

COMPARISON BETWEEN RESILIENT MODULUS AND DYNAMIC MODULUS OF WESTERN AUSTRALIAN HOT MIX ASPHALT BASED ON FLEXIBLE PAVEMENT DESIGN PERSPECTIVES

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ABSTRACT

The modulus of asphalt concrete material is one of the major input parameters in mechanical-empirical pavement design and analysis. In Australia, current pavement design approaches rely on the resilient modulus of the asphalt material, and visco-elastic behaviour cannot be incorporated into this pavement analysis and design. However, in the USA, the NCHRP 1-37A design guide for Mechanistic-Empirical pavement design (ME design) uses the dynamic modulus to express the intrinsic behaviour of this important input parameter, i.e., the visco-elasticity of an asphalt material, over a range of temperatures and loading frequencies. This study aims to examine whether the dynamic modulus which is converted from a resilient modulus test is different to the resilient modulus when considering as a modulus input for pavement design. Three different asphalt concrete mixes, with varying maximum aggregate sizes of 7, 10, and 14 mm were selected as mix representatives. All test specimens were controlled using a gyratory compactor to produce a 5% air void. To determine the resilient modulus and the dynamic modulus respectively, a UTM-25P and an Asphalt Mixture Performance Tester (AMPT) were used. In addition, pavement design exercises were performed on pavement structures typical to Western Australia. The exercises evaluated the difference of tensile strains at the bottom of asphalt layer derived from the different input parameters of the resilient and dynamic moduli.

INTRODUCTION

Asphalt concrete plays a fundamental role in flexible pavement structure systems. In particular, as a surface layer, the concrete must withstand varying traffic loads and constantly changing environmental conditions. Not only can these conditions be extreme, they also vary across locations and over time. As it stands, pavement design considers only one environmental condition in its process, a measure which is unable to provide accurate information on the actual or real effects of the environment on pavement conditions. Thus, the incorporation of a range of design conditions, such as the varying of traffic loads and temperatures, would provide greater accuracy with regard to structural analysis and design. Currently, the Australian design approach relies on a single value for the resilient modulus, and this is obtained from snapshot test conditions with a single loading time and temperature. The difficulties with the varying of traffic loading and environmental conditions to simulate actual pavement conditions include the numerous tests that would be required. These would consume much more testing time than that of the conventional resilient modulus test. The resilient modulus is theoretically an ideal elastic modulus (Huang 2004), which only considers recoverable strain, but an asphalt concrete material is believed to respond as a viscoelastic material.

In the USA, the NCHRP 1-37A design guide (TRB 2004) uses the dynamic modulus as an input parameter which can express the intrinsic behaviour of visco-elasticity across a range of temperatures and frequencies (or loading times). The standard dynamic modulus test by AASHTO TP62-07 (AASHTO 2003) has a significant benefit in that it saves testing time by requiring only one test sample to cover a relatively wide range of test conditions. By doing this, 4°C to 54°C of temperatures and 0.1 Hz to 25 Hz of frequencies are set up to apply to a single

test sample with appropriate loading magnitudes in order to maintain the linear viscoelastic range (LVE) of an asphalt sample across test conditions (more details can be seen in the laboratory work section). The dynamic modulus master curve is the comprehensive test result of which the dynamic moduli corresponding to temperatures and loading frequencies are represented through a sigmoidal function. The results of the dynamic modulus test correspond much more closely to real pavement conditions, and these results can be captured and applied in pavement structural analysis and design.

To prepare a smooth transition for the use of the dynamic modulus in Australian pavement analysis and design, this study aims to investigate Australian mechanistic-empirical pavement design and analysis using the two different input parameters of the resilient modulus and the dynamic modulus, based on the representative asphalt mixture of a typical Australian mix, Dense Graded Asphalt (DGA), with three different maximum aggregate sizes; 7, 10, and 14 mm. If the results from this investigation demonstrate the effect of these two input moduli, then this should provide a guide to improving the Australian mechanistic-empirical pavement design and analysis approach.

THEORETICAL BACKGROUND

Resilient modulus

Based on the standard resilient modulus test for asphalt concrete, the resilient modulus is the ratio of an applied cyclic load to the recoverable horizontal strain of a test sample. The plastic strain occurring while applying a load in any waveform in a vertical direction, with a given rest period, is usually ignored (Huang 2004). The resilient modulus can be generally defined as the ratio between an applied stress (force) and a recovered strain (deformation), shown in equation 1. The formula to obtain the resilient modulus value from the particular resilient modulus test in accordance with AS 2891.13.1-1995 (Australia Standards 1995) is shown in equation 2. Figure 1 demonstrates an example of the pulse shape of an applied force and the induced horizontal deformation measured during the test. Figure 1 also shows standard loading pulse conditions of rise time, pulse repetition period, loading time, and rest period, according to AS 2891.13.1-1995 (Australia Standards 1995). The resilient modulus is the elastic modulus under cyclic loading conditions, but it is known that asphalt concrete is a viscoelastic material, and therefore the elastic theory cannot precisely explain the relatively complex behaviour of an asphalt concrete material with its inherent time and temperature dependency properties. Thus, the resilient modulus may not be efficient and sensitive enough to embrace the range of asphalt concrete properties evidenced at different temperatures and speeds.

$$M_r = \frac{\sigma_d}{\varepsilon_r} \quad (1)$$

$$E = P \times \frac{(v+0.27)}{H \times h_c} \quad (2)$$

Where:

M_r , E	is resilient modulus (MPa)
σ_d	is deviator stress (kN)
ε_r	is recoverable strain
P	is peak load (N)
v	is Poisson ratio (0.4 according to AS 2891.13.1-1995)
H	is recovered horizontal deformation (mm)
h_c	is height of specimen (mm)

