Advanced Material Characterisation of Australian Mixes for Pavement Design

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Abstract

In 2011 AAPA initiated the Asphalt Pavement Solutions for Life (APS-fL) project. This project was initiated to address the concern of industry that current pavement design procedures where producing overly conservative asphalt thicknesses.

One of the two of the primary issues identified by industry was the limited data on material characteristics of typical Australian production mixes. Because of this limited dataset it was believed the values being adopted for the purpose of pavement design were overly conservative. To obtain actual information and fill this gap, the APS-fL project set out to characterise typical Australian production mixes using the dynamic modulus test. The dynamic modulus test was selected; to be consistent with the direction being taken internationally, to enable the development of master-curves, and to enable linking of Australian mix characterisation with overseas research.

The results of the material characterisation of 28 Australian mixes has been used to develop dynamic modulus master-curves, which will enable, for the first time, the calculation of modulus of Australian production mixes at any load frequency and temperature applicable to Australian field conditions.

This paper will present the reasons for the adoption of dynamic modulus test, the process for development of master-curves, the results of characterisation of Australian production mixes, the recommendation of use of Australian dynamic modulus results for initial pavement design development and the validation of Australian measured data with that of testing at overseas research sites, such as NCAT.

1 Introduction

The asphalt material characterisation study is a major component of the AAPA Asphalt Pavement solutions for Life (APS-fL) project. The study was undertaken to provide real data on the performance characteristics of actual standard Australian production mixes. To be consistent with the direction being taken internationally, the experimental design of the project was developed having an ultimate goal of developing a set of dynamic modulus master-curves for Australian production mixes. The primary advantage of the development of master-curves is that the curves can be used for the determination of modulus and visco-elastic properties of Australian asphalt mixes across the full spectrum of temperature and load speeds relevant to Australian field conditions.

The two main objectives of the materials characterisation component of the research where to:

- Determine actual material properties of Australian mixes which can be used in layered elastic analyses to accurately determine the response of the pavement over a range of operational temperatures and vehicle loadings.

- Allow comparison of the material properties of Australian mixes against US and European mixes to confirm similar performance and therefore the transferability of the results from the US and Europe to Australian conditions.

2 Selection of Dynamic Test

2.1 Selection of the Dynamic Modulus Test

Having the ultimate goal of the material characterisation study being the development of modulus master-curves to enable to calculation of asphalt modulus at any temperature or vehicle speed, the dynamic modulus test was selected over other modulus test such as the resilient modulus. This ability to calculate the modulus at any temperature or vehicle speed will offer a substantial improvement on the current Australian method which is based on a single standard laboratory test temperature and time of loading. In addition, the dynamic modulus test was selected as the primary material characterisation test for a number of reasons:

- Researchers such Loulizi et al.(2006) have established that "the dynamic modulus test provided a better characterization of asphalt mixes than the resilient modulus test because of its full characterization of the mix over a range of temperatures and load frequencies".

- The dynamic modulus test and the resulting master-curves are internationally accepted as being able to discriminate key asphalt performance properties. The results NCHRP 9-19 project Witzcak (2002), concluded the dynamic modulus, and creep properties (flow number or flow time) had the best correlation with field performance, observed on major US field trials (WesTrack, MnRoad and the FHWA ALF).

- The dynamic modulus test has been used as a key material characterisation test at a number of international accelerated pavement test tracks, (FHWA ALF, NCAT, MnRoads and WesTrack). This enables the development of a quantitative process for the calibration of the performance asphalt materials in the laboratory, against the performance of real pavements in the field.

- Because of the ability to model the asphalt mixes at any temperature and frequency, the results of the dynamic modulus test and subsequent master-curves will enable the rational and quantitative assessment of asphalt materials used in the historical Long Life Asphalt Pavement sections constructed in the Australia, the US and Europe at the specific temperatures and vehicle speeds encountered at those sites.

Given these benefits, the dynamic modulus test and resulting master-curves will facilitate the ultimate goal of the APS-fL project, which is the structural analysis of the performing Long Life Asphalt Pavement sections and the determination of the distribution of asphalt strains. The finding of these distributions of strains can then be transposed to different environmental conditions found in Australia using the dynamic modulus master-curves to form the basis of the development of a long life asphalt pavement design procedure.

3 Australian Material Database

The objective of the material characterisation component of the APS-fL project was to provide real data on the performance characteristics of actual standard Australian production mixes, however given the combination of binder's, aggregate sources, producers across Australia, obviously not all mixes could be included in the study. Therefore in order to keep the size of the characterisation study to a manageable level, the design of the experiment was rationalised to 30 mixes by the Project Steering Committee. The 30 mixtures were selected to cover the majority of the combinations of aggregate sources and binder types used across Australia, without duplication of relatively similar mixtures. As the overall objective of the project is the development of long life pavement design procedure, the emphasis was placed on the harder binder grades, which are believed to offer greater structural benefit to the pavement. Likewise, as the main structural layers in the pavement will be the larger stone mixes, focus was placed on the 20mm mixes.

Given the objective to model as close as possible actual field performance, the experiment was designed using plant produced asphalt mixes, as it was believed that these materials more closely matched reality of asphalt produced and placed in the field over that produced in the laboratory.

Of the 30 mixes identified for inclusion in the study, 28 were in production over the experimental period and therefore included in the study. Table 1 following summarises the 28 mixes used with their volumetric properties and mix design method.

