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Evaluation of Pavement Responses under Wide Base Tire and Dual Tire Assembly

타이어 종류 (Wide Base Tire and Dual Tire Assembly)에 따른 아스팔트 포장 반응 평가

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ABSTRACT

PURPOSES : The first generation of wide base tires introduced in the early 1980s was found to cause a significant increase in pavement damage compared to dual-tire assemblies. However, wide base tires have evolved considerably, and a new generation of wide base tire is thought to be comparable to conventional dual tires for pavement damage. A challenge associated with using wide base tires is the accurate quantification of pavement damage induced by these tires. The objective of this study was to investigate the responses of flexible pavement to continuously moving vehicular loading under various tire configurations.

METHODS : The comparison of the strain/stress responses of full-depth pavement caused by conventional dual tire assembly and new generation of wide-base tires was performed. The FE model incorporates linear viscoelasticity of asphalt material and continuous moving load using implicit dynamic analysis.

RESULTS AND CONCLUSIONS : The result demonstrates that the new wide-base tires caused slightly more fatigue damage and less primary rutting damage in HMA layer than a dual-tire assembly, but caused more secondary rutting damage in subgrade than a dual tire assembly.

Keywords
asphalt pavement, pavement damage, wide base tire, dual tire assembly, FE analysis

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1. INTRODUCTION

A new technology strongly supported by the trucking industry is the use of wide-base tires to replace conventional dual-tire assemblies. Traditionally, dual-tire assemblies have been used to provide an adequate footprint to carry heavy loads and to distribute axle load over a large area of the pavement. Compared to conventional dual-tire assemblies, wide-base tires offer the trucking industry significant economic advantages such as improved fuel efficiency, increased hauling capacity, reduced tire cost and repair, and superior ride and comfort (Ang-Olson and

Schroeer 2002 and Al-Qadi and Elseifi 2007). However, the first generation of wide-base tires introduced in the early 1980s was found to cause a significant increase in pavement damage compared to dual-tire assemblies. For example, the first generation of wide-base tire was found to cause 1.5 to 2.0 times more rut depth and 2.0 to 4.0 times more fatigue cracking than a dual-tire assembly carrying the same load (Bonaquist 1992). This has led many transportation agencies to discourage their use. After more than two decades of research by the tire industry in conjunction with pavement researchers, a new generation of wide-base tires were recently introduced to reduce pavement damage and to offer other improved safety, environment, and cost-savings characteristics. This new generation of wide-base tires is wider than their predecessors and their structure and design have been improved. In Europe, wide-base tires (having a different design than the ones introduced in the U.S.) have been used successfully on trucks since the early 1980s. In 1997, around 65% of trailers and semi-trailer tires in Germany used wide-base tires (COST 334 2001). A challenge associated with using wide-base tires is the accurate quantification of pavement damage induced by these tires. An understanding of pavement damage due to various tire configurations could be achieved by measuring the in-situ pavement responses complemented by advanced modeling. The objective of this study was to investigate the responses of flexible pavement to continuously moving vehicular loading using advanced modeling approach under various tire configurations (WBT and DTA). The factors to be considered will include the following: three axle loads (35.6kN, 45kN, and 53.3kN) and two tire inflation pressure (690kPa and 760kPa).

2. LITERATURE REVIEW

Accelerated pavement testing was used in Finland to study the effect of tire type and axle configurations (Huhtala 1986 and Huhtala et al. 1989). Flexible pavements with thicknesses of 5.1, 7.6, and 15.2mm (2, 3, and 6 inches) were instrumented and subjected to various axle configurations and tire types. The study concluded that FG-WBT was more damaging than dual-tire assembly; the difference of the amount of damage caused by these two types of tires decreased as the thickness of the AC layer increased (Huhtala 1986). Furthermore, FG-WBT caused between 1.2 and 4 times more damage than the dual-tire assembly (Huhtala et al. 1989).

In 1992, findings regarding FG-WBT were reported in two states: Virginia and Pennsylvania. Dual-tire assembly and FG-WBT were compared by FHWA in Virginia through performance and response analysis (Bonaquist 1992). 12 pavement sections were tested at different environmental conditions, axle loads, and tire inflation pressures. Once more, FG-WBT was found to be more damaging than the dual-tire assembly: as much as two times more permanent deformation and 25% less fatigue life than the dual-tire assembly were reported. On the other hand, the Pennsylvania State University test track used trucks traveling at 40 mph with various tire inflation pressures, tire types, axle loads, and axle configurations in its study. The study showed that the damage caused by FG-WBT was between 50% and 70% greater than the dual-tire assembly (Sebaaly and Tabatabaee 1992).

FG-WBT was also evaluated in overlay systems. A study in California compared the performance of dense-graded AC and asphalt-rubber hot-mix gap-graded (ARHM-GG). The accelerated pavement testing was carried out at high temperature and included aircraft tires. The number of repetitions to failure (excessive rutting) of FG-WBT was between 10 and 60% of the dual-tire assembly (Harvey and Popescu 2000).

Several different countries in Europe also studied WBT at the beginning of the previous decade (COST 334 2001). The study included WBT 495/45R22.5, which was referenced as the new generation of WBT. In the United Kingdom, the comparison between WBT-385 and WBT-495 concluded that WBT-385 produced 70% and 50% more rutting in medium-thick and thin flexible pavements, respectively. Thick pavements were tested in Germany, and the ratio between the rutting generated by WBT-495 and dual-tire assembly (315/80R22.5) was around 1.3. Very thick and stiff pavement structures were built and tested in France. No significant difference was found between measurements from both tires at the bottom of the AC. Finally, the difference in dynamic loading between various types of tires was investigated in Finland. Measurements were taken when a truck traveled at 50 mph. The WBT-495 originated a greater response (COST 334 2001).

