ASPHALT PAVEMENT SOLUTIONS – FOR LIFE

IMPLEMENTATION PROJECT UPDATE

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INTRODUCTION

At the 13th AAPA International Conference (2009) the author identified the need to implement test methods that would allow us to compare Australian and International asphalt materials characteristics and so facilitate access to their substantial Long Term Pavement Performance (LTPP) studies. This message was reinforced at the 24th ARRB Conference in a paper by the author and Peter Armstrong. We highlighted the essential requirement that the design models be calibrated by correlation against LTPP and discussed the results of our investigations locally. We concluded, from the limited results from AAPA's LTPP study despite an enormous effort, that Australia lacks the resources to adequately achieve design model verification in a meaningful timeframe, and that alliance with international researchers was essential.

To their great credit the Australian asphalt industry has taken heed of the opportunity to enhance the design of long life asphalt pavements and has commissioned the 'Asphalt Pavement Solutions – For Life' project and provided substantial resources to ensure its success.

This paper briefly reviews the literature that sustains the Long Life Asphalt Pavement (LLAP) concept including information gleaned in the course of the AAPA study Tour in 2010. The paper describes the program of work to characterise the performance of production samples of asphalt used on major projects around Australia using the Asphalt Materials Performance Tester (AMPT) from which the dynamic modulus master curve, and the elastic and viscous components over the full spectrum of temperature and load frequency is determined. This will be complemented by the characterisation of the bitumen and mastic components of the mixes using the Dynamic Shear Rheometer (DSR). Procedures for new pavement thickness design software, utilising the entire design temperature and load frequency spectrum, have been proposed. The procedure will calculate the cumulative distribution of the tensile strain in the asphalt under load that has promise to provide a more relevant limiting criteria.

To ensure buy-in the project combines the resources of industry, ARRB TR and academia. The project will be conducted with the full knowledge of Austroads. International alliances have been formed to facilitate the verification of our testing procedures and to establish the relative performance of local and international asphalt materials. Once established this will enable us to make direct comparisons with major LTPP studies to validate the LLAP design process.

OBJECTIVES OF THE ASPHALT PAVEMENT SOLUTIONS – FOR LIFE (ASP-FL) PROJECT

The objective of the APS-FL project is to improve the effective deployment of Long Life Asphalt Pavement[1] (LLAP) structures within Australian highway construction practice.

To facilitate this goal a number of essential research tasks must be concluded and these are outlined in following sections. The product of the research will be a summary of international LLAP performance history and practice; dedicated Layered Elastic Analysis (CIRCLY LEA) based software for LLAP thickness design; documented guidelines for the determination of inputs into design of LLAP structures and the procedures for validation against LTPP . Most importantly, recommendations for the high quality construction standards demanded for LLAP's will be provided.

APS-FL PROJECT ACTIVITIES

The APS-FL project comprises a number of research activities which are then, in following sections, described in detail together with the rationale behind them.

- Literature review
- National asphalt materials characterisation study
- LLAP thickness design software development
- Validation of LLAP thickness design by LTPP studies
- Environment and sustainability

LITERATURE REVIEW – SUMMARY OF PERTINENT FINDINGS

Definition of LLAP

The literature[2] particularly from European studies provides a rational means to define the LLAP. It is evident from sequential pavement deflection measurements over many years[3] that in the LLAP the deflection decreases over time indicating an increase in the stiffness of the LLAP. This defining characteristic will enable the identification and selection of LLAP's which will be subjected to analyses in the APS-FL validation activities to calibrate design models.

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[1] The terms 'Long Life Asphalt Pavement' and 'Perpetual Pavement' are used interchangeably in the literature. The general acceptance of the asphalt fatigue endurance limit i.e. below which fatigue damage does not occur, suggests there is some scientific substance to the perpetual descriptor albeit in the asphalt foundation layers only.

[2] Includes the seminal work by Mike Nunn and more recent VALMON study in the UK; the product of the European Long Life Pavement Assessment Group ELLPAG and various member countries

3 Nunn quotes German BASt experience of 170 sites over 23 years

LLAP cracking – identification of source

It is extremely difficult if not impossible to determine the source of cracking from a superficial examination. The literature consistently reports cracking initiating at the surface and migrating downward. It is considered likely that this is generally an environmental and perhaps construction related issue not associated with the structural design of the LLAP.

It is postulated that visible cracking does not necessarily repudiate LLAP status provided the deflection history is static or reducing.

LLAP threshold thickness

Nunn's work has led to the development of the UK Highways Agency thickness design chart. The chart shows the design thickness of asphalt increases with design traffic up to 80 MSA (Million Standard Axles) and then asymptotes[4]. This is based on the UK empirical evidence that asphalt pavements that survive 80 MSA exhibit LLAP performance and deflection history.

It is postulated that the threshold thickness is required in order to limit strain under traffic loadings on the new pavement. The LLAP is in its weakest state early in the life, and the thickness design must ensure adequate thickness (the threshold thickness) such that cracking does not initiate and propagate. Relative to Australian conditions the rate of traffic loading is considerably greater in the UK because of their 11.5t c/f 9.5t legal axle loading. The heavier mass and generally higher loading frequency in the UK and other European countries will result in the typical asphalt strain distribution being higher, relative to Australia, under similar traffic speed and temperature conditions. However this will be, to an extent to be established, offset by the higher pavement temperature regimes in Australia which will result in higher asphalt strain under load.

It is postulated that this factor confirms the potential for validation and calibration of the Australian LLAP design process by the study of LTPP section in the USA and Europe. It cannot reasonably be concluded that our hotter climatic conditions render comparisons unreliable.

Asphalt cracking and the fatigue endurance limit

The concept of the asphalt fatigue endurance limit was postulated in the early '70's by Carl Monismith and his workers from observations of laboratory flexure testing. Considerable research has continued since that time and while there is widespread acceptance of the laboratory fatigue endurance limit concept its implementation into the LLAP design is not yet commonplace.

[4] The thickness design chart assumes a standard foundation of unbound granular base on a subgrade CBR > 5 or with an added thickness of prescribed capping layer if CBR < 5. A number of thickness design curves are shown in the UK Highways Agency design chart based on a statistical compliance with the asphalt modulus used in thickness design.

Asphalt cracking is a complex phenomenon and is comprehensively described by Roque[5]. In regard to asphalt fatigue – the critical asphalt pavement thickness design parameter - he cites extensive research that finds large and variable shift factors to achieve correlation between laboratory[6] and field fatigue performance, and trend reversals i.e. good in the laboratory is worse in the field, and aged materials giving better performance than unaged.

It is postulated that ensuring the LLAP is not subjected to extreme but undefined strain levels is the only broad conclusion that can be drawn to avoid the classical bottom-up fatigue cracking. The trend reversals noted above suggests there are other factors at play in the fatigue resistance of the LLAP structure.

Notwithstanding the wide acceptance of the fatigue endurance limit concept its introduction into LLAP thickness design is problematic and the subject of a major US study under NCHRP project 09-44[7]. One of the key issues under research is the healing of micro-cracks and restriction of fatigue crack propagation from the bottom of the asphalt base.