Table 1 Supplied Materials

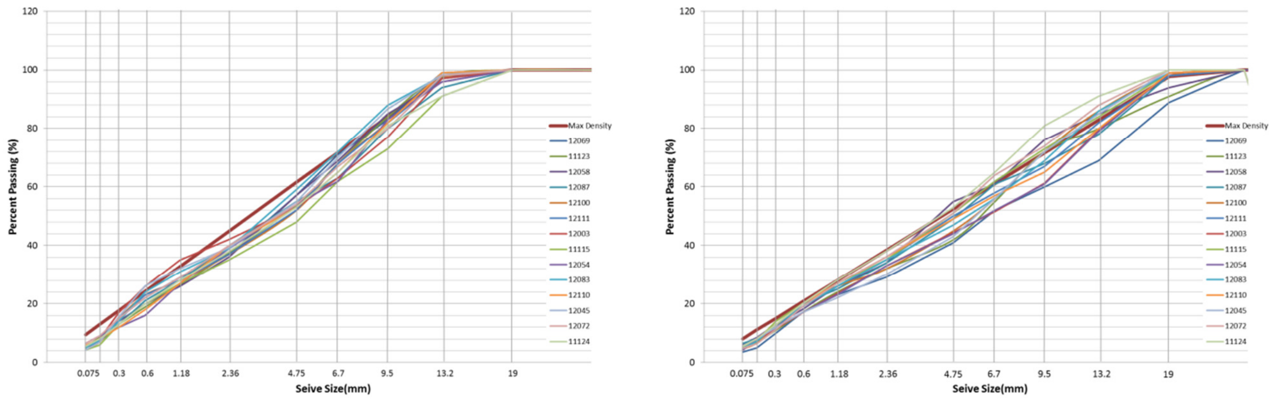
Nominal Size (mm)	Binder Type	Mix Design Method	Design Voids (%)	Design VMA (%)	Design VFB (%)
14	A15E	Marshall 50 blow	4	14.7	73
		Gyratory 120 cycles	5.4	15.5	65
	AR450	Gyratory 120 cycles	4.2	15.5	73
		Gyratory 120 cycles	5	15	72
		Gyratory 120 cycles	4.3	15.5	73
		Gyratory 120 cycles	5.4	15.5	65
	C320	Gyratory 120 cycles	4	15	73
		Marshall 75 blow	5.01	15.17	67
		Marshall	4.9	16	70
		Marshall 75 blow	5.5	16.4	66
		Marshall 50 blow	5.2	15.6	66
		Gyratory 80 cycles	4.5	14.5	69
		Gyratory 80 cycles	4.5	14.6	69
		Marshall 75 blow	3.8	14.2	73
	Multi Grade	Marshall	5.7	15.7	64
20	AR450	Gyratory 120 cycles	4.8	15.5	69
		Gyratory 120 cycles	4.9	14	70
		Gyratory 120 cycles	5.2	15.6	67
	C320	Marshall	5	15.2	67
		Marshall 75 blow	3.8	14.2	73
		Marshall 50 blow	5.3	15.2	69
		Gyratory 80 cycles	4.5	13.5	66
		Marshall 75 blow	3.8	14.2	73
		Gyratory 120 cycles	3.9	14	72
	C600	Marshall 50 blow	5	15.2	68
		Marshall 50 blow	4.8	14.8	68
		Marshall 50 blow	4.6	13.9	67
	Multi Grade	Marshall	4.5	14.6	69

3.1 Asphalt Mix Properties

For each of the 28 supplied production mixes, the volumetric properties and aggregate gradations were supplied by the producer. A comparison of the supplied information was undertaken for each nominal aggregate size in order to obtain an indication of the variability of standard production mixes across Australia. The results of which are discussed in the following section.

3.1.1 Gradation

The gradation of the supplied nominal 14mm and nominal 20mm mixes can be seen graphically in Figure 1 following, on a 0.45 power gradation curve.



(a) (b)

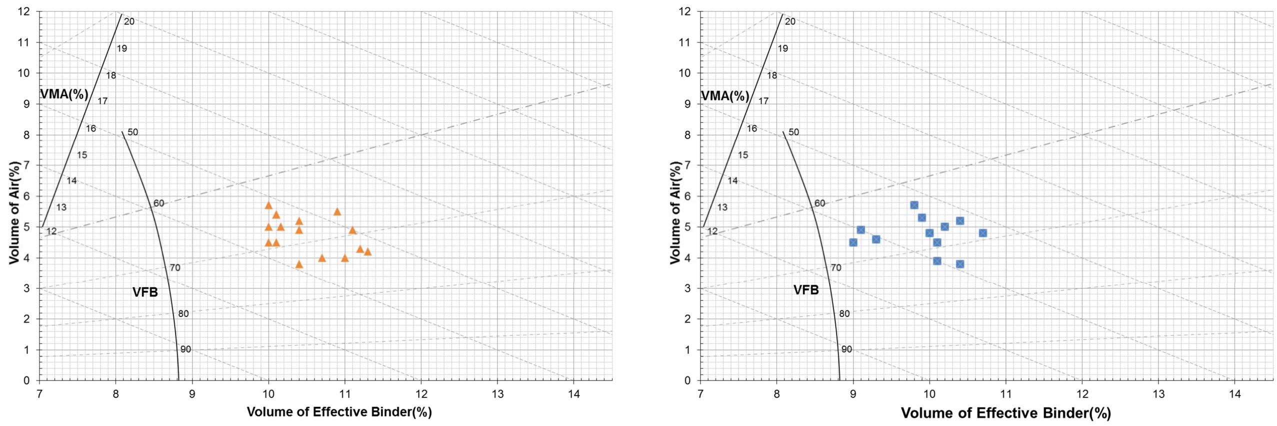
Figure 1 Gradation plots (a) "Nominal" 14mm (b) Nominal 20mm Mixes

The plot shows that for both the 14mm and 20mm nominal mixes, nearly all gradations closely follow the maximum density line, although, nearly all gradations are slightly coarse graded. The results show that fine and gap graded mixes do not appear to be commonly used in production mixes throughout Australia. What is evident in the gradations, particularly in the 20mm mixes, is that the definition of "nominal" does vary across Australia and some mixes defined as 20mm nominal mixes would be classified differently in other states.

