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The Interrelationship between Indirect Resilient Modulus and Dynamic Modulus for Dense Graded Hot Mix Asphalt

Milad Ghorban Ebrahimi[1+], Mofreh Saleh[1], and Miguel A Moyers Gonzalez[2]

Abstract: Permanent deformation is one of the most important types of distress in flexible pavement. Currently and based on the Australian Mechanistic-Empirical Pavement Design Procedure, the indirect tensile test (IDT) is conducted in New Zealand in order to determine the asphalt modulus. This test is carried out on a 100 mm diameter by 50 mm height specimen. However, the current Simple Performance Test (SPT) procedure requires the dynamic modulus to be obtained from the axial compression test performed on 100 mm diameter by 150 mm height specimen. One issue related to the axial compression test is that it is often impossible to obtain this size specimen from actual pavement since a typical asphalt layer thickness is less than 150 mm in New Zealand. Therefore, IDT becomes more appropriate for existing pavement evaluation due to its privilege of testing on cored size specimens. The objective of this research is to perform an experimental and analytical study on the dynamic modulus parameters derived from the aforementioned test methods to improve design accuracy. In this research, two common types of asphalt cement are tested at three different air void percentages. Graphical and statistical comparisons of results from the axial compression and IDT test methods are presented in order to assess their interrelationships. The findings show that, the dynamic modulus determined form IDT test is in good agreement with that form axial compression tests. Based on the statistical analysis, more than 90% of data showed complete similarity for the dynamic modulus calculated from these two tests.

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***Key words**: Asphalt Mixture, Dynamic Modulus, Viscoelastic Analysis.*

Introduction

The Superpave mix design and analysis method was developed more than a decade ago under the strategic highway research program [1] in order to overcome the shortcomings of then available test procedures. The Superpave method was a huge step forward in Hot Mix Asphalt (HMA) design procedure due its robust material selection, aggregate blending and volumetric analysis on compacted mix prepared by Superpave Gyratory Compactor (SGC) [2].

In spite of these meticulous mix preparations, there was not any general strength or mechanical test to complete volumetric procedure as it was in Marshall and Hveem design methods. In this regard, there were number of researchers who had questioned Superpave for relying solely on volumetric data and addressed the need for complementary design methods [3-5].

In response to this requirement, National Cooperative Highway Research Program (NCHRP) conducted a comprehensive research study under the Project 9-19. The aim of this study was to recommend a Simple Performance Test (SPT) in order to complement the Superpave volumetric design procedure. This effort resulted in recommending three sets of testing procedure known as, dynamic modulus, repeated and static creep test, among which the dynamic modulus is considered as the primary input parameter since it is directly implemented at the Mechanistic-Empirical (M-E) Guide for Design of New and Rehabilitated Pavement Structure. The dynamic modulus master curve represents the temperature-frequency (or temperature-time) dependent stiffness characteristic of asphalt material [6, 7].

In order to find the dynamic modulus, the current protocol calls for axial compression testing of 100 mm -diameter- by 150 mm -height- specimen cut and cored from gyratory compacted mixtures [8].

Considering the fact that the actual pavement thickness in New Zealand is, commonly, much less than 150 mm and that coring is the most effective approach for data procurement from actual pavement, the indirect tensile (IDT) test appears to be more desirable for existing pavement evaluation.

However, there are some concerns regarding the interchangeability of dynamic modulus values obtained from compression and indirect tests [9]. First, axial compression test deals with uniaxial state of stress, whereas in indirect test the state of stress is biaxial. Moreover, in the uniaxial test, the applied stress and measured strain are in the same direction as compaction while in indirect testing the directions are perpendicular. Therefore, researchers generally believe that the effect of anisotropy will likely play a factor and create some differences between the dynamic modulus measured from uniaxial test and that calculated from the IDT test.

Background

The use of IDT test mode for dynamic modulus was developed by Kim et.al [9]. In the "Dynamic Modulus Testing of Asphalt

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[1] Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, NEW ZEALAND 4800.