Healing of asphalt micro-cracks

In the ISAP presentation Roque cited a number of researchers (including Shell researchers many decades past) who have observed the healing phenomenon that occurs when rest periods are introduced into the loading cycles in the laboratory. He reports the observations that the rate of healing increases with temperature and the duration of rest periods thus it is reasonable to conclude it is probable, under otherwise similar conditions, that the healing of micro-cracks in the warmer Australian pavement environment will be greater relative to colder climes e.g. much of the USA, UK and Europe.

Sophisticated methods have been proposed in NCHRP Project 9-44 by which the healing phenomenon can be incorporated into designs. At this stage however we are not aware of substantive quantification of the healing phenomenon in the field and the effect on performance. In the warmer parts of Australia the Shell based predictive method in Austroads[8] produces low stiffness estimates for the asphalt structure and analysis indicates relatively high estimates of the magnitude of strain in the LLAP.

Current asphalt thickness design ignores healing and as a consequence detailed analysis suggests the traffic applied at high pavement temperature does a disproportionately greater amount of fatigue damage because of the high strain levels. An example of the application of the proposed healing model in Project 9-44 concludes that the traffic in the high end of the temperature spectrum causes relatively less damage than mid-range due to the healing effect. It is also apparent that at low temperature the high asphalt stiffness/reduced strain more than offsets the reduced healing.

[5] Rey Roque, keynote address to the 2010 ISAP Conference in Quebec.
[6] The asphalt beam fatigue test is still under international scrutiny after more than 50 years. It is the dedicated topic of an International Conference and the 3rd in the series is to be held at U California at Davis in September 2012
[7] NCHRP project 09-44; HMA Endurance Limit Validation Study – Research Plan
[8] The Shell method states the predictive method is not valid at higher temperature where the stiffness of the bitumen is < 5MPa i.e. $\approx 35^{\circ}C$

Empirically determined limiting cumulative distribution of asphalt strain

Research conducted at the NCAT test track includes (among other) constant monitoring of the pavement temperature and strain versus load applications, and regular deflection testing[9]. For each test section data analysis is conducted and the cumulative distribution of the measured strain over the full spectrum of load repetitions is plotted. As is logically to be expected the recorded strain increases with temperature as the asphalt stiffness reduces in the diurnal and seasonal cycles.

The comparison of the field performance and the cumulative distribution of strain for each test section suggest the existence of a limiting cumulative distribution of strain to avoid asphalt fatigue cracking. NCAT have published a tentative limiting cumulative distribution of asphalt strain to avoid cracking but observe that the traffic level was in the order of 20 MSA, much less than common design values for traffic loading on LLAP's[10].

Notwithstanding it is postulated that the concept of LLAP thickness design based on compliance with a limiting cumulative distribution of asphalt strain has considerable merit. It has the potential to avoid the acknowledged uncertainty in theoretical fatigue modeling and constrain management of asphalt fatigue and durability to satisfying compliance hurdles[11].

It provides a basis for the analyses of LLAP field sections to validate and calibrate the models. The interim process is described in later sections. This is considered to be probably the most valuable application of the concept as it is believed to provide a relatively simple albeit pertinent means of validating a rational design method avoiding the great uncertainty inherent in asphalt fatigue modeling.

The dynamic modulus to determine asphalt materials performance characterisation

The dynamic modulus E* master curve has international acceptance as a discriminatory asphalt performance measure. From the large US study detailed in NCHRP Report 465 Witzcak concluded the dynamic modulus E* and creep properties (flow number or flow time) best correlated with field performance observations on major US field trials (Westrack, MnRoad and FHWA ALF) leading to the development and implementation of the Asphalt Materials Performance Tester (AMPT)[12] .

The ability to calculate the E* modulus of asphalt at any prescribed design speed or load frequency over the anticipated operating temperature spectrum offers a substantial improvement on current models derived from standard laboratory tests at a single temperature and frequency and applied at an estimated weighted mean annual pavement temperature.

[9] These data will be used in the validation phase of NCHRP Project 9-44

[10] It is noted the traffic was applied while the pavement was new and consequently the rate of damage may be increased relative to some field conditions

[11] The method adopted by the French is considered appropriate i.e. the prescription of bitumen coating requirements and fatigue hurdles e.g. laboratory fatigue life > 10^6 repetitions at 100$\mu\varepsilon$ under standard test conditions (20^{o}C; 10 Hz)

[12] To enable the construction of the dynamic modulus master curve asphalt cylinders are (generally) subjected in the AMPT to cyclical axial compression cycles; generally 4 temperature conditions apply, and at each the sample is subjected to loading at 6 frequencies. Testing at higher temperatures is conducted with a range of confining stress. The test data is shifted using the time temperature superposition principles to construct the master curve.

The E* master curve of different asphalt materials enables rational performance comparisons to be made. A most significant implication and benefit of this is the ability to rationally and quantitatively calibrate the performance our asphalt materials against the asphalt materials that are used in the historical LLAP sections constructed and monitored in the US and Europe. The E* master curve will enable the structural analysis of the performing LLAP sections and the determination of the cumulative distribution of asphalt strain for each. By the statistical processing of this data a reliable limiting cumulative distribution of strain may be determined.

In the structural design of LLAP's the E* master curve will enable the determination of the cumulative distribution of asphalt strain in candidate LLAP structures as a function of the climatic conditions pertinent to the particular site and the traffic distribution spectrum (e.g. uniform, afternoon or morning peak, or overnight). This provides the means to rationally evaluate the compliance of candidate LLAP structures with the limiting cumulative strain distribution empirically derived from the evaluation of international LLAP's.

Cumulative distribution of strain as a function of varying load groups and mass

Clearly the cumulative distribution of asphalt strain will vary with the applied axle groups (e.g. single, tandem and triaxle) and load mass. In Australian practice the diversity of loading is reduced to repetitions of the standard 80kN axle based on the premise that equal damage is inflicted by diverse axle group provided they produce equal maximum deflection. To test the 'equivalency' the notional equivalent axle group loadings[13] have been modeled using simple elastic layered analysis. Analysis of a candidate thick asphalt (275mm) pavement which would, based on empirical evidence, provide LLAP performance shows this approach is conservative.

The relative fatigue damage of the other axle groups are shown to vary between about 30% and 100% of the 80kN standard axle[14]. The analysis of the output is confounded by changes in orientation of the critical strain – typically it is longitudinal but it is transverse under triaxle groups. On the premise that the magnitude of the stress/strain reversal between load pulses is an important contributor to damage it is observed the amplitude of the strain pulse between multiple axles is much greater in the longitudinal than the transverse direction.

To put the diversity of loading into perspective is it suggested that most agencies in the US and Europe generally police axle limits. It is anticipated overloading (the worst load case) is generally controlled such that 10% of heavy vehicles exceeding axle group limits by 10% would be a conservative estimate. In a LLAP the 10% overloading would equate to an increase in strain by approximately the same proportion and, based on elastic layer modeling, would generally be far less than the damage assumed in the axle load equivalencies calculated in the previous exercise.

