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Influence Of Overlay Thickness On Interface Bonding

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Dedication

I would like to dedicate this thesis to my beloved wife.

INFLUENCE OF OVERLAY THICKNESS ON INTERFACE BONDING

by

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THESIS

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Abstract

Overlaying is an efficient and proven pavement preservation approach for flexible pavements. The overlay thickness varies from 1 in. to 4 in. depending on the conditions of the existing pavement, financial resources, etc. In the recent decade, financial constraints in conjunction with the push for pavement preservation, the overlay thickness is being reduced to less than an in. The ultra-thin overlay is a new cost-effective method that can be used to preserve functional pavement problems and provide satisfactory ride quality. Although studies have been conducted to evaluate pavement systems using numerical simulation, the research in the area of evaluating existing layer and overlay layer as a composite layer is limited. With the advent of Ultra-thin layers, the durability of pavement system will be significantly influenced if both layers separate from each other. The several experimental studies have focused on the interface bonding between the overlay and existing asphalt layer. They evaluated how different criteria like tack coat type, dust, or moisture can affect the interface bonding strength between layers. But the impact of different interface bonding strength on pavement structure and durability of overlay itself has not been extensively evaluated. Overlay thickness impact on pavement structural characteristics is another aspect of the subject that still needs a lot of research.

The main purpose of this study was to perform numerical simulation of several pavements systems with different overlay thicknesses and to evaluate the effect of overlay thickness and overlay-existing asphalt layer interface bonding on pavement performance. Three-dimensional finite element models have been used to simulate different pavement systems using ABAQUS software. Different interface bonding strength has also been implemented for each of the pavement systems to evaluate the effect of interface bonding strength.

Models with linear elastic-perfectly plastic behavior for the base and subgrade was selected for the base and subgrade layer. Viscoelastic behavior of the asphalt material has been modeled using dynamic modulus test results and Prony series. Finite and semi-infinite elements have been developed to model the pavement systems. Passing (moving) vehicle's load used to see the impact

of overlaying in highways or other places that vehicles drive at nearly constant speed. The pavements performance under braking conditions was also necessary to see how overlay works under stop and go traffic conditions or near intersections. Rather than uniform distributed load, the load was non-uniformly distributed in the tire footprint are to simulate actual field conditions. Frictional and cohesive contact approach was followed to define interface layer and bonding between the two layers. Frictional contact has been used to simulate the interface characteristics between existing asphalt and base layer. The cohesive contact was used to define the tack coat layer properties.

Maximum deflection at the top surface of the pavement and the maximum tensile strength at the bottom of the existing asphalt layer has been observed as the two most important criteria determining pavement performance. To evaluate the durability of the overlay itself, contact opening between the overlay and existing asphalt layer has been observed. The evaluation results identified that overlay thickness of less than 2 in. doesn't add structural strength to the pavement system. The overlays with the thickness of less than 1 in. significantly influences stress levels at the interface; therefore, bonding between the two layers is important. The moving load versus braking loads should be considered for evaluating the composite pavement design system.

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1. Introduction and Background

1.1 Introduction

Overlaying is an effective and proven pavement preservation approach for flexible pavements. The overlay thickness varies from 1 in. to 4 in. depending on the conditions of the existing pavement, financial resources, etc. In recent decade, financial constraints in conjunction with push for pavement preservation, the overlay thickness is being reduced to less than an in.. Ultra-thin overlay is a new cost-effective method that can be used to preserve functional pavement problems and provide satisfactory ride quality. For placement of ultra-thin overlay layer, the State Highway Agencies (SHAs) have been specifying micro-milling of existing pavements followed by placement of ultra-thin overlays. These ultra-thin overlays are usually placed to preserve functional issues like roughness, raveling, weathering, and loss of skid resistance [1].

Although ultra-thin overlay has been gaining acceptance, there will be stress concentration at the interface and slight separation between overlay and existing hot mix asphalt (HMA) layer will eventually lead to slippage of overlay especially at places where vehicles stops, decelerates, or accelerates. Therefore, the level of bonding between the two layers will influence performance of overlaid pavement structure. Additionally, it has been accepted that the overlaying improves the structural characteristics of the pavements, but detailed research on how much of structural improvement is achieved by milling before overlaying is still needed.

To identify stress levels at the interface and enhancement in structural properties due to milling, numerical modelling of the pavement structure was performed using commercially available ABAQUS software. Although researchers have simulated pavement systems numerically, the number of studies that considered overlaid pavement are limited.

This study performed three dimensional modelling of pavement systems with different overlay thickness and different interface layer characteristics to observe their impact on the pavement performance.

1.2 Research Objectives

The following objectives are formulated for this study:

- Analyzing the influence of the depth of the interface layer, or overlay thickness, on the induced deformation at the pavement surface and strains at the bottom of the surface layer.
- Identifying the influence of overlay thickness and interface bonding on pavement structure.
- Identifying the impact of the HMA layer thickness and its contact characteristics on the pavement structural characteristics

In this study, several pavement systems with different overlay and existing layer thicknesses have been modeled to evaluate the difference in behavior of overlays with different thickness and interface bonding strength and their influence on the induced strains and deformations.

The thickness of the overlay and its interface bonding with the existing layer have, obviously, major influence on the final pavement performance. But, the number of researches on detailed relationship between these two main criteria and pavement responses are very limited. This study tries to take a careful look on how changing the thickness of overlay and the interface bonding between overlay and existing layer changes overlaying impact on the pavement responses.

Defining and implementing the viscoelastic behavior of asphalt in FEM software and defining an appropriate contact characteristic between overlay and existing asphalt layer are the most deterministic criteria assuming the other criteria like model size, loading, and element size and type has been chosen correctly.

1.3 Organization

This chapter introduces the problem and research objectives of this study. The Chapter Two documents literature review performed to identify existing literature. The Chapter Three presents selected pavement designs that have been modeled to do a complete parametric study.

Chapter Four encompasses developing the finite element models in ABAQUS to simulate different pavement systems. Thickness of different layers in each pavement system, load, material, and interface characteristics, size of the final models, and the type and size of the finite and infinite elements has been decided and introduced in this chapter.

Chapter Five presents the results and discussion for all different pavement designs and the last Chapter Six includes summary of the findings, conclusions drawn and recommendations for the future research.

2. Review of information

Using Boussinesq theory, Burmister used layer elastic theory to analysis a pavement for the first time [2]. The main shortcoming of this method is actually its unability in considering the real behavior of the materials. The layered elastic theory assumes that all pavement layers behave like a linear elastic material. But considering all possible designs, materials in a flexible pavement structure could have elastic, viscoelastic, and plastic behavior. This broad range of material behavior and the complicated contact characteristics between layers means that the mathematical analysis of the pavement could not be exact enough [2]. Considering circular tire foot print, uniform loading at the contact area, and assuming all layers to be fully bonded are additional shortcomings of layered elastic theory.

With increase in computational capacity, numerical methods have become more popular for analyzing pavements behavior under loading in last several decades. Among several different numerical methods, the Finite Element Method (FEM) is the most popular because of its ability to simulate:

- different materials' behavior (elastic, viscoelastic and plastic)
- more realistic tire foot print area (rectangular)
- non-uniform loading in the contact area
- different types of the contacts between layer
- different layers of varying thickness and boundary conditions.

Considering all of above mentioned advantageous, different research groups have used FEM software to observe different aspects of the pavement. First attempt in modeling the pavement system using FEM theory has been done in two dimensional (2D) space. ILLI_PAVE and MICH_PAVE are two software that have been created around 1985 that used 2D method to model pavements as an axisymmetric solid domain [2, 3, 4].

With increase in computational capacity, three dimensional finite element models have been used to evaluate pavement behavior more accurately. A research that have been done in 1996

suggested that accuracy in 3D models assuming linear elastic behavior for all layers [5, 6] is higher in comparison to 2D models.

Implementing more realistic material behavior in FEM software was the next step in FE simulation of pavement systems. Although the viscoelastic behavior of HMA is known for more than 50 years, this behavior was not implemented in a FEM software until recent years [7]. A study conducted by Al-Qadi and associates in 2006 [8] showed the importance of defining viscoelastic behavior for HMA layer in predicting HMA material responses. They compared the results for models with linear elastic behavior and viscoelastic behavior and concluded that assuming linear elastic behavior for HMA material results in way less critical responses in compare to the experimental results. This suggests that linear elastic behavior overestimates the pavement structural characteristics and could lead to premature failure [7, 8] because HMA is a viscoelastic material. In another research, a pavement system was simulated that assumes viscoelastic behavior of HMA layer to observe the damage caused by dual and wide base tires [7, 9]. In 2007, researchers modeled a pavement system with viscoelastic behavior of the HMA layer to simulate the pavement behavior under vehicles with different speeds [7]. Nowadays, most of the researches in this area with the focus on HMA layer uses viscoelastic behavior in their simulations.

Considering the plastic part of the HMA material behavior, there are also some researches that implement the HMA material in FE software as a viscoplastic material. In 2002, Hua and White used the viscoplastic behavior of HMA layer to predict the permanent deformation at the pavement surface [10]. This method has its own advantages and disadvantages. The main advantage of this method is its ability to predict the permanent deformation at the pavement surface. However, defining the viscoplastic behavior of the HMA material becomes challenging because it needs triaxial test machine. Compressive strength test at different strain rates and confinement pressures have to be performed to obtain parameters that are needed to define the viscoplastic behavior of HMA material [11]. Besides the requirement of especial equipment, modeling HMA layer with viscoplastic behavior underestimates the critical strains at the peak of the loading time. In general, running viscoplastic models needs more computational time in

comparison to viscoelastic models. Additionally, very thin layers of HMA material (thin or ultra-thin layer) makes the model unstable under loading.

With regard to pavement overlay, there are a lot of experimental research observing the impact of different aspects of overlay on pavement performance. Interface bonding strength is one of the most important characteristics of the interface layer which could affect the pavement performance has been the focus of several experimental researches in recent years. Simple shear test has been used on laboratory prepared specimens to evaluate the influence of tack coat types, rates of application, and test temperatures on the interface shear strength [12]. In 2013, Salinas et al. [13] conducted comprehensive research to examine the field performance of different tack coats and validate the laboratory determined application rate. In addition to tack coat types and application rates, several field cores were obtained and tested to evaluate the effects of existing pavement surface, different cleaning methods, and different paving procedure [13] on properties. In 2001, Romanoschi and Metcalf [14] developed a constitutive model for AC interface layer. Using direct shear test, they found out that up until interface failure the shear strength- shear displacement curve would be linear with a constant slope. The shear strength, then, drops significantly near failure. There would be a constant friction coefficient between two layers after interface failure. The slope of the linear part of the curve which is named interface reaction modulus (K) was different for interface with and without tack coat [14].

The depth of the interface layer (vertical distance between interface layer and pavement surface) is another important aspect of overlay which has a significant effect on pavement performance. The interface depth, or overlay thickness, is a key factor influencing the pavement responses. With change in the thickness of the overlay, the structural behavior will change. On the other hand, by changing the vertical distance between interface layer and pavement surface, the influence of loading on interface would be different. Therefore, pavement systems with different overlay thicknesses would have different performance. An experimental research has been done by Texas Department of Transportation suggests that thickener overlay would have more durability due to its resistance to transverse cracking [15] in comparison to thinner overlay.

Based on the review of information, viscoelastic behavior of HMA material implemented in ABAQUS software. The viscoelastic behavior of HMA was estimated using dynamic modulus tests performed at different temperatures and frequencies. Although the soil (base and subgrade) layers below are elastoplastic in nature, the soils layers were considered to be linear elastic in this study. In addition, 3D finite element simulations have been performed in this study to simulate overlaid pavement systems with different overlay thickness and interface bonding strength. A complete parametric study was performed to identify trends that impact pavement performance.

3. Pavement Designs

In this study, the two main type of pavement designs were simulated using ABAQUS software (pavements with and without overlay). Four different original pavements (without overlay) were modeled in the first step to observe the effect of the asphalt layer thickness on pavement performance. Six different contact characteristics were also selected to observe the impact of the HMA-base layer contact on the final results. As the focus of this research is on the HMA layer, the thickness of base layer was kept constant at 6 in. To minimize the influence of boundary conditions, a 12 in. of subgrade layer thickness has been assumed in all models. Although the strains and deformations will be different for different base and subgrade thicknesses, the selection of base and subgrade thicknesses was to reduce computational time while reducing the significance of base and subgrade layer thicknesses.

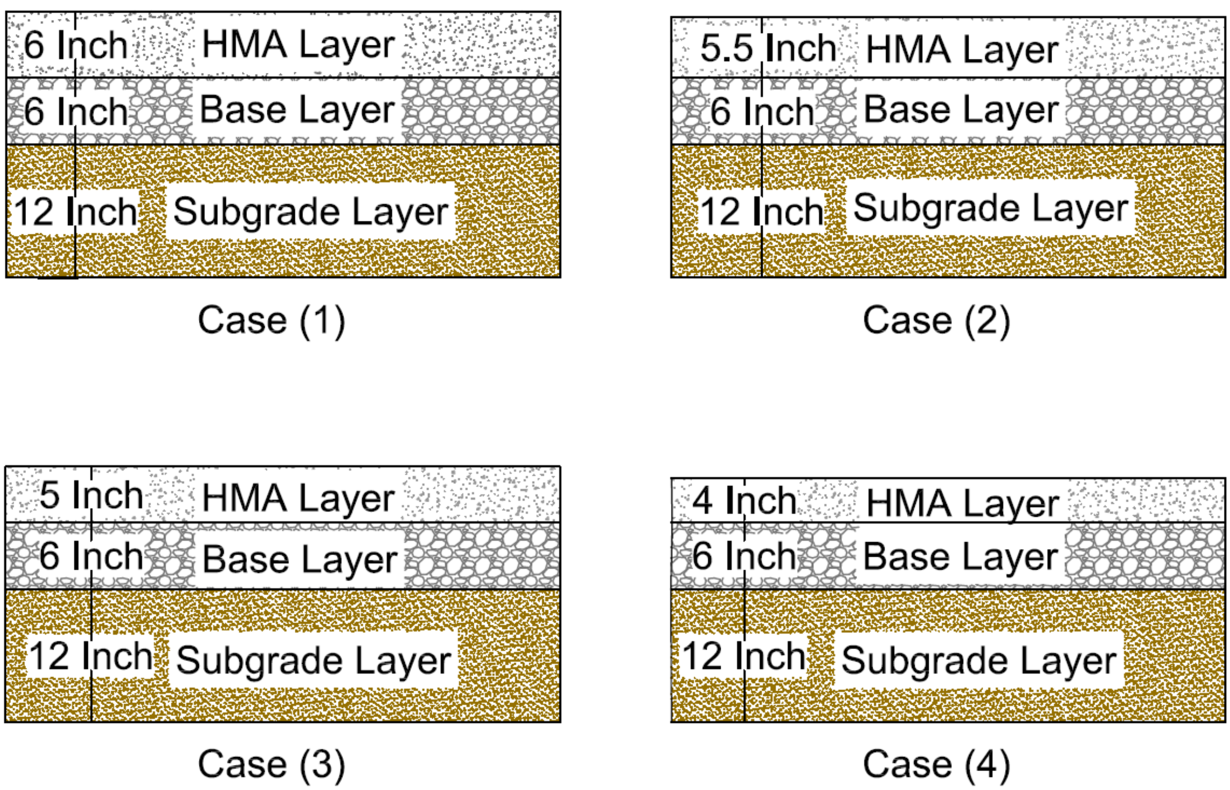


Figure 1 Four Different Original Pavement Designs (Pavements without Overlay)

In order to analyze the overlay impact on pavement structural characteristic, the six different pavement designs with different existing asphalt layers and overlay thicknesses were modeled (Figure 2):

- Cases 5, 6, and 7 have 4 in. of existing HMA layer and 2.0, 1.0, and 0.5 in. of overlay, respectively.
- Cases 8, and 9 have 5 in. of existing HMA layer and 1.0 and 0.5 in. of overlay, respectively.
- Case 10 has 5.5 in. of existing HMA layer and 0.5 in. of overlay.

These pavement designs have been chosen to analyze all different ranges of existing layers and overlays. It worth mentioning that overlays with 0.5 or 1.0 in. thickness would be considered thin and ultra-thin overlay which works mostly as a functional layer. But an overlay with 2 in. thickness is expected to work as a structural layer and improves the structural characteristics of the pavement.

To perform a parametric study on how the overlay thickness impacts the structural characteristics of the pavement and durability of overlay itself, three different overlay thicknesses and three different existing HMA thicknesses were considered. On the other hand, to make sure that the impact of the interface bonding strength has been covered completely, 5 different cohesive contact strength were defined for each of the overlaid pavement designs. This means that 30 different runs were conducted for each loading situation. As mentioned in the following chapter, the inclusion of two different loading conditions (passing and braking of vehicles) increased the total number of runs to 60.

As it can be seen in chapter five, the results of the runs of overlaid pavements should be considered in four major categories. The effect of the overlay thickness on the pavement structural characteristics and the durability of overlay itself would be the first two categories and the impact of interface bonding strength on the pavement structural characteristics and overlay durability would be the third and fourth category, respectively.