[2] Mathematics and Statistics, University of Canterbury, Christchurch, NEW ZEALAND 4800.

[+] Corresponding Author: E-mail milad.ghorbanebrahimi@pg.canterbury.ac.nz

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Concrete in Indirect Tension Mode" Kim and his colleagues, used linear viscoelastic method and they came up with an analytical solution that they believe can be used as a standard test procedure to determine the dynamic modulus of asphalt mixtures using the IDT testing configuration. In that study, they tried to overcome the obstacle of stress-strain distribution in the IDT test in which, unlike the uniaxial compression mode, the load distribution is in biaxial nature.

The biaxial load distribution could lead to inaccurate material properties determination if it is not properly accounted for in the mathematical derivation in stress-strain calculation. This could cause enough difference between the dynamic modulus determined from the IDT test and that from axial compression test so that these two methods cannot be used interchangeably in forensic studies. Therefore, having a testing procedure which could yield similar results but run on a smaller size specimen is highly required in countries such as New Zealand.

The difference between axial and biaxial form of loading can be well understood by considering Hooke's law. In uniaxial cases (i.e. the dynamic modulus test) one can simply obtain the modulus (E) by dividing the axial stress (σ_y) by the axial strain (ε_y) as follows:

$$\sigma_y = E * \varepsilon_y \quad \text{or} \quad E = \frac{\sigma_y}{\varepsilon_y} \tag{1}$$

Whereas in the biaxial cases (i.e. IDT test), the modulus cannot be considered as an outcome of the horizontal stress (σ_x) to the horizontal strain (ε_x) division. Instead, in here, the biaxial stress ($\sigma_x - \nu\sigma_y$) is what needed to be considered in modulus calculation:

$$\varepsilon_x = \frac{1}{E}(\sigma_x - \nu\sigma_y) \quad \text{or} \quad E = \frac{(\sigma_x - \nu\sigma_y)}{\varepsilon_x} \tag{2}$$

Linear Viscoelastic Solution

By assuming the plane stress state in the IDT test, Hondros [10] developed the following stress-strain relationship:

$$\varepsilon_x = \frac{1}{E}(\sigma_x - \nu\sigma_y) \tag{3}$$

with,

$$\sigma_x(x) = \frac{2P}{\pi a d}\left\{\frac{1-\left({x^2}/{R^2}\right)\sin\alpha}{1+\left({2x^2}/{R^2}\right)\cos 2\alpha + {x^4}/{R^4}} - \tan^{-1}\left[\frac{1-{x^2}/{R^2}}{1+{x^2}/{R^2}}\tan\alpha\right]\right\} = \frac{2P}{\pi a d}\left[f(x) - g(x)\right] \tag{4}$$

$$\sigma_y(x) = \frac{2P}{\pi a d}\left\{\frac{\left(1-{x^2}/{R^2}\right)\sin 2\alpha}{1+2\left({x^2}/{R^2}\right)\cos 2\alpha + {x^4}/{R^4}} + \tan^{-1}\left[\frac{1-{x^2}/{R^2}}{1+{x^2}/{R^2}}\tan\alpha\right]\right\} = -\frac{2P}{\pi a d}\left[f(x) + g(x)\right] \tag{5}$$

where,
P = applied load, N;
a = loading strip width, m;
d = thickness of specimen, m;
R = specimen radios, m;
x = horizontal distance from specimen center;
y = vertical distance from specimen center; and
α = radial angle.

Based on [9], the stress strain relationship for viscoelastic materials under the sinusoidal load can be rewritten as:

$$\varepsilon_x = \frac{1}{E^*}(\sigma_x - \nu\sigma_y) \tag{6}$$

$$E^* = |E^*| \,.\, e^{i\varphi} \tag{7}$$

where,
E^* = complex modulus,
$|E^*|$ = dynamic modulus,
$i = \sqrt{-1}$, and
φ = phase angle.

