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Transportation Research Procedia 69 (2023) 783–790

Transportation Research Procedia

www.elsevier.com/locate/procedia

AIIT 3rd International Conference on Transport Infrastructure and Systems (TIS ROMA 2022), 15th-16th September 2022, Rome, Italy

A Study on Indirect Tensile Strength for the Determination of Resilient Modulus of Warm Mix Asphalt

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Abstract

The advent of Warm Mix Asphalt (WMA) incorporating Recycled Asphalt Pavement (RAP) as a long-term solution to partially or totally participate in remediating the problem of global warming and the regression of environmental resources has been expanding and gaining interest throughout the world. The WMA-RAP technology created as an improved WMA technology has shown to possess mechanical properties closely similar to Hot Mix Asphalt (HMA). Though searching for environmentally sustainable asphalt technologies have become vital, the quest to construct economically sustainable highways cannot be neglected. The dynamic modulus tests (DMT) is among the most accurate yet expensive laboratory tests performed to determine the resilient modulus of asphalt mixes. Therefore, this paper aims to determine the resilient modulus of asphalt mixes (WMA-RAP and HMA) through both the indirect tensile strength (ITS) and the correlation formula method (CFM) and compares them against the dynamic modulus tests method (DMTM). Furthermore, this study utilises the resilient modulus found through CFM and DMTM to predict and compare the mechanical performances of asphalt pavement systems. Finite Element Modelling (FEM) and Linear Elastic Analysis (LEA) were used to modelling and analysing the mechanical behaviour of pavement systems. Both the WMA15% RAP and WMA30% RAP samples were mixed with 50/70 grade bitumen modified with Sasobit additive. The HMA samples on the other hand were mixed with non-modified 50/70 grade bitumen. Findings show that the resilient moduli of HMA and WMA-RAP mixes obtained through CFM is 77% close to the DMTM. In addition, the HMA and the WMA-RAP pavements with CFM and DMTM resilient moduli also show very close mechanical performance. This signifies that the CFM can be used as a reliable and cost effective alternative method to determine the resilient modulus of asphalt mixes.

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2352-1465
10.1016/j.trpro.2023.02.236

Keywords: warm mix asphalt; recycled asphalt pavement; hot mix asphalt; fatigue cracking; rutting failure; finite element modelling

1. Introduction

Warm Mix Asphalt (WMA) was initially found to overcome environmental impact caused by the production techniques and procedures of the conventional Hot Mix Asphalt (HMA). The low mixing and compaction temperature of the WMA varies depending on the type of additive technology with which it is made. However, the low production temperature of the WMA plays a positive role in lowering the emission of greenhouse gases and other traditional gaseous pollutant. Kheradmand *et al*. (2014) add further benefits related to the use of WMA which include less fuel consumption, lower energy consumption, early site opening to traffic, less ageing, possibility of paving in cold weather conditions, better workability of asphalt mix and extended paving window. Contrary to the HMA, the WMA also has the advantage of accommodating a high percentage of Recycled Asphalt Pavement (RAP) due to its increased workability. Thus, the capability of the WMA to accommodate high percentage of RAP directly contributes to reducing its dependency on natural aggregates which, in turn, has a positive impact on the preservation of the natural resources.

Inasmuch as significant attentions have been given toward finding highways construction materials that are environmentally sustainable, equal attention should be given to constructing economically sustainable highways. The determination of the resilient modulus property of asphalt mixes through the dynamic modulus test (DMT) is the most accurate method currently recommended by highway engineers. Though effective and reliable, the dynamic modulus test is among the most expensive and time consuming laboratory tests. Thus, this study aims at utilizing the indirect tensile strength (ITS) test together with the correlation formula method (CFM) to determine the resilient moduli of asphalt mixes (WMA15% RAP, WMA30% RAP and HMA) and compares them against the resilient moduli found through the dynamic modulus test method (DMTM). It further aims at using the resilient moduli found through CFM and DMTM to investigate the mechanical performances of the WMA15% RAP, WMA30% RAP and HMA pavement structures.