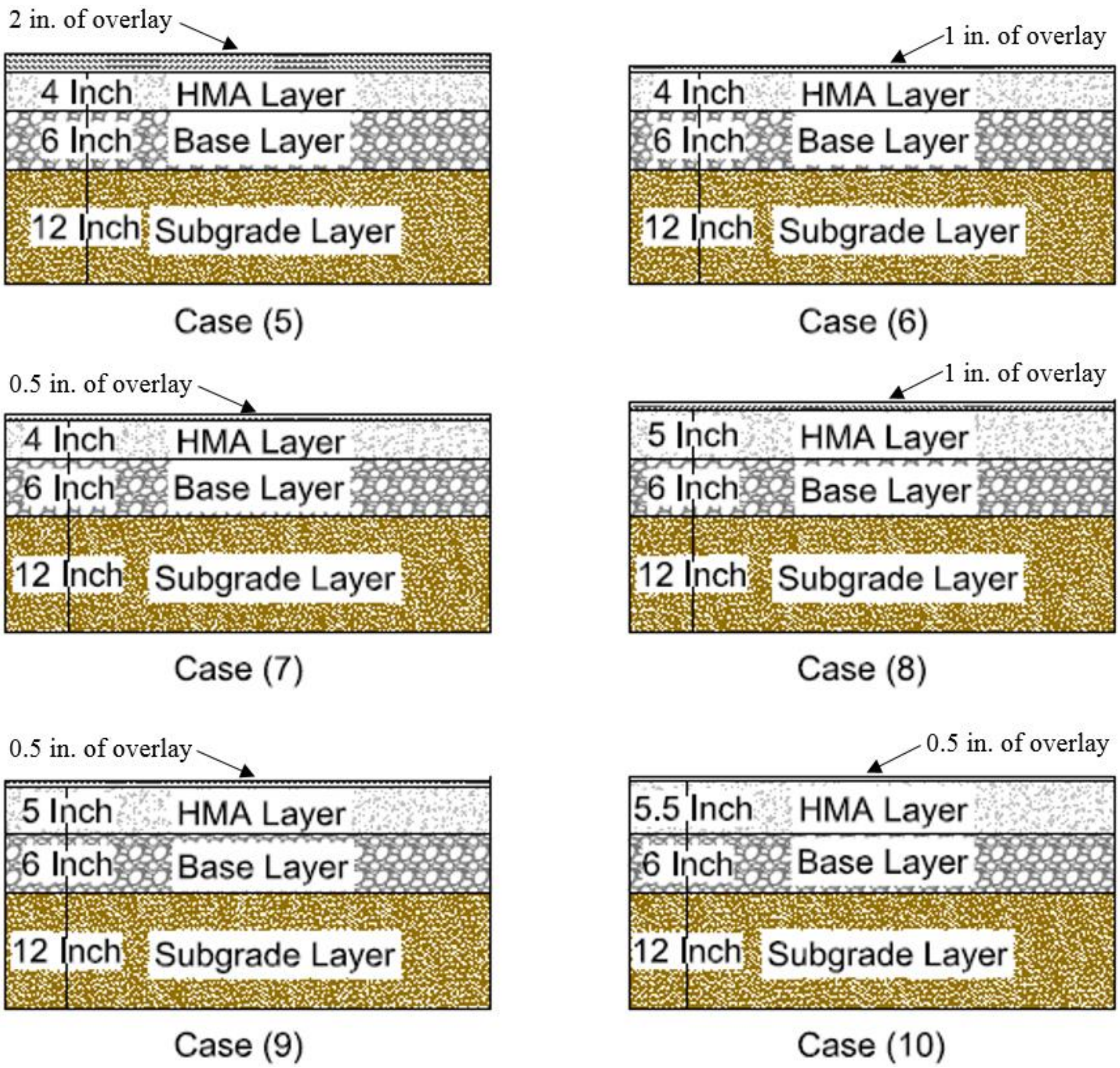


Figure 2 Pavement Designs with Overlay

4. Development of Finite Element Model Using ABAQUS

4.1 Loading Characteristics

Two different types of loading conditions have been modeled in this study: loading condition in which a vehicle passes over the pavement with a constant speed (passing vehicle), and loading condition in which a vehicle is braking over the pavement surface with a constant deceleration rate (braking vehicle). In either of these two different situations, vehicles put both vertical and transverse loads on pavement surface, but, obviously, the amount of the load in horizontal direction would be different in these two different situations.

Although for a vehicle passing over the pavement surface with a constant speed, vertical load would be the major influence on pavement responses, but there would be also some horizontal loads in the tire foot print area. Researchers have previously verified that the amount of the horizontal load that a passing vehicle puts on the pavement is almost negligible. In this study, test runs have been performed for a basic pavement design to check the aforementioned statement. The pavement responses to the two different loading situations, with and without horizontal loading, have been analyzed to make sure that implementing the horizontal loading caused by a passing vehicle with a constant speed does not have a meaningful impact on the results. So, in the simulation of pavements under passing vehicles, the only load that has been implemented in the final models would be vertical load due to the vehicle's weight.

As the vertical load of a vehicle on a pavement is due to its weight, the amount of the vertical load of a braking vehicle on a pavement surface is equal to vertical load of a passing vehicle. The horizontal load of the braking vehicle, on the other hand, needs to be implemented to simulate behavior of pavements under braking vehicles. Therefore, in all simulations of pavements under braking vehicles, vertical load due to the vehicle's weight and horizontal load due to the braking was introduced in the ABAQUS runs.

4.1.1 Passing vehicle's load

According to "Pavement Analyses and Design" reference book [16], the contact pressure created by a vehicle and its tire pressure can be assumed to be equal. It also assumes that the tire pressure is uniform over the tire foot print surface. Based on these assumptions, the tire footprint can be calculated by dividing the total load on each tire to the tire foot print. Considering these assumptions, each tire contact has a single wheel load of 4,500 lb (20 kN) of a 18,000 lb (80 kN) single axle with dual wheels. Since tire pressure is 80 psi, the tire contact area can be calculated using the following equation [17]:

$$Tire\ Contact\ Area = \frac{Single\ wheel\ load}{Tire\ pressure} = \frac{4{,}500\ lb}{80\ psi} = 56.25\ \ sq.in$$

The actual tire foot print area is composed of a rectangle and two semicircles area, but to make the simulation easier, the equivalent rectangle area can be used [16]. Using above mention assumption, the length and width of the contact area would be 6.22 in. and 9 in., respectively.

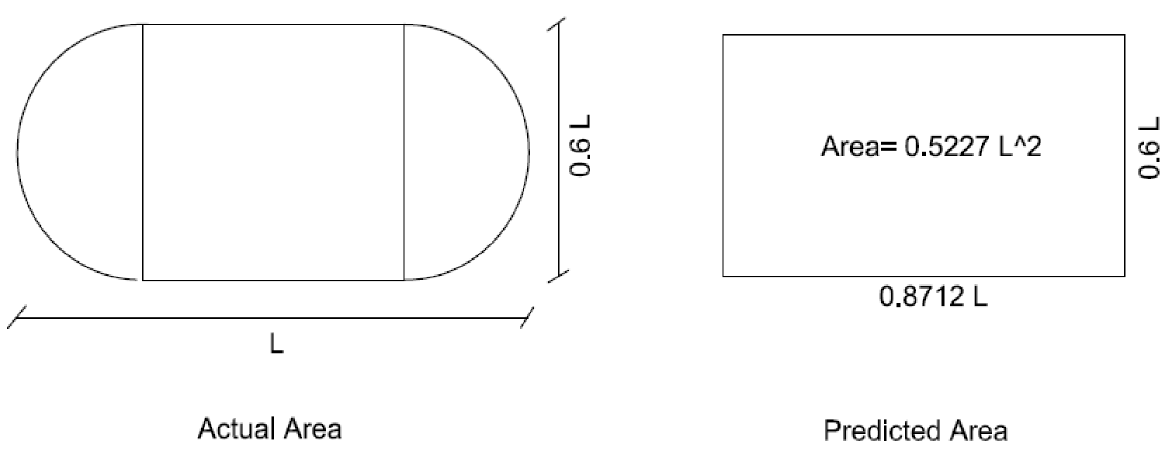


Figure 3 Actual and Equivalent Tire Contact Area [16]

Although initially it had been assumed that the tire pressure is uniform, the research over the years has identified that the tire pressure is non-uniformly distributed over the tire footprint

area. In the longitudinal direction, the maximum tire pressure has been observed to be in the middle of the contact area and it decreases gradually by moving toward the tire walls. For a heavy truck loading, the average maximum tire pressure is 100 psi (689.5 kPa) and it would be almost zero at the two sides of the contact length. Various researchers have suggested that the loading distribution over the contact length is similar to the one shown in Figure 4 [18, 19, and 20]. It is worth mentioning that to make the simulation easier, the dotted curve have been used as the loading distribution in this study.

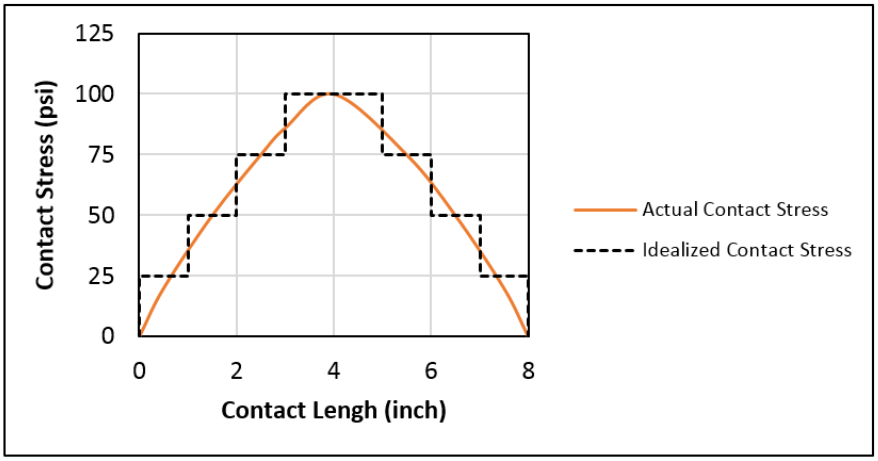


Figure 4 Actual and Idealized Tire Contact Stress [20]

Assuming that the effect of each side of a single axle on the pavement responses at the other side would be negligible, all models in this study simulate one side of a single axle with dual wheels.

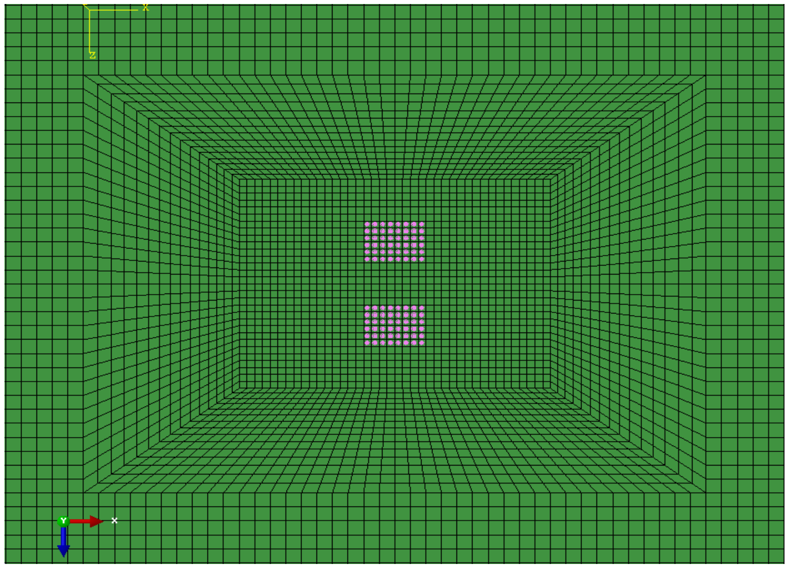


Figure 5 Vertical Loading Pattern for a Single Axle Dual Wheel Vehicle.

To be more accurate in simulating the wheel's load on a pavement, the shear component of the wheels' load should also be considered. Surface shear force on a pavement surface can be classified in too longitudinal and transverse shear force. Just like the vertical component of the contact force, shear components are also non-uniform. On the other hand, unlike the vertical stress, shear forces change their direction within the tire foot print area.

As shown by Figure 6, the longitudinal loading implemented in ABAQUS software changes its direction twice. Dividing the contact length to four sub-length and assuming four equal contact sub-area, compressive longitudinal shear force increases from the entrance of the tire footprint to the end of the first sub-area. Then it decreases to reach to the zero at the end of the second sub area. Going through third and fourth sub-area, the tensile force reaches to its maximum in between [21]. The maximum longitudinal and transverse stress at the contact area are between 12 to 16 percent of vertical stress [21, 22]. As the transverse shear stress direction changes within each tread of the tire, its total effect on the final results would be negligible. It means that the transverse shear force in each tread counteract and the effect on the final results can be ignored [21].

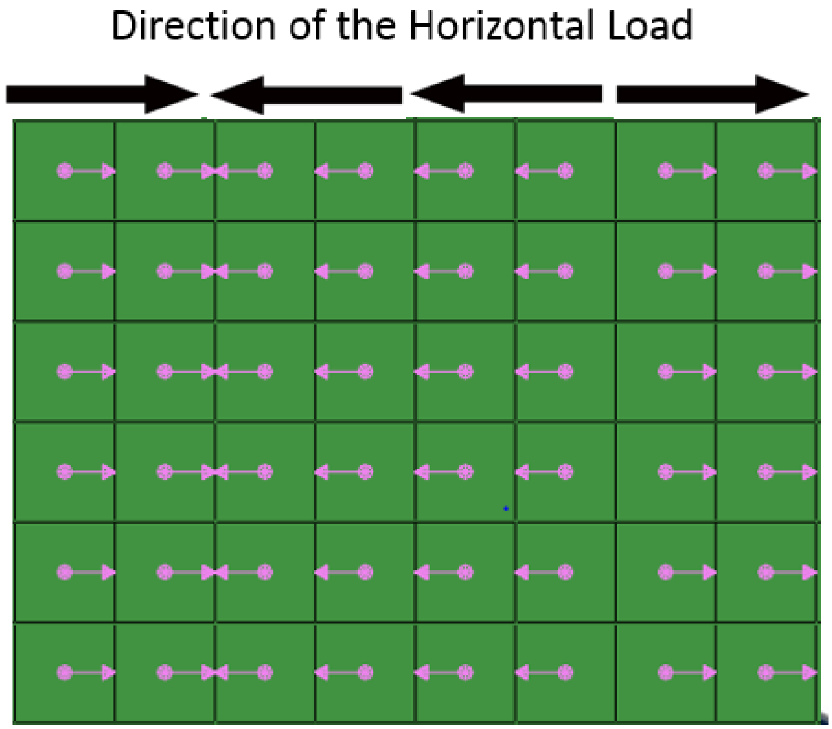


Figure 6 Compressive Longitudinal Force at the First Half (Left Half) and Tensile Force at the Second Half (Right Half) of the Tire Foot Print

The main purpose of the longitudinal and transverse contact forces was to evaluate pavement strain induced at the interface layers. Obviously, pavement design with 0.5 in. overlay is the most critical when considering the interface responses. So, pavement with 5.5 in. of existing asphalt layer and 0.5 in. of overlay was evaluated and the results of with and without longitudinal load identified no meaningful difference between the two conditions. It seems that longitudinal stresses in different directions works again each other and the final effect on the results would be negligible. Considering the negligible effect of longitudinal stress in most critical pavement design, surface shear forces were not further modeled.

4.1.2 Braking Vehicle's Load

As mentioned before the vertical loading for passing and braking vehicles would be equal considering the fact that the vertical load that a vehicle puts on a pavement is due to its weight. So,

the amount of the vertical load in all simulations of pavements under braking vehicle would be just like the passing vehicles.

Vehicles' braking put a horizontal load over the pavement and tire contact area which is dependent mostly to the vehicles' initial speed and deceleration rate. Generally speaking, higher initial speed and deceleration rate results in higher horizontal load on pavement surface layer. But, assuming the uniform deceleration rate during the whole stopping process for all different speeds, the braking load for all different speeds can be assumed to be equal. In this way, a uniform load over the loading area can be assumed for full braking situation which is just dependent of vehicles weight and its axle characteristics. The contact stress towards the wheel direction (longitudinal direction) at full braking situation has been calibrated in simulations at this study with Wang et al. [23] work (Figures 7 and 8).

Since the tire contact area for passing and braking vehicles considered to be equal, the only difference between loading condition for a braking vehicle with the one for a passing vehicle, would be a uniform horizontal load simulating the braking horizontal load on the pavement surface.