These results may indicate it may be difficult to distinguish between Australian asphalt based on aggregate gradation, due to the limited variation.

3.1.2 Volumetric Properties

The volumetric properties of the supplied mixes are shown graphically on a four axis volumetric plots, for the 14mm nominal mixes and the 20mm nominal mixes, in Figure 2 following.



(a) (b)

Figure 2 Volumetric Plots (a) 14mm, (b) 20mm

What is noteworthy, given the variability in the design methods (Marshall, gyratory and Superpave) and the differing compaction efforts, is that all mixes fit into a very small volumetric window.

- For the 14mm nominal mixes all mixes had VMA between 14 and 16%, VFB between 65 and 75% and volume of effective binder between 10 and typically 11%.

- For the 20mm mixes there was a slightly higher variation but still surprisingly small variation, with all mixes having VMA between 13.5 and 15.5%, VFB between typically 60 and 70% and volume of effective binder typically between 9 and 10.5%.

All mixes had design voids between 4 and 6%.

As with the results of the gradation analysis these results may indicate it may be difficult to distinguish between Australian asphalt based on volumetric properties due to the limited variation in mixes across Australia.

4 Dynamic Modulus Testing and Results

4.1 The Dynamic Modulus Test

To obtain real information and on the characterisation of standard production mixes used throughout Australia, the APS-fL project undertook dynamic modulus test on all of the supplied 28 actual production mixtures. As at the time of testing it was unknown what state of stress would be required to accurately model of the response of the pavement to cover all possible stress states, the AAPA study conducted dynamic modulus testing in both unconfined and confined state. For the confined state three levels of confinement where used: 50, 100 and 200kPa.

For each of the 28 supplied mixes the dynamic modulus test was performed according to AASHTO TP62-07 using an IPC AMPT. To minimise potential damage to the specimen, testing was undertaken in the following order, before the next sequential test, the reason for this approach is asphalts are stronger at lower temperatures and higher frequencies.

- For each test temperature, E* tests were conducted on each specimen at a full sweep of loading frequencies (25,10, 5, 1, 0.5 and 0.1Hz).
- Testing was conducted at 200, 100, 50 and 0kPa confining pressures.
- Test temperatures where used from coolest to highest 5, 20, 35 & 50°C.
- Two replicates samples were tested for each factor combination for both confined and unconfined testing.

4.1.1 Master-Curve Development and Time Temperature Superposition

For Australia, it was agreed by the APS-fL Project Steering Committee, to use a reference temperature of 25°C, as opposed to the standard of 20°C used in the US. The 25°C temperature was selected to be consistent with current Australian characterisation methods. It was also agreed that dynamic modulus master-curve should be modelled using a sigmoidal (S shaped) function, as recommended by Witczak (2002). However, due to the current debate over the definition of time in the dynamic modulus test, the sigmoidal function should was to be determined as a function of frequency, not time, as described by the following function:

$$\log(|E^*|) = \alpha + \frac{\beta}{1 + e^{(\gamma + \delta(f_r))}}$$

Where:

f_r = reduced frequency at the reference temperature

α = the minimum value of E*

$\alpha+\beta$ = the maximum value of E*

γ, δ = shape fitting parameters, determined through numerical optimisation of experimental data.

In this process a shift factor, a_T is used to calculate the reduced frequency, f_r, required to shift the dynamic modulus test results on the frequency scale to form a continuous curve at the 25°C reference temperature. The shift factor can be mathematically shown in the following form:

$$a_T = \frac{f_r}{f}$$

Where;

a_T = shift factor

f = frequency of loading at desired temperature

f_r = reduced frequency of loading

T = temperature

While classical viscoelastic fundamentals suggest a linear relationship between $\log(a_T)$ and T, Anderson et al. (1994), research Pellinen (2001), has shown that a higher precision is achieved by the use of a second order polynomial relationship between the logarithm of the shift factor ($\log(a_T)$) and the temperature (T). The use of 2nd order polynomial relationship can be further simplified by directly incorporating the reference temperature in the polynomial form. This polynomial shift factor approach was adopted by the Steering Committee as the method to be used for the AAPA study, as shown following:

$$a_T = 10^{a(T-T_{ref})^2+b(T-T_{ref})}$$

where:

T = temperature of interest

T_{ref} = 25°C

a, b = coefficients of the polynomial

This process of master-curve development is shown graphically in Figure 3, which shows the measured dynamic modulus results of a typical mix as a function of frequency for four test temperatures.

Firstly the results at the four individual test temperatures are shifted to the reference temperature (25°C) on the frequency scale to form a continuous curve as shown in Figure 3(a). Once the continuous curve is formed, the sigmoidal function is fitted to the measured data to construct a master-curve, the curve is usually fitted by using a numerical optimisation procedures, such as the Solver function in Excel®, by minimising the sum of the of squared errors between the measured and predicted values. The figure shows how the data very accurately fits the sigmoidal function, with all master-curves in the AAPA study having R^2 values of greater than 0.98 and typically being greater than 0.99.