The correlation formula method CFM for the determination of resilient moduli was achieved through variables which were found by performing the indirect tensile strength (ITS) tests on asphalt specimens. The investigation of mechanical performances of the considered flexible pavement systems was achieved using numerical methods which include the Finite Element Model (FEM) with linear elastic material characterization in Abaqus and the Layered Elastic Analysis model (LEA) in mePADS.

2. Asphalt Mix Design and Production of Asphalt Mixes

The materials used for the fabrication of the HMA and the WMA-RAP include various sizes of coarse virgin aggregates (28mm, 20mm, 14mm and 10mm), crusher dust, fillers (lime), fine RAP, virgin binder (50/70), and Sasobit organic additives. The virgin materials and the RAP were mixed at various proportions to achieve the production of HMA, WMA15% RAP and the WMA30% RAP. Grading tests and grading analysis were then performed on the materials mixed in accordance with the standard test method SANS 3001-AG1 to ensure that the proportion of aggregate sizes and RAP aggregates are adequately distributed within the mix and therefore avoid any kind of adverse effects due inadequate material mix design.

The HMA premix produced at 150°C contained 4.5% of 50/70 grade bitumen. On the other hand, the WMA-RAP premixes produced at 120°C contain 3.7% of 50/70 grade bitumen and 0.8% Sasobit organic additive. It is worth adding that the densities and the volumetric property tests were performed on the HMA and the WMA-RAP in accordance with the South National Standard (SANS 3001-AS10) tests and procedures. The determination of the densities and volumetric characteristic of the WMA-RAP and the HMA fully complied to the SANS 3001-AS10.

3. Determination of Resilient Modulus

3.1. Indirect Tensile Strength Test (ITS)

The ITS test is generally performed on an asphalt mix to obtain its tensile strength which is directly related to the fatigue cracking performance of that asphalt mix. However, the ITS test performed in this study is rather intended for the determination of resilient modulus via the method of correlation formula. The ITS test was achieved on four HMA, WMA15% RAP and WMA30% RAP fabricated samples by following techniques and procedures prescribed by the SANS 3001-AS1. The asphalt briquettes samples measuring 63mm in thickness and 101.5 mm in diameter were produced at 140°C for the HMA samples and 110°C for the WMA-RAP samples. The asphalt briquettes were then conditioned to 25°C in an oven before being subjected to loading in a Marshall Compression Testing Machine.

The ITS results of the CM-HMA, the WMA15% RAP and the WMA30% RAP presented in Table 1 were determined based on the following model:

$$ITS = 2P/\pi L\phi \qquad (1)$$

Where: ITS = Indirect Tensile Strength (kPa); P = Load causing failure (kN); L = Thickness of the specimen (mm); $\boldsymbol{\phi}$ = Diameter of the specimen (mm).

Table 1. ITS Response Data

	No. of Briquettes	1	2	3	4	Ave.
HMA	**ITS (kPa)**	**1412.00**	**1324.11**	**1346.89**	**1262.37**	**1336.34**
WMA15% RAP	**ITS (kPa)**	**1642.70**	**1535.62**	**1722.34**	**1627.57**	**1632.05**
WMA30% RAP	**ITS (kPa)**	**1657.35**	**1747.23**	**1317.44**	**1589.00**	**1577.75**

3.2. Determination of Resilient Modulus Using Correlation Formula Method (CFM)

Table 2 presented below contains correlation formula used to determine the resilient modulus of the HMA and the WMA-RAP. The load to failure, the horizontal deformation, the thickness as well as the Poisson's ratio of the asphalt samples presented in Table 1 above were used as variables within the correlation formula proposed by Baldo *et al.* (2010) (Equation 2 in Table 2) and Barksdale *et al.* (1997) (Equation 3 in Table 2). Both correlation formulas are simple and have the capacity to fit the response data of the ITS test. However, the model proposed by Barksdale *et al.* (2010) was chosen in this study based on its ability to exhibit elastic modulus that are close to the ones determined through DMT. The results of calculated resilient modulus based on the preferred correlation formula are presented in Table 3.