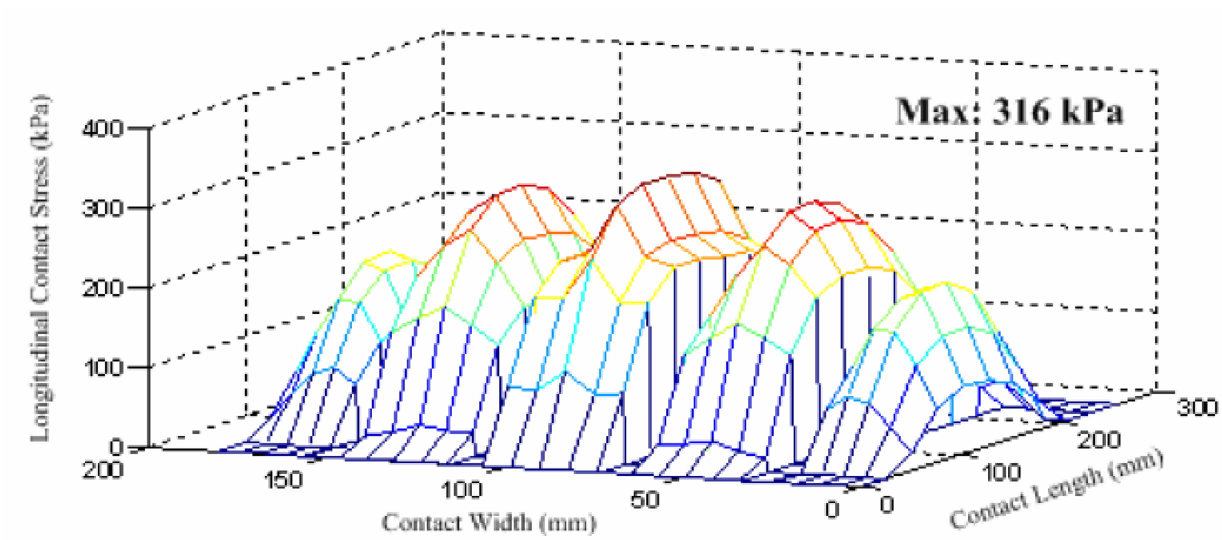


Figure 7 Results for Longitudinal Contact Stress at the Full Braking Condition at Wang et al. work [23]

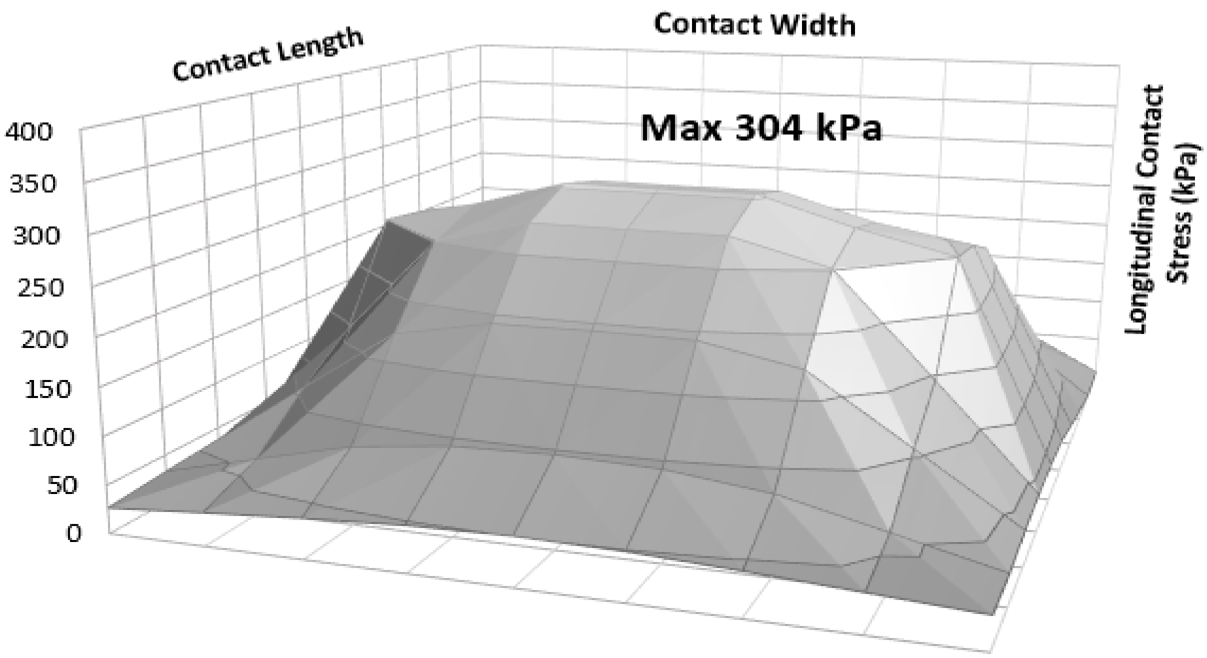


Figure 8 Simulation Results for Longitudinal Contact Stress after Calibration with Wang et al. [23] Results

4.1.3 Loading Duration

Since HMA is a viscoelastic material, the stiffness is dependent of speed and duration of loading. It means that if a vehicle with constant weight passes over a pavement with different speeds, the stresses, strains, and deformations would be different. This is a valid assumption that for viscoelastic materials, the intensity of the load changes with time according to below haversine function [16]:

$$L(t) = q \times Sin^2(\frac{\Pi}{2} + \frac{\Pi \times t}{d})$$

where t is the time which assumed to be 0 at the pick, q is the intensity of the load and d is the load duration. As it can be seen in figure 7, with t=d/2 from the two sides of the peak, the load on the surface is zero and by moving toward the peak, the load increases gradually [16].

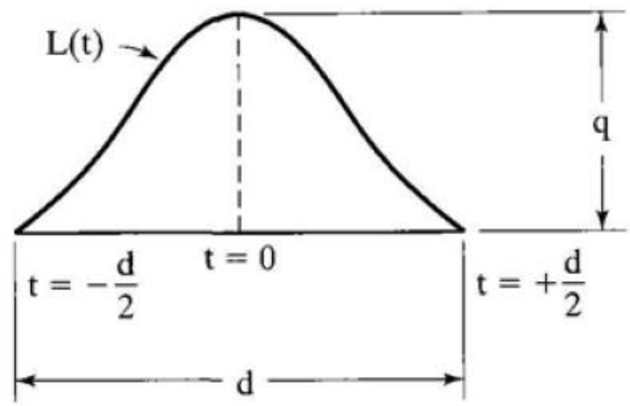


Figure 9 Haversine Function of Moving Load [16]

Considering different vehicles' speed and contact radius, loading time can be different. Following equation can be used to calculate the loading time for vehicles with different speed and contact radius:

$$d = \frac{12a}{s}$$

Where d is the total loading duration, a is the contact radius and s is the vehicles' speed. Using above equation, the total loading duration for a vehicles with 40 mph (64 km/h) and 6 in. of contact radius would be 0.1 second. Considering the haversine shape of the moving load, it can be concluded that, both loading and unloading time for this vehicle is 0.05 second [16]. In this study, 0.05 second of loading, 0.05 second of unloading and 0.9 second of resting time assumed for simulation of passing cars.

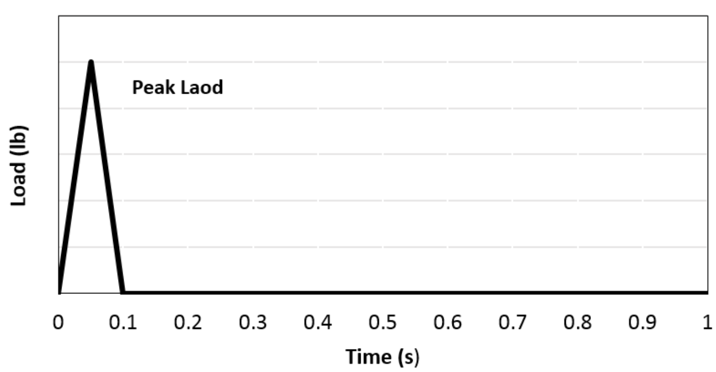


Figure 10 Loading, Unloading, and Resting Time for Vehicles with
40 mph Speed [16]

4.2 Material Characteristics

In order to simulate a pavement section in finite element analyses software, the behavior of materials under different ranges of stress and strain should be defined. Linear elastic and linear elastic-perfectly plastic models are the two most common behaviors that researchers usually uses to model base and subgrade. Linear elastic, viscoelastic and viscoplastic models are three different behaviors that can be used for asphalt concrete simulation.

A linear elastic simulation assumes that material has a constant modulus of elasticity in all different ranges of stresses and strains and always behaves linearly. The advantage of linear behavior is decreasing the computational time. However, it can only be used when the stresses and strains of the base and subgrade would not exceed their linear behavior boundaries or the amount of plastic strains are negligible that can be ignored. In linear elastic-perfectly plastic model, material behaves linearly up to the certain stress or strain level. But beyond that level, the relationship between stress and strain becomes nonlinear. This behavior modelling can be used when the plastic strain of the base or subgrade needs be observed. Although the results of simulation would be more accurate in linear elastic-perfectly plastic modeling, considering increased computational time and requirement of more experimental data to define the plastic behavior of the material, it is not always the optimum choice. Triaxial test results can be used to implement linear elastic-perfectly plastic behavior of base and subgrade in the ABAQUS software.

In some limited cases, especially when the focus of research is on base and subgrade behavior, linear elastic behavior can be used to model HMA. In these cases, the elastic modulus of asphalt concrete at the desired temperature and loading frequency should be used. Observing the behavior of asphalt layer and its stresses and strains, linear elastic theory would not be accurate enough to model the HMA layer. Usually asphalt concrete contains binders around 4 to 6 percent by total weight of the mix. Asphalt binder is a viscoelastic material. Therefore, viscoelastic theory is one of the most common theories that have been used by different research groups to model the asphalt concrete behavior.

Viscoelastic materials shows both viscous and elastic characteristics when undergoing deformation. The response of stress is immediately in elastic material while there is a delay of 90° in case of viscous material. Viscoelastic materials is neither purely elastic nor purely viscous. This means that the phase difference between stress and strains in viscoelastic materials is somewhere between 0 to 90 °.

Viscoelastic materials stiffness changes by changing the temperature and loading frequency. Generally speaking, viscoelastic materials stiffness decreases by increasing the temperature and decreasing the loading frequency. This means that asphalt concrete would be stiffer in colder weather. The deformation of the asphalt concrete would be also higher undergoing parked or very slow vehicles' loading.

Viscoelastic behavior can be implemented in ABAQUS by using dynamic modulus test results. Using NCHRP 1-37A [24, 25], the dynamic modulus test has to be done in 5 different temperatures (-12.5, 4.4, 21.1, 37.8, and 54.4˚ C) to consider the effect of different ranges of temperature on materials stiffness. On the other hand, tests in each temperature has to be done in 6 different frequencies (0.1, 0.5, 1, 5, 10, 25 Hz) to observe the dependency of the materials stiffness to the rate of loading. Loading frequency covers the effect of passing vehicles speed on asphalt concrete stiffness. Having 30 different modulus at different temperatures and frequencies, the dynamic modulus master curve can be constructed by using a proper shift function [25].

The Williams-Landel-Ferry Equation (or WLF Equation) can be used to do the time-temperature superposition and have one final master curve representing the dynamic modulus of asphalt concrete in all different temperatures and loading frequencies.

According to WLF equation:

$$\log(a_T) = \frac{-C1(T - T_r)}{C2 + (T - T_r)}$$

where T is the temperature, T_r is the reference temperature, C1 and C2 are the constants that should be determined in a way that the superposition variable (a_T) fits [25].

Figure 11 shows the superimposed master curve for asphalt stiffness based on its viscoelastic behavior resulted from dynamic modulus test results. The main benefit of using time-temperature superposition is having the stiffness of asphalt in a consistent way from very low to very high frequencies. Obviously, the dynamic modulus test cannot be done neither at frequency of 10^{-10} nor at frequency of 10^{10}. The frequency is the reverse of the loading time. As it can be seen in Figure 11, the modulus of asphalt increases by reducing the loading time and decreases by increasing the loading time. The minimum asphalt stiffness which happens at the highest frequency is around 10000 psi and the highest stiffness is more than 4,000,000 which happens at frequency of 10^9.

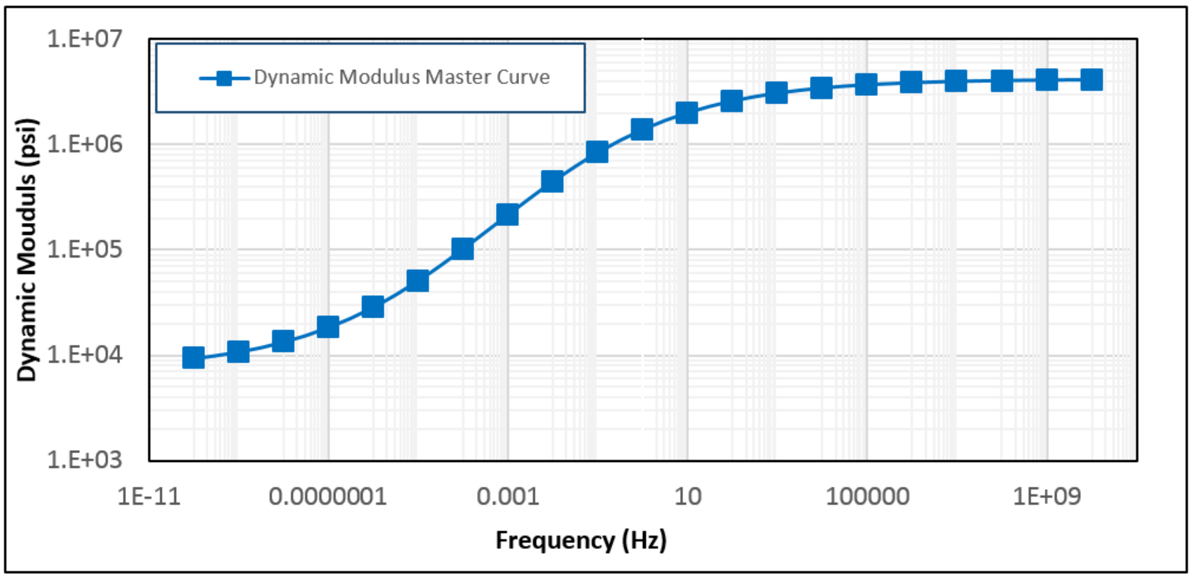


Figure 11 Dynamic Modulus Master Curve

4.3 Interface Layer Characteristics

As measuring the friction coefficient between asphalt and base layer is extremely difficult and there is not any code or standard method to do that, different researches used different coefficients in their simulation. Using unbonded interface layer in simulation, increases the strains unrealistically [21]. Therefore, frictional bonding would be used between asphalt and base layer

in researches in this area. Unbonded and fully bonded (Coefficient of Frictions between 0 and 1) are different interface bonding characteristics that have been used by researches. In this study, in order to observe the effect of interface layer characteristics definition on the final results, six different coefficient of frictions were evaluated (unbonded, 0.2, 0.4, 0.6, 0.8, and fully bonded). To define a frictional contact between two layers of materials, penalty method in ABAQUS software can be used. Using this method, user can choose the layers that are in contact with each other and assign the coefficient of friction to their interface contact. This contact works like a common frictional contact between layers which means that there would be a coefficient of friction and there would be linear relationship between the input force, coefficient of friction, and movement of the layers on top of each other.

The contact between overlay and existing HMA layer would be different, because materials are the same in these two layers and the tack coat creates cohesion between two layers. So, recent researches suggests using the cohesive contact between overlay and existing asphalt layer. In this way, the cohesion between two layers would be the deterministic criteria to define the contact. Based on different types of tack coats that could be used before overlaying, the cohesion between two layers would be different. Assigning different numbers to different levels of the cohesions between layers, ABAQUS cohesive contact module can be used to define different interface bonding. To define the overlay-existing asphalt interface layer characteristics Romanoschi and Metcalf method [14] has been used. Milling the existing asphalt layer and adding the hot mix asphalt as an overlay, there would be a cohesive bounding between overlay and existing asphalt layer. Romanoschi and Metcalf [14] did direct shear test at four levels of normal loads and three different temperatures. They did all the tests for samples with and without tack coat at the interface layer. They used the result of these direct shear tests to develop their new constitutive model. According to their results, there is linear proportional relationship between the shear stress and displacement until the shear stress reaches to the shear strength of the interface and it fails. This proportional relationship between shear stress and displacement can be modeled by a cohesive

bonding between layers. As it shown in Figure 12, after failing stress, two layers are sliding on each other and the interface layer can be defined by a constant coefficient of friction [14, 26, 27].

The slope of the proportional part of the shear stress-displacement curve defined as the interface reaction modulus (K). For samples with tack coat at the interface layer, K would be constant for different levels of normal stress and can be used to describe the interface layer. Their results for tests at 25˚C for four different tack coats are as follows: 504. 8 X 10^6 N/m^3 (1859 lbf/in^3), 480.4 X 10^6 N/m^3 (1769 lbf/in^3), 516.2 X 10^6 N/m^3 (1901 lbf/in^3), 504. 8 X 10^6 N/m^3 (1931 lbf/in^3). It means that, K would be different for different types of tack coats and it can be used as the main characteristics of the interface bounding to implement in ABAQUS software. in this study , considering new tack coats with improved cohesive characteristics, interface layers with K from 975 to 7720 has been used for each pavement design with overlay.

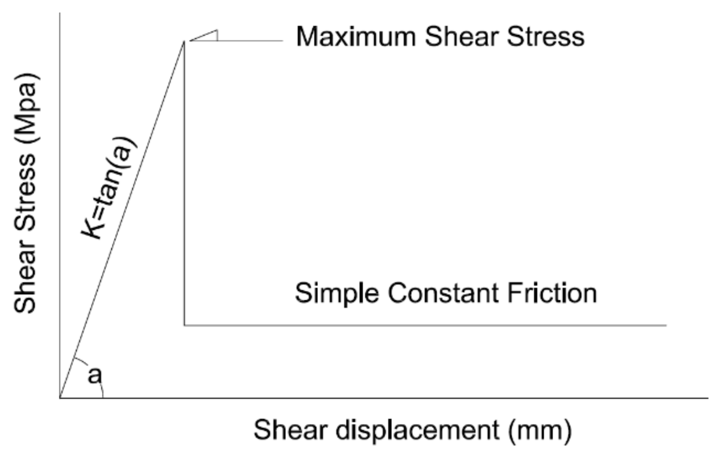


Figure 12 Romanoschi and Metcalf Model for Asphalt to Asphalt Interface Bonding Simulation [14]

4.4 Finite Element Model Size in Three Dimensions

One of the main issues is determining the size of the pavement, in each direction, that needs to be modeled to make sure that the final results would not be affected by the model size. In other word, by having load at the tire foot print, there would be stresses and strains in different directions in the modeled pavement section and if the model size in not large enough that these stresses and

strains can distribute thoroughly, the final results would be different with what we have in real world. On the other hand, large model means more computational time and storage place. Therefore, finding an optimum size of the model is an important consideration. To find the optimum model size, finite element analysts increase the model size step by step to see the convergence in the results. The optimum size would be when the results does not change more than 5 percent by increasing the size for one more step.

To find the optimum model size, in this study, 80 by 60 in. pavement section in longitudinal and transverse direction was modeled. Increasing the model size by 10 in. more in either direction, the difference in deformations, stresses, and strains between the first and second model was less than 5 percent. It means that increasing the model size after this step will just increase the computational time with minimal impact on accuracy.

In the end, the final model size to simulating pavement response was selected ro be 100 by 80 by 24 in. in X, Y and Z direction respectively. It means that 100 in. of the pavement section has been modeled in longitudinal direction (vehicles' passing direction) and 80 in. of the pavement section has been modeled in transverse direction.

The depth of the model has also need to be justified to make sure that it does not affect the final results. Considering very small stress transferred to the depth of 12 in. of the subgrade (about 2 psi), it would be a valid assumption that the increasing the thickness of the subgrade will not change the results meaningfully.

Figure 13 shows the two models with different sizes and results are summarized in Table 1. The comparison of results from these two models and observing very small difference between the models, the smaller model size was selected for final simulations. In this way, the results are accurate enough and considerable computing time would be saved.

Using the deformation at the surface of the asphalt layer and tensile strain in horizontal and longitudinal direction at the bottom of the asphalt layer, the results of the models with two different sizes has been compared. The results shows that the difference between results of models with

different sizes are less than 5 percent. So, the model size shows the convergence in the results and the dimensions of the smaller model can be used as the final dimensions of the model.