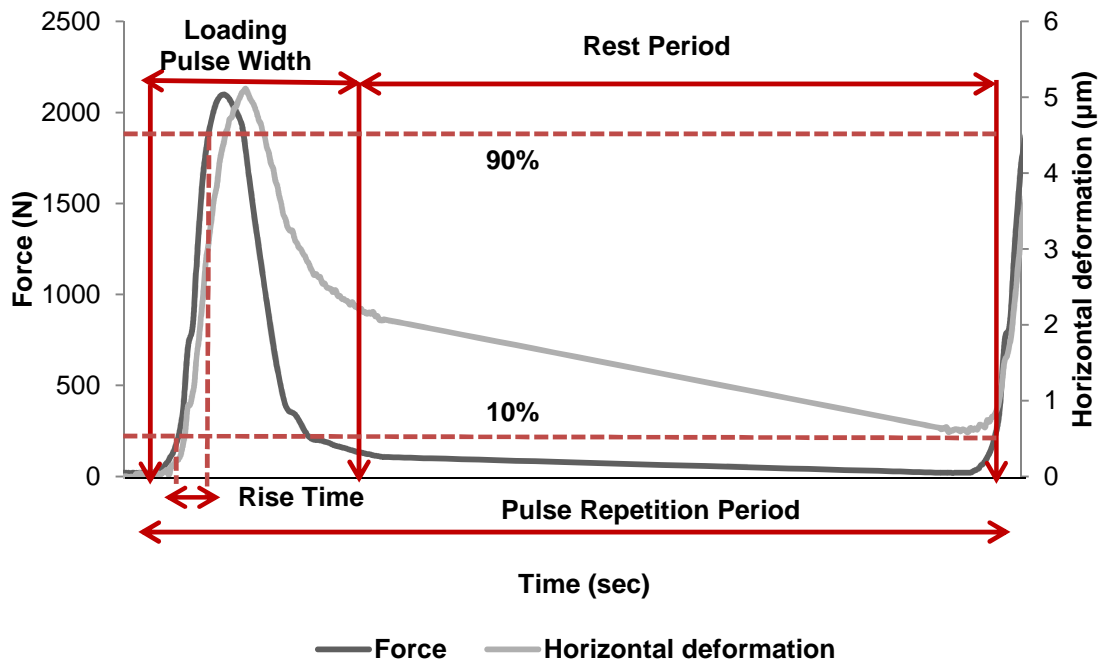


Figure 1: Force and Horizontal Deformation Pulse Shapes for Resilient Modulus.

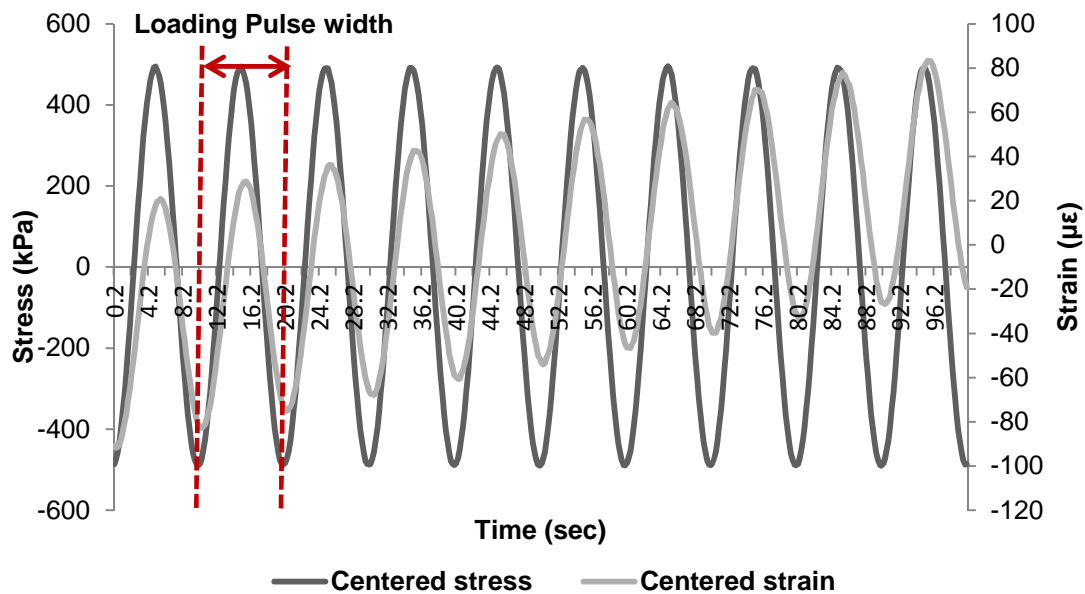


Figure 2: Stress and Strain Pulse Shapes for Dynamic Modulus.

Dynamic modulus

The stress-strain relationship of viscoelastic material can be described by the complex modulus (Kim 2009) which consists of two parts; the real value part represents the elastic stiffness, and the imaginary part represents the internal damping (Huang 2004). The dynamic modulus is the absolute value of the complex modulus which is derived from a continuous sinusoidal (or haversine load), without a rest period. The dynamic modulus value is the ratio between an applied stress and an induced strain as shown in equation 3. Figure 2 shows the continuous sinusoidal pulse applied stress shape along with an induced strain wave, of which can be expressed by equation 4 and 5 respectively.

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \quad (3)$$

$$\sigma = \sigma_0 \sin(\omega t) \quad (4)$$

$$\varepsilon = \varepsilon_0 \sin(\omega t - \phi) \quad (5)$$

Where:

- |E*| is dynamic modulus (MPa)
- σ_0 is peak stress (kN)
- ε_0 is peak strain
- ω is angular frequency (rad/sec)
- t is time (sec)
- ϕ is phase angle (degrees)