Table 2. Correlation Formula for Resilient Modulus via ITS data

Equation No.	*Resilient Modulus Models*	*Reference(s)*
2	$M_r = \frac{P_{cyclic}(\mu + 0.27)}{\delta_t \times t}$	Austroads, 2008; Baldo *et al*., 2010
3	$M_r = \frac{P_{cyclic}}{\delta_t \times t}(0.2339 + 0.7801\mu)$	Barksdale *et al*., 1997

Where: M_r = Instantaneous or total resilient modulus (MPa); δ_t = Recoverable horizontal deformation (mm); P_{cyclic} = Cyclic load applied to specimen (N); t = thickness of the cylindrical specimen; μ = Instantaneous or total Poisson's ratio.

Table 3. Elastic Modulus of the Asphalt Mixes - Correlation Formula Method (CFM)

Asphalt mix Sample	*Ave. P_{cyclic} (N)*	*Ave. δ_t (mm)*	*Ave. t (mm)*	*Ave. ITS (kPa)*	*Poisson ratio*	*Ave. Elastic Modulus (MPa)*
HMA	1342500	2.24	63.00	1336.34	0.44	**5490**
WMA15% RAP	1640000	1.70	63.05	1632.05	0.44	**8830**
WMA30% RAP	1593800	2.10	63.43	1577.75	0.44	**6905**

3.3. Determination of Resilient Modulus Using Dynamic Modulus Test Method (DMTM)

The dynamic modulus test method (DMTM) was performed to determine the resilient moduli of the HMA and the WMA-RAP specimens and to compare them against the resilient moduli determined via the indirect method of correlation formula (CFM). Furthermore, the resilient moduli determined with DMTM were used as input data to model and analyze the WMA and HMA asphalt pavement structures. The production, the preparation and the tests performed on HMA and WMA-RAP samples were achieved following the AASHTO TP 79 standard (AASHTO, 2013). The cylindrical asphalt mix samples measuring 100mm in diameter and 150mm in depth were conditioned at 20°C before being subjected to compressive stress in an Asphalt Mixture Performance Tester machine at a varying range of loading frequencies, which include 0.1 Hz, 0.5 Hz, 1 Hz, 5 Hz, 10 Hz, and 25 Hz. Only resilient moduli measured at frequency of 1 Hz were considered and therefore compared with the theoretical resilient moduli (CFM resilient moduli) (Table 5).

4. Numerical Modeling of Asphaltic Pavement Structures

The prediction of pavement mechanical performance can be very complex and tedious. Such complexity is related to factors such as the numerous combinations of layer thickness within the pavement structure, the layer material property, the interaction of layers within each other, the imposition of heavier loads and the climatic conditions. The simulation of pavement structure to predict their distress performance can be achieved through the Accelerated Pavement Testing or mechanical response models build in software packages such as Abaqus, ANSYS, CIRCLY, ASTRAN, STRAND and much more. Wu *et al*. (2011) reported the high cost related to the accelerated loading devices and the construction of full-scale pavement structure; hence the choice of this study to make use of the Abaqus computer program based on Finite Element Model (FEM) and mePADS computer program based on LEA to simulate the pavement structure scenarios and therefore to predict their mechanical performances.

In this study, the WMA15% RAP and the WMA30% RAP pavement structure scenarios were simulated and their performances were compared against the CM-HMA pavement performances. The WMA15% RAP, WMA30% RAP and CM-HMA pavement structures each consist of asphalt open grade surface layer laid over a stabilized base course and an in-situ sub-grade layer. The simulation of pavement structures through Abaqus and mePADS computer packages was achieved while considering static and dynamic loading. The 2D asymmetric model and linear elastic material characterization were considered for the simulation of pavement structures in Abaqus. Furthermore, the rutting and fatigue cracking performances of the pavement structures were determined through empirical transfer functions.