Table 1 Maximum Shear Stress and Tensile Strain in Models with Different Sizes

Simulation Results	**Small Model**	**Large Final Model**
Maximum Surface Deformation (in.)	8.23E-3	8.16E-3
Maximum Longitudinal Tensile Strain(με)	99.41	98.56
Maximum Transverse Tensile Strain(με)	145.12	144.18

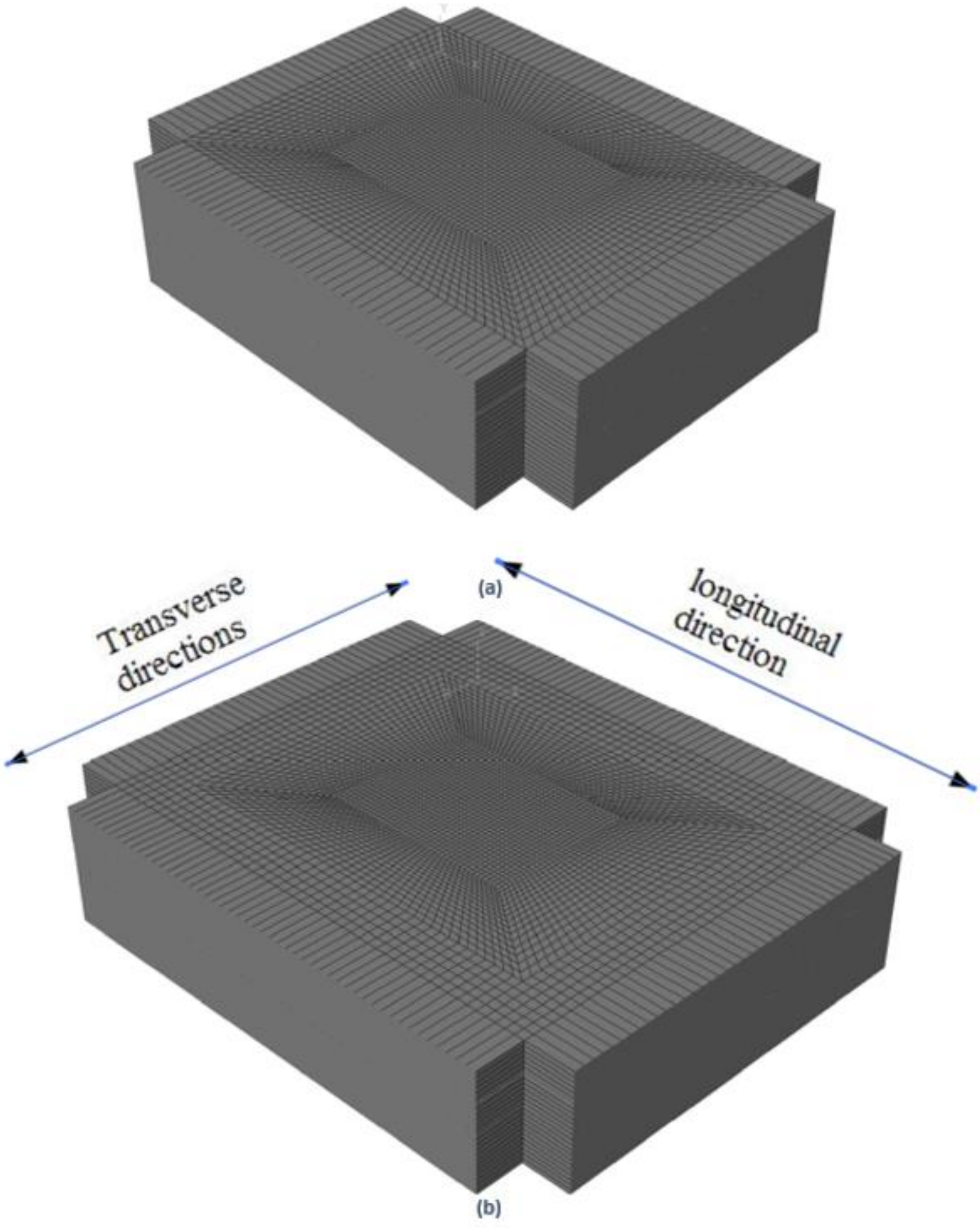


Figure 13 Less Than 5 % Differences between Results for (a) Smaller Model and (b) Larger Model

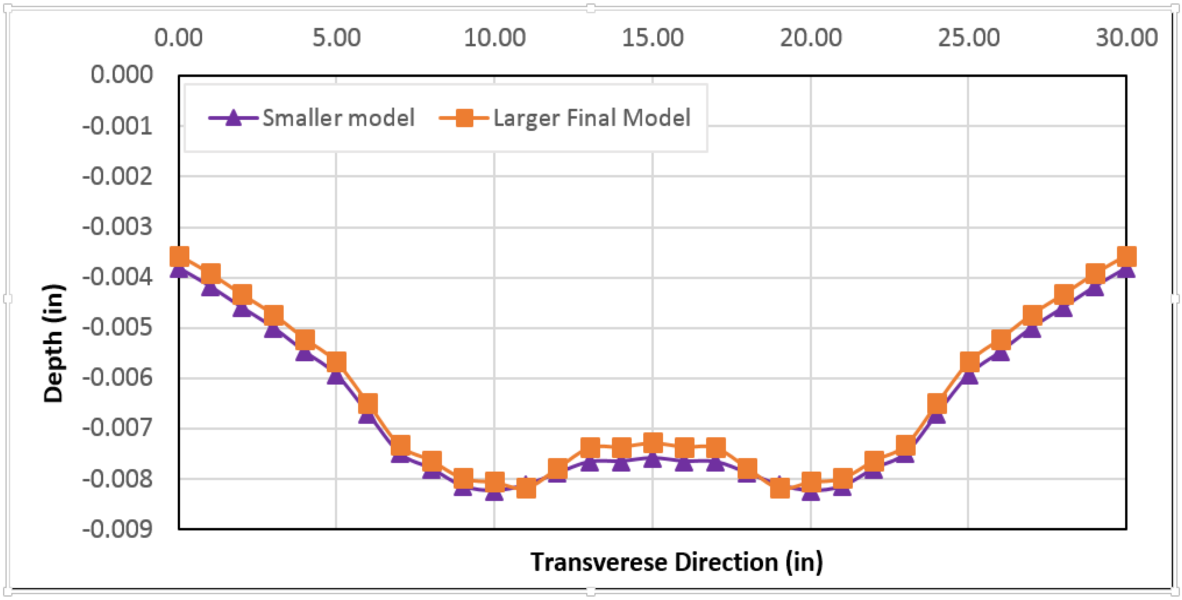


Figure 14 Less Than 5% Difference between Surface Deformations in Models with Different Sizes

4.5 Finite Element Types and Sizes

Eight node brick element with reduced integration (C3D8R) have been used for finite elements at this study. This element is more accurate in compare to regular eight node brick element (C3D8) and works well when the model does not have a complex shape.

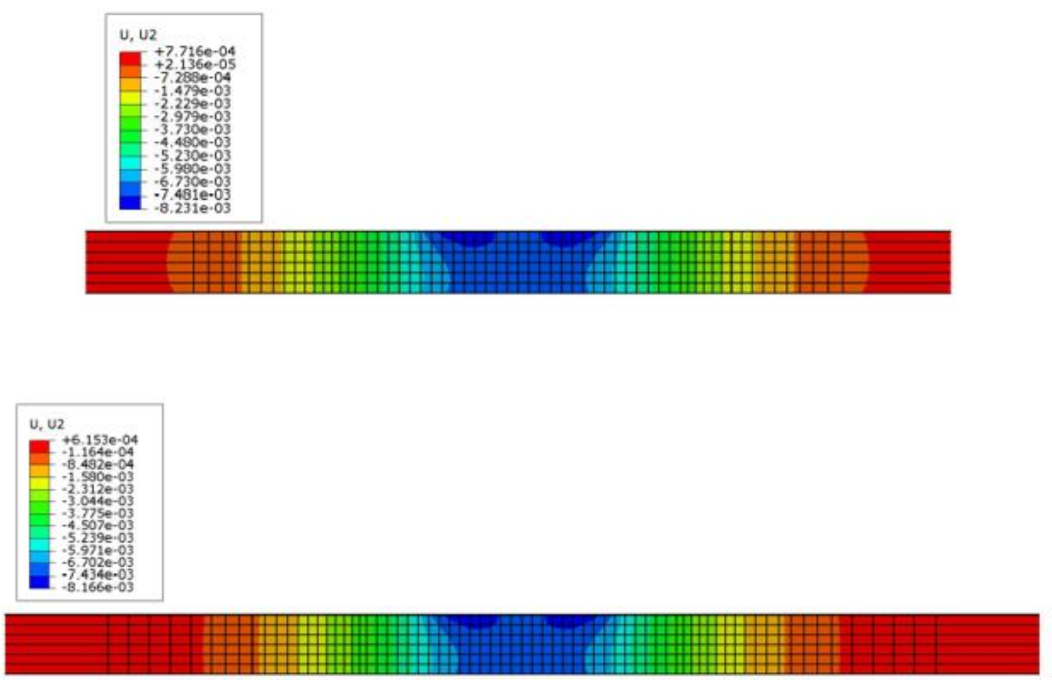


Figure 15 ABAQUS Results for Surface Deformation at Models with Two Different Sizes.

Having voscoelastic material and very small loading time, especially in overlaid pavements, the finite element equations cannot converge and the simulation would be aborted even for very small time increments (0.001 second). To overcome this problem, infinite elements (CIN3D8) needs to be defined at the outer boundaries of the models. The infinite elements would be merged with finite elements at one side and helps the software to finish the simulation [23].

Elements' size is a very important factor which influences the simulation accuracy and computation time. Smaller elements increase the accuracy of the results, but, at the same time, increases the computational time. To reach to the optimum point of accuracy and computation time, it is better to have smaller elements near the loading area where the stresses and strains are higher. Far enough of the loading area, the elements' size can be increased gradually.

In this study, 1 $in.^3$ cubical elements were used in the rectangular central part of the model. Then, the element size were gradually enlarged to reach to size of 2 $in.^3$ cubical element size.

It is necessary to decrease the size of the elements at the overlay part of the models. For models with 1 in. overlay, the elements' size at the overlay start with 0.5 in. by 0.5 in. by 1 in. at the central rectangular area and gradually increases to 1 in. by 1 in. by 1 in. For models with 0.5 in. overlay the elements' size at the overlay start with 0.25 by 0.25 by 0.5 in. and it gradually increases to the 1 by1 by 0.5 in.

5. Results for All Different Pavement Designs

5.1. General Results

The pavement response in terms of deflection, vertical stress and strain, shear stress and strain, and, compressive or tensile stress and strain can be visualized when modeled in 3-D. The data is summarized in the figures for a pavement modeled with 6 in. of asphalt layer, 6 in. of base, and 12 in. of subgrade depth.

As expected, surface deformation (figure 14) reflects the non-uniformity of the loading at the tire footprint. Maximum surface deformation happens right under the middle of the tire footprint at the center part of the loading area. Figure 16 is a sectional view of the vertical deformation obtained from ABAQUS software that helps in visualizing the vertical deformations over the surface and downward to the depth of the pavement at the same time. Reflection of the wheels' load can be seen (dark blue). Extracting the vertical deformation at all surface points at the center part of the model, 3D view of the surface deformation can be achieved (Figure 17)

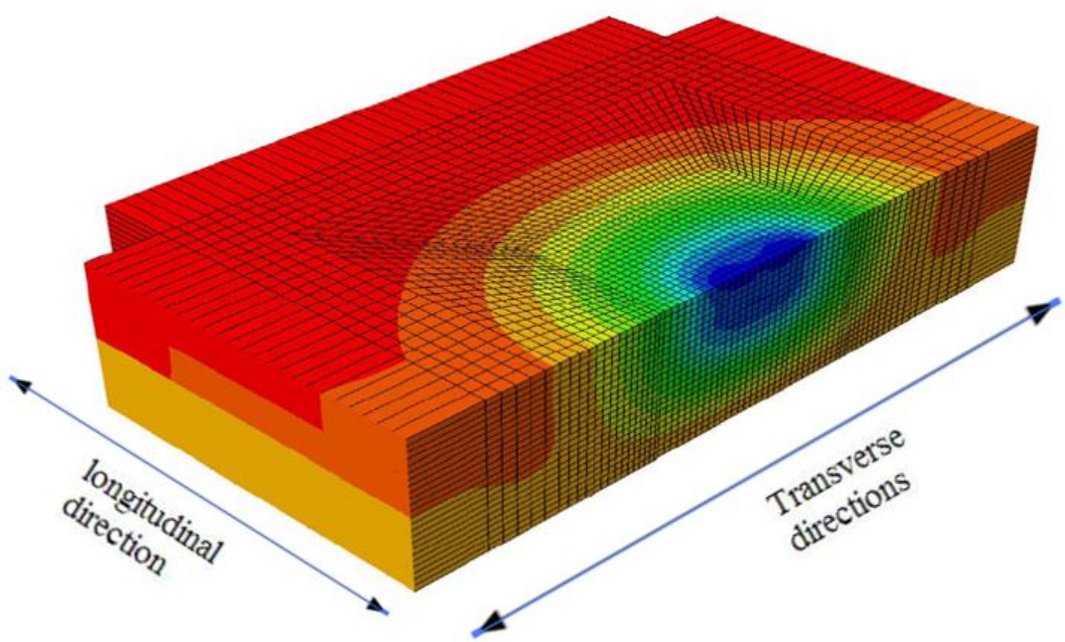
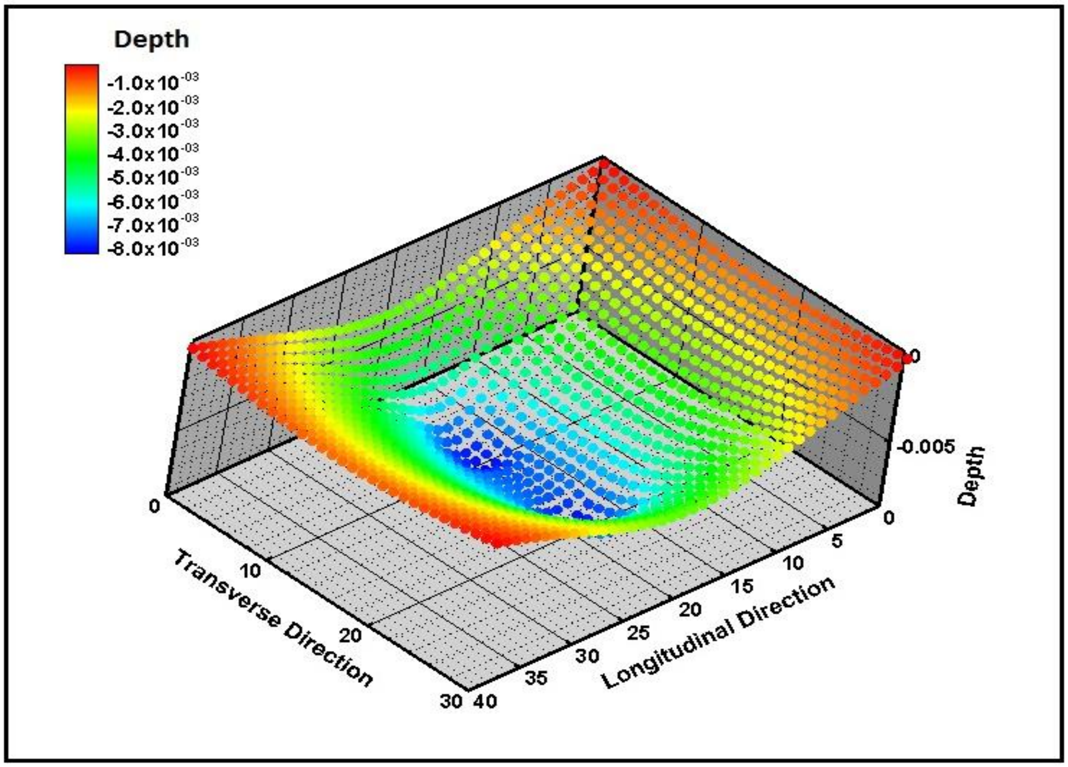
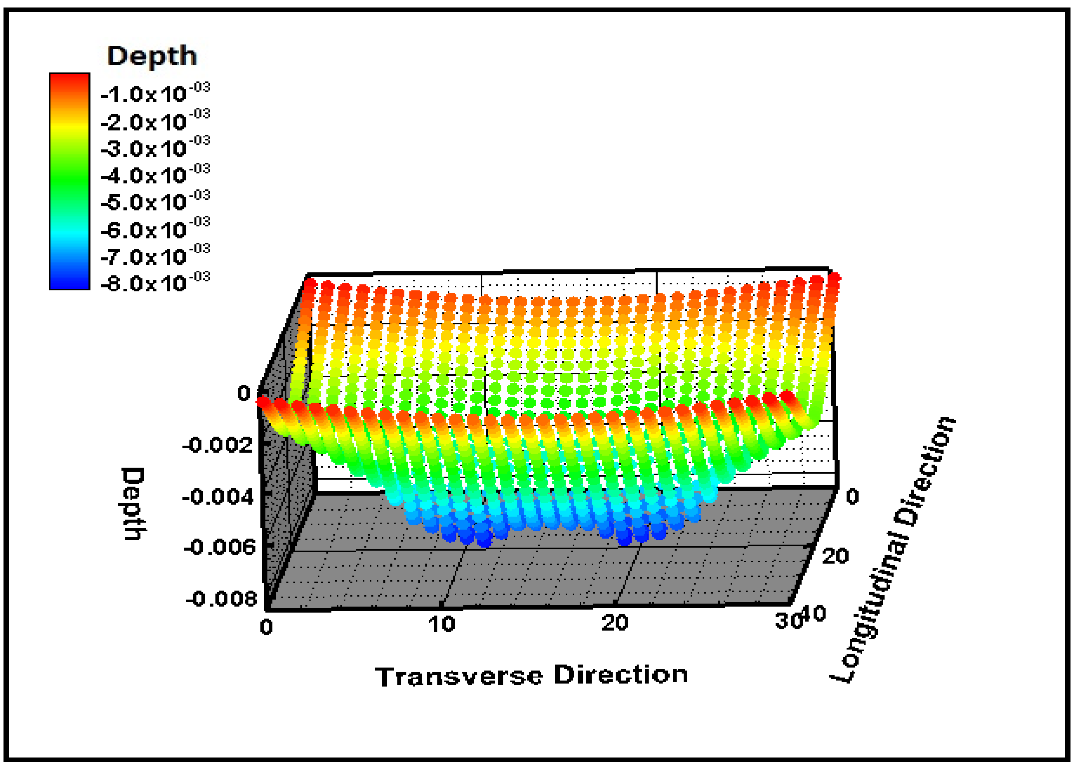