Since the test is performed in a *linear* state, the response to the sinusoidal load will be the imaginary part of the complex load, P:

$$P = P_0 e^{iwt} = P_0(\cos wt + i\sin wt) \tag{8}$$

where,
P_0 = amplitude of the sinusoidal load,
w = angular frequency, and
t = time.

So, the strain in the viscoelastic state can be calculated by substituting Eqs. (4), (5), (7) and (8) into Eq. (6):

$$\varepsilon_x(x,t) = \frac{2P_0}{|E^*|\pi a d} e^{i(wt-\varphi)}\left[(1+\nu)f(x) + (\nu-1)g(x)\right] \tag{9}$$

To find the horizontal displacement U(t), Eq. (8) is integrated over the gauge length (l is considered as half of the gauge length):

$$U(t) = \int_{-l}^{+l}\varepsilon_x(x,t)dx = \frac{2P_0}{|E^*|\pi a d} e^{i(wt-\varphi)}\begin{bmatrix}(1+\nu)\int_{-l}^{+l} f(x)\\ +(\nu-1)\int_{-l}^{+l} g(x)\end{bmatrix} \tag{10}$$

Finally, the dynamic modulus from the horizontal displacement can be determined from the imaginary part of the total response.

$$|E^*| = \frac{2P_0\sin(wt-\varphi)}{\pi a d . U(t)} A \tag{11}$$

where

$$A = \left[(1+\nu)\int_{-l}^{+l} f(x) + (\nu-1)\int_{-l}^{+l} g(x)\right] \tag{12}$$

with

$$f(x) = \frac{\left(1-{x^2}/{R^2}\right)\sin 2\alpha}{1+2\left({x^2}/{R^2}\right)\cos 2\alpha + {x^4}/{R^4}} \tag{13}$$

and

$$g(x) = \tan^{-1}\left[\frac{1-{x^2}/{R^2}}{1+{x^2}/{R^2}}\tan\alpha\right] \tag{14}$$

By having $U(t) = U_0\sin(\omega t - \varphi)$, the final of form the dynamic modulus would be as follows:

$$|E^*| = \frac{2P_0}{\pi a d U_0}\left[\gamma_1 + \nu\gamma_2\right] \tag{15}$$

with

$$\gamma_1 = \int_{-l}^{+l} f(x)dx - \int_{-l}^{+l} g(x)dx \tag{16}$$

$$\gamma_2 = \int_{-l}^{+l} f(x)dx + \int_{-l}^{+l} g(x)dx \tag{17}$$

The coefficients γ_1 and γ_2 for specimens with the diameter and gauge length of 100 mm and 12.7 mm loading strip are presented in the Table 1.

Material and Specimen Fabrication

In this study, AC 20 mix is used. AC 20 is commonly used hot mix asphalt in New Zealand; it has 20 mm maximum nominal aggregate size. Table 2 shows the AC 20 aggregate gradation used in this study. Two types of asphalt binders were used in this research; 60/70 and 80/100 penetration grades. The aggregates and binders and job mix formula of the mix was taken from a local contractor in Christchurch**.** More than twenty asphalt mixture specimens were mixed and compacted in the University of Canterbury Transportation laboratory. Asphalt mixtures with binder 60/70 were tested at two different air percentages (VTM = 4.0 & 5.0%). Three different air percentages (VTM = 4.0, 4.5 & 5.0%) were considered for mixes with binder 80/100.

The asphalt mixture was prepared based on Australian standard AS 2891.2.1 “Methods of Sampling and Testing Asphalt” [11]. Accordingly, the asphalt cements were mixed and compacted at 150°C. All mixtures were also aged at 150 °C for one hour before compaction.

For the axial compression test, cylindrical specimen with 100 mm -diameter- by 150 mm -height- were cut and cored from 150 mm -diameter- by 180 mm -height- gyratory compacted specimen. For IDT test, 100 mm -diameter- by 150 -height- gyratory compacted specimen specimens were sawn into three specimens each has 100 mm diameter and 40 mm height. Two replicates of each combination were prepared for axial compression and three replicates for indirect tensile test.