4.1. Geometry of Pavement Structures

The modelling of the layered pavement system requires the selection of a convenient geometrical model (i.e. 2D Axisymmetric and 3D). The pavement structures modelled in 3D is known to possess the most probable inclusive simulation of the actual problem based on its highly accurate results. However, the 3D model was not considered in this study, as it demands expensive hardware and software licences and requires relatively high computational time (Myers *et al*., 2001). As part of this study, 2D Axisymmetric in Abaqus software was selected to model asphalt pavement structures. In real life, the actual road pavement has a longitudinal dimension and width in which the unit of measure is in several kilometres and/or meters. Hence, modelling a limited pavement area very close to the tyre contact in 2D model is necessary. Thus, the flexible pavement structures measuring 3000 mm in the transversal direction was modelled. The depth of the sub-grade layer is generally assumed infinite. So, instead of having an -infinite depth at the sub-grade layer, a 2000mm was selected. Fabrice et al. (2020) adopted a similar geometry to avoid edge error during the sequence of analysis. Furthermore, Raman (2011) study recommended a depth of 2000 mm, as there was no deformation occurring after a certain amount of layer depth and for the sake of boundary conditioning.

Each layer of the pavement structure idealised as a beam had a stabilised base (C3) measuring 150mm in thickness and an in-situ treated materials sub-grade (Soil) measuring 2000 mm in depth. Only the asphalt surface layer made of WMA15% RAP (AC20), WMA30% RAP (AC20) and the CM-HMA (AC20) technology had its depth varying from 50 to 150 mm. The depth variation of the asphalt top layer at 50mm increment was done to determine the ideal depth which will sustain the pre-determined imposed load without exhibiting considerable distress failures. The interfaces between the asphalt layers and the lower layers were fully bounded.

4.2. Material Characterization of Pavement Layers

Flexible pavements are generally composed of asphalt layers, granular treated or untreated layers and sub-grade of in-situ layers. Each of these layers behaves differently because of the different material properties of which they are made. Therefore, the asphalt layer may possess one of the three types of model characteristic: the elastic model, the viscoelastic model, or the viscoelastoplastic model. The granular and the sub-grade layers, on the other hand, are usually modelled as a linear elastic model, non-linear elastic model or linear elastoplastic model. However, this paper only considers the linear elastic model accounting both for the asphalt top layer and for the lower layers; this is because the 2D Axisymmetric model considered in this study only accommodates linear elastic materials properties. The material properties of the asphalt layer used in this study were obtained through the ITS and the DMT tests. The material properties of the stabilized base layer used in this study were proposed by Heyns and Mostafa Hassan (2013). The South African design manual, on the other hand, recommended the properties of the sub-grade materials. Table 4 below contains the characteristics of materials used to effectively model and simulate pavement structures in Abaqus and mePADS.

Table 4. Material Characterizations of Pavement Layers

Pavement Layer	*Layer Thickness (mm)*	*Density (kg/m^3)*	*Elastic Modulus (MPa)*	*Poisson Ratio*	*Material Code (Colto2008)*
Asphalt (HMA)	50	2512	Varies (Table 5)	0.44	AC20
Asphalt (WMA15% RAP)	50	2512	Varies (Table 5)	0.44	AC20
Asphalt (WMA30% RAP)	50	2490	Varies (Table 5)	0.44	AC20
Stabilised Base	300	2133	2560	0.35	C3
Sub-grade	2000	1680	60	0.35	Soil

4.3. Interactions, Conditioning and Loading

The boundary condition was selected in a way that it resembles the real-life boundary condition. Thus, a roller was used to restrict the degree of freedom on individual layers. The asphalt surface, the gravel base layer, as well as the treated sub-grade layer, were restrained from moving in the transversal and the longitudinal directions (i.e. the degree of freedom 1 and 3). The sub-grade layer, on the other hand, was restrained from moving not only in the transversal and horizontal direction but also in the vertical direction (i.e. the degree of freedom 1, 2 and 3). The fixation at the bottom of the sub-grade layer is intended to prevent any displacement or rotation that may be caused by the velocity and the acceleration. Saad *et al*. (2006) recommended the meshing to be fine near the loading area and coarse at the remote distance where the tyre load is being applied. The meshing of the models in this study was done by selecting axisymmetry with reduced integration as elements type, the selection of this element type was based on the fact that they have the potential and the capability of showing large deformation and material linearity.