Figure 16 Deformation toward the Depth for Pavement



(a)



(b)

Figure 17 Surface Deformation in Model from Two Different Directions

Several previous theoretical researches has been done to predict the general shape of the stress distribution in pavement under a passing wheel [28]. Based on the theory, the vertical and horizontal stress is expected to be maximum right under the rolling wheel load, but the maximum of shear stress is expected at the borders of the tire footprint. The shear stress would be zero right under the center part of the loading area

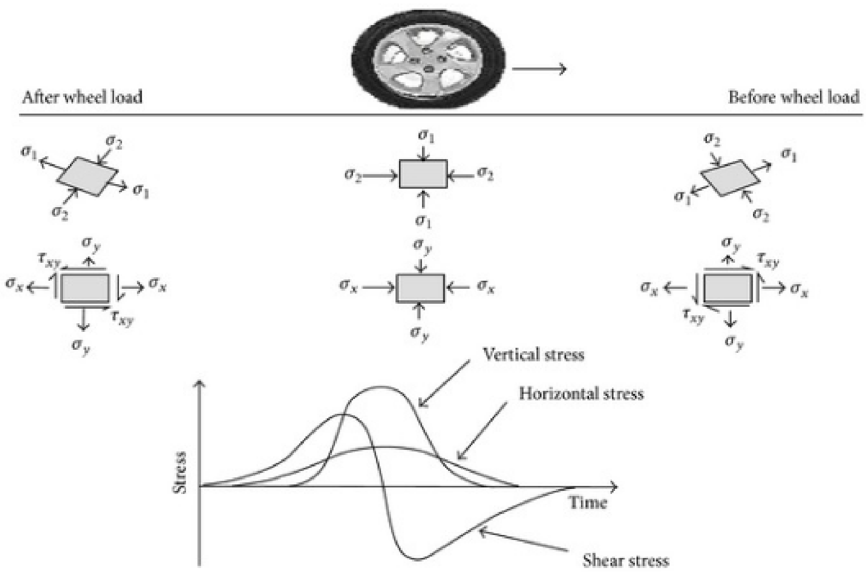


Figure 18 Stress in Different Directions under the Rolling Wheel [28]

Figure 19 shows the resulted vertical stress in the asphalt layer in this study which verifies the general form of the vertical stress distribution according to previous researches.

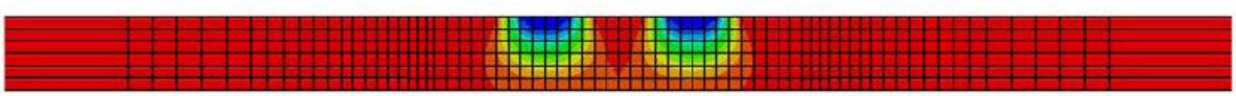


Figure 19 Vertical Stress in Asphalt Layer (Transverse View Right under the Loading Area)

Assuming the asphalt layer as a beam with vertical load at the middle of its span, compressive vertical strain at the top surface and tensile strain at the bottom surface of the asphalt layer is expected (Figure 20).

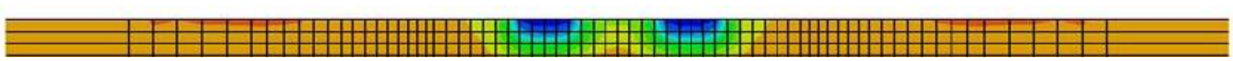


Figure 20 Vertical Strain in Asphalt Layer (Transverse View Right under the Loading Area)

As it mentioned above, the shear stress changes its direction from the entrance of the loading area to the end of it for one time. In fact, the maximum shear stress with positive direction happens at the onset of the tire footprint. Then it decreases to become zero right under the center of the loading area and it continues to decrease to reach to its maximum negative value at the end of the tire footprint. Figure 21 shows the ABAQUS visualization of the shear stress under the passing vehicle. Figure 22 shows a 3D graph of shear stress at the depth of the 2 in. of the asphalt layer.

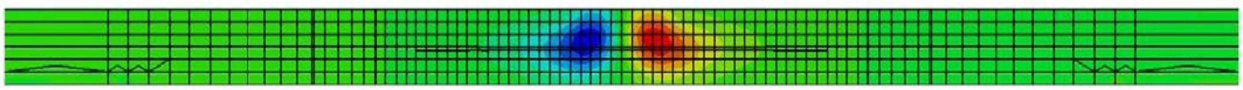


Figure 21 shear stress in asphalt layer (longitudinal view right under the loading area)

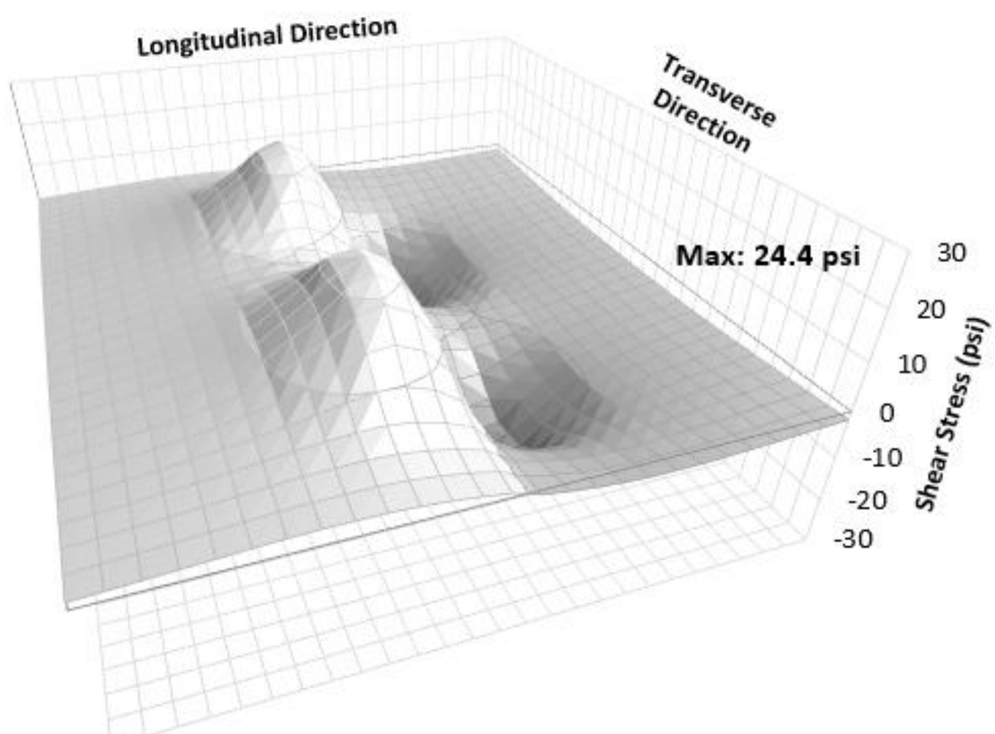


Figure 22 Shear stress at the depth of the 2 in. of at the asphalt layer

Tensile strain at the bottom of the asphalt layer in two directions can be seen in Figure 23 and 24.

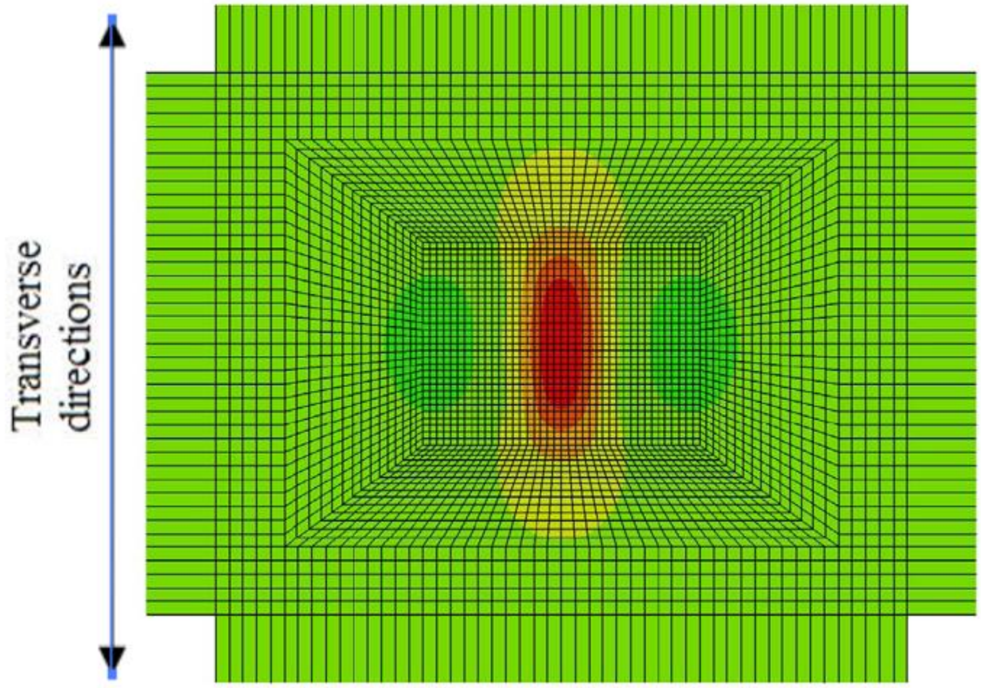


Figure 23 Tensile strain in transverse direction at the bottom of the asphalt Layer

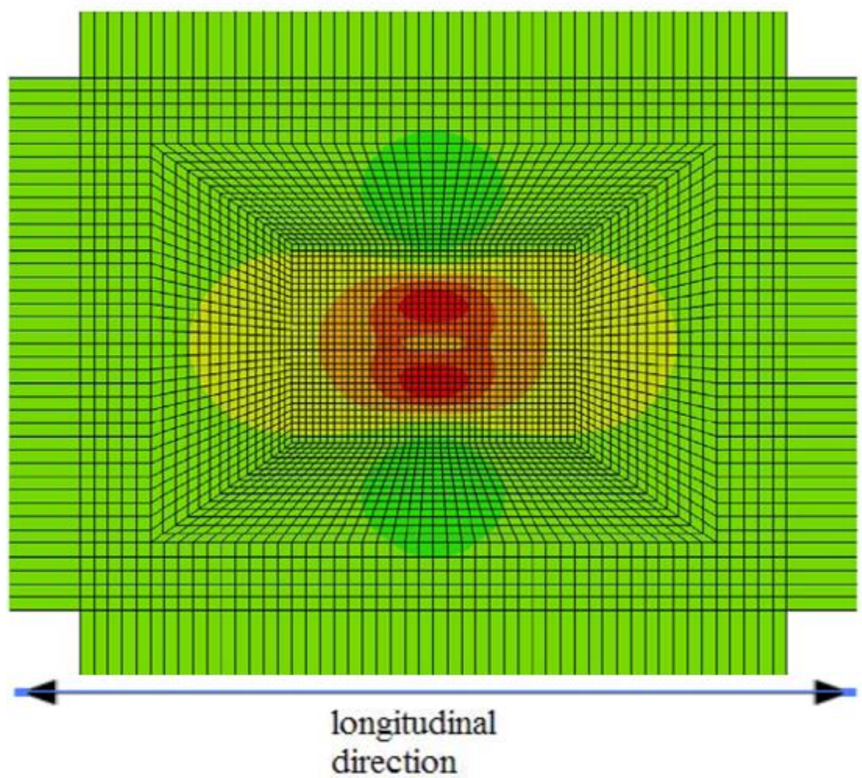


Figure 24 Tensile strain in longitudinal direction at the bottom of the asphalt Layer

5.2 Pavements without Overlay

Asphalt layer is the main structural element evaluated in this study. The thickness of the asphalt layer and the contact characteristics of the asphalt-base interface layer has been studied to analyze their impact on the structural characteristics of the pavement. The previous studies and field experience have documented that increase in thickness of asphalt layer improves the pavement structural strength and was observed in this study as well. Although the increase in thickness resulted in increase in structural strength, the increase was nonlinear. For instance, the reduction in surface deformation from a pavement with 4 in. of asphalt layer to a pavement with 5 in. of asphalt layer is 1.42 times bigger of reduction than from a pavement with 5 in. of asphalt layer to a pavement with 6 in. of pavement layer (Figure 25).

Asphalt –base interface bonding is also analyzed as a criteria which can affect the structural characteristics of the pavement. Although stronger interface bonding would naturally improves pavement's integrity, but considering the thickness of the asphalt layer, the influence of interface bonding on the final simulation results should be observed carefully.

There are two main category to model the interface bonding between asphalt and base layer. The first one is assuming fully bonded interface. In this assumption, there would not be any separation or sliding between asphalt and base layer. The second main category would be assuming a frictional interface between asphalt and base layer. In this way, asphalt and base layer have a possibility of sliding on each other. Having no standard method to define the frictional characteristics of the asphalt-base interface, different coefficient of frictions were used in this study to observe the effect of frictional characteristics of the interface on final results.

Observing the difference in results between fully bonded and frictional characteristics shows the significance of the asphalt-base interface definition. It means that there is a meaningful difference between the results of the fully bonded and frictional interface. On the other hand, the results for different coefficients of friction in frictional definition are almost identical which means that by assuming a frictional definition for asphalt-base interface, the coefficient of friction would have a negligible impact on the final results.

Four different pavement designs were modeled in this study to observe the effect of the asphalt layer thickness. As mentioned before, the only difference between the four pavement designs is the thickness of the asphalt layer. Pavement with asphalt layer thickness of 6, 5.5, 5, and 4 in. were modeled in this study.

Six different bonding characteristics were also used to model the contact between base and asphalt layer in each of above mentioned pavement designs. Five frictional contact and one fully bonded contact characteristic were used to observe the effect of the definition of the asphalt-base interface layer on the structural characteristics of the pavement. In this way, there are 24 different simulations to observe the effect of the asphalt layer thickness and contact characteristic of the asphalt-base interface layer on the deflection at the top of the asphalt surface and tensile strain at the bottom of the asphalt layer. The result of the analyses are discussed in the following paragraphs.

As presented by Figure 25, the surface deflection of the asphalt layer decreases by increasing the asphalt layer thickness. It also should be mentioned that the relationship between increasing the asphalt thickness and having more structurally sound pavement is not linear. This means that decreasing the asphalt layer thickness from 6 to 4 in. surface deflections increases. However, the difference between surface deflections for pavement with 6 and 5 in. of HMA is 0.00183 in., but the difference between surface deflections in pavements with 5 and 4 in. of HMA is 0.0026 in.

Comparing the maximum tensile strain at the bottom of the asphalt layer for these four pavements, the same trend can be observed. The maximum tensile strain at the bottom of the asphalt layer increases by decreasing the asphalt layer thickness and the relationship between the asphalt thickness and the maximum tensile strain is not linear (Table 2).

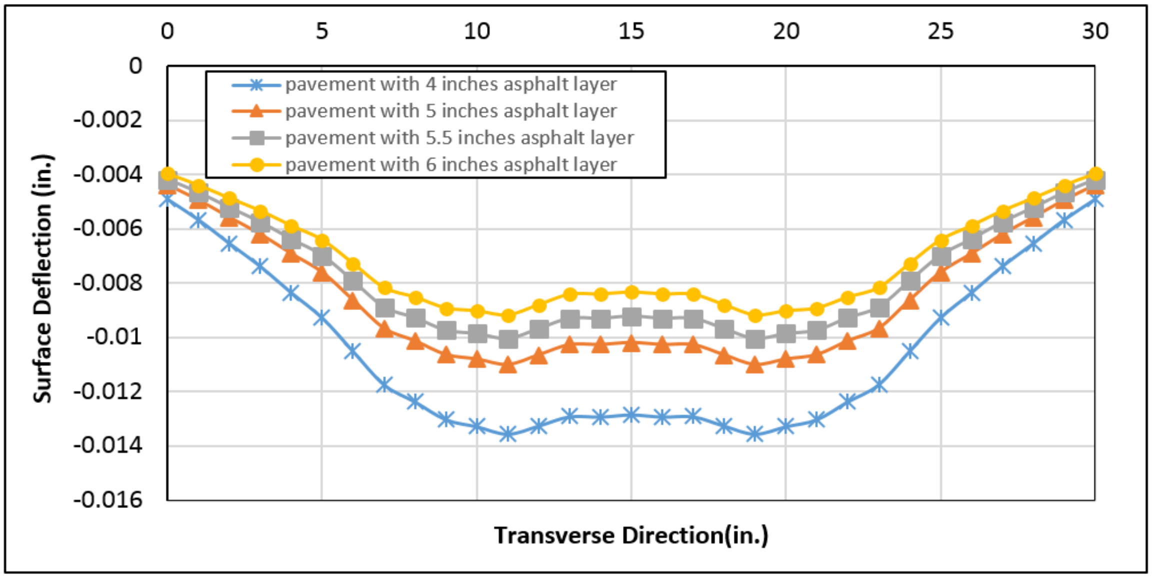


Figure 25 Surface Deflection at Pavements without Overlay with Coefficient of Friction of 0.6 for the Base and Asphalt Interface Layer

Table 2 Maximum Tensile Strain at the Bottom of the Asphalt Layer at Pavements without Overlay with Coefficient of Friction (COF) of 0.6 for the Base and Asphalt Interface Layer

Maximum Tensile Strain (με)	**Pavement with 4 in. asphalt layer**	**Pavement with 5 in. asphalt layer**	**Pavement with 5.5 in. asphalt layer**	**Pavement with 6 in. asphalt layer**
Longitudinal tensile strain(με)	177.9	149.7	131.1	120
Transverse tensile strain(με)	286.9	238.3	210.5	194.8

As there are no standard method to determine the friction characteristics between asphalt and base layer, different research groups have been using different frictional characteristics in their simulations [21]. To observe the effect of the friction at the asphalt-base interface, in this study, different friction situations were modeled (Frictionless interface, interface with Coefficient of Friction (COF) of 0.2, 0.4, 0.6, and 0.8, and fully bonded interface) for each of the four pavement designs.