[13] The equivalent load on single steer axle; tandem axle dual and triaxle dual is 53; 135 and 181kN respectively.

[14] The equivalent single steer axle about 0.3; the tandem dual about 0.6 to 0.8 and the tridem dual about 0.8 to 1

It is calculated that the variation in the cumulative strain distribution as a consequence of the pavement temperature / stiffness spectrum[15] would far outweigh the variation between the actual and the standard axle spectrum. Accordingly it is postulated that subsequent analyses of LLAP sections to estimate the cumulative distribution of strain may be based on estimates of the spectrum of standard axle repetitions versus temperature. Load repetitions will be determined in terms of the applicable standard axle load which is related to their legal limits e.g. France 130kN; Germany and many other European countries 100kN, and UK 80kN (albeit the legal axle limit is 11.5t). It is concluded there is no significant benefit in doing a detailed LLAP performance analysis using the complex distribution of axle mass (even if it were available). The proposed methodology is detailed in a subsequent section.

Pavement temperature spectrum

The considerable research by Dr Dickenson (ARRB) in the 70's on the subject of pavement temperature regimes in Australia highlighted the complexity of the elements contributing to the pavement temperature and gradient. Unfortunately much of the source data from this research is lost.

Recently CSIR published research in South Africa[16] offers a promising set of solutions to the estimation of pavement temperature regimes in asphalt which has had empirical validation in the Southern hemisphere.

We may have to rely on US research to determine the relationship between ambient and pavement temperature regimes for the analyses of LLAP sections in the northern hemisphere. Certainly the NCAT instrumentation of their test sections has provided data from which pavement temperature regimes can be determined and related to ambient temperatures. It is noted the climate in Alabama is similar to the lower East coast of Australia[17] and this could assist the verification of the South African model. Further research is required to identify pavement temperature and climatic regimes in the European LLAP sections.

It is postulated that the conservatism in the estimation of the standard axle repetitions used in the estimation of the cumulative strain distribution will more than offset any inaccuracies in the estimation of the relevant pavement temperature spectrum.

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[15] For example the strain induced by the standard axle in a 275mm thick asphalt with a mid-layer temperature range of 6^{o} to 54^{o}C would exhibit a range of strain from about 30 to 150$\mu\varepsilon$ – a five-fold increase.

[16] E Denneman, CSIR Pretoria, South Africa

[17] Average maxima and minima in Alabama near NCAT site; Summer 32/22^{o}C; Winter 13/4^{o}C

NATIONAL ASPHALT MATERIALS CHARACTERISATION STUDY

The purpose of the asphalt materials characterization component of the Asphalt Pavement Solutions – For Life (APS-FL) project is to provide hard data on the performance characteristics of Australian asphalt materials. Consistent with the directions being taken internationally dynamic modulus E* master curves will be generated[18] in order to enable the derivation of mix modulus and visco-elastic properties across the spectrum of temperature and load frequency pertinent to Australian field conditions. Additionally the complex shear modulus G* master curve will be generated[19] for the bitumen and bitumen mastic component of the mixes.

There are two main objectives for the materials characterization component of the APS-FL project:

- The material properties will be used in CIRCLY layered elastic design analyses to determine the cumulative distribution of asphalt strain over the pavement temperature and loading spectrum
- The material properties will be compared with materials manufactured in the US and Europe to confirm similar performance thus the transferability of their research. This will facilitate the adoption and implementation of the findings of their Long Term Pavement Performance (LTPP) projects[20]

Experimental Design

The performance characteristics of asphalt are primarily influenced by the following key factors:

- Mix size and gradation
- Bitumen type and content
- Aggregate type and proportions
- Air void content

The study will focus on the standard asphalt materials produced by Australia's major asphalt producers for use in major projects where the LLAP concept is most likely to be implemented. Approximately 30 mixes have been identified for the study and will cover the spectrum of aggregate types and non-modified Australian bitumen (Classes 320; 450; 600 and Multigrade).

[18] Using the Asphalt Materials Performance Tester (AMPT)

[19] Using the Dynamic Shear Rheometer (DSR). G* is considered the parameter that provides the superior performance of the Hirsch E* prediction model.

[20] The results of the major AAPA LTPP over the decade 1998 – 2008 project graphically demonstrated the enormous resource demand required to successfully complete LTPP projects. It was concluded that alliance with overseas research agencies was essential if the design improvements were to be realized in a meaningful timeframe (refer Rickards and Armstrong; ARRB TR Conference 2010)

In order to constrain the size of the experimental design the following recommendations were made for the reasons stated:

- Adopt 4% air voids in samples; 4% air voids are to be the specified compliance target for the asphalt base layer in LLAP construction contracts
- In states where multiple suppliers use common aggregate types select a single supplier for mix samples, provided each supplier manufactures to a similar gradation and aggregate composition; the gradation has a significant effect on modulus as does the quantity shape and texture of the fine components

Sample Manufacture & Testing Capability

There are limited resources in Australia capable of conducting the proposed characterization project work. Principal among them is the Fulton Hogan central research laboratory in Sydney which has considerable experience in sample manufacture using the shear box compactor, and E* testing using the AMPT.

The ARRB TR bitumen laboratory has been approached to carry out the bitumen and bitumen mastic characterisation using the DSR (Dynamic Shear Rheometer). All binder and mastic combinations from the asphalt mixes will be subjected to DSR testing.

Asphalt sample manufacture

Asphalt samples will be taken from plant production, cooled and delivered to the laboratory. After reheating the mix samples will be compacted in the shear box compactor. Some repeats are sometimes required to quantify the effect of boundary conditions (mix texture) on sample density. When the required sample mass is determined 4 asphalt sample prisms[21] will be manufactured – one to be cored for AMPT testing (i.e. 3 by 100 x 150mm cylinders); one for possible fatigue testing; and two held in reserve for correlation studies with overseas agencies and for unexpected issues.

The US generally uses the Superpave Gyratory Compactor (SGC) for sample compaction and it is to be expected that the AMPT results on samples manufactured using this mode of compaction may vary relative to shear box compacted samples. A small subset of mixes will therefore be tested after compaction in the Servopac gyratory compactor which is believed to replicate the SGC and the scale of any variation recorded.

Under normal circumstances the AMPT dynamic modulus test inflicts little damage on the samples except at high temperature, slow loading frequencies which are conducted last. Accordingly these samples may be sent overseas for correlation studies to limit the number of variables. Alternatively or as well additional cores can be cut from the surplus prisms.

Any remnant of each of the uncompacted mix materials will be retained in their original drums for possible future examination.

[21] The dimension of each shear box compactor prism is 450 x 150 x 180 to 200mm (L x W x D)

The asphalt sample prisms will be cored to produce 3 cylinders and the density of the trimmed samples will be calculated and tested for consistency and conformity with the target voids. Only 2 of the 3 cylindrical samples are to be tested in the AMPT.