Research regarding WBT has been also performed in Canada (Pierre et al. 2003). Strains near the surface of a flexible pavement with a 4-in AC layer were measured and compared considering different tire types, speeds, loads, and tire inflation pressures. The damage of NG-WBT and dual-tire assembly was found to be dependent on the environmental conditions and location. For instance, strains at the base resulted from NG-WBT and dual-tire assembly loading during summer are close in magnitude. However, during spring NG-WBT produced higher strains (Pierre et al. 2003). NCAT also reported that the horizontal strains at the bottom of the AC and the stresses on top of the subgrade produced by NG-WBT and dual-tire assembly are comparable (Priest and Timm 2006).

The effect of dual-tire assembly, FG-WBT, and NG-WBT on full-depth pavements were compared in a study at the University of Illinois at Urbana-Champaign (Al-Qadi and Wang 2009a; Al-Qadi and Wang 2009b). The thickness of the flexible pavements varied between 6 and 16.5 in. After testing at different tire-inflation pressures, axle loads, and temperatures, it was observed that WBT-425 (FG-WBT) is more damaging than WBT-455 (NG-WBT). Similar tests carried out on low-volume road test sections showed that NG-WBT is more damaging to this type of pavement (Al-Qadi and Wang 2009c).

A study performed in Florida that focused on permanent deformation compared WBT-445, WBT-455, WBT-425, and dual-tire assembly. Foil strain gauges close to the surface were installed, and the pavement was tested at high temperatures (Greene et al. 2009). Dual-tire assembly had the highest number of passes to reach a 0.5 in rutting, and WBT-425 needed the least number of passes.

3. NUMERICAL MODELING

The current design method for flexible pavements is based on the structural response that uses inappropriate assumptions. Static analysis of multilayer elastic systems where the tire load is applied on a circular contact area under constant pressure equal to the tire inflation pressure does not accurately represent the actual problem of a flexible pavement subjected to truck loading. Furthermore, the interface between two layers is not characterized by a full continuity of stresses and strains. Therefore, to accurately predict the response of the system composed by a flexible pavement subjected to moving load, a powerful tool which is able to capture its actual complex characteristics is needed. The Finite Element Method (FEM) offers the capabilities needed to address, in a successful manner, the response of the mentioned system. This system is a multilayer viscoelastic structure, where there is no full continuity between layers. In addition, it is subjected to dynamic loading with three-dimensional non-uniform contact stresses.

3.1. The Finite Element Method

Following is a description of each of the improvements that was implemented in this study in the FEM and how the improvements compared to multilayer linear elastic analysis. In addition, a brief explanation of how each assumption of the simplified theory affects the response of the system is included.

3.1.1. Viscoelastic Asphalt Material

One of the main weaknesses of the conventional models to analyze flexible pavements is the assumption that asphalt behaves as a linear elastic material. It is well known that the mechanical response of AC depends not only on the rate of loading but also on the temperature, and that these characteristics cannot be captured by a linear elastic model. The effect of the viscoelastic nature of AC is even more important at high temperatures. The viscoelastic characteristics of the AC are considered in this study.

3.1.2. Dynamic Analysis

Three methodologies are usually used to describe the applied load in a flexible pavement: static, quasi-static, and dynamic. The static load does not change its magnitude or position during the analysis. On the other hand, in a quasi-static analysis, the load changes its position, but the inertial and damping forces are not considered. Finally, the dynamic analysis accounts not only for the change in magnitude and position but also for the inertia and damping forces. The conventional analysis of flexible pavement assumes the applied load as static. It is evident that the nature of moving loads, such as the ones applied by moving trucks, is dynamic. As a consequence, the assumption of static load is incorrect and hence results will be inaccurate. Quasi-static analysis underestimates the response of the pavement and therefore predicts a higher number of repetitions to failure than the pavement can actually withstand. Therefore, dynamic analysis is considered in this study to simulate actual loading.

3.1.3. Three-Dimensional Contact Stresses

Another inaccurate assumption used in the conventional analysis of pavements deals with the shape of the contact area and the magnitude and distribution of contact stresses. Currently, the design is based on circular contact area between the pavement and the tire. In addition, it is assumed that the contact stresses are applied only in the vertical direction and are equal to the tire inflation pressure. Measurements of contact stresses showed that a tire actually applies three-dimensional stresses on pavement surfaces. The distribution of these contact stresses are far from being uniform and equal to the tire inflation pressure. In fact, the peak vertical contact stress can be between 50% and 70% higher than the tire inflation pressure. Hence, actual tire-pavement contact stress distributions greatly influence the response of flexible pavements close to the surface, and they diminish with depth. As a result, in order to obtain an accurate prediction of the distresses associated with the stresses and strains close to the surface, tire contact stresses in three dimensions are included in the analysis using actual measured 3D stresses.

3.1.4. Continuous Moving Load

When the tire load is not considered static, two methodologies can be used to define the variation of the amplitude: impulsive loading (e.g. trapezoidal shape) and continuous moving loading. For the impulse assumption, the loading amplitude in the contact area is constant during each step, and it suddenly changes from one to zero for the next step. This method of loading underestimates the pavement response and the difference is increased as temperature increase. On the other hand, the continuous moving loading assumes that the amplitude linearly changes from the value in the current step to the new value in the next step. This allows for the consideration of the variation between the entrance and the exit of the tire, as measurements of tire contact stresses show. Hence, continuous moving load, which better simulates better vehicle loading, is considered in this modeling.