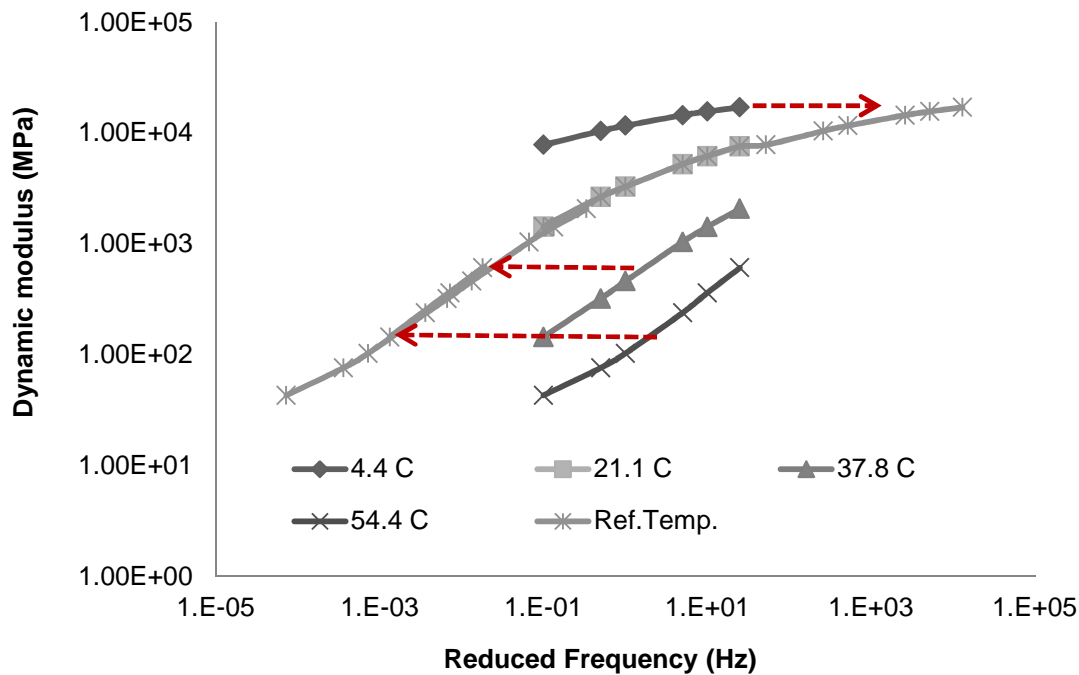


Figure 3: Dynamic Modulus Master Curve

Master curve

A single smooth curve which aligns multiple temperatures of dynamic modulus values in frequency domains is called the master curve. This curve represents the dynamic modulus values over an observed range of temperatures and frequencies. To achieve a single smooth line, the Time Temperature Superposition principle (TTS) (Pellinen et al., 2002, Kim, 2009) is applied by multiplying an actual frequency with a shift factor, $a(T)$, to create one domain called the reduced frequency (equation 6). According to AASHTO PP62-09 (AASHTO 2009), there are two recommended shift factor functions, the MEPDG shift factor and the second-order polynomial function. Both functions rely on a reference temperature. The MEPDG shift factor function requires more viscosity properties from the asphalt binder as inputs. As such this shift factor is not practical for use in Australia, where suitable test facilities are limited. Consequently, this study investigated only the second-order polynomial function (equation 7) which is likely to be more practicable in terms of existing Australian test facilities obtaining its function inputs.

$$\log f_r = \log f + \log[a(T)] \quad (6)$$

$$\log[a(T)] = a_1(T_R - T) + a_2(T_R - T)^2 \quad (7)$$

Where:

f_r	is reduced frequency (Hz)
f	is frequency (Hz)
$a(T)$	is shift factor
T_R	is reference temperature (°C)
T	is temperature (°C)
a_1, a_2	is fitting coefficient

A sigmoidal function (Bonnaure et.al. 1977) was used in conjunction with the second-order polynomial shift factor function to create a smooth and more reliable master curve due to the sigmoidal function having a slight swing at low and high temperatures when compared to the polynomial function. As a result, it is possible to make predictions and even extrapolate moduli, outside the range of test conditions, to any temperature and frequency.

$$\log(|E^*|) = \delta + \frac{\alpha}{1 + e^{\beta - \gamma \log f_r}} \quad (8)$$

Where:

$ E^* $	is dynamic modulus (MPa)
δ	is minimum $\log(E^*)$
α	is span of $\log(E^*)$
β, γ	is shape parameter

LABORATORY WORK

Two major test methods were used in this study for the determination of the asphalt concrete modulus; the Resilient Modulus in accordance with AS 2891.13.1-1995 (Australia Standards 1995) and the Dynamic Modulus in accordance AASHTO TP62-07 (AASHTO 2003).

Materials

Three types of Dense Graded Asphalt (DGA) of maximum sizes were selected (7 mm, 10 mm, and 14 mm) to prepare the test samples for both modulus test methods. The gradation details of the 3 DGA mixes are shown in Table 1. One bitumen binder type, C170 (Standards Australia 1997), was used throughout this study, 5% by total weight.

Sample preparation

Two sizes of cylinder moulds were selected, namely a 150 mm mould for the dynamic modulus tests and a 100 mm mould for the resilient modulus test. These were then used to prepare test samples using the gyratory compaction method, following AS 2891.2.2-1995 (Australia Standards 1995), to achieve target heights of 170 mm and 65 mm for the dynamic modulus test and the resilient modulus test respectively. The Survopac gyratory compactor (IPC 2000) was utilised to compact test samples until they reached a $5 \pm 0.5\%$ target air-void at $150 \pm 5^\circ\text{C}$. The dynamic modulus test samples required sample-coring and top-bottom cutting to obtain the standard test sample dimension of 100 mm in diameter and 150 mm in height according to AASHTO TP62-07 (AASHTO 2003).

Testing procedure

Resilient modulus

The resilient modulus tests were conducted in accordance with AS 2891.13.1-1995 (Australia Standards 1995), where repeated load indirect tensile (IDT) techniques are applied to determine the resilient modulus of a test sample. A Universal Testing Machine with a 25kN load capacity (UTM-25P) was utilised with a conditioning sample placed in the temperature cabinet at a single temperature of $25 \pm 5^\circ\text{C}$ for 2 hours. Following the temperature conditioning stage, the resilient

modulus test was performed by applying haversine load pulses to generate the recoverable horizontal strain of $50 \pm 20 \mu\epsilon$ with a rise time of 0.04 ± 0.005 s and a pulse repetition period of 3.0 ± 0.005 s.

Dynamic modulus

The Asphalt Mixture Performance Tester (AMPT) (IPC 2010), a stand-alone testing machine, with an environmental chamber and a measuring system, was utilised to perform the dynamic modulus tests in accordance with AASHTO TP62-07 (AASHTO 2003). This study set a testing range of four temperatures; 4°C, 21°C, 37°C, and 54°C, along with six loading frequencies of 0.1 Hz, 0.5 Hz, 1 Hz, 5 Hz, 10 Hz, and 25 Hz, to obtain a series of dynamic modulus values for the generation of the master curve. Stress levels, equilibrium time and the number of cycles were as recommended by AASHTO TP62-07 (AASHTO 2003), and can be seen in Table 2.