Checking the deflection at the top of the surface of the asphalt layer and the maximum tensile strain at the bottom of the asphalt layer, the effect of the friction characteristics of the asphalt-base interface can be observed.

As it can be seen in the Figures 26 to 29, the difference in surface deflection between fully bonded and unbonded situation is between 13.5 to 22 percent for different pavement designs. It means that having thinner asphalt layer the characteristics of the interface become more and more crucial due to stress concentration at the interface. On the other hand, the maximum tensile strain results at the bottom of the asphalt layer in both directions shows up to 40 percent difference between fully bonded and frictional definition of the asphalt-base interface layer. It means that finding a standard method to define the behavior at the interface of any two layers is crucial in pavement modeling especially in the presence of thin layers.

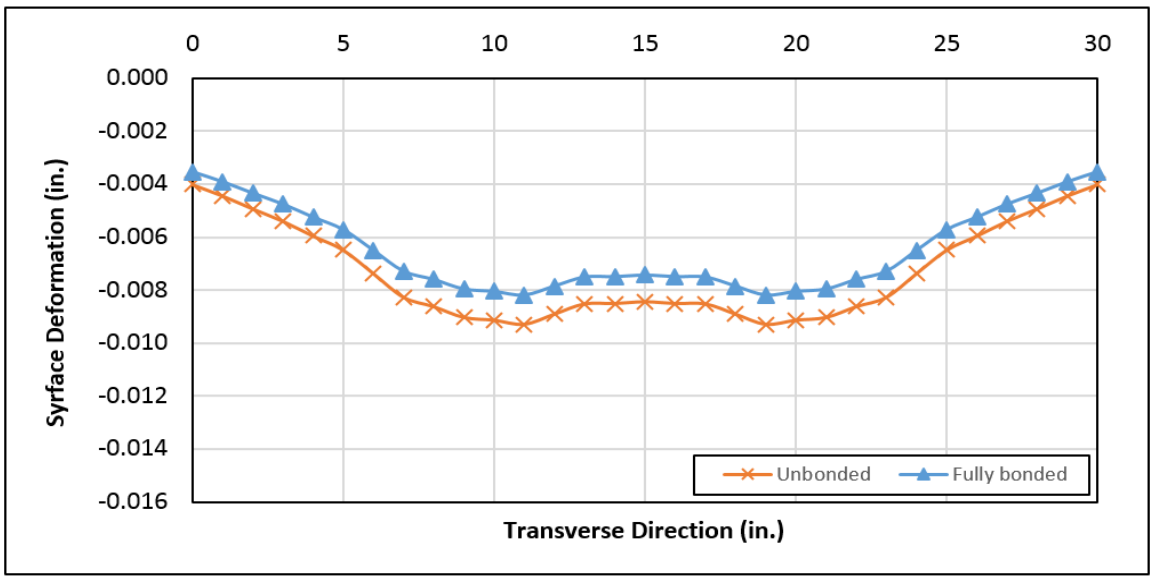


Figure 26 Surface Deformation in Pavement with 6 in. of Asphalt Layer for Fully Bonded and Unbonded Friction Characteristics of the Asphalt-Base Interface Layer

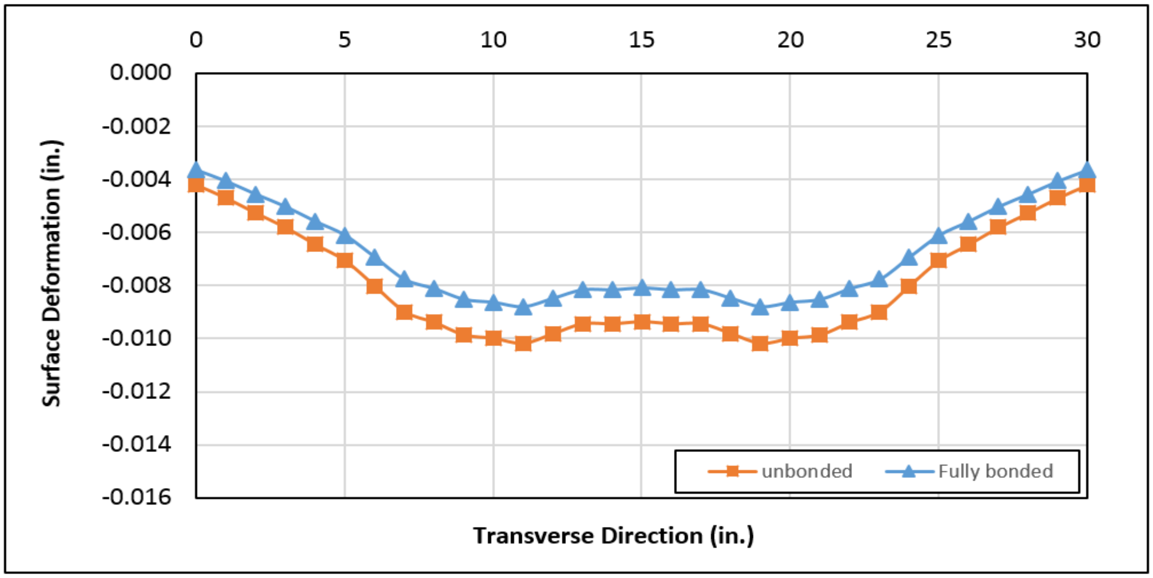


Figure 27 Surface Deformation in Pavement with 5.5 in. of Asphalt Layer for Fully Bonded and Unbonded Friction Characteristics of the Asphalt-Base Interface Layer

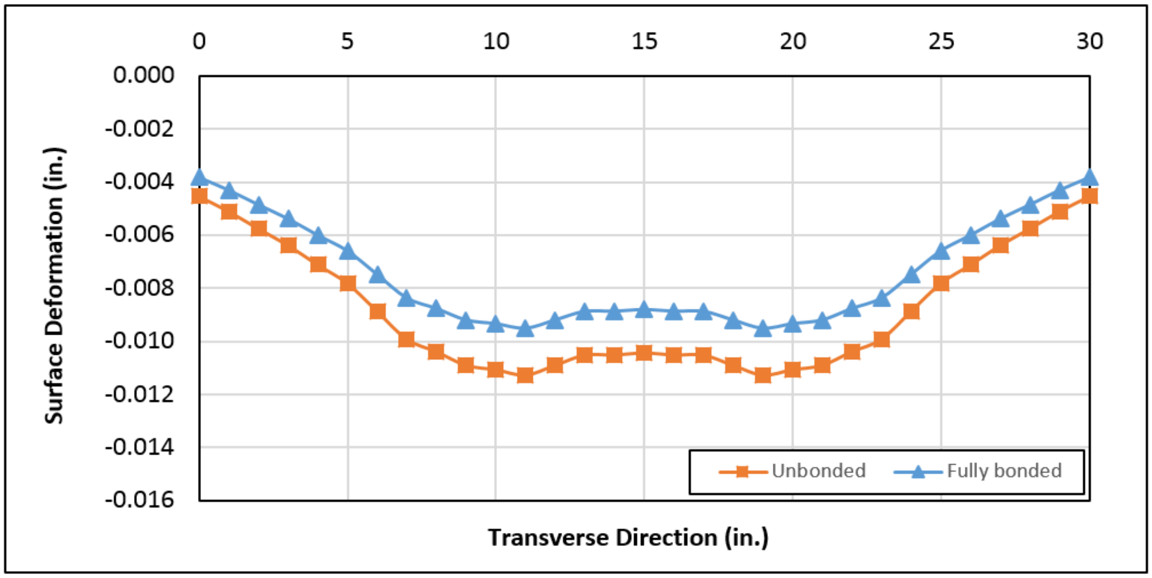


Figure 28 Surface Deformation in Pavement with 5 in. of Asphalt Layer for Fully Bonded and Unbonded Friction Characteristics of the Asphalt-Base Interface Layer

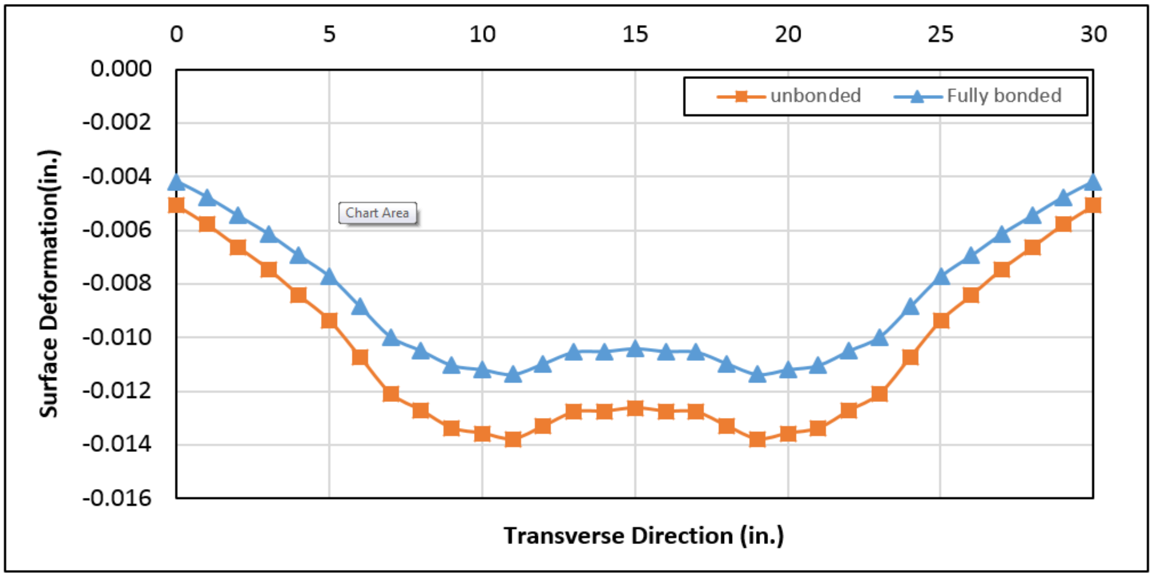


Figure 29 Surface Deformation in Pavement with 4 in. of Asphalt Layer for Fully Bonded and Unbonded Friction Characteristics of the Asphalt-Base Interface Layer

The maximum surface deformation and maximum tensile strain in two directions at the bottom of the asphalt layer have been summarized in Tables 3 through 6. Observing the numbers carefully, it can be seen that for different range of frictions, the results changes negligibly. It means that, especially for simulation of pavements without overlay, changing the COF at asphalt-base interface minimally influences deformations.

Defining a fully bonded contact characteristic, in comparison to frictional contact, between the top surface of the base layer and bottom surface of the asphalt layer, influences the results significantly. There are no standard methods to verify which contact characteristic simulates the real behavior in the field but this study shows that finding an experimental method to determine the correct contact characteristic between the two layers could be of a major importance.

Table 3 Simulation Results for Pavement with 6 in. of Asphalt Layer

Simulation Results	COF=0	COF=0.2	COF=0.4	COF=0.6	COF=0.8	Fully bonded
Maximum Surface Deformation (in.)	9.29E-03	9.24E-03	9.20E-03	9.17E-03	9.14E-03	8.23E-03
Maximum longitudinal tensile strain(με)	124.8	122.9	121.3	120	118.9	99.4
Maximum transverse tensile strain(με)	204.3	200.6	197.4	194.8	192.6	145.1

Table 4 Simulation Results for Pavement with 5.5 in. of Asphalt Layer

Simulation Results	COF=0	COF=0.2	COF=0.4	COF=0.6	COF=0.8	Fully bonded
Maximum Surface Deformation (in.)	1.02E-02	1.01E-02	1.01E-02	1.00E-02	9.99E-03	8.67E-3
Maximum longitudinal tensile strain(με)	136.9	134.7	132.7	131.1	129.7	105.3
Maximum transverse tensile strain(με)	221.1	217.9	213.8	210.5	207.8	162.3

Table 5 Simulation Results for Pavement with 5 in. of Asphalt Layer

Simulation Results	COF=0	COF=0.2	COF=0.4	COF=0.6	COF=0.8	Fully bonded
Maximum Surface Deformation (in.)	1.13E-02	1.12E-02	1.11E-02	1.10E-02	1.09E-02	9.50E-03
Maximum longitudinal tensile strain(με)	158.1	154.2	151.8	149.7	147.9	119
Maximum transverse tensile strain(με)	253.2	247.8	242.6	238.3	234.9	181.3

Table 6 Simulation Results for Pavement with 4 in. of Asphalt Layer

Simulation Results	COF=0	COF=0.2	COF=0.4	COF=0.6	COF=0.8	Fully bonded
Maximum Surface Deformation (in.)	1.38E-02	1.37E-02	1.37E-02	1.36E-02	1.35E-02	1.13E-02
Maximum longitudinal tensile strain(με)	186	183.1	180.5	177.9	175.5	145.1
Maximum transverse tensile strain(με)	302.6	297.1	291.8	286.9	281.2	213.0

5.3 Pavements with Overlay under Passing Vehicles

There are two main issues that needs to be considered regarding overlaid pavements: the impact of the overlaying on the structural characteristics of the pavement, and structural strength and durability of the overlay itself. Overlay thickness and the characteristics of the overlay-original asphalt interface are the two major elements in this regard.

Results regarding pavements with overlay under the passing vehicles can be categorized in the following four subsections:

- The impact of the overlay thickness on structural characteristics of the pavement,
- Overlay thickness impact on structural strength and durability of the overlay itself,
- Impact of the overlay-existing asphalt layer contact on the pavement structural strength, and
- The impact of the overlay-existing asphalt layer contact on durability of overlay itself.

Thickness is the most important element in determining the impact of an overlay on the pavement structural characteristics. Obviously, by increasing the overlay thickness, the structural impact of the overlay increases. Modeling pavements with 2, 1, and 0.5 in. of overlay identified that the structural characteristics improved with increase in overlay thickness. Deflection at the top surface of the overlay, as the top surface of the asphaltic materials, and tensile strain at the

bottom of the existing asphalt layer, as the bottom surface of the asphaltic materials, used to analyze the impact of the overlay thickness on structural characteristics of pavements.

Overlay thickness influences the structural strength and durability of the overlay itself. Considering the overlay-existing asphalt layer interface as a weak link in the pavement structure, the distance between this weak link and the loading area affects the structural strength and durability of the overlay. It means that by decreasing the overlay thickness the distance between the weak link and loading area decreases and the effect of this weak link on the structural strength of the overlay increases. Separation of overlay from existing asphalt layer can cause serious distresses in overlay. There would be opening at the interface layer when a vehicle passes over the pavement. The maximum opening between two layers have direct relationship with the thickness of the overlay.

As discussed in the previous section, the characteristics of the contact at the interface of different layers changes the structural characteristics of the pavements. Here, for the contact characteristics of the overlay-existing asphalt interface layer, Romanoschi and Metcalf method [14] has been used. They used direct shear test results to define the contact characteristics between two asphalt layers. According to their study, the reaction modulus of K= 504 X 10^6 N/m^3 (1930 lbf/in^3) is the average number for regular tack coats. Considering the improvement in tack coat production in last recent years, the range of the K=965 lbf/in^3 to K=7720 lbf/in^3 assumed to be a good consideration for reaction modulus of the tack coats today. To analyze the effect of the contact characteristic of overlay-existing asphalt layer interface 5 different reaction modulus (K=965, 1930, 3860, 5970, and 7720 lbf/in^3) has been used for each overlaid pavement design in this study. Considering 6 different overlaid pavement designs (Figure 2), 30 different models simulated for this part of the research. It is worth mentioning that although the contact characteristics used in the modeling of overlay does not include the fully bonded situation, but, as the thickness of the overlays is lower in comparison to original asphalt layers, it is expected that the impact of the different reaction modulus of the overlay-existing asphalt layer interface would not be negligible. Deflection at the top surface of the overlay, as the top surface of the asphaltic

materials, and tensile strain at the bottom of the original asphalt layer, as the bottom surface of the asphaltic materials, used to analyze the impact of the overlay-existing asphalt layer contact characteristics on structural characteristics of pavements.

Overlay-existing asphalt layer contact also impacts the durability of the overlay itself. The poor contact at the interface of overlay and existing asphalt layer results in separation between the two layers. This may cause crack initiation and propagation in overlay. In very poor condition, it may also cause total separation and slippage of the overlay over the existing asphalt layer. The amount of the opening at the interface caused by passing vehicle has been used as a criterion to evaluate the effect of the contact characteristic on the durability of the overlay.

5.3.1 Impact of the Overlay Thickness on Structural Characteristics of the Pavement

Results of the three different overlay thicknesses which has been modeled in 6 different pavement designs (Figure 2) are discussed in this section. To remove the influence of the contact characteristics on the final results, the average reaction modulus of K=3,860 lbf/in^3 has been used in all simulations.

With 2, 1, and 0.5 in. of overlay thickness on top of 4 in. of existing asphalt layer, the results suggest that increasing the thickness of the overlay enhances structural strength of the pavement (Figure 30). It should also be noted that the improvement of the structural strength of the pavement with regard to increasing the overlay thickness happens almost linearly. It means that the improvement resulted by adding 1 in. of overlay is almost half of the improvement resulted by adding 2 in. of overlay over the existing asphalt layer.

Adding 2 in. of overlay over the existing asphalt layer decreases the surface deflection at the pavement surface meaningfully. In fact, adding 2 in. of overlay, with average interface bonding, recovers 40 percent of the surface deflection growth caused by decreasing the thickness of existing consistent asphalt layer for 2 in. So, considering 2 in. of overlay as a structural member of the pavement section is a valid assumption.