3.1.5. Layer Interaction

Regarding the interaction between layers, it was mentioned that the conventional analysis assumes full continuity of stresses and strains at layer interfaces. However, this is not a proper consideration, mainly at the interface between AC and granular materials. In addition, numerical modeling suggests that the characterization of the interface is relevant when evaluating the response of flexible pavements. The simple friction model and the elastic stick model using FEM were considered. The simple friction model assumes that the stresses along the interface are proportional to the normal stresses at the interface. On the other hand, the elastic stick model assumes a linear relationship between the shear force and the shear displacement up to a point where the interface "fails." When the interface crosses this point, the behavior at the interface is governed by the simple friction model.

3.2. Pavement Response Prediction

In this analysis, full structure for the thick pavement was used. The pavement section is composed of a 40mm dense-graded surface course, a 150mm base mix, a 75mm asphalt treated drainage layer, a 150mm cement stabilized base, and subgrade. Figure 1 represents the 3D FE model that was developed. The in-plane dimension of the FE model was 1,800×1,588mm. This dimension was selected to reduce the boundary effect on the pavement responses, while keeping the elements' sizes within the proper aspect ratio. A fine mesh was used around the loading area along the wheel path, and a relatively coarser mesh was used far away from the loading area. Infinite boundary conditions are utilized on four vertical boundaries, and at the bottom of the mesh. This study considered two tire configurations, dual-tire assembly and new generation of wide base tire, at three types of load (35.6kN, 45kN, and 53.3kN) and two type of inflation pressure (690kPa and 760kPa). The simulation was performed at a speed of 5km/h during one pass of a moving load at a low temperature (5℃).

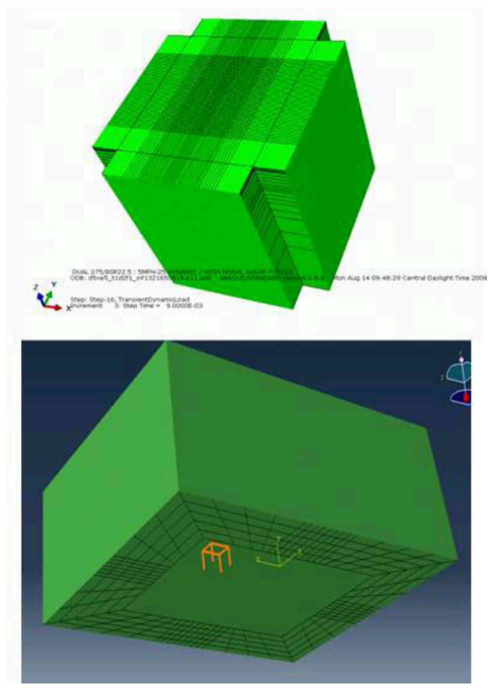

Fig. 1 3D FE Model and Boundary Conditions

The stress and strain is exported from Abaqus program for two directions; transverse direction to wheel path and direction of depth. Figure 2 shows considered directions in this study. From the exported data, the plots for stress/strain were drawn about horizontal distribution at the one inch depth and about variation of depth at the inner edge, outer edge, middle of tire, and middle of tire assembly (for dual tire assembly).

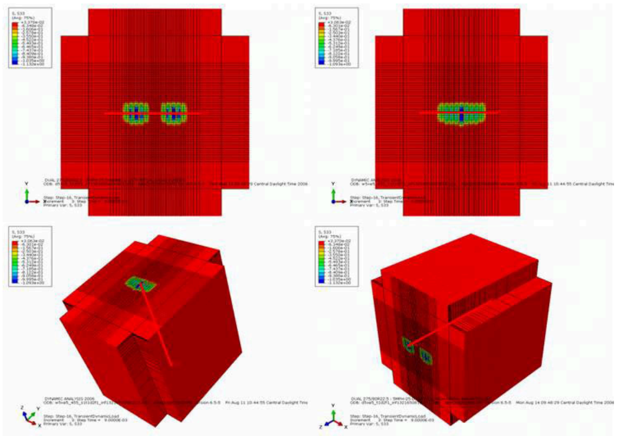

Fig. 2 Considered Directions for Analysis of Stresses/Strains

4. MATERIAL CHARACTERIZATION

Material characteristics are needed as inputs for pavement modeling. The following tests are suggested in this study.

4.1. Complex (Dynamic) Modulus

The axial complex modulus is defined as the ration between sinusoidal axial loading and the resulting strain. On the other hand, dynamic modulus is given by the ratio between the amplitude of the applied sinusoidal strain and amplitude of the resulting strain (Kim 2009). The amplitude of the dynamic load is defined by a haversine pulse, and it is applied so that the deformation of the AC specimen is kept in the viscoelastic range. Time-temperature dependent dynamic modulus of AC is used by MEPDG to calculate critical response of the pavement structure (ARA 2004b).

The viscoelastic properties of AC will be measured using frequency-sweep dynamic modulus tests at various temperatures as described by AASHTO TP-62. The measured complex modulus data and constructed master curves are considered as the base of inter-conversion to other viscoelastic properties (relaxation modulus or creep compliance). Figure 3 presents the experimental configuration of the dynamic modulus test. As described by AASHTO TP-62, the test were performed at five temperatures (-10℃, 5℃, 21℃, 38℃, and 54℃((14°F, 40°F, 70°F, 100°F, and 130°F)), each temperature being tested at five frequencies (0.1, 0.5, 1, 2, 10, and 25Hz).