Table 1: Particle Size Distribution for this study

Size Sieve (mm)	Percent Passing (%)		
	7 mm	10 mm	14 mm
26.5	100.0	100.0	100.0
19.0	100.0	100.0	100.0
13.2	100.0	100.0	98.0
9.5	100.0	97.9	83.8
6.7	98.3	81.0	68.2
4.75	83.1	65.5	52.8
2.36	57.6	44.2	35.7
1.18	41.9	30.6	25.1
0.6	31.4	20.9	17.4
0.3	18.4	13.4	11.5
0.15	8.6	8.0	7.2
0.075	4.8	5.2	5.1

Table 2: Recommended Stress Level, Equilibrium Time and Number of Cycles

Temperature (°C)	Stress level (kPa)	Equilibrium time (Hour)	Frequency (Hz)	Number of Cycles
			25	200
			10	200
4	700-1400	4 hrs or overnight	5	100
21	350-700	3	1	20
37	140-250	2	0.5	15
54	35-70	1	0.1	15

Test results

Resilient modulus (M_r)

Only one resilient modulus value for each mix was obtained from the one resilient modulus test. Figure 4(a) demonstrates that resilient modulus values vary with the maximum size of the

aggregates. The resilient modulus values increase where there is an increase in the aggregate size in the mixture (see figure 4(a)). This trend is in line with the recommended Australian standard, which states that the 14 mm asphalt mixture (i.e., a coarser aggregate size mixture) is likely to be suitable for heavy-duty applications.

The resilient modulus test was conducted under controlled strain conditions in a specific range of $50 \pm 20 \mu\epsilon$ with the applied cyclic stresses being varied to suit the mixture types of different aggregate sizes. Thus, the applied cyclic stresses or loading forces are additionally significant parameters that would be carefully considered to obtain precise resilient modulus values. The applied cyclic loading forces from this study, presented in figure 4(b), show the same trend as the resilient modulus values, by increasing as aggregate sizes become larger (Standards Australia 2005).

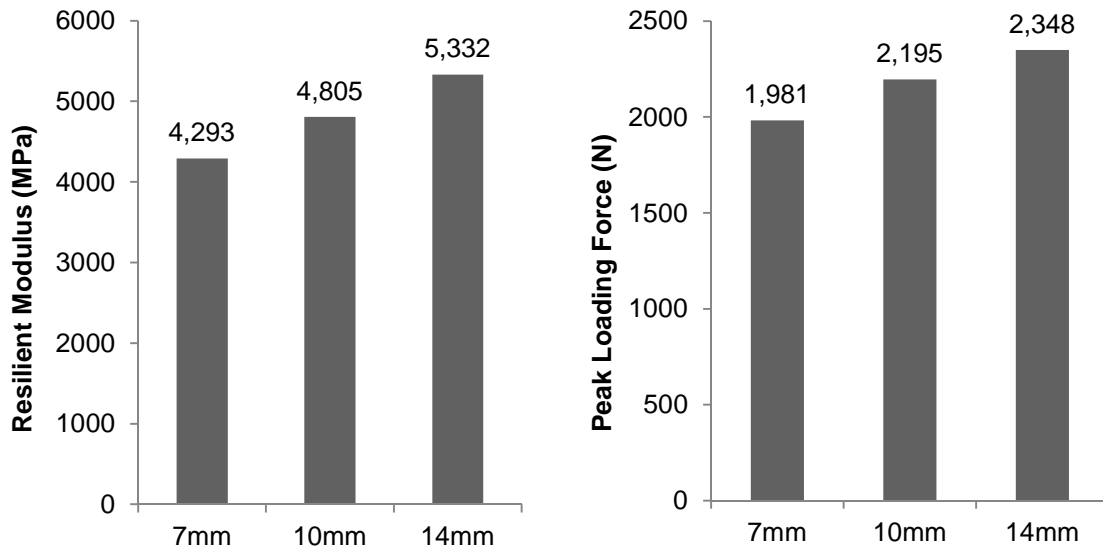


Figure 4: Indirect tension test result; (a) Resilient modulus, and (b) Peak loading force.

Dynamic modulus ($|E^*|$)

Generally, the dynamic modulus test produces two major outputs. These are the dynamic modulus ($|E^*|$) and the phase angle (ϕ), which in this case were derived from the testing conditions using four temperatures and six frequencies (loading time). As a result, a series of dynamic modulus and phase angle values were obtained but only the dynamic modulus values were used to construct the master curve. The second-order polynomial and sigmoidal function were applied for fitting shift factors and constructing the master curve, in conjunction with the non-linear least square method. Optimisation techniques were used to determine the value of fitting coefficients. The computer program, SPSS and the Solver function in MS EXCEL were used as optimisation tools for the purposes of this study. Once all the coefficients were obtained, the master curve was created by applying shift factors to generate reduced frequencies, as seen in Figure 5. Details of the fitting coefficient for each mix are shown in Table 3.

Based on the dynamic modulus test results, asphalt concrete responses to cyclic loading conditions are temperature and frequency dependent. The aggregate sizes may have affected the dynamic modulus values of the asphalt concrete at high frequencies (or low temperatures), as shown in figures 5(a) and 5(b) where the 14 mm master curve line is above the aggregates of 7 mm and 10 mm. Moreover, the fitting coefficient α , a span of the modulus value of the 14 mm mix, is the highest of all. This result is consistent with the resilient modulus values in relation to the aggregate sizes given in the previous section. In addition, the phase angles and the shift factors, representing the visco-elastic properties and temperature dependency of asphalt concrete respectively, are not affected by aggregate sizes due to the slight difference among the phase angles and shift factor values of all mixes, as shown in Figure 5(c) and 5(d).