A standard equivalent wheel load of 80 KN was uniformly applied on the pavement structure. The contact area between the applied single tyre load and the pavement surface was assumed to have a circular shape with a radius of 192.108mm and a total area 28985.5 mm^2. Furthermore, the tyre pressure against the surface of the pavement structure was assumed to be 690 KPa or 0.69 MPa (Theyse *et al*., 2011). It is essential to further emphasize that the loading assumed in this study did not take into account the effect of the moving tyre. However, the focus was instead made on the impact caused by repeating the load cycle on the same spot. The same approach was previously adopted by Bodhinayake (2008) and Al-Qadi *et al*. (2010). Based on the previous study by Bodhinayake (2008), the load moving at a speed of 100 km/hr was simulated in a way that it would remain on the area of interest for 0.1s followed by 0.9s period of rest.

5. Results and Discussions

5.1. Resilient Moduli

The resilient moduli based on CFM were compared against the resilient moduli based on DMTM and presented in Table 5. The differences in the resilient modulus obtained through theoretical method (CFM) and experimental method (DMTM) ranges from 5.29% - 48.31% and it is on an average of 23%. The 23% average difference can be further reduced if the asphalt mixes are adequately designed and consistently compacted.

Table 5. Comparative Results of CFM and DMTM

Type of Asphalt Mix	***Elastic Modulus***		***Percentage Difference btw CFM & DMTM***
	CFM *(MPa)*	**DMTM *(MPa)***	
HMA	5490	5207	5.29
WMA (15%RAP)	8830	10419	16.51
WMA (30%RAP)	6905	4218	48.31

5.2. Effect of Resilient Modulus on Pavement Surface Deformation

HMA, WMA15% RAP and WMA30% RAP surface layers with resilient modulus based both on CFM and DMTM were simulated in Abaqus. Figure 1 below shows the deformation sustained by the top layer as a result of resilient modulus based on CFM and DMTM and Figure 2 only illustrates the 2D mechanical responses of WMA15% RAP pavements with CFM and DMTM resilient moduli. Surface deformation, called rutting, is the longitudinal surface depression that occurs in the wheel paths of a flexible pavement due to impact of the repeating passage of traffic. The observation made indicates that there is no major difference in the performance of the asphalt surfacing characterised by resilient modulus based on CFM and DMTM. This minor deformation signifies that the resilient modulus obtained through CFM can be used as a reliable technique for the determination of asphalt concrete resilient modulus intended for the construction of low and medium volume road.