Fig. 3 Dynamic Modulus Test Set-Up

4.2. Semi-Circular Beam (SCB)

SCB is a controlled displacement test usually performed at low temperature that is used to obtain measurements for fracture energy, fracture toughness, and stiffness. The applied load will generate a constant Crack Mouth Opening Displacement rate. The load-displacement variation will be plotted, and the work of fracture will be obtained as the area under this curve. The fracture energy will be calculated as the ration between the work of fracture and the ligament area.

In order to characterize the fracture behavior at low temperature

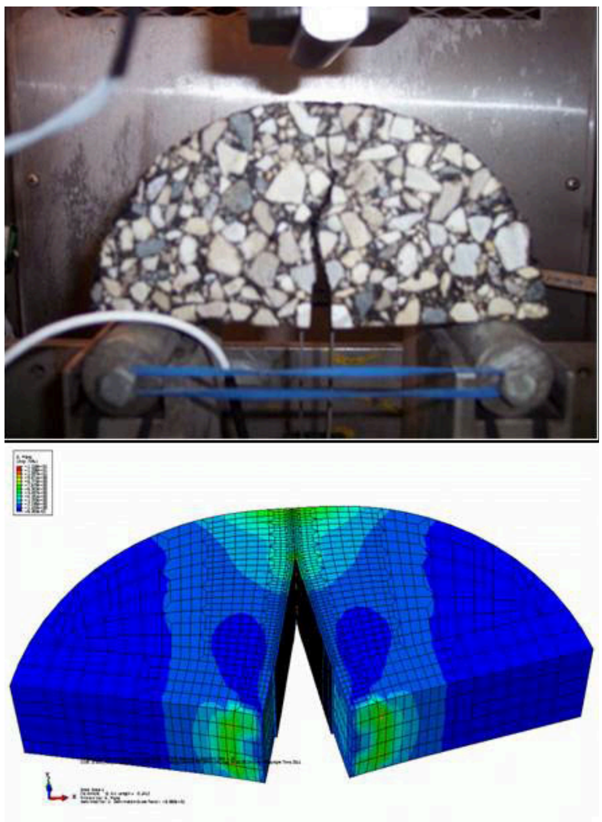

Fig. 4 SCB Test Configuration and 3D Modeling

of AC, the semi-circular beam (SCB) test is performed. Figure 4 shows the set-up of the SCB test and 3D modeling for the SCB test. SCB test will help to provide a failure criterion for low temperature cracking.

4.3. Cross-Anisotropic Characterization of Granular Materials

In order to model the variation of the elastic properties of granular material with direction and stress level, the procedure presented by AASHTO T307 will be followed. In this test, a cyclic loading is applied to the specimen. This cyclic loading is composed of a period of loading and a period of unloading. This will allow the computation of the resilient deformation, which will be used to calculate the resilient modulus.

5. ANALYSIS OF TEST RESULTS

An advanced three-dimensional (3-D) finite element (FE) model was used to predict the viscoelastic pavement responses under DTA and WBT configurations. Figure 5 presents the distribution of surface horizontal vertical stresses as a result of loading by a dual-tire assembly and wide-base tire, respectively.

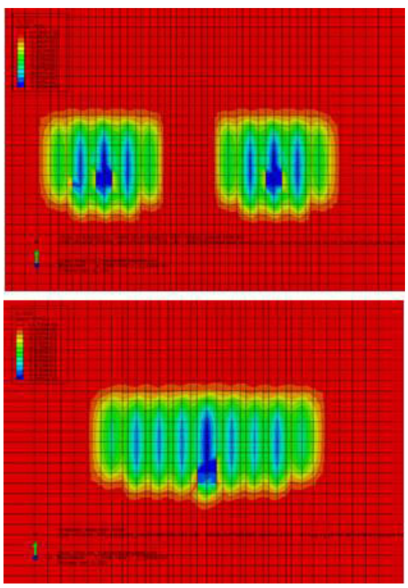

Fig. 5 Vertical Stresses at the Pavement Surface for Dual-Tire Assembly and Wide-Base Tires

Two of the main distresses in flexible pavements are rutting and fatigue cracking. Fatigue cracking is thought to be caused by the repetition of horizontal tensile strains at the bottom of HMA. Rutting is the permanent deformation occurring in the pavement structure, including HMA (primary) rutting and subgrade (secondary) rutting. HMA rutting is mainly induced by the material shear flow in hot weather under a slow moving vehicle.

The plots for stress/strain were drawn about horizontal distribution at the one inch depth and about variation of depth with variation of load and inflation pressure. Figure 6 shows the transverse tensile strain at the pavement surface and at the deeper pavement depth for both the wide-base tire and the dual-tire. As shown in this figure, dual tire assembly resulted in higher transverse tensile strain than did the wide base tire at the pavement surface. However, as the pavement depth goes deeper, wide base tire has higher transverse tensile strain. This trend is shown in all cases with variation of load and inflation pressure.

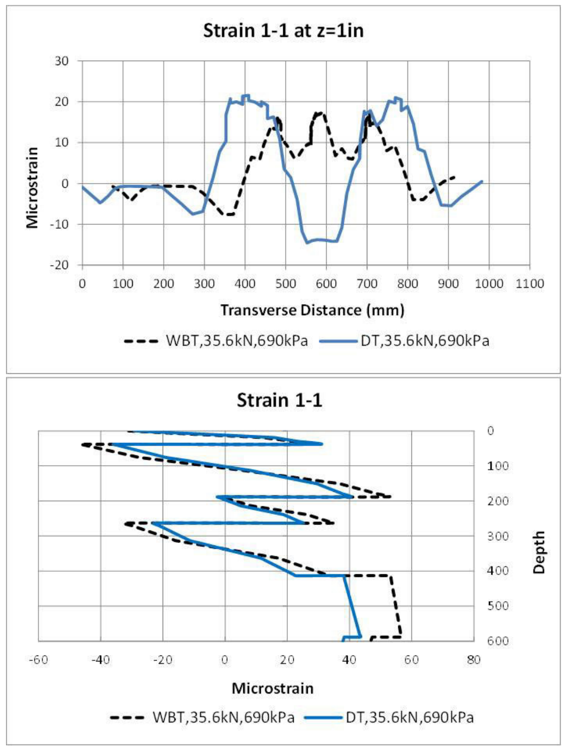

Fig. 6 Transverse Tensile Strain at the Pavement Surface and at the Deeper Pavement Depth