Test Setup

Considering the uniaxial compression test, three on specimen vertical Linear Variable Displacement Transformers (LVDTs) with a gauge length of 100 mm were mounted on specimen at 120° from one another. Fig. 1 shows the setup for uniaxial compression test. To maintain a uniform stress distribution and reduce the friction between the load platens and the specimen, two layers of friction reducers were used in this study. One layer was under the bottom face of the specimen and the other one at the top of the specimen under the top load platen.

Samples were tested at 5 different temperatures (4.4, 15, 21.1, 30 and 40°C) and frequencies (10, 5, 1, 0.1, and 0.01 Hz) in order to plot the Master Curve.

For the IDT test, it was carried out based on the Australian Standard AS 2897.13.1 “Determination of the Resilient Modulus of Asphalt – Indirect Tensile Method” [12]. In this procedure, two horizontal LVTDs were used to measure the specimen deformation as can be seen in Fig. 2. The IDT test was also conducted at 5 different temperatures (4.4, 15, 21.1, 30, 40°C) and frequencies (2, 1, 0.6, 0.2 and 0.1 Hz). Due to software limitations, the authors were not able

Table 1. Coefficients for Dynamic Modulus.

Specimen Diameter [mm]	Gauge Length [mm]	Loading Strip [mm]	γ_1	γ_2
100.00	100.00	12.7	0.0053	0.0198

Table 2. AC 20 Mix Aggregate Gradation.

	% Passing	
Sieve Size (mm)	Blend Result	AC 20 Specification
19	100	100
13.2	91	83 - 95
9.5	78	70 - 90
6.7	70	60 - 79
4.75	66	52 - 70
2.36	44	40 - 55
1.18	32	29 - 43
0.6	24	20 - 32
0.3	17	13 - 23
0.15	9	8-16
0.075	5	4-10

Fig. 1. Uniaxial Compression Test Setup.

Fig. 2. IDT Test Setup.

to run the test at the same frequencies without rest period similar to the uniaxial test.

To control the temperature during the test, a temperature cabinet with a temperature range from -5 to 60°C and accuracy of ± 0.1°C was used. Dummy specimens with the temperature sensor mounted at center were used in order to monitor the test temperature.

Experiment

Among the triaxial compression tests, dynamic modulus is the oldest and the best documented test. It was first standardized in 1979 as ASTM D3497, "Standard Test Method for Dynamic Modulus of Asphalt Concrete Mixtures". Dynamic modulus test was addressed by NCHRP 9-19 as one of the best indicators for the rutting in asphalt mixtures [13].

The test consists of applying a uniaxial sinusoidal (or haversine) compressive stress to an unconfined or confined hot mix asphalt cylindrical test specimen. Measured stresses and strains are used to calculate the resulting dynamic modulus and phase angle. Fig. 3 represents a schematic of typical data from the dynamic modulus test. The dynamic modulus and phase angle are defined by Eqs. (18) and (19), respectively.

As it was mentioned earlier, specimens with the dimension of 100 by 150 mm were used at 5 different temperatures and frequencies in order to plot the Master Curve. The dynamic modulus test is considered as a non-destructive test which means, one specimen can be used for the whole range of temperatures and frequencies.

In order to minimize any damage or changes of the volumetric properties of the test specimens, testing program began with the lowest temperature and proceeded to the highest. At any given temperature, the test started up with the highest frequency of loading and progressed to the lowest. This sequence is intuitive because asphalt concrete becomes stiffer at low temperatures and high frequencies. Therefore, that helps to minimize the chance of damaging the specimen.

In the uniaxial test, to keep the stress state in the linear viscoelastic region, the loading patterns were applied in a way that the generated strains were in the target range of 50 to 150 με to maintain linearity.

The IDT test was conducted on specimens with 100 mm diameter by 40 mm height. The test was run based on the same concept of linearity to prevent probable damages. The only difference, apart from frequencies magnitude due to software limitation, was the target strain. According to the Australian Standards [12], the applied load level was adjusted so that the recoverable horizontal strain is in the range of 50 ± 20 με.