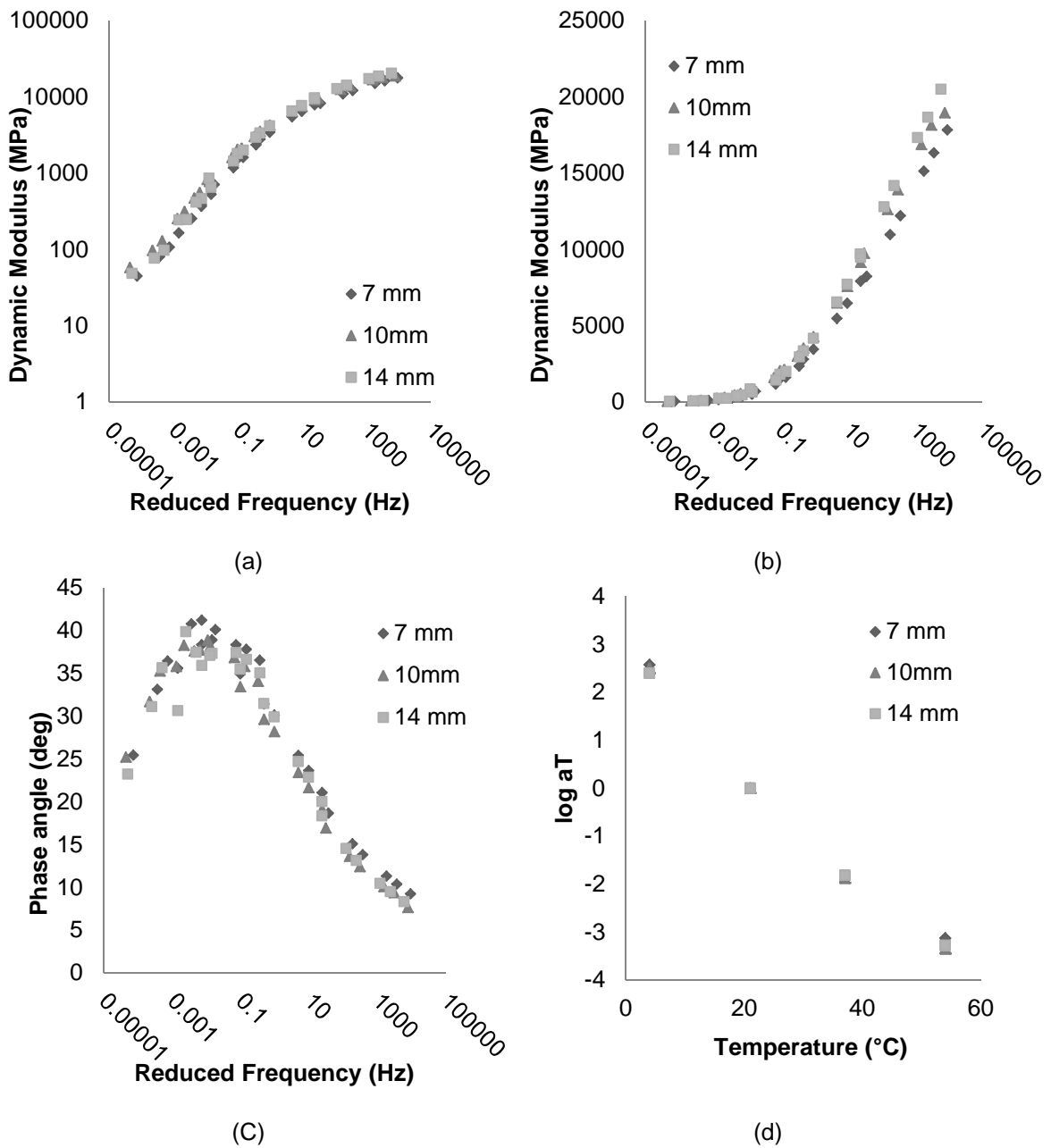


Figure 5: Characterisation of asphalt concrete; (a) $|E^*|$ in logarithmic space, (b) $|E^*|$ in semi-logarithmic space, (c) Phase angle, and (d) Shift factor.

Table 3: Fitting coefficient for constructing master curve

Parameter	Initial value	Estimated value		
		7mm	10mm	14mm
δ	0.5	-0.25286	-0.2965	-0.29847
α	3	3.740696	3.842805	3.870229
β	-1	-1.31576	-1.42346	-1.36451
γ	-0.5	-0.55419	-0.51654	-0.54018
a_1	0.1	0.073573	0.073165	0.070497
a_2	0.0001	0.000353	0.000283	0.000257

Comparison between M_r and $|E^*|$

Based on the fundamental definitions of the resilient modulus and the dynamic modulus, it is almost impossible to directly compare the resilient modulus and the dynamic modulus. As mentioned previously, the resilient modulus test was performed under only one temperature and frequency testing condition and the dynamic modulus test was performed across a range of temperature and frequency testing conditions. However, it was possible to compare the dynamic modulus value with the resilient modulus value by using the master curve and the fitting coefficients (Loulizi et al., 2006). Loulizi et al., (2006) suggested that a comparison between both modulus values could be made under the single testing condition (of temperature and frequency) of the resilient modulus test. However, based on the attempt of Loulizi et al., (2006), there is some controversy as to how to convert the loading time from the resilient modulus test into a frequency domain of the dynamic modulus master curve. This issue is discussed in detail in the next section.

Conversion of frequency

The first important matter regarding how to obtain a suitable frequency which can reasonably represent the resilient modulus testing condition could be a magnitude of loading time. According to the conversion method of Loulizi et al., (2006), the resilient modulus tests were performed in accordance with the American standard of ASTM D7369 (ASTM, 2011), of which the loading time was defined as a loading pulse width (one complete loop) of the sinusoidal wave form. However, in Australia, based on the Australian standard of AS 2891.13.1-1995, the loading time could be differently defined as the rise time which is the time of increasing in an applied load from 10% up to 90% of a peak load (see Figure1). It can be seen that due to different applied loading wave forms between ASTM D7369 (ASTM, 2011) and AS 2891.13.1-1995 (Australia Standards 1995), the loading times from both test standards to rationally represent the test condition of resilient modulus tests is differently defined, leading to different $|E^*|$ after conversion. Consequently, this study examined the effect of the 0.04s loading time of the rise time according to AS 2891.13.1-1995 (Australia Standards 1995) and the 0.2s loading time of the loading pulse width to make it similar to the method of Loulizi et al., (2006), considering one loop of an applied load (with no consideration of a rest period). It should be noted that ASTM D7369 recommended 0.1s of the loading pulse width but this study specified 0.2s because a loading shape was adjusted to reach the target recoverable horizontal strain in the range of $50 \pm 20 \mu\epsilon$ according to AS 2891.13.1-1995.