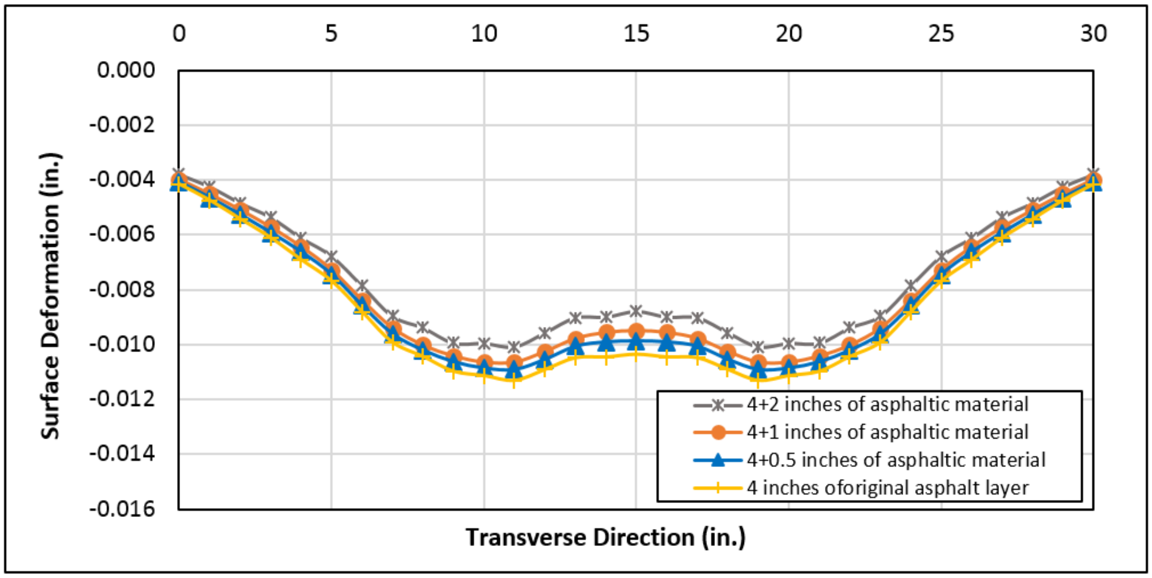


Figure 30 Surface Deformation for Pavements with 4, 4+0.5, 4+1, and 4+2 in. of Asphaltic Material

It should also be noted that though the 2 in. of overlay improves the structural characteristics of the pavement (Figure 31), the structural strength of overlaid pavement (4+2 in. of asphaltic materials) is still less than structural strength of a pavement with 6 in. of original pavement (without overlay). It means that, because of the weak line at the overlay-existing asphalt layer interface, overlaid pavement would be structurally weaker. Obviously, by improving the boding strength at the interface, the difference between results of overlaid pavement and original pavement decreases (discussed later). Figure 31 shows the surface deflection for three different pavement to observe the effect of 2 in. of overlay on structural strength of the pavement. The results for maximum surface deformation and maximum tensile strain at the bottom of the asphalt layer are summarized in Table 7. For K=3860 lbf/in^3, the 2 in. overlay covers around 40 percent of the difference in results between pavement with 6 in. and 4 in. of original asphalt layer.

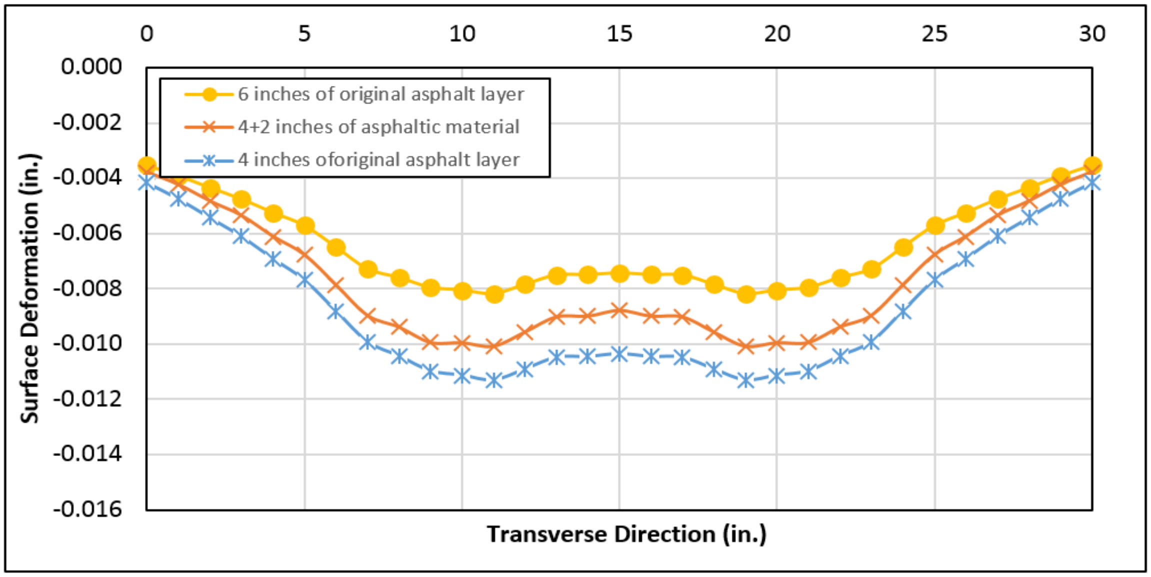


Figure 31 Deflection at the Top Surface of the Asphaltic Materials

Table 7 Effect of the 2 in. of Overlay on Pavement Structural Characteristics

Simulation Results	6 in. of original asphalt layer	4+2 in. of asphaltic materials	4 in. of original asphalt layer
Maximum Surface Deformation (in.)	8.23E-03	1.00E-02	1.13E-02
Maximum longitudinal tensile strain(με)	99.4	125	145.1
Maximum transverse tensile strain(με)	145.1	186.4	213.0

The difference in the deformation and strain results for pavements with 4+1 in. and 4 in. of asphaltic materials is 6 and 5.5 percent, respectively. Difference in results for 5+1 and 5 in. of asphaltic material is even smaller (3 and 2.5 percent). It means that, especially if there is not a very good bonding between overlay and existing asphalt layer, the 1 in. overlay should not be considered as a structural layer.

Checking the results for the pavements with 0.5 in. overlay, it can be seen that difference between results are less (around 3 percent). It means that 0.5 in. of overlay should also not be considered a structural member as well. In other worlds, overlay with 0.5 in. thickness just

improves the ride quality of the pavements and may prevent growth of small distresses. It should be noted that by increasing the thickness of the existing asphalt layer, the impact of the overlays with 1 and 0.5 in. thickness decreases. For example, the effect of the 0.5 in. overlay for pavement with 5 or 5.5 in. of existing asphalt layer is less than 3 percent.

The next three tables (Tables 8 through 10) shows the results for all overlaid and without overlay pavement modeled under the passing vehicles for K=3,860 lbf/in^3.

Table 8 Pavement with 4 in. of Original Asphalt Layer and Pavements with 4 in. of Existing Asphalt Layer and 2, 1, and 0.5 in. of Overlay

Simulation Results	**4+2 in. of asphaltic materials**	**4+1 in. of asphaltic materials**	**4+0.5 in. of asphaltic materials**	**4 in. of original asphalt layer**
Maximum Surface Deformation (in.)	1.00E-02	1.06E-02	1.08E-02	1.13E-02
Maximum longitudinal tensile strain(με)	125	141.6	144.6	145.1
Maximum transverse tensile strain(με)	186.4	207	211.3	213.0

Table 9 Pavement with 5 in. of Original Asphalt Layer and Pavements with 5 in. of Existing Asphalt Layer and 1, and 0.5 in. of Overlay

Simulation Results	**5+1 in. of asphaltic materials**	**5+0.5 in. of asphaltic materials**	**5 in. of original asphalt layer**
Maximum Surface Deformation (in.)	8.95E-03	9.21E-03	9.50E-03
Maximum longitudinal tensile strain(με)	114.1	116.8	119
Maximum transverse tensile strain(με)	171.6	177.8	181.3

Table 10 Pavement with 5.5 in. of Original Asphalt Layer and Pavements with 5.5 in. of Existing Asphalt Layer and 0.5 in. of Overlay

Simulation Results	**5.5+0.5 in. of asphaltic materials**	**5.5 in. of original asphalt layer**
Maximum Surface Deformation (in.)	8.51E-03	8.67E-03
Maximum longitudinal tensile strain(με)	103.8	105.3
Maximum transverse tensile strain(με)	159	162.3

5.3.2 Impact of the Overlay Thickness on Structural Strength of Overlay

Separation between overlay and existing asphalt layer is one of the most important concerns regarding the durability of the overlay. Because of the interface between overlay and existing asphalt layer, these two layers do not work as one structural elements. When a vehicle passes over a pavement, having a significant load over the pavement, there would be a separation between layers around the loading area. By decreasing the thickness of the overlay, this contact opening between layers increases.

Figure 32 shows the ABAQUS visualization for the contact opening between layers. The opening around the loading area can be seen in this figure.

Figure 33, 34 and 35 are 3D graphs that shows the contact opening between overlay and existing asphalt layer for pavements with 4 in. of existing asphalt layer and 2, 1, and 0.5 in. of overlay, respectively. As it can be seen in these figures, the maximum opening between layers increases by decreasing the overlay thickness. Separation between layers can initiate cracks at the bottom of the overlay. It also can cause total slippage of the overlay over the existing asphalt layer.

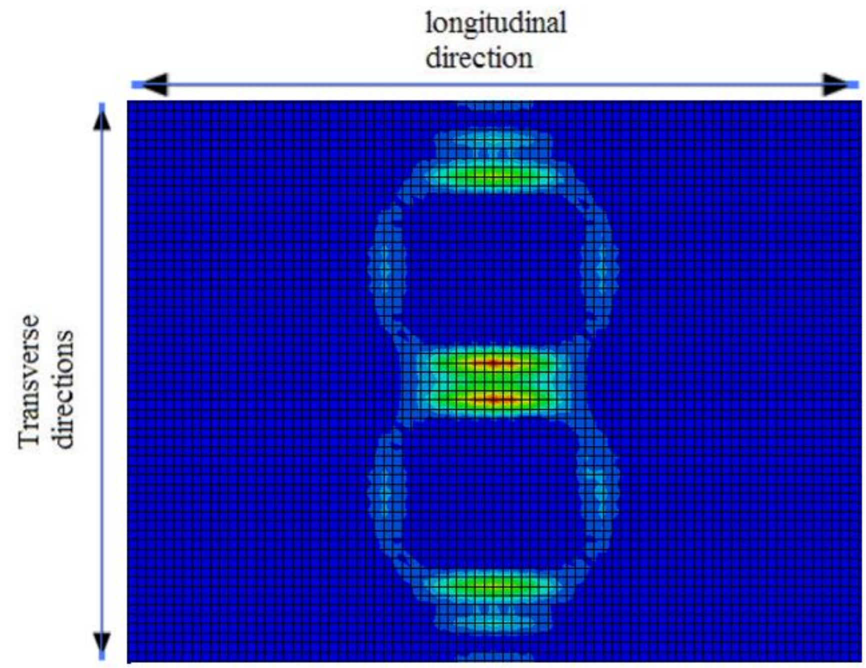


Figure 32 Contact Opening between Overlay and Existing Asphalt Layer under a Passing Vehicle

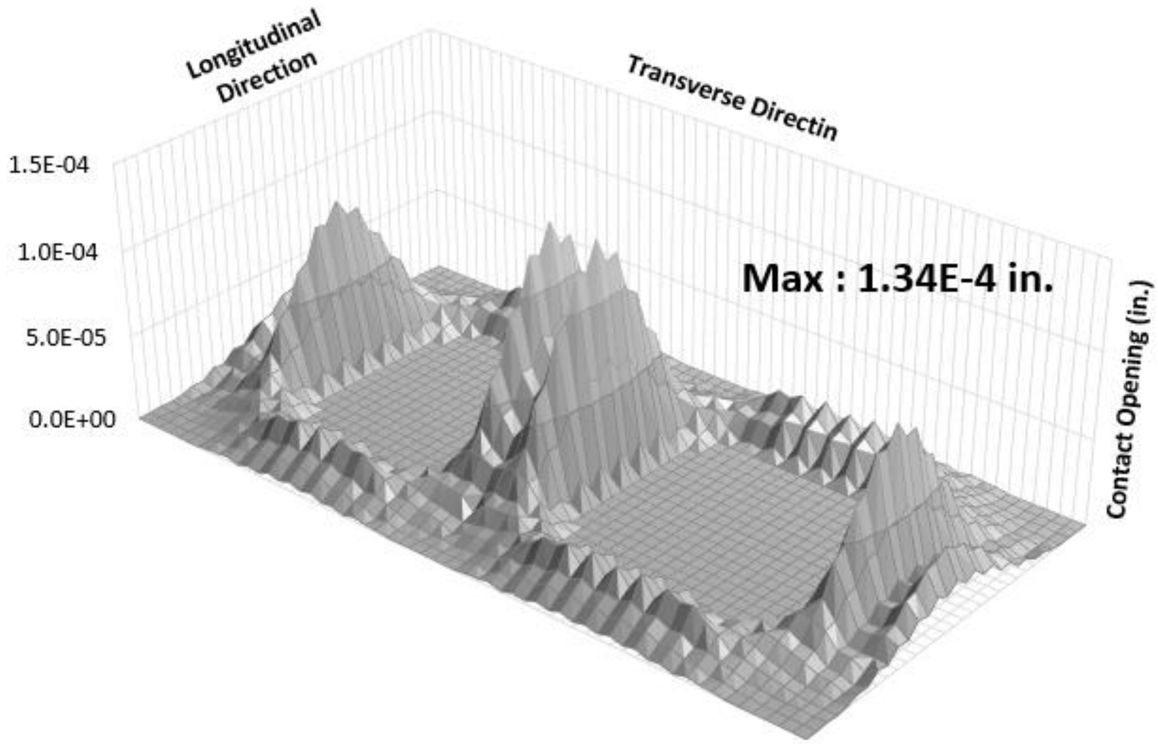


Figure 33 Contact Opening for Pavement with 4 in. of Existing Asphalt Layer and 0.5 in. Overlay (K=3860 lbf/in^3)

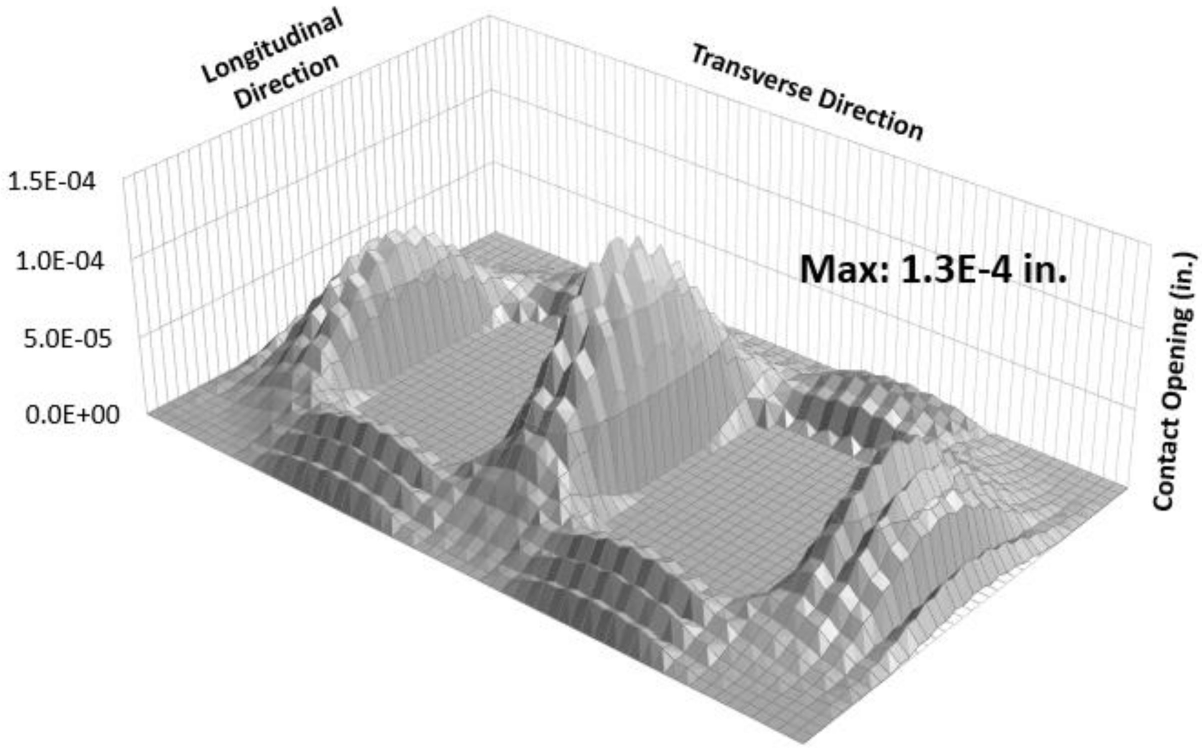


Figure 34 Contact Opening for Pavement with 4 in. of Existing Asphalt Layer and 1 in. Overlay (K=3860 lbf/in^3)

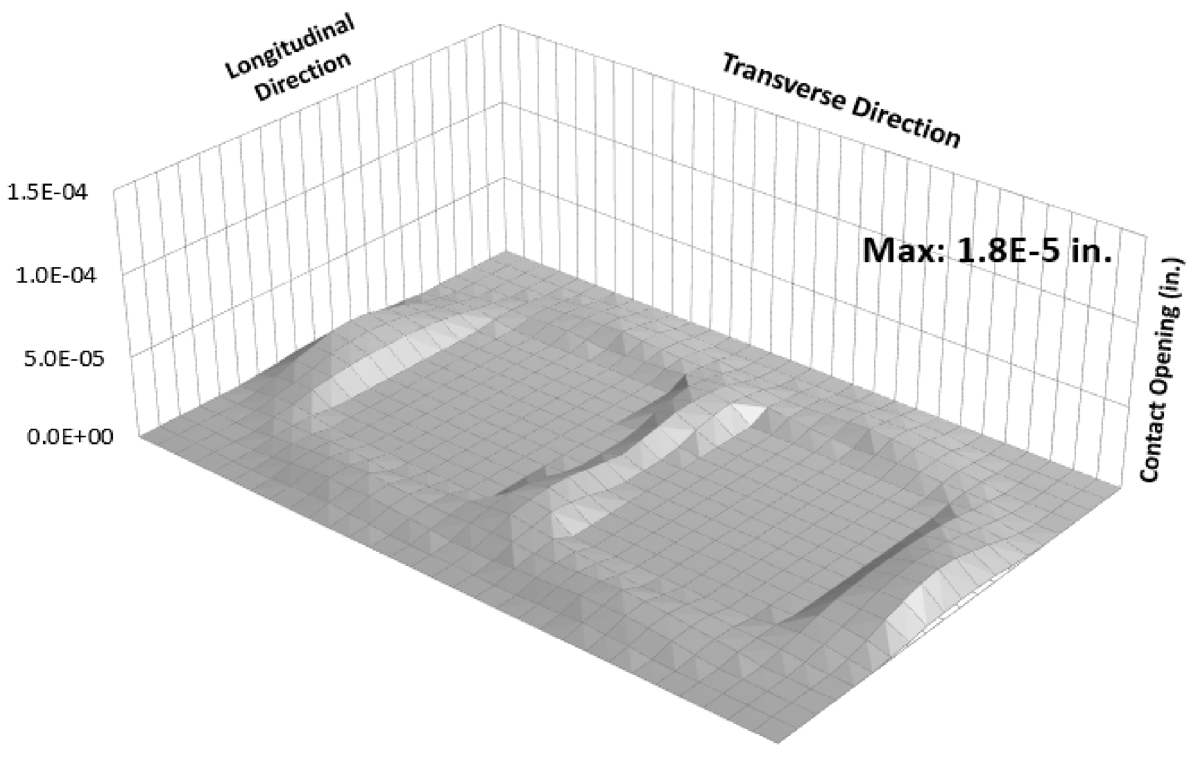


Figure 35 Contact Opening for Pavement with 4 in of Existing Asphalt Layer and 2 in. Overlay (K=3860 lbf/in^3)

The results for maximum contact opening at pavements with different overlay thicknesses are summarized in Table 11. To remove the impact of the overlay- existing asphalt layer interface bonding, all the results presented at this subsection are for K=3860 lbf/in^3.