Sample test conditions

The asphalt samples will be tested in the AMPT at 4 temperatures (5; 20; 35 & 50^{o}C); 6 load frequencies (0.1; 0.5; 1; 5; 10 & 25 Hz); and at 4 confinement pressures (nil; 50; 100 and 200 kPa) when tested at 35 and 50^{o}C. The generation of the E* master curve to cover the spectrum of the pavement temperature and load frequency conditions pertinent to Australian conditions is derived using this data.

The DSR testing will be carried out at temperatures of between 20 & 60^{o}C in 5^{o}C increments; at 11 frequencies varying between 0.1 & 10 Hz; and the complex shear modulus (G*) master curves generated[22]. The DSR testing will be completed on both the bitumen and bitumen mastic i.e. bitumen plus filler at the relevant mix filler/bitumen ratio. Regression analyses will be conducted to evaluate the potential improvement in the asphalt stiffness prediction models using the mastic properties rather than just the bitumen.

Future Work

The effective stiffness of the conventional asphalt mixes measured over a typical range of pavement temperature and load frequency will be used in CIRCLY modeling of a number of perpetual pavement configurations, to estimate the probable cumulative distribution of the asphalt tensile strain. The calculated distribution will then be compared with the interim tolerable cumulative distribution of strain determined at the NCAT test site[23].

The laboratory characteristics of the Australian materials will be compared with the laboratory characteristics of asphalt materials used in overseas studies. This will require the assistance of overseas research agencies – firstly to gain access to their data, and ultimately to engage selected agencies to duplicate some of the Australian testing to verify the accuracy of the testing.

On confirmation that our test results show good correlation it is then reasonable to conclude that the performance of the asphalt materials with similar laboratory performance will, in a comparable environment, perform in a similar manner in the field. It is then legitimate to conclude that the findings from the overseas LTPP studies are relevant in Australia. This is the only practical method by which we can validate the limiting performance criterion in our LLAP thickness design method.

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[22] The complex shear modulus (G*) parameter is used in the Hirsch asphalt E* dynamic modulus predictive model which has been shown to exhibit the best correlation with laboratory measurement

[23] Refer presentations of Timm and Tran in the AAPA study tour records

LLAP THICKNESS DESIGN SOFTWARE DEVELOPMENT

The project objective is the development of Perpetual Pavement design software based on the layered elastic program CIRCLY which is currently adopted in Austroads Pavement Design Guide (APDG).

The proposed modifications to the current APDG method, specifically for LLAP design are;

- The use of asphalt materials characteristics derived by laboratory measurement that cover the spectrum of temperature and load frequency anticipated for specific LLAP project locations[24]
- The use of traffic loading data to represent the distribution of loads over the pavement temperature spectrum
- Calculate the cumulative distribution of the asphalt strain under the design 80 kN standard axle loading over the site temperature spectrum
- Compare with the interim limiting cumulative asphalt strain distribution (to be validated against LTPP studies of LLAP's) to ensure compliance

Background

This section recaps on many issues discussed previously to bring the process together. Conventional Mechanistic-Empirical (ME) design theory for flexible pavements is based on the principal that repeated flexure of the asphalt under loading induces repeated tensile strains which ultimately result in asphalt fatigue failure. The objective of the design process is then to ensure that the magnitude of the tensile strain is limited, according to theoretical damage relationships, in order to control fatigue cracking.

This convention has endured and been the subject of international research over decades, none of which has produced categorical damage relationships between the stress/strain conditions in asphalt and fatigue damage. The reasons for this are numerous – the disparity between laboratory and field conditions; the complexity of the pavement structure and the environment in which it operates; innate material variability and the effect of construction.

In the Austroads (Shell) asphalt fatigue relationship fatigue life is a function of the volumetric properties of the mix, its stiffness and the magnitude of tensile strain. As stated previously an anomalous situation arises when detailed design analyses are carried out over the pavement temperature spectrum rather than wMAPT. It is found that the repetitions of load at high temperature conditions induces (in theory) significantly disproportionate damage. At high pavement temperatures the asphalt stiffness significantly reduces and the tensile strain magnitude increases so, according to the model, increasing fatigue damage. Particularly in thick asphalt structures the ME model does not reasonably portray the conditions at high pavement temperature in two primary aspects:

[24] The current APDG method uses a simplifying approach in which the full spectrum of pavement temperature is, for the calculation of critical strain values, reduced to a single temperature i.e. the weighted Mean Annual Pavement Temperature (wMAPT)

- The loss of stiffness in the asphalt model is overestimated as it largely ignores the effect of the aggregate skeleton in the compression zone in the pavement and the confining stress of the pavement
- The healing of micro-cracks which halts crack propagation

The research[25] has established the concept of the Fatigue Endurance Limit (FEL) in asphalt i.e. if the asphalt strain magnitude is constrained at a low level then repeated flexure does not cause fatigue damage. This certainly holds true in laboratory testing and various researchers have prescribed limiting FEL strain conditions. Notwithstanding implementing the FEL in pavement design is not straight forward because of the translation of the laboratory conditions to the field.

The data emanating from the NCAT[26] full scale test pavement shows the spread of measured asphalt strain magnitude as a function of pavement temperature variation – diurnally and seasonally. This leads to the logical conclusion that in real life the proposition of a single FEL value for design purposes is fraught. The data indicates that in real life the pavement design process should constrain the asphalt strain distribution as illustrated in the following Figure 1 extracted from NCAT presentations.

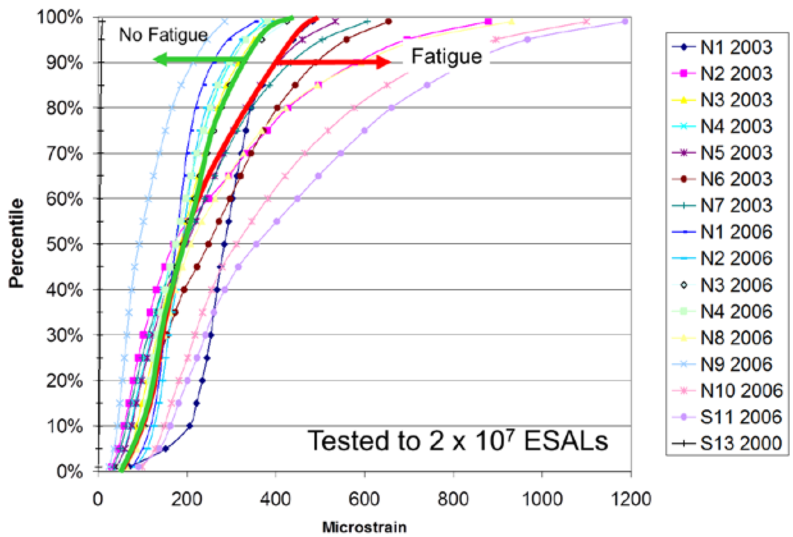

Figure 1. NCAT field test data; distribution of asphalt strain over > 1 year testing and observed condition

This suggests a valuable guide to an improved asphalt pavement thickness design approach. It will utilize the enhanced asphalt materials characterization (AMPT) to provide asphalt stiffness properties over the design loading and temperature spectrum, and enable the calculation of the cumulative distribution of asphalt strain generated under the standard axle load. To ensure design compliance this calculated distribution of strain may then be compared with the limiting

[25] NCHRP Report 646, 2010. 'Validating the Fatigue Endurance Limit for Hot Mix Asphalt'

[26] National Centre for Asphalt Technology Report 09-08 'Phase III NCAT Test Track Findings'

distribution of strain which has been determined from LLAP studies. The proposed validation studies are discussed in the following section.