The second important matter is an appropriate type of a frequency which should be used for conversion. The applied loading time from the resilient modulus test can be converted into two forms of frequencies; an angular frequency, and a time frequency. However, based on the definitions of frequencies (see equations 9 and 10), the values (or magnitudes) of both frequencies could be significantly different. If so, this would lead to an incorrect conversion from the resilient modulus to the dynamic modulus. Consequently, the right frequency for this modulus conversion must be defined. As mentioned in the theoretical background, the dynamic modulus is calculated from the ratio of magnitudes of applied cyclic stress and induced total strain (see equation 4). The magnitude of the applied stresses and induced strains result from the sinusoidal function with angular frequencies. Therefore, to comply with the periodic (sinusoidal) function with angular frequencies from the dynamic modulus test, the applied loading time in the resilient modulus test would be converted to *the angular frequency*.

$$\text{Angular frequency; } f = 1/2\pi t \quad (9)$$

$$\text{Time frequency; } f = 1/t \quad (10)$$

Where:

- f is frequency of dynamic modulus master curve (Hz)
t is loading time of resilient modulus (s)

DISCUSSION OF THE MODULUS CONVERSION BETWEEN THE RESILIENT AND DYNAMIC MODULI

Based on Australian standard resilient modulus test conditions of the 0.04s rise time, the time can be converted into 4 Hz of angular frequency (see equation 9) and 25 Hz of time frequency (see equation 10). For a full one loop of an applied load, the 0.2s loading pulse width can be converted into 0.8 Hz (see equation 9) of angular frequency and 5 Hz of time frequency (see equation 10). For those frequencies, the dynamic modulus of each frequency can be determined graphically from the master curve. Figure 6 shows the comparisons of the resilient moduli (M_r , IDT) and the dynamic moduli ($|E^*|_{R_Angular}$, $|E^*|_{R_Time}$, $|E^*|_{L_Angular}$ and $|E^*|_{L_Time}$) derived from the resilient modulus conversions at 4 Hz, 25 Hz, 0.8 Hz and 5 Hz, respectively.

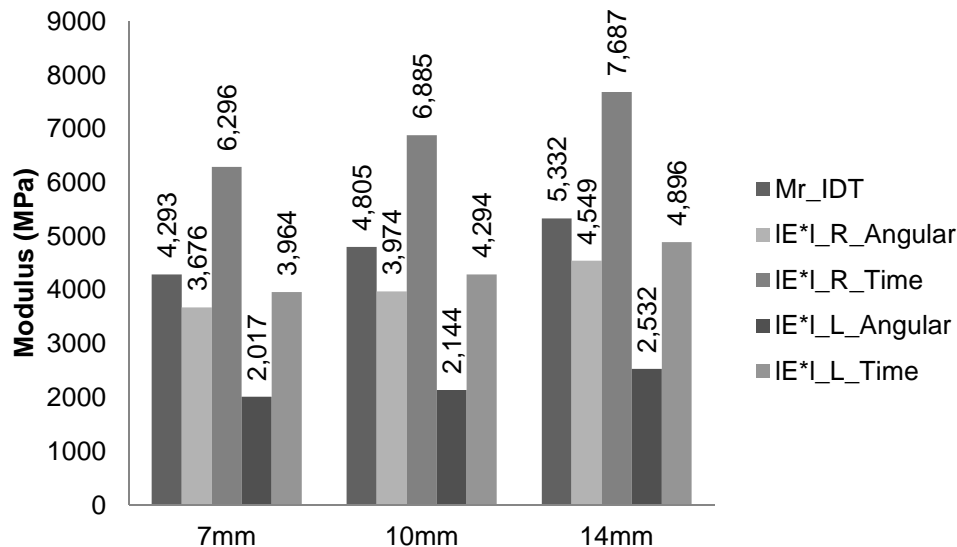


Figure 6: Comparison between M_r and $|E^*|$ under different conditions.

From Figure 6, the resilient modulus conversions to obtain the dynamic moduli show different values corresponding to frequency inputs. Dynamic moduli converted from time frequencies are considerable higher than such moduli converted from angular frequencies.

Furthermore, it can be observed that the resilient moduli are different from the dynamic moduli from the conversions. This would lead to a question about suitability of selecting a modulus input for pavement design. This study also examine how those moduli (M_r and dynamic moduli from M_r conversions) as modulus inputs for pavement design affect to pavement design outputs, through pavement design exercise shown in the next section.

PAVEMENT DESIGN EXERCISE

Modulus of a pavement material in a multi-layered pavement structure is an essential input for pavement design. In Australia, moduli of pavement layers rely entirely upon the resilient moduli. This includes an asphalt surface layer. According to an explanation in the previous sections, the resilient modulus value is significantly different from the value of the dynamic modulus of conversion under the same test conditions (temperature and loading rate). Different values in both moduli as pavement design inputs could result a discrepancy in pavement life predictions. This section aims to examine an important output in terms of tensile strain at the bottom of asphalt layer while using resilient modulus and dynamic modulus from conversion as modulus inputs for pavement analysis. In this study, the number of Equivalent Single Axles (ESALs) to failure (N_f) as a design output was not considered due to the transfer function (i.e., the equation to determine N_f) recommended in the Austroads pavement design guide (Austroads 2010) is based on flexural stiffness modulus of which value can be transformed from the a

resilient modulus value.. The dynamic modulus is not an input of Austroads' transfer function. Consequently, based on the Austroads pavement design guide (Austroads 2010), N_f could not be used to examine an effect of using different modulus inputs in pavement design, therefore tensile strains at the bottom of asphalt layer were used instead. The modulus inputs of this study were set up as; the resilient modulus (M_r _IDT), the dynamic modulus of the resilient modulus conversion from the time frequency ($|E^*|$ _Time), and the dynamic modulus of the resilient modulus conversion from the angular frequency ($|E^*|$ _Angular). To examine difference in such tensile strains in pavement, a pavement design exercise was set up in accordance with the design procedures of the Austroads pavement design guide (Austroads 2010).