The amount of shifting required on the frequency axis to make the continuous curve is the shift factor. The amount of shifting for each temperature is then plotted against the temperature, as can be seen in Figure 3(b), to develop the temperature shift factor equation. The figure clearly illustrates the higher precision of the polynomial shape of the shift factor relationship recommended by the Steering Committee.

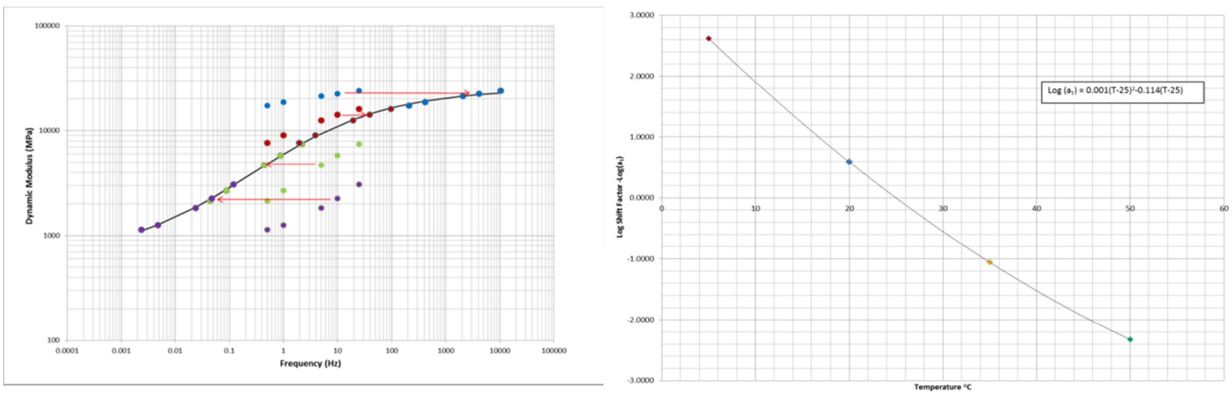


Figure 3 Construction of Dynamic Modulus Master-curve and Temperature Shift Factor Function

4.2 Sample Preparation, Compaction

For the each of the 28 production mixes used in the experiment 300kg of a representative sample asphalt was taken from plant production mixes from actual projects, cooled and delivered to Fulton Hogan's National Technical Laboratory in sealed nominal 20kg containers.

Prior to compaction all mixes were reheating using a standardised procedure across all mixes to minimise any effect aging may have on the measured material characterisation. To accomplish this, the following reheating process was undertaken:

- Material was warmed to 70°C and broken down by hand on a quartering tray and quartered to give representative 28-30kg for each shear-box block.
- The mix was placed into two separate shear-box feeding trays.
- The shear-box trays where covered and placed in preheated ovens at 150°C for conventional binder and 165°C for the polymer modified binders
- Temperature was monitored via the thermal couples inserted in the sample until the required temperature of the mix was achieved.

The compaction method chosen for the production of laboratory samples was the FH Shear-box compactor, while it was recognised, the Shear-box compactor is not used in AASHTO and Europe standards for material characterisation and the method has not been adopted by Austroads. The shear-box compactor was selected for the study as:

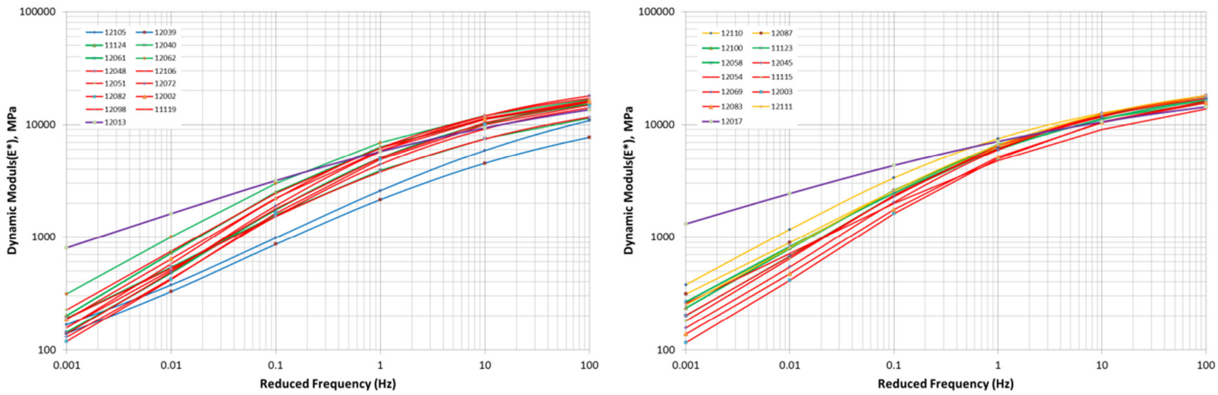
- The current Austroads practice (gyratory compactor) would not produce specimens of the correct size and air void distribution for use in dynamic modulus test.
- In the US the standard compaction method, the Superpave Gyratory Compactor (SGC), is not readily available in Australia and produces samples with a higher degree of variability, and requires more laboratory time and material than the shear-box.

4.3 Master Curves and Dynamic Modulus Test Results

The dynamic modulus results for the 28 mixes tested were used to generate master-curves for each individual mix. As per the agreed standard all master-curve were all created at a single reference temperature (25°C). For all master-curves, all fitting parameters in both the sigmoidal function and the temperature susceptibility function were free to be optimised to obtain the best fit between the measured and predicted data.

The resulting master-curves allow the stiffness of the Australian mixes to be viewed without temperature as a variable, which in turn allows for relative comparisons to be made between multiple mixes and can be seen in Figure 4 following.