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \qquad (18)$$

$$\Phi = \frac{t_i}{t_p} * 360 \qquad (19)$$

where

$|E^*|$ = dynamic modulus

σ_0 = peak (maximum) stress

ε_0 = peak (maximum) strain

Φ = phase angle, degrees

t_i = time lag between a cycle of stress and strain (s)

t_p = time for a stress cycle (s)

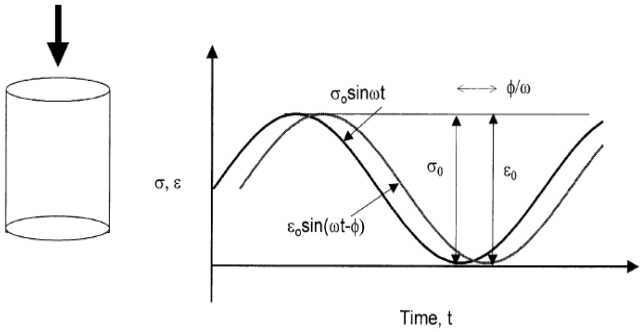

Fig. 3. Haversine Loading Pattern or Stress Pulse for the Dynamic Modulus Test.

Results and Discussion

The dynamic modulus master curve is constructed based on the concept of the time-temperature superposition principle. This principle, as Kim *et.al* put it, is applied to thermorheologically simple (TRS) materials. For this class of materials, the same modulus value can be obtained either at low test temperatures and long times loading or at high test temperatures but short times loading. In other words, the material exhibits similar behavior either at high temperature and fast loading rate or at low temperature and slow loading rate [13].

In the original AASHTO test protocol, the dynamic modulus test was required to be conducted at five temperatures (-10, 4.4, 21.1, 37.8 and 54.4 ℃) and six frequencies (25, 10, 5, 1, 0.5 and 0.1 Hz). However, through the course of time, it was felt that the testing protocol requires some modifications in order to reduce both the time and the cost of testing procedure. After a number of robust testing [13, 14] it was found that the test can be successfully run at three temperatures (4, 20 and 40 ℃) and four frequencies (10, 1, 0.1 and 0.01). With this new regulation, considerable time saving could be effected for the dynamic modulus test.

In this study in order to, thoroughly, have the required overlap on obtained data for a feasible master curve, authors decided to perform the test at more temperatures and frequencies as it was mentioned previously in the text.

The IDT test data were analyzed with analytical solution as it was discussed previously. Axial compression test data were analyzed according to NCHRP 1-37 protocol. The resulting dynamic modulus master curves from these analyses are plotted in the Figs. 4 and 5.

It needs to be noted that since the IDT part of testing was performed based on the Australian standard procedure, Poisson's ratio during the course of this research was considered as a constant value of 0.4.

Table 3 summarizes the dynamic modulus calculated from the axial and IDT tests. Due to having large amount of data collected in this experiment, only selected groups of these data are presented for the purpose of comparison. Two sets of mix are brought in Table 3 for this matter. The sets chosen are; the mix AC 20 with "binder