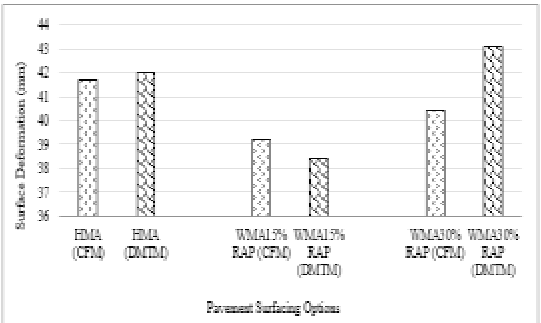

Figure 1. Surface deformation based on Pavement Surfacing Options

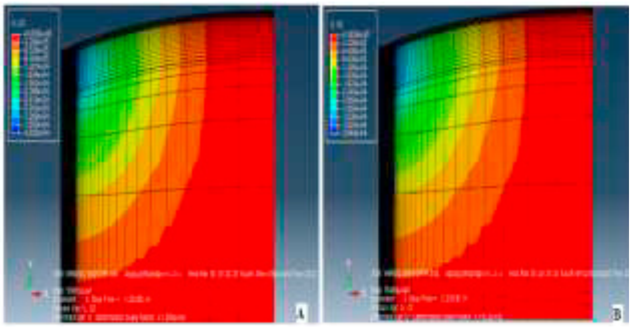

Figure 2. Surface deflection for WMA15% RAP Pavement (a) CFM Resilient Modulus and (b) DMTM Resilient Modulus

5.3. Mechanical Response of Pavements with CFM and DTMT Resilient Moduli

The HMA, WMA15% RAP and WMA30% RAP pavement structures at 50 mm layer thicknesses were modelled and analysed using mePADS and the Abaqus computer programmes. Figure 3 presented below compares the mechanical responses (tensile strain at the bottom of the asphalt surface layer and the vertical compressive strain at the top of the sub-grade layer) of HMA, WMA15% RAP and WMA30% RAP pavement structures with both CFM and DMTM resilient moduli. HMA pavements with CFM and DMTM resilient moduli show close similarity in tensile strain and compressive strain. The same observation applies to the WMA15% RAP pavements with CFM and DMTM resilient moduli. However, the WMA30% RAP pavements with CFM and DMTM resilient moduli indicate significant difference in horizontal tensile strain only. This significant difference eventually results from the 48% gap between CFM and DMTM resilient moduli of the WMA30% RAP found in Table 5 above.

Furthermore, the 2D Axisymmetric model in Abaqus gives very close results to that of the multi-layered elastic model in mePADS as the percentage differences between them varies between 2.44% and 12.67% (Figure 3). Dwelling on the fact that the majority of the differences between the Abaqus and mePADS are less than 4%, it implies that modelling and analysing of pavement structures using the multi-layered elastic model in mePADS or FEM Axisymmetric in Abaqus will not make much difference. However, the FEM Axisymmetric in Abaqus would be of more advantage than the mePADS as the stress, and the strain can be accurately determined at any dissected single element of the entire pavement structure be it in horizontal or in the vertical axis.

5.4. Comparative Study of Pavements Distress

Comparing the HMA, WMA15% RAP and WMA30% RAP pavement structures in terms of resistance against fatigue cracking, the HMA pavement structure exhibit lower fatigue performance compared to the WMA-RAP pavements structures (Table 6). However, the WMA15% RAP pavement structure shows higher fatigue cracking performance against the WMA30% RAP pavement structure. Similarly, as far as the resistance against rutting failure is concerned, the WMA15% RAP and the WMA30% RAP pavements at 150mm thickness present better performance when compared to the HMA pavements. Overall, the WMA15% RAP pavement structure shows highest rutting performance of them all. This leads to conclude that though the WMA15% RAP and WMA30% RAP may present lower rutting performance against the HMA in the laboratory experiments, it can exhibit higher rutting performance when laid as a surface layer on the pavement structure at an appropriate thickness.

Table 6. Asphalt Pavement Distresses

Pavement Type	***Pavement Responses***	***mePADS***	***Abaqus Axisymmetric Model***	***No. of Load Repetitions to Failure (N_f/ N_r) mePADS***	***No. of Load Repetitions to Failure (N_f / N_r) Abaqus Axisymmetric***
CM-HMA (CFM)	***εt (10^{-6})***	26.16	25.35	**1.00** x **10^{15}** ***(N_f)***	**9.70 x 10^{8}** ***(N_f)***
	εc (10^{-6})	507	494.80	2.60 x 10^{6} *(N_r)*	0.86 x 10^{6} *(N_r)*
WMA15% RAP (CFM)	***εt (10^{-6})***	5.62	14.77	**1.00** x **10^{15}** ***(N_f)***	**6.06 x 10^{10}** ***(N_f)***
	εc (10^{-6})	476	464.20	4.99 x 10^{6} *(N_r)*	1.14 x 10^{6} *(N_r)*
WMA30% RAP (CFM)	***εt (10^{-6})***	15.86	16.40	**1.00** x **10^{15}** ***(N_f)***	**3.34 x 10^{9}** ***(N_f)***
	εc (10^{-6})	497	479.20	3.57 x 10^{6} *(N_r)*	0.99 x 10^{6} *(N_r)*