According to Austroads pavement design guide (Austroads 2010), the modulus input has to be adjusted to suite with construction and in-service conditions. Air void, temperature, and vehicle speed are considered for the adjustment of a modulus input value. This study used a 5% target air void from a laboratory condition equivalent to an in-service air void. For in-service temperature, Weight Mean Annual Pavement Temperature (WMAPT) is used for temperature adjustment as shown in equation 11. This study selected Perth as a study area in which WMAPT of Perth is 29°C (Austroads 2010). From equation 11 and 29°C, the in-service temperature adjustment is 0.73. For in-service rate of loading (vehicle speed), 80km/hr is selected to be a design speed because the typical speed limit for an arterial road in Western Australia ranges between 60 km/hr and 90 km/hr, therefore the speed adjustment of this study is 0.94 (from equation 12). After adjustments, modulus inputs of a pavement design exercise in this study are shown in Figure 7.

$$\frac{\text{Modulus at WMAPT}}{\text{Modulus at test temperature (T)}} = \exp(-0.08[\text{WMAPT} - T]) \quad (11)$$

$$\frac{\text{Modulus at Speed V}}{\text{Modulus at test loading rate}} = 0.19V^{0.365} \quad (12)$$

Where:

T	is test temperature (°C)
WMAPT	is Weight Mean Annual Pavement Temperature (°C)
V	is in-service vehicle speed (km/hr)

While considering the dynamic modulus as an input of this pavement design exercise, since in-service temperature (29°C) and vehicle speed (80km/hr) were used for the in-service adjustment of resilient modulus, 80 km/hr of the in-service vehicle speed has to be converted into designed frequency based on the effective frequency concept of NCHRP 9-19 (Witczak&Satil, 2004) as shown in equation 13 and 14. Then, designed speed (effective frequency) was converted into angular and time frequencies for using in this pavement design exercise. As a result, 7.9 Hz and 49.5 Hz of angular and time frequencies respectively were used for dynamic modulus conversions, of which results can be seen in Figure 7.

$$t = \frac{2(a+h_{ac})}{17.6v} \quad (13)$$

$$f_{eff} = \frac{1}{t} \quad (14)$$

Where:

f_{eff}	is effective frequency (Hz)
t	is time of loading (second)
a	is the radius of tyre pressure (4.886 inch)
h_{ac}	is thickness of asphalt concrete layer (3.93 inch)
V	is speed of vehicle (mph)

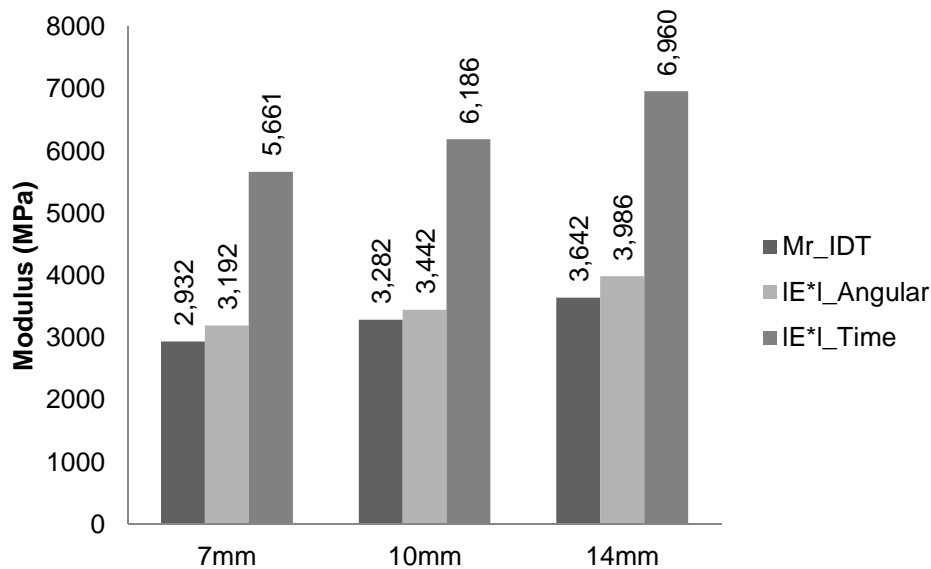


Figure 7: Comparison between designed M_r and $|E^*|$.

Figure 7 shows the comparison between designed resilient modulus (M_{r_IDT}), the dynamic modulus of the resilient modulus conversion using the angular frequency ($|E^*|_{_Angular}$), and the dynamic modulus of the resilient modulus conversion using the time frequency ($|E^*|_{_Time}$). In Figure 7, it can be seen that there is considerable difference in dynamic modulus values between converted from angular and time frequencies. $|E^*|_{_Angular}$ illustrates slightly higher values than M_{r_IDT} for all mixes.

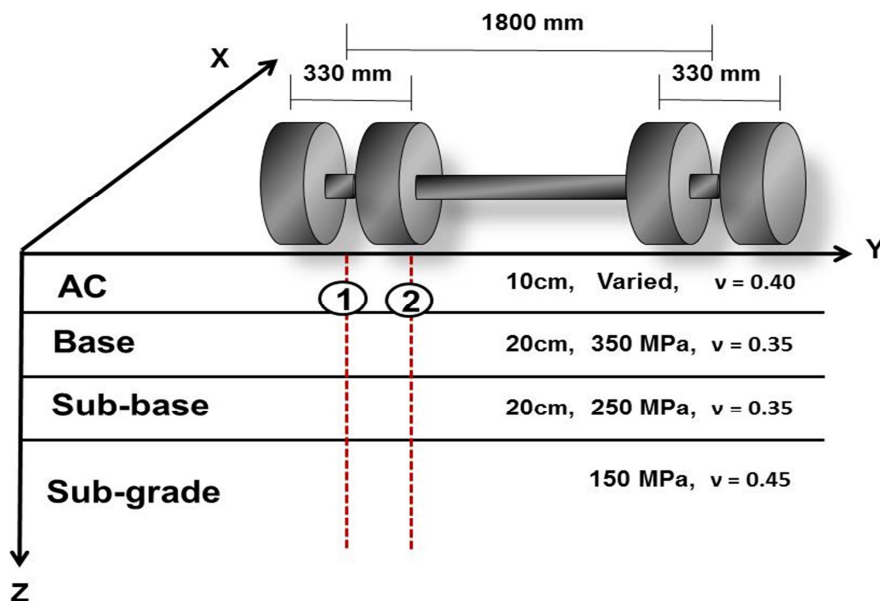


Figure 8: Pavement structure and load configuration.

A typical four-layer pavement structure was used for this pavement design exercise. Figure 8 shows the pavement and ESAL configurations, along with the input values of the layer properties: thicknesses, moduli and Poisson's ratios. It should be noted that the wheel load representing the ESALs complied with Austroads' pavement structural design (Austroads 2010), in which the lengths of the wheel spacing, centre to centre, measured 330 mm, 1470 mm, and 330 mm (see Figure 8). The magnitude of load applied per wheel was 20kN with an applied stress of 750kPa. Figure 8 also shows where the two critical strain locations in the asphalt layer were determined.