The studies will be facilitated by our ability to directly compare the stiffness and temperature sensitivity of our materials with those of overseas researchers because we use identical E* test methods. When satisfied our materials have similar performance properties it is then reasonable to apply the model correlations derived from full scale and Long Term Pavement Performance (LTPP) studies.

It is pertinent to reflect on the observations[27] of Dr Mike Nunn. In the HMA Endurance workshop closing he states:

'Pragmatic, evidence based approach suggests that fatigue is not a problem even on relatively thin pavements in the UK ……………… (It is) Important to observe phenomenon closely in-situ and understand as much as possible before modeling. Models need to fit reality and not vice-versa'

Based on the LTPP studies[28] conducted in Australia under the auspices of AAPA, and at a much greater scale in the US and Europe, the pragmatic evidence based conclusion must be drawn that the continued application of our current design models for thick asphalt will result in overly conservative and wasteful designs.

PROPOSED DESIGN ELEMENTS

Temperature Spectrum

The procedure will require user defined cumulative distribution of pavement temperature. The following example is based on ARRB TR records of work done by Dickenson in the 70's and published in the document 'Pavement Temperature Regimes in Australia'[29]. The source data for this report is rumoured to have been purged in the course of an earlier mainframe computer upgrade. We are seeking access to CSIR South Africa program (refer Footnote 14) which appear able to calculate the asphalt pavement temperature regime with adequate reliability.

An example from the Dickenson report is shown in the histogram Figure 2. This records the measured temperature data at a level of 100mm in the pavement sections across a number of states. From this data a cumulative distribution of temperature for a limited number of sites and pavement depth has been derived and is presented in figure 3.

[27] HMA Endurance Workshop: August 2007. National Academies Keck Centre, Washington DC

[28] Rickards and Armstrong 'Long tern full depth asphalt pavement performance in Australia' 24th ARRB Conference Melbourne 2010

[29] ARRB Special Report 23, August 1981.

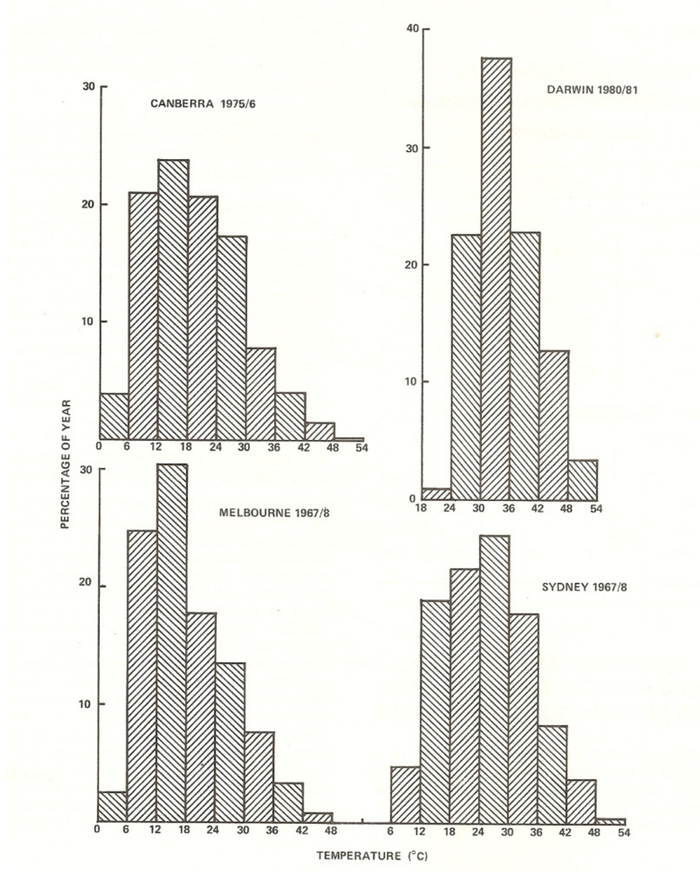

Fig. 15 — Distribution of temperature over a year in AC at a depth of 100 mm (four sites)

Figure 2: Temperature histogram from Dickenson

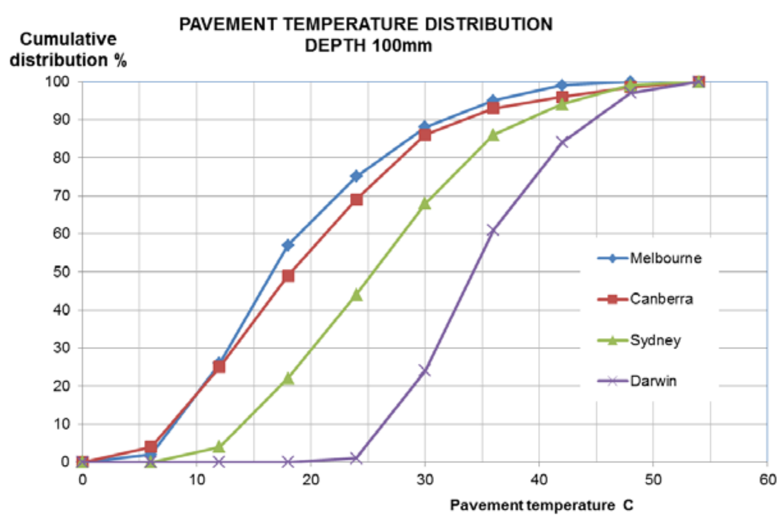

Figure 3 Plot of cumulative distribution of temperature at 100mm selected Australian sites over one year

Figure 4 is a plot showing the relative cumulative distribution of pavement temperature over one year at depths of 50 and 100mm.