The fitted parameters for the sigmoidal function and the temperature shifting factor for the 28 different mixes examined in the study can be found in Sullivan et al. (2013). While the master-curves can be seen graphically in Figure 4 following. In the figure the red curves are for C320 mixtures, green are AR450, yellow are C600, blue are A15E and purple are Multigrade mixes.



(a) (b)

Figure 4 Master-curves (a) 14mm, (b) 20mm

The initial examination of the results shows that the minimum modulus values as expected increase with an increase in binder grade, with C320 mixes being lower than AR450, which are lower than C600 and Multigrade binders. As expected nominal 20mm mixes are also typically higher than the 14mm mixes. This is consistent with the latest version of the Witczak model, with Bari (2006) finding the minimum modulus value, α, was affected by aggregate gradation, volume of air, volume of binder and binder stiffness. This finding suggests the minimum modulus value appears to best at distinguishing between different binder grades. As there was little to no change in air void level of typical Australian mixes (typically 5%), the effect of air void level on the minimum modulus value could not be assessed.

Unexpectedly, no correlation was found between the minimum modulus and RAP content indicating that at current RAP contents, RAP content has little effect on the minimum modulus value and therefore overall modulus values (plant characteristics appear to be more important). While the minimum modulus value appears to be influenced by effective binder content, and the amount of filler, due to the relatively small change in the effective binder volume, the effects to changes in the volume of binder are small and cannot be easily assessed.

The β parameter or the maximum modulus value parameter appears not to be sensitive to changes in binder grades for conventional (neat) binders or maximum aggregate size, which is the same finding as Bari who found that the β value was a function of volumetric properties of the mix and finer fraction of the gradation.

The examination of the relative shape of the master-curves tend to indicate that for the current Australian mixes, the design method, aggregate source and the relatively small variance in volumetric properties appears to have little effect on the shape of the master-curve, with results of the γ and δ factors showing little change within binder types.

For conventional binders, the shape factors (γ and δ) appear to be relatively consistent regardless of the grade of binder. However, this is not the case for the two non-conventional binders, the multi-grade and A15E, which have a different shape to the conventional binders indicating lower time-temperature susceptibility. This is somewhat consistent with the findings of Bari (2006), who found γ the shape factor was a function of binder properties only. However, for Australian binders, this change of shape is only evident when comparing conventional and modified binders. It is clear that the shape factor, γ, should not be constant across different binder classes.

On first examination, due to the consistency of these parameters within a binder grade and nominal aggregate size, it may be practical for design purposes to define the whole master-curve using one point only and use this point to shift the master-curve either up or down based on a limited number of test points. While this will not be as accurate as the measurement of the whole master-curve and risk may be associated with its use, it may be a practical solution for level 2 analysis, with level 1 being typical modulus values and level 3 being the measurement of the whole master-curve.

4.4 Grouping of Australian Mixes

The initial intent of the APS-fL project was to validate and calibrate one of the two well-known prediction models for dynamic modulus. However this may not be necessary. Unlike the US, Australia has limited grades of binder and these grades are controlled under and Australian Standard. Also, as show in Section 3, the volumetric properties and gradations for typical Australian mixes do not vary to a great extent between suppliers and even between states regardless of the design method used or specification. Given the consistency of; gradation, volumetric properties, and the consistency of the shape of the master-curve, for a given binder type and nominal mix size. It may not be necessary in Australia for practical implementation to develop complex master-curve equations such as the Witczak or the Hirsch model for routine pavement designs. It may be more relevant to group or sub group mixes to have typical modulus values.

To investigate the applicability of this approach the dynamic modulus results were grouped by nominal aggregate size (14 and 20mm) and binder grade (C320, AR450 and C600) to produce six subgroups within the study. The data from each of these subgroups was then used to create a typical master-curve for all results with that subgroup. The validity of using these typical master-curves for design will understandably depend on the accuracy of the typical master-curves in the prediction of modulus and the degree in which confidence can be obtained around those results.

To investigate this validity, the relative accuracy of the proposed approach was compared against the accuracy of the two well-known models for the prediction of dynamic modulus, the Witczak and Hirsch models. To undertake this comparison the accuracy obtained from the prediction of modulus using the grouped results was compared against the published accuracy of both the Witczak and Hirsch models in terms of the coefficient of determination and the standard error (R^2, S_e).

As shown by Bari (2006), the current versions of the Witczak and Hirsch models have a R^2 of 0.9 and 0.92 respectively in the log space and 0.8 in the arithmetic space for the Witczak model. Given the range of data used in the two published data sets (Witczak/Hirsch) and the AAPA database are very similar (500 to 25000MPa), comparison of the coefficient of determination alone, will provide a good comparison of the relative accuracy of the two approaches.

The accuracy of the grouping approach can be seen in Figure 5 following, which shows the measured modulus against and the typical modulus master-curve for the six grouped mixes, grouped by nominal aggregate size, 14 and 20mm mixes and the three primary binder classes used in Australia, C320, AR450 and C600.