Figure 7 shows the longitudinal tensile strain at the pavement surface and at the deeper pavement depth for both the wide-base tire and the dual-tire assembly. In this figure, the wide-base tire causes greater responses at the deeper pavement depth, including longitudinal tensile strain at the surface of HMA. In other words, the peak longitudinal tensile strains under the wide-base tire are greater than the peak longitudinal tensile strains under a dual-tire assembly at the whole pavement depth. Usually, critical tensile strain (transverse or longitudinal tensile strains) at the bottom of HMA is used to estimate the fatigue cracking damage potential of

HMA. In this study, compared with the transverse tensile strain at the bottom of HMA, the longitudinal tensile strain has a higher strain, so the pavement fatigue response is dominated by longitudinal tensile strain. This becomes a critical strain at the bottom of HMA. Therefore, the result demonstrates that the new wide-base tire is caused slightly more fatigue.

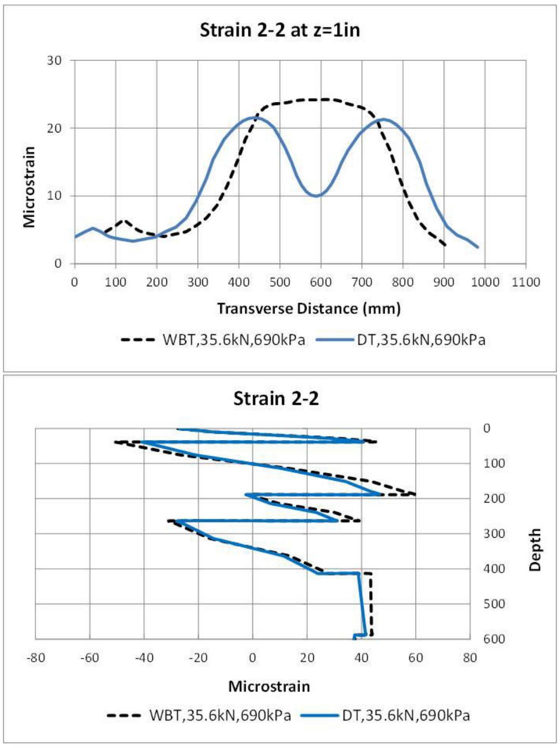

Fig. 7 Longitudinal Tensile Strain at the Pavement Surface and at the Deeper Pavement Depth

The analysis is also conducted at the various tire locations (inner edge, outer edge, middle of tire, and middle of tire assembly) under the wide-base tire and dual tire assembly. Figure 8 and Figure 9 show the transverse tensile strain and longitudinal tensile strain with a variation of pavement depth for both the wide-base tire and the dual-tire respectively.

As shown in the Figure 8, at the surface, the transverse tensile strain of dual tire assembly at the inner edge has higher value than wide base tire. However, as the depth goes deeper, wide base tire has higher transverse strain value. And, the transverse tensile strain of dual tire assembly at the middle of tire shows the same trend as the inner edge case, but with higher value. Figure 9 shows that the longitudinal tensile strain of dual tire assembly at the inner edge has a higher value than wide base tire. In contrast, at the outer edge, the longitudinal tensile strain of dual tire assembly is smaller than wide base tire. However, at the middle of tire, the longitudinal tensile strain of wide base tire has a higher value than dual tire assembly at the inner edge, which means this location is more critical location than inner edge. And, because the longitudinal tensile strain also has a higher strain value than transverse tensile strain, the pavement fatigue response is dominated by longitudinal tensile strain value. So, this shows a similar analysis result which