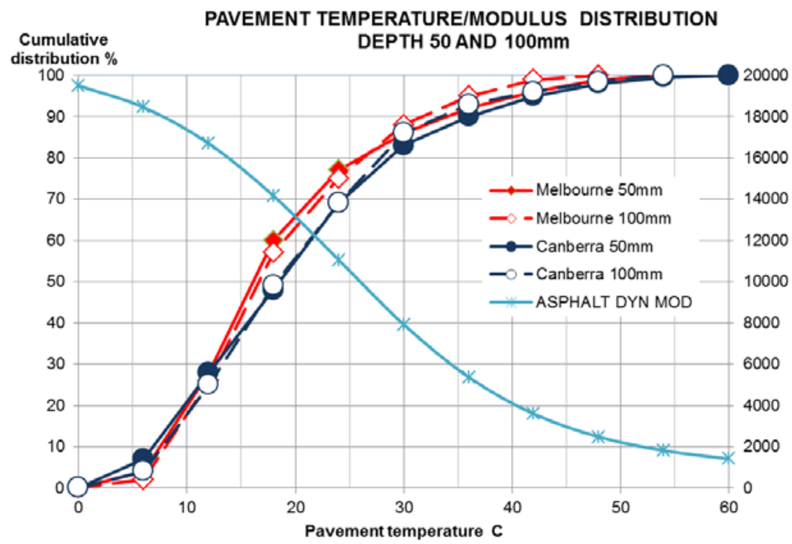

Figure 4. Comparison of pavement temperature distribution at different depths over a year

It is observed that the variation in distribution is relatively small and that it changes from cool to hot periods. Our initial view is that it is reasonable to adopt the simplifying assumption that the pavement temperature distribution at mid depth in the asphalt layer is a reasonable and conservative approach. It will be shown later that the critical strain magnitude increases with temperature as the asphalt modulus reduces. The temperature distribution in the deeper pavement layers will be lower relative to that at 100mm.

Also shown in Figure 4 is the cumulative distribution of asphalt dynamic modulus as a function of mix temperature. It is observed, by way of example, that at 90% cumulative distribution the difference in temperature between 50mm and 100mm is only 2 to 3^{o}C and that the modulus will vary by a few hundred MPa i.e. it will be higher at 100mm depth relative to 50mm depth.

Certainly further sensitivity analyses need be completed but at this stage of development it is believed to be reasonable (and conservative) to adopt a temperature distribution at a single depth. The empirical evidence suggests the threshold thickness for the LLAP is between about 250 and 300mm thus the temperature at 100 - 150mm seems an appropriate mean value for design purposes.

The software will require the user to input the cumulative distribution of temperature relative to the traffic load application. The user manual will provide representative values for key sites around Australia.

Asphalt modulus and distribution

As shown in Figure 4 we are able to determine the variation of the dynamic modulus of asphalt across the temperature spectrum. For each pavement analysis the relevant design traffic speed and load duration is calculated and used in the determination of E* modulus. Given all the other uncertainties and the normalization that will occur by using the cumulative distribution of strain as the limiting criterion, a simple approach is recommended. This assumes the load footprint diverges at 45^o such that the loaded distance is the length of contact (say 200mm) plus the depth of asphalt as shown in Figure 5.

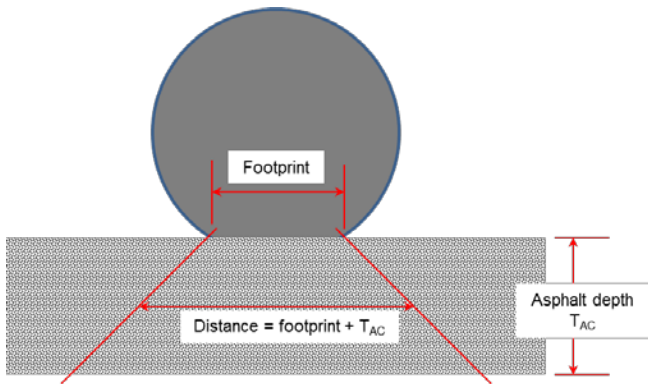

Figure 5. Model used to calculate load duration

In the calculation of asphalt modulus in Figure 4 a design speed of 80kph is used thus for a 300mm thick the time of loading T_L is calculated using the relationship velocity = distance/ time

$$T_L = 0.5/80.1000/3600 = 0.0225 \text{ sec}$$

The load duration at the bottom of the asphalt is of course longer (i.e. calculated modulus will be lower) but it will be confirmed that this is more than offset by the lower temperature at depth in the pavement when designing for the critical higher temperature conditions that occur during afternoon peak traffic.

The dynamic modulus (E*) of the asphalt is derived from laboratory testing using the Asphalt Materials Performance Test (AMPT). The shape of the E* master curve of the mix is characterized by the parameters shown in Figure 6. These parameters are calculated using the measured responses in the course of the laboratory testing.

Calculated Parameters			
Time Temperature Shift Curve		Master Curve Parameters	
a	0.000819	α	2.68223723
b	-0.156212	δ	1.63092016
c	3.393407	β	-0.16366307
		γ	0.80236887
Phase lag parameters			
a'	-0.67570389		
b'	4.66302053		
c'	-7.50395971		

Figure 6 Mix parameters used to determine E*

Initially the user will be required to input these laboratory derived parameters into the LLAP design analyses. It is anticipated that typical values will ultimately be developed and provided to users as part of the package. It is our belief that any reduction in the design accuracy using typical values is minor relative to the current Austroads design assumptions.

The following are the design parameters:

User input:

Effective temperature T_E (via the cumulative distribution of temperature)

Time of loading T_L (as above)

Calculations for E* (using parameters in Figure 6)

Temperature shift factor T_{SF}

$$T_{SF} = a.T_E^2 + b.T_E + c$$

Reduced time T_R

$$T_R = LOG(T_L) - T_{SF}$$

Dynamic modulus E*

$$E^* = 10\text{\^{}}(\alpha + \delta / (1 + EXP(\beta + T_R.\gamma))$$

These relationships have been applied in spreadsheets to develop the distribution of E* v temperature such as plotted in Figure 4. The raw data for this plot is derived from the testing of an AC20 with C320 bitumen from NSW. The Particle Size Distribution (PSD) or gradation of the mix is near maximum theoretical density thus it will be typical of widely used basecourse asphalt.

The asphalt stiffness master curve plotted in Figure 7 is the same mix tested under differing conditions of confining stress at test temperatures 35°C and 50°C. The divergence noted at low temperature is as a result of the regression of the measured data and the sensitivity of the readings. At low temperature / high stiffness the sample response to load is extremely small and minor measurement errors become significant.

It is noted that at sample temperatures below about 30°C the measured modulus is not affected by confinement. This is consistent with the Shell observations that the method for the prediction of mix stiffness applies only when the stiffness of the binder > 5MPa. Below this temperature the effect of the aggregate skeleton begins to dominate and this is augmented by confinement.

In Figure 6 the phase lag parameters are listed. At this time these data are for materials comparison only and do not form parts of the thickness design process. The phase lag data provides insight into the relative viscous and elastic properties of the mix that may be useful in the selection of binders - for instance to enhance deformation resistance.