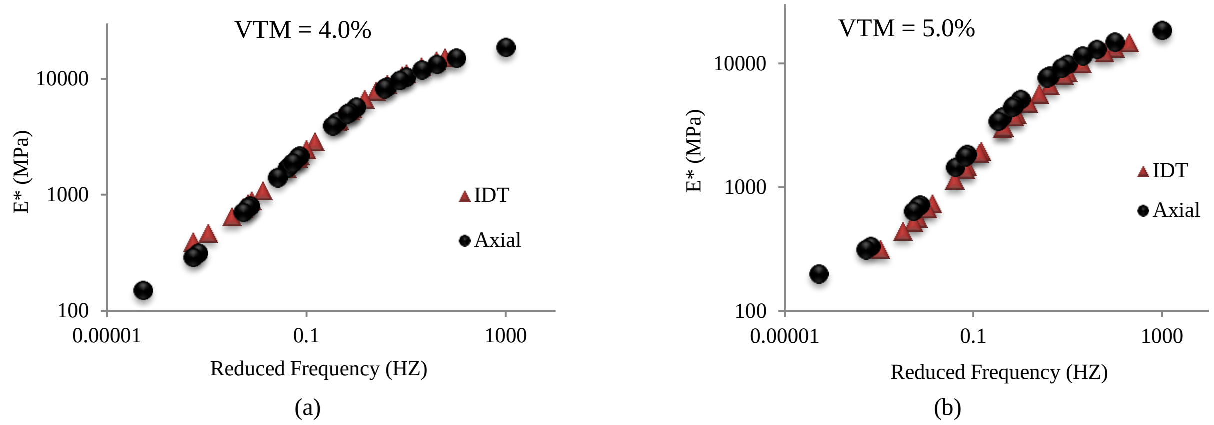

Fig. 4. Dynamic Modulus Master Curve for (a) VTM = 4.0%, Binder 60/70, (b) VTM = 5.0%, Binder 60/70.

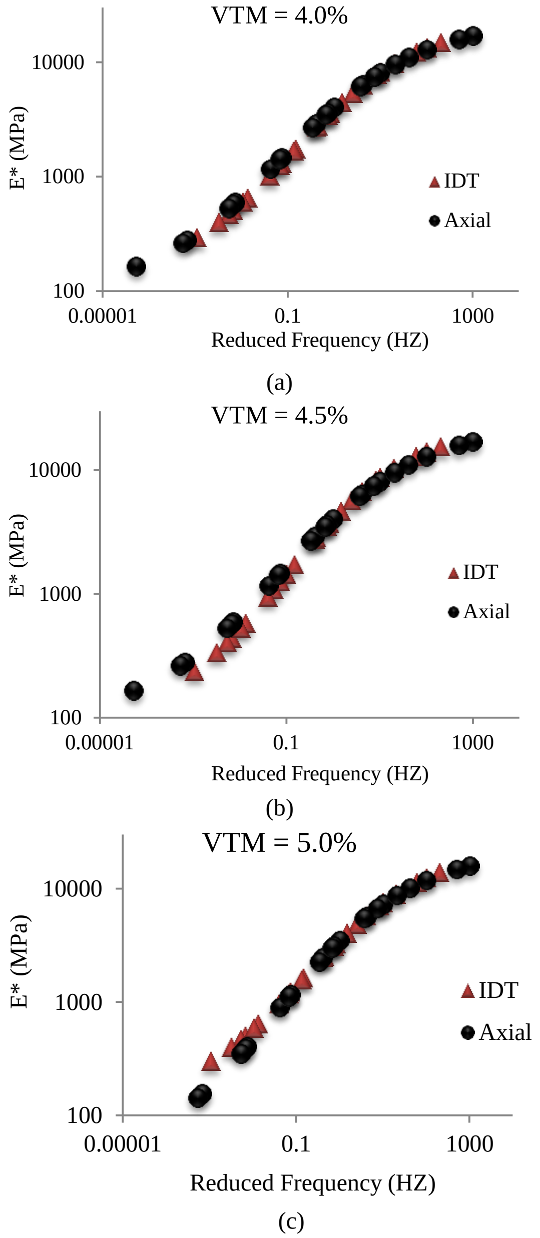

Fig. 5. Dynamic Modulus Master Curve for (a) VTM = 4.0%, Binder 80/100, (b) VTM = 4.5%, Binder 80/100,(c) VTM = 5.0%, Binder 80/100.

Table 3. Dynamic Modulus for Axial and IDT Tests.

	AC 20 - Binder 60/70-VTM = 4.0%		AC 20 - Binder 80/100 -VTM = 5.0%	
Reduced Frequency - Hz	Dynamic Modulus - MPa			
	Uniaxial	IDT	Uniaxial	IDT
100	15023	15210	11854	12595
10	10350	12550	7547	7281
4	8470	9032	5820	5664
0.7	5152	5324	3143	3108
0.07	2167	2178	1239	1162
0.007	775	842	508	389
0.0005	290	395	261	143

Table 4. *P* Values for Dynamic Modulus from Complex Modulus and IDT Tests.