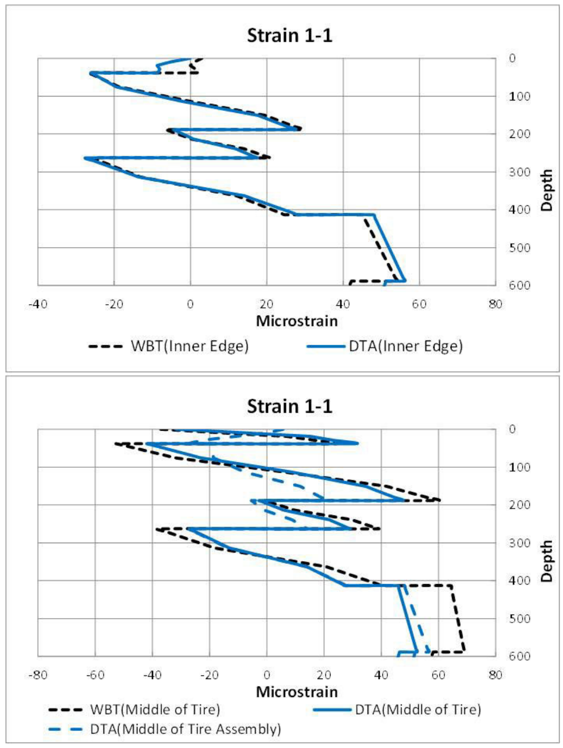

Fig. 8 Transverse Tensile Strain at the Various Tire Locations

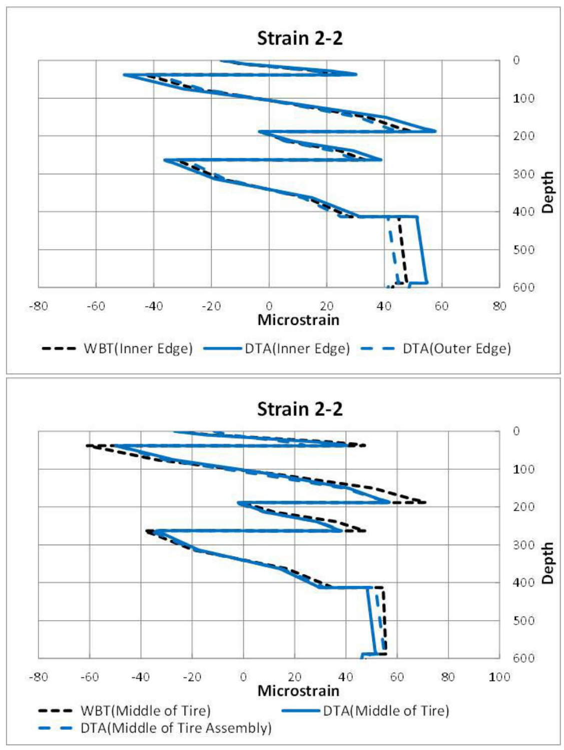

Fig. 9 Longitudinal Tensile Strain at the Various Tire Locations

the new wide-base tire is caused slightly more fatigue.

The primary rutting in asphalt surface is thought to be controlled by the dominated shear strains (E23) in this study. In other words, shear strains at shallow depths can lead to primary rutting of the HMA. Figure 10 shows a dominated shear strain for both the wide-base tire and the dual-tire assembly. The results demonstrate that the dual-tire assembly caused greater shear strain on the HMA layer than wide-base tire. As the pavement depth increases, the strain difference between the dual-tire assembly and wide-base tire diminishes. Figure 11 indicates that the strain of dual tire assembly at the inner edge and outer edge has a higher shear strain than wide base tire. The shear strain of wide base tire at the middle of tire has lower value than dual-tire assembly. As a result for this analysis, the results demonstrate that dual tire assembly causes more damages for rutting in asphalt surface.

Subgrade rutting (secondary rutting) is controlled by the vertical compressive strains on top of the subgrade. Figure 12 shows the compressive strain at the whole pavement depth under dual tire assembly and wide base tire. As shown in this figure, the vertical compressive strain of wide base tire indicates a higher strain value than dual tire assembly at the whole depth and particularly on top of the subgrade. Figure 13 indicates the vertical compressive strain of dual tire assembly at the middle of tire has higher value than strain value of wide base tire at the surface (0~20mm). But, as the depth goes deeper, wide base tire has more vertical compressive strain. Considering the comprehensive result analysis, the results demonstrate that the wide-base tire causes greater compressive strain on top of subgrade than the dual-tire assembly. Therefore, this means that the wide-base tire causes more damages for rutting in the subgrade.