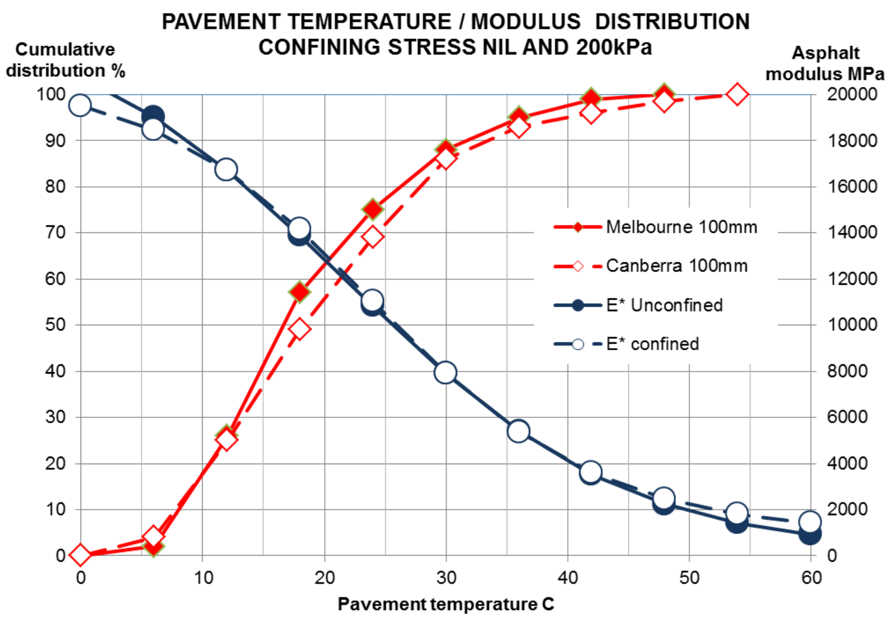

Figure 7 Asphalt modulus and effect of sample confinement

The effect of confinement at high temperature is considered important. This is not so apparent at high speed / short load duration but becomes significant when modeling slow speed traffic. The evidence (and logic) suggests confinement has a significant structural benefit. Researchers[30] have observed from the analysis of deflection data that the stiffness of asphalt tends to asymptote, despite increasing test temperature, at a value in the order of 1500 MPa. The confined laboratory data tend to confirm this observation.

[30] Marchionna, A., Fornaci, M.G. and Malgarini, M. (1987). 'Evaluation of flexible pavements and overlay design based on FWD tests'. 6th Int. Conf. Structural Design of Flexible Pavements

In the interim it is recommended that the modulus master curve determined at 200kPa confinement be used in the design process, but that this be validated against LTPP sections.

Calculation of Cumulative Strain Distribution

The asphalt strain at selected temperatures over the relevant spectrum of pavement temperature is then calculated using CIRCLY. In the following the asphalt strain has been calculated at 6°C increments and is plotted in accordance with the cumulative distribution of pavement temperature (at 100mm depth) determined by Dickenson and as shown in Figure 3.

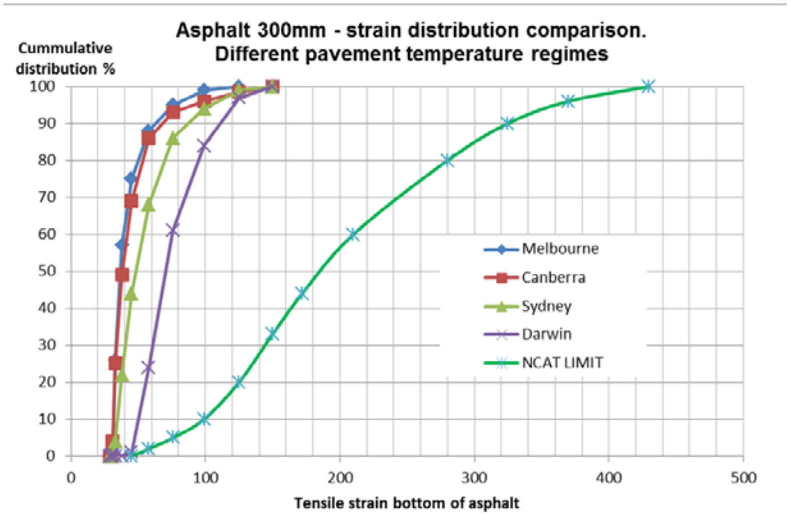

Figure 8 Cumulative strain distribution calculated for 300mm thick asphalt pavement compared against the NCAT interim tolerable distribution

This chart has been derived for illustrative purposes using the asphalt layer modulus based on the temperature distribution at 100mm depth, and load duration at traffic speed of 80kph. The interpretation of the chart is that it provides graphic evidence that the 300mm thickness of asphalt (on a standard foundation ≥ CBR5 and an unbound granular base) results in a cumulative distribution of strain significantly below the interim threshold value suggested by NCAT to represent a LLAP status in the broad spectrum of pavement temperature conditions in Australia.

The procedure avoids the reliance on asphalt fatigue and cumulative damage calculations using Miner[31]. Given the acknowledged difficulties in fatigue testing and application in models this should not cause alarm. Reference is also made to Mike Nunn, and his exhortation that models need to fit reality and not vice-versa. The reality is that the empirical evidence suggests the current Austroads design method, relying on fatigue modeling, results in overly conservative and wasteful designs for heavily trafficked roads and industrial pavements.

[31] Because the mix stiffness and strain parameters are known it is a simple matter for the software to calculate the cumulative damage factors. The calculation will be of academic interest only because no account is taken of rest periods and the effect of temperature. The design traffic should not exceed 80-100MSA i.e. the threshold value.

Consideration must be given to more detailed sub-layering of the asphalt structure representing the varying layer temperature and stiffness. Further analysis will be conducted but my preliminary view is that it is an unnecessary complication provided the reference temperature is adequately conservative.

The chart also assumes that the cumulative strain distribution under loading is consistent with the pavement temperature distribution. This will not be the case if peak loading occurs at specific times e.g. afternoon peak periods when the pavement temperature is at its maximum. In this case the user will need to estimate an appropriate distribution of temperature (and consequent strain).

Simplistically it may be that the cumulative pavement temperature distribution can be derived ignoring the low temperatures (e.g. the lower 20 %tile) that represents the conditions in the morning. Considering the data in Figure 8 it is suggested this simple method would result in a shift in the distribution for Melbourne and Canberra a little to the right but clearly not as far the Darwin distribution.

So far as the software is concerned it will only require that the user input the pavement temperature spectrum over the applied traffic spectrum. The asphalt material parameters and calculated strain will then reflect the actual loading and temperature distribution.

SUGGESTED METHOD FOR VALIDATING LLAP THICKNESS DESIGN BY LTPP STUDIES

The following procedures suggested for use in the validation of the proposed LLAP thickness design procedure are in the planning phase. Essentially the validation process involves the desk top analysis of overseas LTPP data. The work will be carried out in the course of PhD studies in nominated Universities.

The interim methodologies proposed rely on access to data that has been obtained - at great cost – by overseas researchers and agencies. Accordingly the proposals rely substantially on their good will and generosity. To some extent this may be offset by Australian researchers providing supplementary resources to the agencies undertaking the necessary desk top studies and analyses and sharing the results, or other quid pro quo activities.

While the tentative plans for the validation process make a number of simplifying assumption they constitute a big advance on past practice. The limited resources applied to Australian LTPP studies has resulted in there being no validation of the thickness design method currently in use for thick asphalt pavement structures.