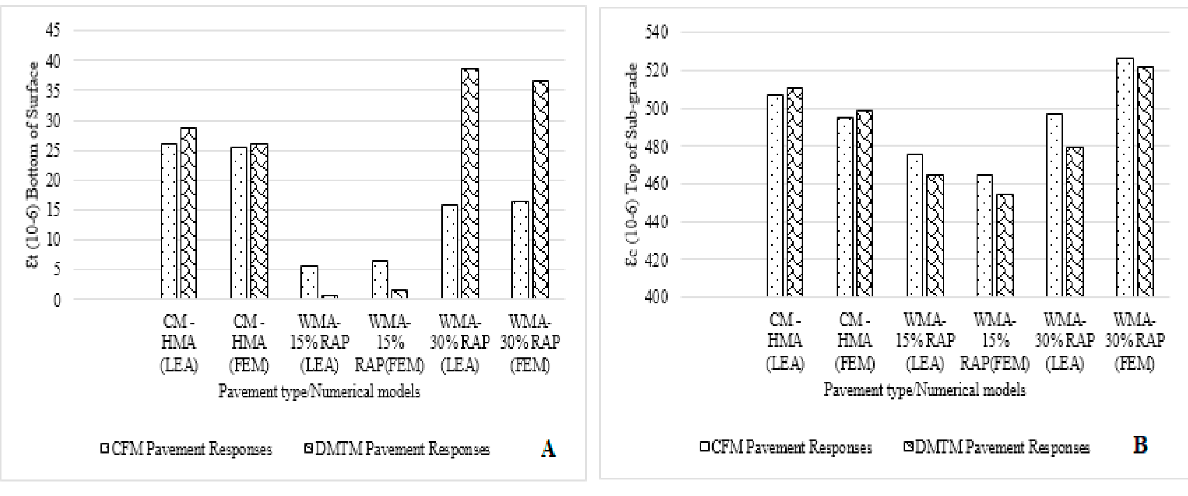

Figure 3. Mechanical responses of pavements in CFM and DMTM Resilient Moduli (a) Horizontal strain at the bottom of the surface (b) Vertical compressive strain at the top of Sub-grade

6. Conclusion

The study focuses on developing reliable resilient modulus using the ITS test together with the correlation formula (CFM). Findings of the HMA and WMA-RAP resilient moduli indicate a close similarity of 77% between the resilient moduli determined with CFM and the resilient moduli determined with DMTM. Furthermore, the HMA and the WMA15% RAP pavements with CFM and DMTM resilient moduli show very close similarity in tensile strain and compressive strain. The WMA30% RAP pavements with CFM and DMTM resilient moduli also show close similarity in compressive strain but large difference in tensile strain.

Overall, the close proximity between the resilient moduli determined with CFM and DMTM resulting in close similarities of pavements compressive strains and tensile strains do indicate that the response data of the ITS test can be adequately used as parameters in correlation formula to determine reliable resilient moduli of asphalt mixes. In addition, the determination of resilient moduli through CFM can be used as a less expensive and quicker alternative technique to determine the resilient moduli of asphalt mixes.

The large percentage difference (48%) of the WMA30% RAP resilient moduli determined with CFM and DMTM may have been caused by the inadequate mix of WMA30% RAP resulting in the production of poor quality of WMA30% RAP mix samples. Therefore, the adequate mix and the quality production of the WMA30% RAP specimens are recommended to improve the resilient modulus of the WMA30% RAP mix.

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