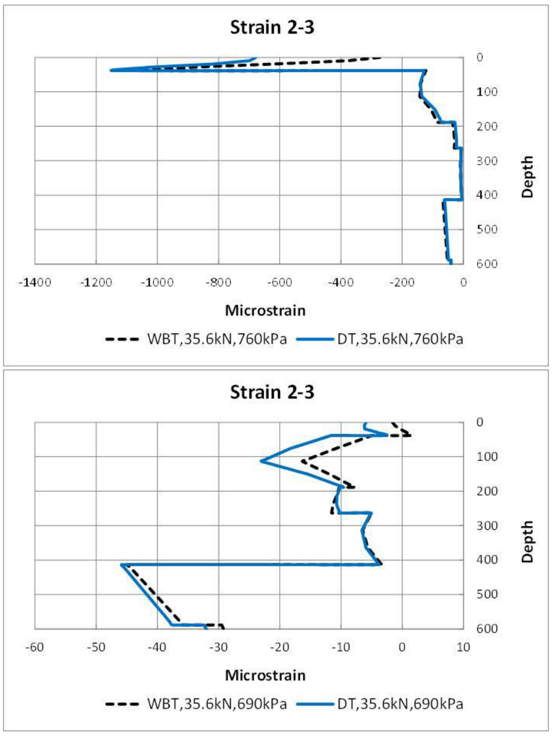

Fig. 10 Shear Strain for Both the Wide-Base Tire and the Dual-Tire Assembly

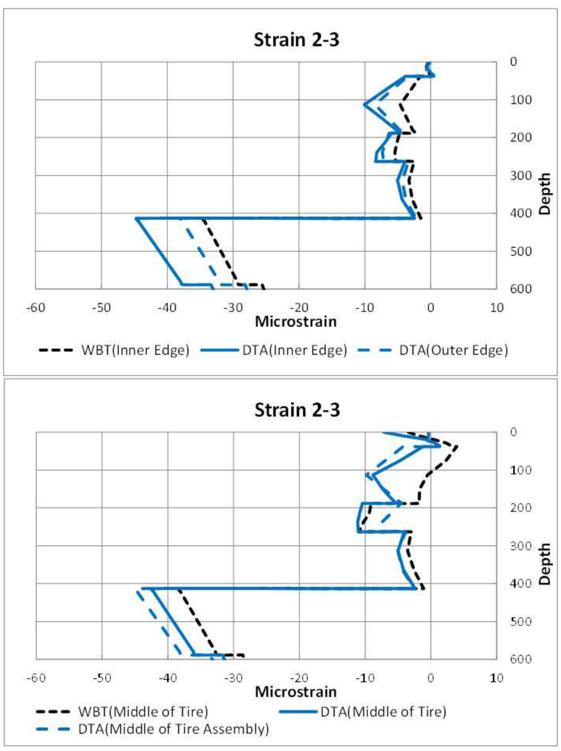

Fig. 11 Shear Strain at the Various Tire Locations

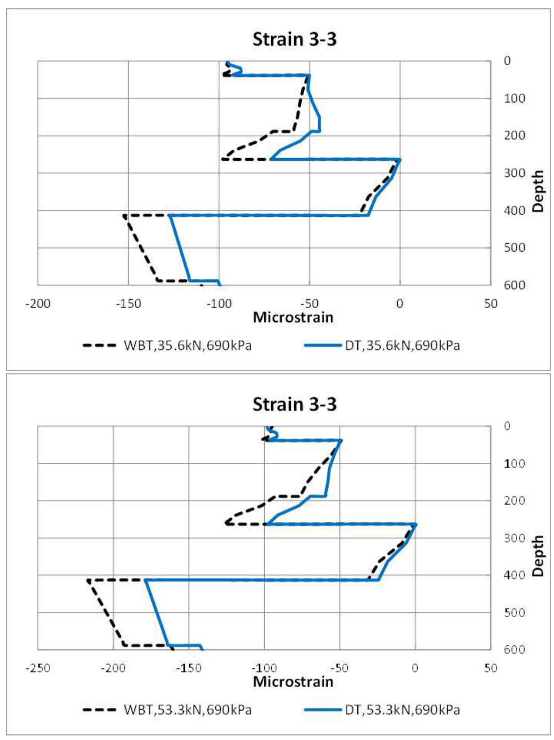

Fig. 12 Compressive Strain at the Whole Pavement Depth

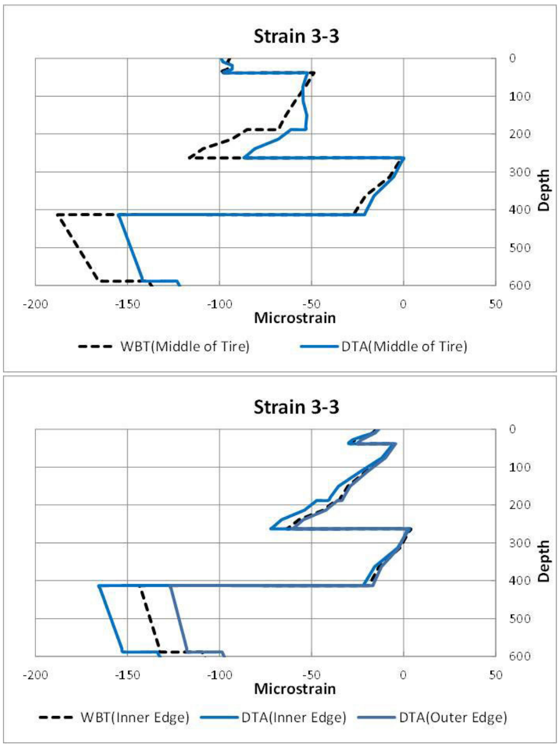

Fig. 13 Compressive Strain at the Various Tire Locations

Figure 14 shows the tensile stresses at the whole pavement depth under dual tire assembly and wide base tire. As shown in this figure, the tensile stress of wide base tire indicates a higher tensile stress value than dual tire assembly at the whole depth. This will give more damages on pavement.

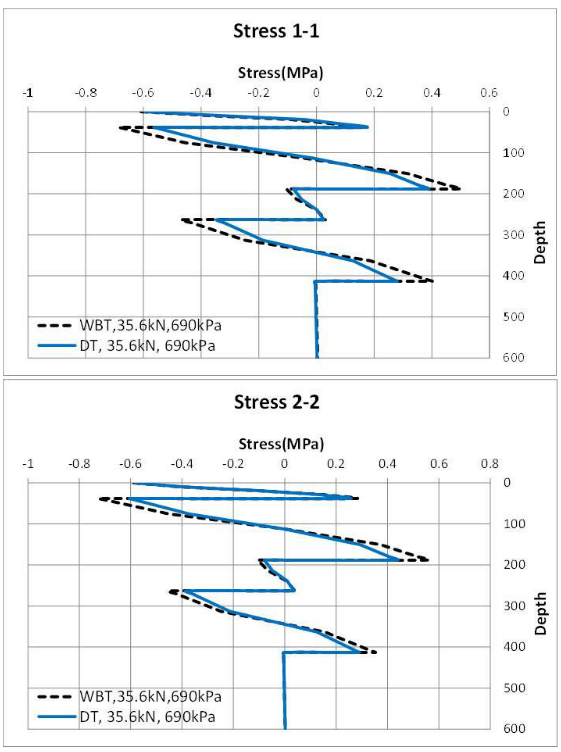

Fig. 14 Tensile Stress under Dual Tire Assembly and Wide Base Tire

Figure 15 presents the shear stresses at the whole pavement depth under dual tire assembly and wide base tire. In this figure, the shear stress of dual tire assembly indicates a higher shear stress value than wide base tire at the load of 35.6kN and the pressure of 690kPa. But, if tire pressure and load are increased, the shear stress for wide base tire shows a higher stress than dual tire assembly.