The validation process is considered to entail two primary facets;

- Verification of E* values for use in LLAP designs (e.g. using NCAT data)
- Verification of LLAP design method by LTPP studies

These are briefly outlined in the following.

Verification of E* values for use in LLAP designs

The E* values will vary between laboratory and field conditions. The sources of variation are numerous and include the different mixing and compaction conditions, the extent of ageing and – particularly at high temperatures - the degree of confinement[32] which is at least intuitively a positive factor. It is thought that the critical condition is early in the life of the pavement when the mix is fresh i.e. strain is at a maximum thus laboratory characterisation of plant mixed samples probably represents the worst case scenario provided the sample density / voids is equal to the field condition.

As previously noted the typical Australian asphalt plant mixed materials representing those used on major projects will be characterised using the AMPT. The E* relationships so derived will then be compared with those of the materials in LTPP studies overseas. Ideally the comparison would be between samples taken at the time of construction but the sources of these data are yet to be determined. If it is established that the asphalt materials have similar properties it is then reasonable to assume the LTPP results would be applicable to the Australian scene under similar conditions of load and environment.

[32] At the bottom of a thick asphalt structure elastic layer analysis shows the vertical compressive stress is the greatest, and the horizontal tensile stress is relatively low.

A potentially valuable source of this data is the NCAT field trials from which the interim tolerable distribution curve was derived (Figure 8). NCAT have comprehensive records of pavement temperature and measured strain from which (knowing the pavement profile) the stiffness of the asphalt materials in-situ can be estimated. This will provide a measure of the relationship between the field and laboratory modulus data and assist the determination of the appropriate laboratory test conditions (e.g. confined or unconfined) for use as design input[33].

Verification of LLAP design method by LTPP studies

The interim LLAP thickness design proposal relies on compliance with a limiting cumulative distribution of strain under the equivalent standard axle over the spectrum of pavement temperature. It was previously noted that NCAT has suggested an interim tolerable cumulative distribution of strain but obviously further verification and calibration is required. An interim suggestion is provided in Annexure 1 describing the possible steps in the validation process.

It is suggested the theoretical examination of the UK and European LTPP data (over a much longer period of time) may prove beneficial. Numerous sites have been identified that clearly achieve the LLAP status i.e. the pavement deflection is reducing with time. With the assistance of the UK Highways Agency and/or TRL and the members of the European Long Life Pavement Assessment Group (ELLPAG) details of some of the pavements may be available. With knowledge of the appropriate climatic data the cumulative strain distribution in these pavements may be determined for comparison with and possible refinement of the NCAT model.

We are aware the NCHRP Project 9-44 proposes a very sophisticated approach in which the tolerable distribution of strain is determined in part based on the laboratory estimation of the relative healing of micro-cracks as a function of bitumen type, temperature and rest period conditions. This approach is obviously more scientifically thorough however, at this time, it is considered beyond the Australian resource levels[34] and will take a long time to achieve field validation.

This proposal is based on the premise that the estimation of the cumulative distribution of asphalt strain on LLAP sites will accrue the effects of the significant variables in thickness design provided a consistent methodology is followed, as suggested in Annexure 2 for instance.

The calculated strain will be derived using the spectrum of E* values estimated from back-analyses and possibly calibrated against laboratory measures or predictive models using consistent assumptions of ambient temperature versus pavement temperature and load duration. The back analysis of deflection data taken soon after construction will enable the estimation of the cumulative distribution of strain in the LLAP at what is generally regarded as the critical condition i.e. in fresh asphalt material when first trafficked.

[33] This work may have been concluded by NCAT however we are not aware of it being published.

[34] It is understood NCHRP Project 9-44 is in the order of 4 years duration and USD 1.5m cost.

Conclusion

It is concluded that great benefit will be realised by Australian agencies and the community by adopting a fundamental empirically derived limiting design parameter for LLAP structures. Notwithstanding the simplified validation process the design method does incorporate significantly improved modeling of materials and the temperature effects. It also achieves a degree of empirical validation that exceeds that applied to the current Austroads pavement design methodology.

On balance it is concluded that effort put into a focus on construction and the assurance the asphalt materials supplied will have the performance attributes assumed in the design process will offer greater performance benefit and risk mitigation than the pursuit of the scientifically pure design solution.

Annexure 1: Suggested E* verification procedures

VERIFICATION OF E* VALUES FOR LLAP DESIGNS USING NCAT DATA			
Data requirements	**Compare lab/field E* value v temperature**	**Compare asphalt properties Australian & NCAT**	
Pavement composition; materials thickness	Develop elastic layer model of test sections	Provide laboratory E* values from Aust. characterisation study	
Asphalt material gradation, volumetrics, binder	Load input: to represent field condition / FWD deflection	Provide Aust. premixed samples for NCAT compaction and E* testing	
Pavement material properties; lab & field measures	Input lab E* values at frequency relative to load speed	Compare Aust. NCAT E* values to confirm agreement	
Binder DSR data	Calculate strain & deflection over the temperature spectrum	Determine asphalt material gradation, volumetrics, G* binder	
Pavement temperature records	Compare calculated and measured strain/deflection v temperature	Complete Hirsch modeling for all mixes; use as basis of comparison	
Traffic records ESAL's	Determine relationship between lab and field E*	Conclude relative performance Aust. and NCAT mixes	
Traffic distribution versus pavement temperature	Conclude appropriate E* test condition for use in design modeling		
Traffic speed / load duration			
Asphalt strain data			
Deflection records			

Annexure 2: Suggested LLAP verification procedures

VERIFICATION OF LLAP DESIGN METHOD BY LTPP STUDIES				
Data requirements	**LLAP site selection process**	**Estimate E* asphalt by deflection back-analysis**	**Asphalt E* material properties**	**Estimate Cumulative distribution of asphalt strain**
Deflection records - time series	Confirm data requirements are available	Select sites for deflection back-analysis; use upper 95%tile	Determine asphalt material gradation, volumetrics, binder	Develop elastic layer model of test section; simple 3 layer model.
Historical traffic estimates ESAL's	Review deflection records - time series	Adopt 3 layer pavement profile; asphalt, subbase, subgrade	Agency lab E* data if available; test cores if available	Calculate load duration mid asphalt layer using normal traffic speed
Daily traffic distribution estimates	Confirm deflection is stable or reducing with time	Back analysis to estimate layer moduli	Original E* asphalt properties; predictive or lab data	Use E* master curve estimates at adopted load duration
Pavement composition; materials thickness	PROCEED	Estimate mid asphalt layer temperature at time of test	Compare E* with back analysis estimate	Calculate asphalt strain v mid layer temperature spectrum
Pavement material properties		PROCEED	Estimate master curve using typical binder characteristics	Estimate traffic load distribution v ambient temperature
Asphalt material gradation, volumetrics, binder			PROCEED	Estimate traffic load distribution v mid asphalt layer temperature
Climatic averages; monthly mean min and max				Plot cumulative distribution of estimated asphalt strain