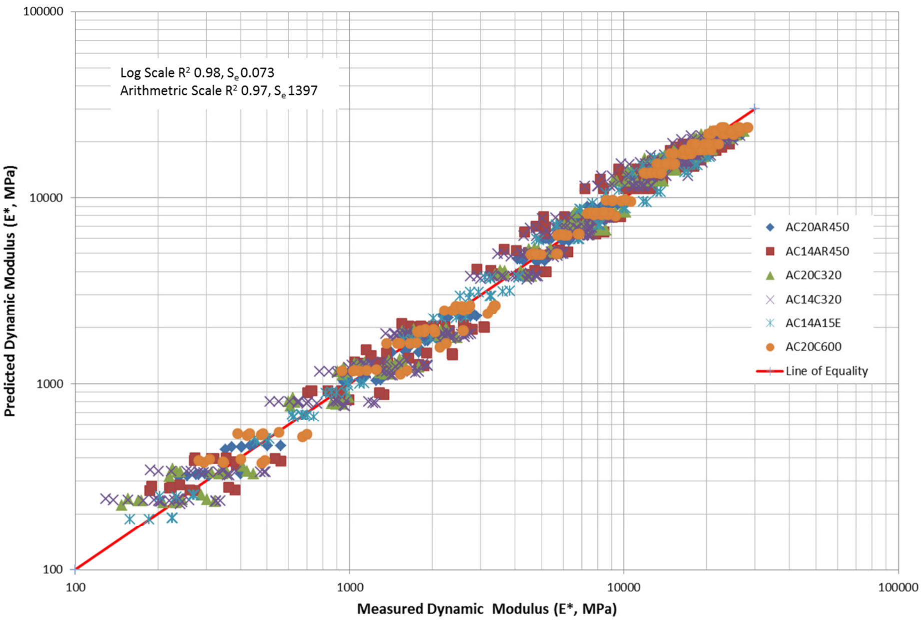


Figure 5 Accuracy of Grouping Approach

As can be seen in the Figure the grouping of results provided and “excellent” fit with the coefficient of determination (0.98), this accuracy is significantly better than both the Witczak and Hirsch models (0.9 and 0.92) in both the log and arithmetic space.

These findings are significantly beneficial to Australia, with the results indicating that Australia can achieve a higher degree of confidence in the predicted modulus values by grouping common mixes together, than from the use of complex model forms, such as the Hirsch and Witczak models which require volumetric properties, binder shear modulus and aggregate gradation, all of which will not be typically available to the consultant.

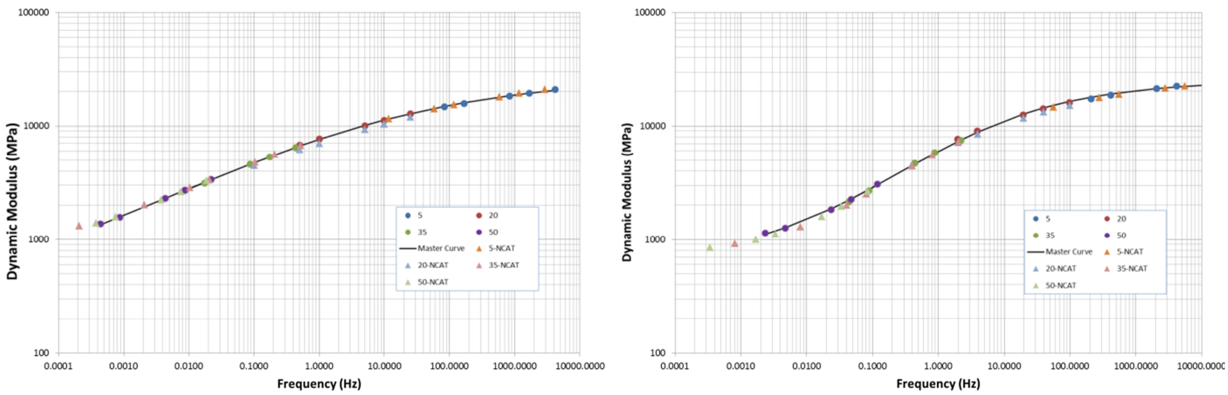
4.5 Correlation with NCAT

In order establish if there was any bias or variability between the Shear-box compacted samples and samples compacted using the US by the Superpave Gyratory Compactor and most importantly, if Australia can use the results of NCAT testing to develop and calibrate performance models, four Shear-box compacted samples compacted in Australia were shipped to NCAT for comparison testing. In addition, two loose mixes were sent to NCAT for compaction in the SGC. This was undertaken to enable a direct comparison to be made between the Shear-box compacted samples and the SGC samples. It needs to be noted that because of the time between compaction and testing the Shear-box compacted samples sent to the NCAT could have been up to up to 3 month old.

For the two mixes where a direct comparison of the NCAT testing could be undertaken (Shear-box and SGC), similar behaviours where observed in the dynamic modulus results at different frequencies and temperatures. However, for both mixes, the shear-box compacted specimens were slightly stiffer than the SGC fabricated specimens across the full range of temperatures and frequencies. For both mixes, there was an increase in stiffness of typically 10% between the Shear-box compacted samples in comparison to the SGC prepared samples. For each mix, the master-curves behaved in identical fashion over the full range of temperatures and frequencies but were separated by an offset. This separation in the curves could be caused by several variables. Initially it could be concluded that the most likely differences are in the way the specimens were handled and compacted in the laboratory during the specimen fabrication process. However, the direct comparison between samples tested in Australian just after fabrication and by NCAT after fabrication in the SGC, shows this is not the case.

The direct comparison between the two approaches was undertaken by comparing the dynamic modulus results obtained at NCAT against that of the dynamic modulus results obtained in the AAPA study using the shear-box compacted samples. What was quickly noticed is that the trend was the same as the trend found in the direct comparison undertaken by NCAT, that the older samples (results obtained by NCAT) were about 10% higher than that recorded in the APPA study. Given the trend was the same as found by NCAT, the results it would indicate a slight aging of the samples and that the stiffness has increased in the period between fabrication and testing.