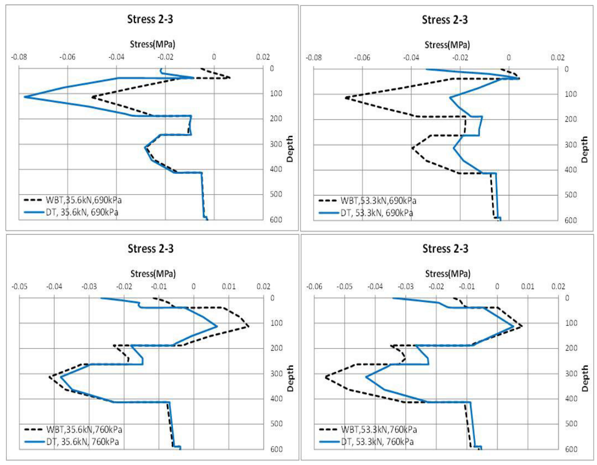

Fig. 15 Shear Stresses at the Various Loads and Pressures

Figure 16 shows the vertical compressive stresses at the whole pavement depth under dual tire assembly and wide base tire. As shown in this figure, the vertical compressive stress is almost same at the pavement surface, but as the pavement depth is

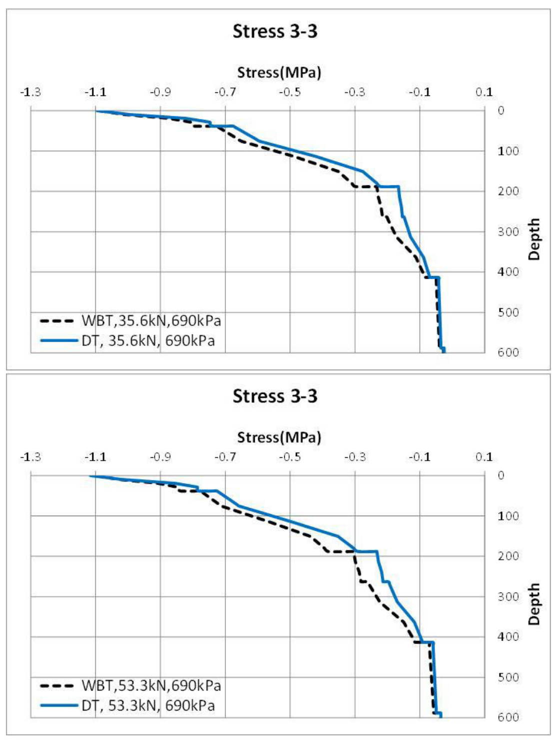

Fig. 16 Vertical Compressive Stress under Dual Tire Assembly and Wide Base Tire

increased, the vertical compressive stress of wide base tire indicates a higher compressive stress value than dual tire assembly which giving more damages to pavement.

In this study, the Mises stress was considered. Mises is one of the failure criteria and is calculated by combining stresses as the following equation. It needs to be considered because failure is occurred by the combination of stress components, not the max value of stress components.

$$\sigma_v^2 = \frac{1}{2}\left[(\sigma_{11}-\sigma_{22})^2 + (\sigma_{22}-\sigma_{33})^2 + (\sigma_{11}-\sigma_{33})^2 + 6\left(\sigma_{23}^2+\sigma_{31}^2+\sigma_{12}^2\right)\right] \quad (1)$$

Figure 17 shows the Mises stress at the various tire locations under dual tire assembly and wide base tire. As shown in this figure, the Mises stress of wide base tire has higher stress than dual tire assembly which gives more damages to pavement at the surface part and deeper layer part.

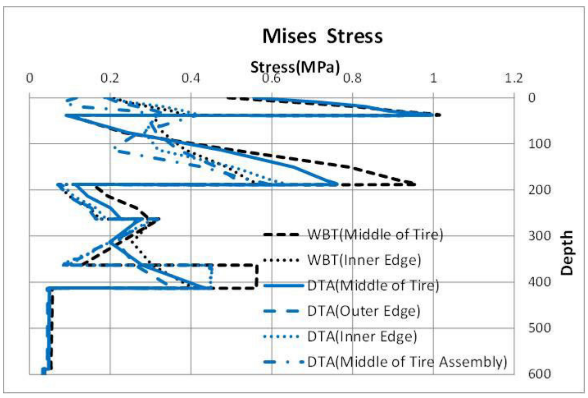

Fig. 17 Mises Stress at the Various Tire Locations

6. CONCLUSIONS

The first generation of wide base tires was found to cause a significant increase in pavement damage compared to dual-tire assemblies. However, after more than two decades of research by the tire industry in conjunction with pavement researchers, a new generation of wide base tire is thought to be comparable to conventional dual tires for pavement damage. The primary objective for this study was to investigate the pavement damages and responses of flexible pavement to continuously moving vehicular loading caused by dual tires assembly and new generation of wide-base tire. This study considered two tire configurations at three types of load (35.6kN, 53.3kN, and 45kN) and two type of inflation pressure (690kPa and 760kPa). The analysis is also conducted at the various tire locations (inner edge, outer edge, middle of tire, and middle of tire assembly) under the wide-base tire and dual tire assembly. The results of this study are as follows:

1. This study concludes that new wide base tires lead to slightly more fatigue damage than dual tire assembly on the HMA layer.
2. As a result for shear strain analysis, this study concludes dual tire assembly causes more damages for rutting in asphalt surface (primary rutting problem).
3. The results for vertical compressive strain analysis demonstrate that the wide-base tire causes greater compressive strain on top of subgrade than the dual-tire assembly. Therefore, the wide base tire causes more damages for rutting in the subgrade.
4. The shear stress of dual tire assembly indicates a higher shear stress value than wide base tire. But, if tire pressure and load are increased, the shear stress for wide base tire shows a higher stress than dual tire assembly.
5. The Mises stress of wide base tire has higher stress than dual tire assembly which gives more damages to pavement at the surface part and deeper layer part.

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