P value	AC 20				
	Binder 60-70		Binder 80-100		
	VTM		VTM		
	4.0%	5.0%	4.0%	4.5%	5.0%
Less than 0.05	5%	15%	5%	25%	5%
Greater than 0.05	95%	85%	95%	75%	95%

60/70, 4.0% air voids" and with "binder 80/100, 5.0% air voids" as follows.

As can be seen from the presented figures, the visual observation suggests rather promising link between IDT and uniaxial compression test data. The data are closely matched in a wide range of frequency. But recognizing the existence of sample to sample variation, a statistical analysis was considered with the unequal variance t-test. The t-test assesses whether the means of two groups are *statistically* different from each other [15]. The null hypothesis in here is that the dynamic modulus obtained from IDT test is equal to that from the axial compression test. The level of significance, α which is probability of type 1 error for the test is considered equal to 0.05. In order to reject or accept the hypothesis the P-value was calculated and compared with α. P-value indicates the probability of getting a mean difference between the groups as high as what is observed by chance. The lower the P-value is, the more significant the difference between the groups will be. Therefore, in this study a P-value greater than 0.05 indicates the statistical similarity between IDT and axial compression test results.

Table 4 shows the *P* values for 35 tests (5 mixtures by 7 frequencies). Based on the statistical analysis, around 90.0% of the test data indicate absolutely no statistical difference between dynamic modulus resulted from complex modulus test than that from IDT test. The major difference was detected at 4.5% air void for binder 80/100. This could be due to specimen to specimen differences since 95% compatibility is observed at 4.0% and 5.0% air void for the same binder type. Hence, the statistical analyses advice that the dynamic modulus determined from the IDT test with the linear viscoelastic solution *could be* the same as the one measured from the axial compression test.

Given that the Poisson's value changes with the change of temperature and frequency, the authors believe that assuming constant Poisson's ratio contributed to some of the small differences observed between the dynamic modulus from the IDT test and uniaxial test. In addition, the effect of anisotropy is another expected factor as previously discussed. The uniaxial test is carried out in the same direction as the compaction of the specimen while in the IDT, the loading is perpendicular to the compaction of the specimen. The effect of anisotropy is intrinsic nothing can be made to avoid it, however, the assumption of constant Poisson ratio can be rectified by adding another set of vertical LVDTs to measure the vertical deformations in addition to measuring the horizontal deformation in the IDT test.

Further study is currently taken into consideration at the Canterbury University. In the forthcoming research, new set of mounting LVDTs will be considered to record both vertical and horizontal deformation. In this way, the correct Poisson's ratio will be calculated and we will be able to verify if the small discrepancy between the moduli obtained from these tests is due to our assumption of a constant Poisson's ratio. Also, there will be a unique comparison between the Australian and the new method of IDT test by the end of the upcoming research program.

Conclusion

This paper looked at the common current approach of testing asphalt specimen in New Zealand (i.e. IDT) and tried to utilize the data from this test to determine dynamic modulus and also compare the difference in dynamic modulus measured by the IDT method and the axial compression test. The IDT test is reasonably well known by the industry in New Zealand due its simplicity and practicality. In New Zealand, thin asphalt pavement are the most predominant type of pavements, therefore, it is difficult to core 150 mm height specimen form the actual pavement for the current axial compression test method. Thus, this study tried to apply an analytical method derived from the theory of linear viscoelasticity to calculate dynamic modulus of asphalt mixtures from the IDT test procedure. The data were assessed by the statistical approach to check the significance of the observed difference level between these two methods. It was found that, more than 90% of the test data showed absolute statistical similarity between the dynamic modulus determined form IDT and axial compression tests. According to the statistical analysis, the dynamic modulus determined from the IDT test with the linear viscoelastic solution *is likely to be the* same as the one measured from the axial compression test.

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