The linear elastic computer program, BISAR (Shell 1985) was utilised to determine the critical tensile strains occurring at the locations illustrated in Figure 8. The results of the strain determination demonstrate that the higher the moduli (i.e., larger aggregate sizes of asphalt mixtures), the lower the critical tensile strain values. Figure 9 shows the comparison of the critical tensile strains corresponding to the modulus inputs. In Figure 9, it is evident that the dynamic modulus of the resilient modulus conversion using the time frequency ($|E^*_I|_{Time}$) results in the lowest critical strain, which may lead to an over-estimated N_f . The designed resilient modulus input (M_{r_IDT}) and the dynamic modulus of the resilient modulus conversion using the angular frequency ($|E^*_I|_{Angular}$) result in close critical strain values. When comparing critical tensile strains from both locations, the inner wheel location exhibits the larger critical strain, which can be used for a design purpose with an aim of conservative or safer design.

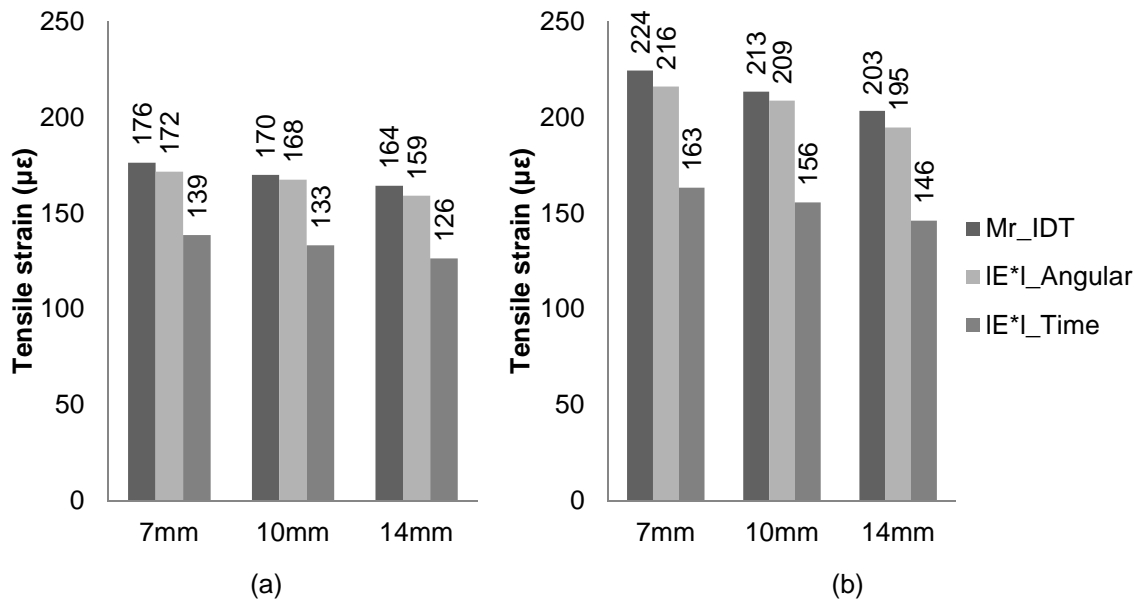


Figure 9: Critical tensile strain at; (a) centre of dual wheels (b) centre of inner wheel.

Based on the results of an pavement design exercise, shown in Figure 9, the question of whether the dynamic modulus from the resilient modulus conversion can be used in pavement design still exist. A conclusive solution cannot be made but the outcomes of tensile strains derived from the designed resilient modulus and the dynamic modulus of the resilient modulus conversion using the angular frequency have approximately no discrepancy.

CONCLUSION

The resilient modulus and dynamic modulus of an asphalt concrete material are the input parameters for the mechanistic-empirical pavement design and analysis protocols used in many countries. However, there is debate among the engineers and practitioners involved in road pavement design over which modulus should be used to obtain a reasonable and acceptable design outcome. In Australia, where the resilient modulus is a commonly used design parameter, the dynamic modulus may be considered in the next generation of pavement design. However, to date there is no such design platform for the dynamic modulus based on current Australian pavement design protocol (Austroads 2010). This begs the question of how to make the smooth transition of using both moduli in pavement design. The solution to this question would prove valuable to all countries including Australia.

This study's primary aim has been to find an answer, in academic terms, to the question raised above. The outcomes of this study show that both moduli of the representative mixes (DGA; 7 mm, 10 mm, 14 mm) demonstrated an increase in resilient and dynamic modulus values where larger sized aggregates were present in the mixes. Due to the differences in the definitions of and the test methods for the resilient and the dynamic modulus, it is almost impossible to compare both moduli directly without a reliable conversion method which is not yet available.

The comparison of both moduli can be made at the point where the test conditions, in terms of temperature and frequency, are the same. It may be posited that in terms of a conversion concept, the dynamic modulus conversion to a resilient modulus occurs at a particular point, where temperature and frequency are the same as those for the resilient modulus test conditions on the master curve, which show ranges of dynamic modulus values and frequencies.

For the dynamic modulus determined from conversion of the resilient modulus test in accordance with AS 2891.13.1-1995 (Australia Standards 1995), there is an important matter of how to define loading time which is used to specify a frequency corresponding to the dynamic modulus. The resilient modulus rising time of 0.04s and the full time loop of an applied stress wave of 0.2s were considered to be the loading time of the dynamic modulus conversion in this study. The dynamic moduli obtained from conversions of both loading time concepts are considerable different (Figure 6). However, in pavement design procedures, the matter of different loading time concepts from the resilient modulus tests can be disregarded due to such loading time can be determined from a vehicle designed speed suggested by Australian pavement design protocol (Austroads 2010). However, based on one loading time, two frequency types of angular and time frequencies were examined in the study whether both frequencies affect to the dynamic moduli after conversions. The results demonstrate that at the same loading time, the dynamic modulus of the resilient modulus conversion using the time frequency is considerably higher than that using angular frequency. Moreover, the values between designed resilient modulus (i.e., after in-service adjustment) and the dynamic modulus of angular from angular frequency conversion have no discrepancy.

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