This aging was confirmed when the results of the NCAT prepared SGC prepared samples where compared directly to the results obtained in the AAPA study, as shown in Figure 6 following. The results show that for all practical purposed the two master-curves are identical.



(a)

(b)

Figure 6 NCAT and APPA Modulus Results (a) mix 14-10, (b) 14-13

This would indicate that the differences seen in the comparison of the results obtained by NCAT between the SGC samples and Shear-box compacted samples, as well as the difference seen between the NCAT tested Shear-box samples and the AAPA results are primarily due to a slight aging of the samples.

The comparison of the results on the two un-aged samples show that the difference in the compaction method and test method have no practical influence on the dynamic modulus results, with identical results obtained. Therefore, it can be concluded that the APS-fL project can utilize NCAT modulus results and performance data with confidence for those sites where dynamic modulus testing has been undertaken to:

- Correlate dynamic modulus estimates from back analysis of deflection data
- Validate measured strain and predicted strain using Linear Elastic Analysis
- And, develop threshold strain levels based of calibrated strain and field performance.

5 Typical Master-curves and Development of Confidence Intervals

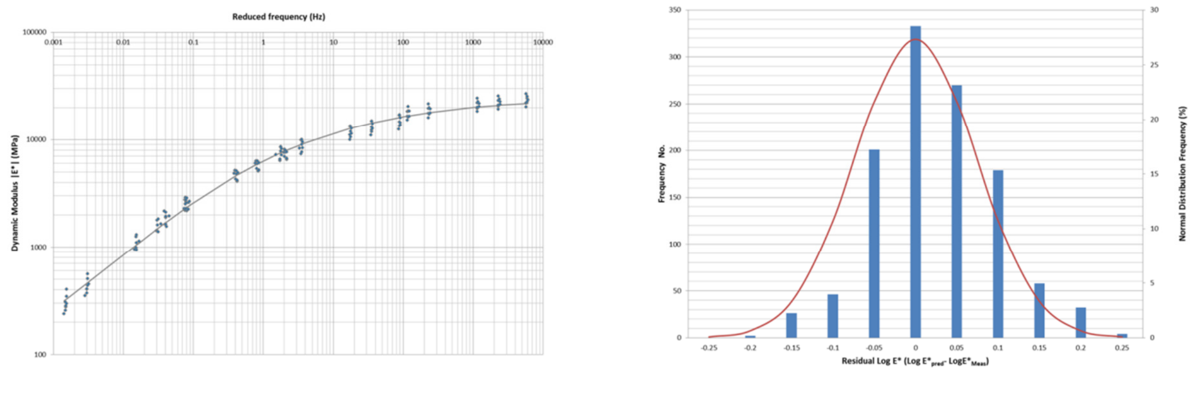
As already established the modulus of the grouped mixes will vary throughout Australia in production due to use of RAP, binder source, and effective binder content amongst others factors. At least initially this variation will not be known to the pavement designer who will not know the binder source, aggregate gradation and percentage of RAP. The designer will generally only specify a grade of binder and a nominal aggregate size. While the results of the grouping approach showed that the variation prediction was small compared to published prediction models, it does present some risk in the design process. Therefore the designer should consider the risk, or the level of confidence required from the modulus, when assigning a design modulus for the purposes of pavement design.

One of the main benefits of the grouping approach is that this risk can be rationally assessed as confidence limits can be developed around the prediction of modulus. There rational confidence levels can be established because, like most engineering parameters the prediction of modulus should follow a normal distribution and by using this distribution and the variation or standard error in the prediction, it is possible to assign confidence to the prediction of modulus values. This is a significant benefit over the typical median values developed by standard predictive models.

5.1 Distribution of Errors Around Master-curve

Like most of the engineering parameters the prediction of dynamic modulus is assumed to follow a normal distribution, this assumption can be easily checked by plotting a histogram of the residuals or errors (difference between measured and predicted values). If the results are normally distributed a plot looking like a normal distribution centred on zero should be obtained.

For the prediction of dynamic modulus from the grouped data, it was found that the residuals followed a normal distribution where the residual was in the log space i.e. $\log(E^*_{measured})$-$\log(E^*_{predicted})$. A typical plot of the residuals, in the log space, is shown in Figure 7 in this case for the AC14 C320 mixes.



(a) (b)

Figure 7 Typical Modulus Grouping Results and distribution of errors around the master-curve

As can be seen from the previous figure, the shape of the distribution closely follows that of a normal distribution with the standard deviation equal to that of the standard error. This results show that for practical purposes the errors can be assumed to follow a normal distribution in the log space. This finding is important in developing confidence in the prediction of results, as it shows that a normal distribution can be placed directly around the sigmoidal function in the log space

5.2 Development of Confidence Based Master-curves

Given the residual errors around the master-curve, can be assumed to follow a normal distribution with the standard error equal to the standard deviation, it is possible to establish confidence limits using this normal distribution and the known standard error, for each of the proposed grouping of Australian production mixes. The practical result of this will be the designer will be able to say they are x% confident that the adopted modulus value used in design will not exceed the design value.

As the residuals are normally distributed around the master-curve, for practical purposes the master-curve can be simply shifted up and down on the modulus axis to obtain any degree of confidence. This means that for design purposes confidence limits can be simply established by simply varying the α parameter to shift the curve up or down to cover a greater or lesser number of results or simply assigning the normal distribution to the minimum modulus value. Because of the limited sample size used in the grouping of mixes, it was decided that a student's t distribution would give a better measure of confidence than that of the normal distribution. The student's t distribution was used in preference to the normal distribution to account for the limited observations obtained from the normal distribution for estimating the confidence value of the α parameter.

