left(\frac{\frac{113000}{E^{0.804}}+191}{\mu\varepsilon}\right)^{12} \quad (8)$$

$N_f = 1.3704*10^8$

$$CDF = \frac{12*DESA}{N_f} = \frac{12*10^7}{1.3704*10^8} = 0.876$$

For subgrade Rutting using modified subgrade criterion Eq. (6)

$$N_f = \left(\frac{3065}{198.6}\right)^{9.3469} = 1.2833*10^{11}$$

$$CDF = \frac{6.8*DESA}{N_f} = \frac{6.8*10^7}{1.2833*10^{11}} = 5.2988*10^{-4}<1$$

Table 3 shows summary of the current Austroads design compared to modified design alternatives. The maximum surface deflection for the modified design is less than the current Austroads design. Therefore, it is expected that the asphalt fatigue for the modified design will be much less and it will likely last the design period.

Conclusions

In this research paper, a new tolerable deflection criterion was developed based on calibrating the current Austroads tolerable deflection criterion. Deflection and traffic data for 30 pavement sections from Queensland were used to develop the calibration factor of the tolerable deflection criterion. Maximum deflection and maximum compressive strain generated using Circly software for 200 pavement sections were used to develop new compressive strain criterion. Weigh in Motion data collected over three years were used to developed damage factors to relate Equivalent Standard Axles to the Standard Axle Repetitions for rutting damage. A new subgrade criterion was developed to control the maximum surface deflection to be within the design tolerable deflection. By controlling the maximum surface deflection for thin surfaced asphalt pavements, the fatigue life of these pavements is expected to last the design period and will limit the risk of premature fatigue cracking. A case study for the effect of the new criterion on the resulted design showed that the new criterion will require a thicker or stiffer pavement to reduce the maximum surface deflection. In this case, the designer can choose between stabilized base course to achieve the high stiffness or use a thick base course of high quality gravel.

Acknowledgement

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