The students t distribution and standard error where then used to determine the minimum modulus value, α, which would give 50, 75 and 95% confidence in prediction of modulus for all sub groups of Australian mixes. The full listing of confidence values and master-curves for each subgroup can be found in Sullivan (2013). Figure 8 following shows one of the typical confidence interval plots, in this case AC14 AR450 mixture.

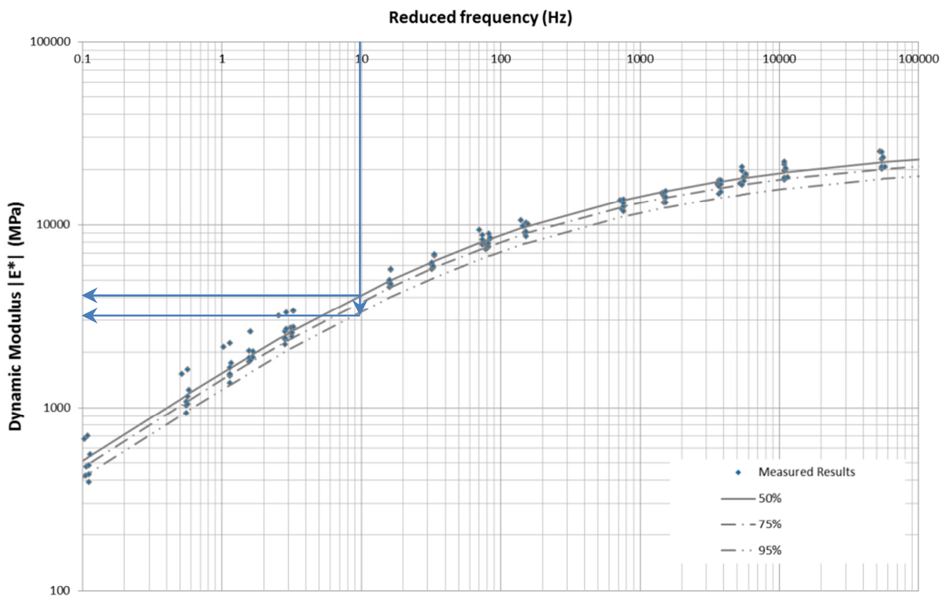


Figure 8 Confidence Interval Master-curve

Using this figure the designer can easily establish the modulus of a standard Australian mixt at any temperature, frequency of loading and confidence level.

For example if the designer wants to establish the modulus of the mix at a frequency of 10Hz and 25°C. The first step would usually be to calculate the reduced frequency, however because the temperature required is the reference temperature, no shift is required on the frequency axis and the reduced frequency is the frequency required. The designer then simply selects 10Hz on the horizontal scale and follows the value down till it meets the desired confidence master-curve. The value is then read off the vertical axis, in this case 3000MPa at 95% confidence or 4000MPa at 50% confidence.

6 Conclusions and Recommendations

International research has established that the dynamic modulus test provides a better characterization of an asphalt mix over the resilient and other modulus test because of its ability to fully characterise a mix over a range of temperatures and load frequencies. Additionally, the dynamic modulus test is, internationally accepted as being able to discriminate key asphalt performance properties. For these reasons, and most importantly, the ability to link dynamic modulus to a number field studies, APPA selected the dynamic modulus test to undertake a full characterisation of standard Australian production mixes for the APS-fL project.

Examination of the gradation and volumetric properties of the standard Australian production mixes shows that remarkably given the variability in the design methods (Marshall, gyratory and Superpave) and the differing compaction efforts, all mixes fit into a very small volumetric window. Additionally it was found the design gradation of all standard Australian production mixes closely follow the maximum density line, with nearly all mixes being slightly coarse graded. Indicating that distinguishing between Australian mixes based on gradation and volumetric properties may be difficult.

The comparison of the results obtained by AAPA and NCAT on two un-aged samples show is that the difference in the compaction method and test method had no influence on the measured dynamic modulus results, with identical results obtained. Therefore, it can be concluded that the APS-fL project can utilize the results of NCAT testing for modulus and performance data with confidence:

- Correlate dynamic modulus estimates from back analysis of deflection data
- Validate measured strain and predicted strain using linear elastic analysis
- And, develop fatigue endurance limits.

Examination of the master-curves of standard Australian production mixes suggests the minimum modulus value appears to be the best at distinguishing the different between binders and nominal aggregate size. As there is little difference in the volumetric of Australian mixes, no significance could be found in air void levels or binder contents within sub mix types. Unexpectedly no correlation was found between the minimum modulus and RAP content, indicating that at current RAP levels, RAP has little effect on the minimum modulus value and therefore overall modulus values. The results showed that most likely because of the small variance in aggregate gradation and volumetric properties there was no change in the shape of the master-curve within grouped binder types and nominal aggregate size.

Because of the consistency of the master-curve for a given binder type and nominal mix size for practical implementation, it was found that it was not necessary to develop complex master-curve equations for routine pavement designs. With the results of grouping of Australian mixes together showing that Australia can achieve a higher degree of accuracy by grouping common mixes together than from the use of complex model such as the Witczak or the Hirsch models.

It was found that because the errors in the prediction of modulus followed a normal distribution with the standard deviation equal to that of the standard error, confidence could be established from the grouped data by simply varying the minimum modulus data to move the dynamic modulus curve down the modulus scale. By doing this it was shown that confidence level master-curves could be established for the nominal 14 and 20mm mixes and the three primary binder classes used in Australia, C320, AR450 and C600.

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