Table 11 Maximum Contact Opening between Overlay and Asphalt Layer under a Passing Vehicle for K=3860 lbf/in^3

Simulation Results	**4+2 in. of asphaltic materials**	**4+1 in. of asphaltic materials**	**4+0.5 in. of asphaltic materials**	**5+1 in. of asphaltic materials**	**5+0.5 in. of asphaltic materials**	**5.5+0.5 in. of asphaltic materials**
Maximum Contact Opening (in.)	1.80E-05	1.30E-04	1.34E-04	1.28E-04	1.32E-04	1.26E-04

The difference in maximum contact opening for 1 and 0.5 in. of overlay is very small (Table 11). However, the maximum contact opening for 2 in. of overlay is of a different magnitude. This means that the performance of overlay with 2 in. of thickness would be completely different than the performance of pavement with 1 or 0.5 in. thick overlay.

Observing the difference between maximum contact opening of the pavements with 4, 5, and 5.5 in. of existing asphalt layer and 0.5 in. of overlay, it can be concluded that the durability of the 0.5 in. overlay does not largely depends on the thickness of the existing pavement layer.

5.3.3 Impact of the Interface Bonding Strength on Structural Characteristics of the Pavement

The contact characteristics of the overlay-existing asphalt layer interface is an important element which can affect the structural characteristics of the pavement. It means that having poor interface bonding between overlay and existing asphalt layer, the structural improvement resulted by putting overlay over the pavement decreases.

As it can be seen in Figure 36, for reaction modulus of K=965 lbf/in^3 (the lowest modeled interface bonding), the surface deflection in pavements with 4 and 4+2 in. of asphaltic materials are very close. On the other hand, the surface deflection is becoming more and more smaller by

increasing the bonding strength between overlay and existing asphalt layer. As a results, by increasing the interface bonding strength between overlay and existing asphalt layer, the surface deflection at a pavement with 4+2 in. of asphaltic materials move towards to the surface deflection of a pavement with 6 in. of original asphalt layer.

Observing the surface deflection at the top surface of the asphaltic materials, the importance of the bonding strength of the overlay-existing asphalt layer interface has been improved. In fact, increasing the reaction modulus infinitely, theoretically, the structural characteristics of a pavement with 6 in. of original asphalt layer and a pavement with 4+2 in. of asphaltic materials should be identical.

Tables 12 through 17 shows the impact of the interface bonding between overlay and existing asphalt layer on maximum deformation at the pavement surface. It is worth mentioning that, based on the above results, by decreasing the interface bonding strength to lowest amount, the difference between results for pavement with 2, 1, and 0.5 in. become very small.

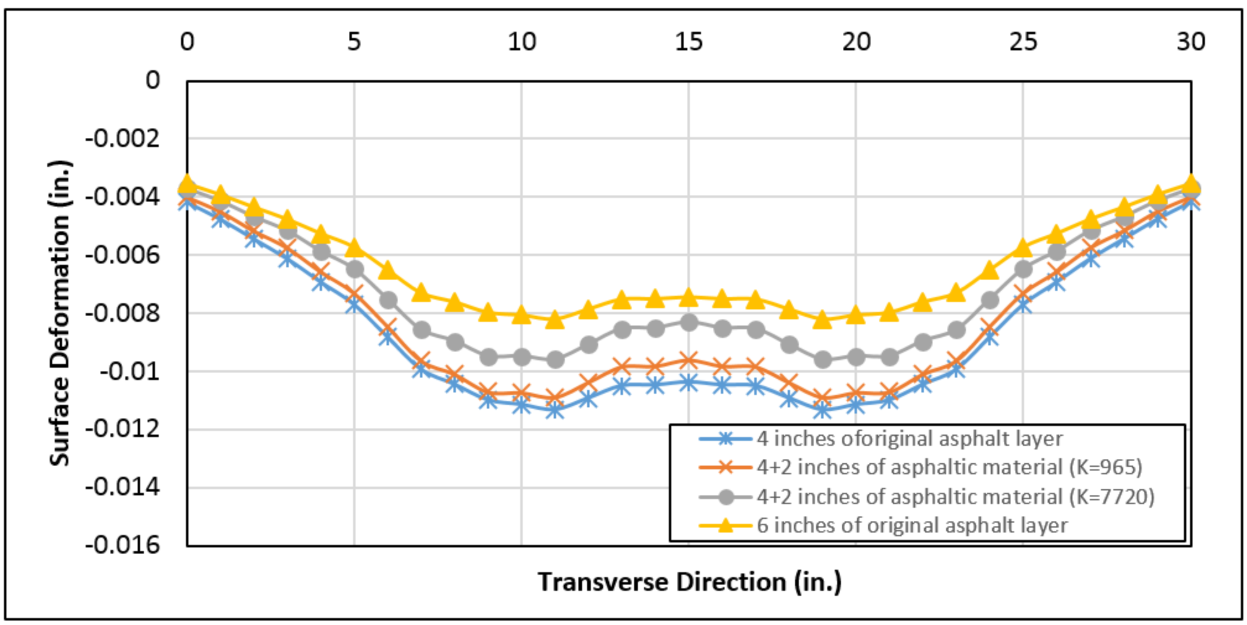


Figure 36 Reaction Modulus Impact on the Surface Deformation of Pavement with 4+2 in. of Asphaltic Material

Table 12 Maximum Surface Deformation for Pavement with 4+2 in. of Asphaltic Materials

Simulation Results	**K=965 lbf/in³**	**K=1930 lbf/in³**	**K=3860 lbf/in³**	**K=5790 lbf/in³**	**K=7720 lbf/in³**
Maximum Surface Deformation (in.)	10.9E-03	10.5E-03	10.0E-03	9.78E-03	9.58E-03

Table 13 Maximum Surface Deformation for Pavement with 4+1 in. of Asphaltic Materials

Simulation Results	**K=965 lbf/in³**	**K=1930 lbf/in³**	**K=3860 lbf/in³**	**K=5790 lbf/in³**	**K=7720 lbf/in³**
Maximum Surface Deformation (in.)	11.1E-03	10.8E-03	10.6E-03	9.90E-03	9.81E-03

Table 14 Maximum Surface Deformation for Pavement with 4+0.5 in. of Asphaltic Materials

Simulation Results	**K=965 lbf/in³**	**K=1930 lbf/in³**	**K=3860 lbf/in³**	**K=5790 lbf/in³**	**K=7720 lbf/in³**
Maximum Surface Deformation (in.)	11.3E-03	1.00E-03	10.8E-03	10.7E-03	1.06E-02

Table 15 Maximum Surface Deformation for Pavement with 5+1 in. of Asphaltic Materials

Simulation Results	**K=965 lbf/in³**	**K=1930 lbf/in³**	**K=3860 lbf/in³**	**K=5790 lbf/in³**	**K=7720 lbf/in³**
Maximum Surface Deformation (in.)	9.35E-03	9.17E-03	8.95E-03	8.82E-03	8.72E-03

Table 16 Maximum Surface Deformation for Pavement with 5+0.5 in. of Asphaltic Materials

Simulation Results	**K=965 lbf/in³**	**K=1930 lbf/in³**	**K=3860 lbf/in³**	**K=5790 lbf/in³**	**K=7720 lbf/in³**
Maximum Surface Deformation (in.)	9.74E-03	9.41E-03	9.21E-03	9.10E-03	9.01E-03

Table 17 Maximum Surface Deformation for Pavement with 5.5+0.5 in. of Asphaltic Materials

Simulation Results	**K=965 lbf/in^3**	**K=1930 lbf/in^3**	**K=3860 lbf/in^3**	**K=5790 lbf/in^3**	**K=7720 lbf/in^3**
Maximum Surface Deformation (in.)	8.72E-03	8.62E-03	8.51E-03	8.45E-03	8.41E-03

Observing the pavements with 1 or 0.5 in. of overlay, it can be seen that for very poor bonding strength (K=965 lbf/in^3) between overlay and asphalt layer, the overlay does not improve the pavement performance meaningfully. But, increasing the bonding strength step by step, the impact of the overlay on structural characteristics of the pavement increases.

In summary, the bonding strength between overlay and existing asphalt layer determines the impact of the overlay on structural characteristics of the pavement. In case of minimal bonding, overlay and existing asphalt layer work as two separate layer. In this way, considering small thickness of the overlay and very short distance between loading area and interface, the overlay does not improves the structural strength of the pavement meaningfully.

5.3.4 Impact of the Interface Bonding Strength on Structural Durability of the Overlay Itself

The bonding strength between overlay and existing asphalt layer has major impact on the durability of the overlay itself. In fact, having stronger interface bonding, the opening between overlay and existing asphalt layer due to the vehicle passing over the pavements decreases. Less opening results in decreasing the crack initiation and propagation rate and eventually separation between layer and total slippage.

As it can be seen in Figures 37, 38, and 39, in the pavement with 4+0.5 in. of asphaltic materials, the contact opening is 9.3 X 10^{-5} in., 1.34 X 10^{-4} in., and 2.18 X 10^{-4} in. for interface bonding of K=7720 lbf/in^3, K= 3860 lbf/in^3, and K= 965 lbf/in^{3,} respectively.

One very important results can be achieved by comparing the difference in contact openings between pavement with different overlay thickness (0.5 or 1 in. of overlay) and constant interface bonding characteristics (K= 3860 lbf/in^3) and pavement with constant overlay thickness (0.5 in. of overlay) and different interface bonding characteristics (K=965 lbf/in^3, K= 3860 lbf/in^3, and K= 7720 lbf/in^3). In fact, the difference between contact opening results in pavement with 0.5 in. of overlay and different interface bonding is higher in comparison to the difference between contact opening between pavement with constant interface bonding but different overlay thickness (0.5 or 1 in. of overlay). This means that for overlay with 1 in. or less thickness, the impact of the interface bonding is actually higher than the impact of the thickness. Results for all contact openings between overlay and existing asphalt layer under a passing vehicle can be seen in table 18 to 23.

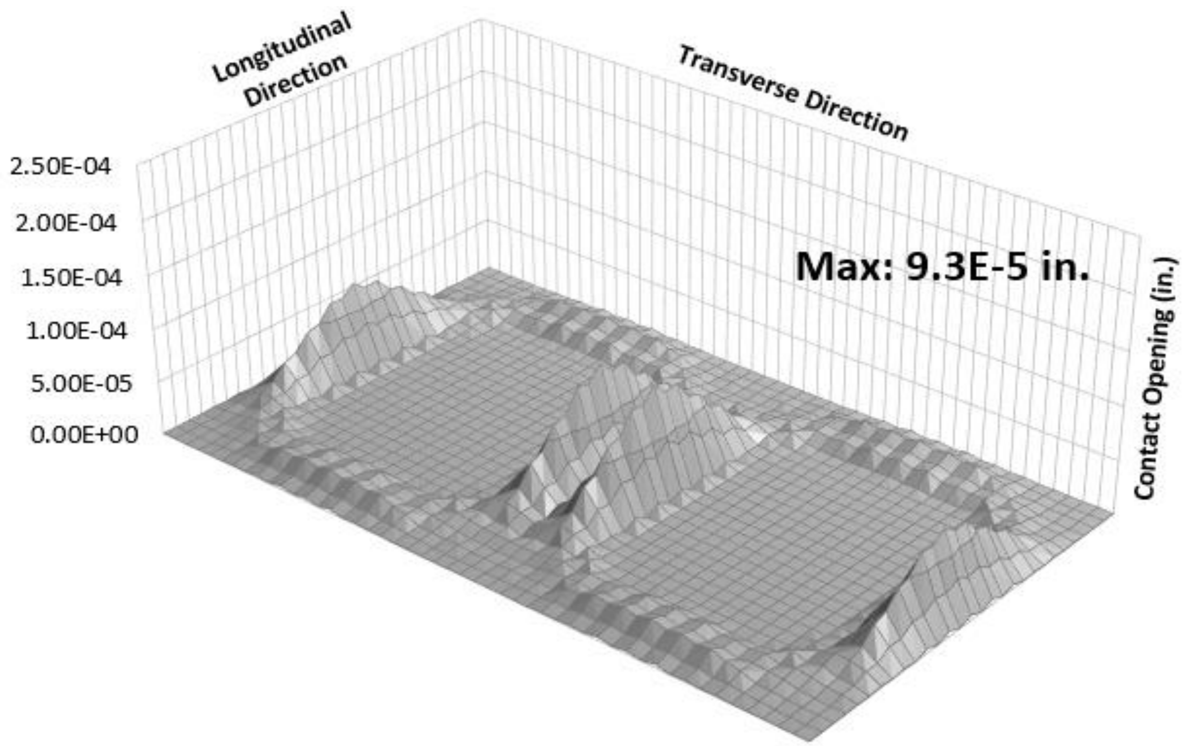


Figure 37 Contact Opening for Pavement with 4+0.5 in. of Asphaltic Materials and K=7720 lbf/in^3

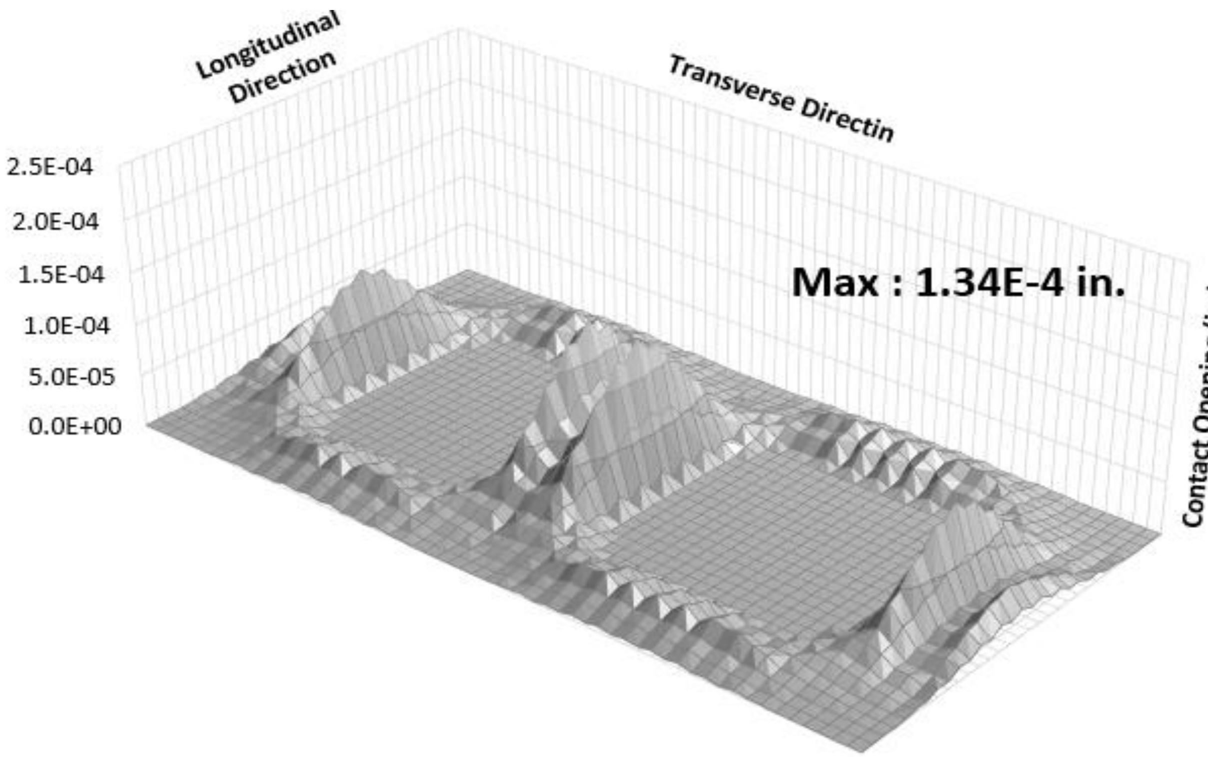


Figure 39 Contact Opening for Pavement with 4+0.5 in. of Asphaltic Materials and K=3860 lbf/in^3

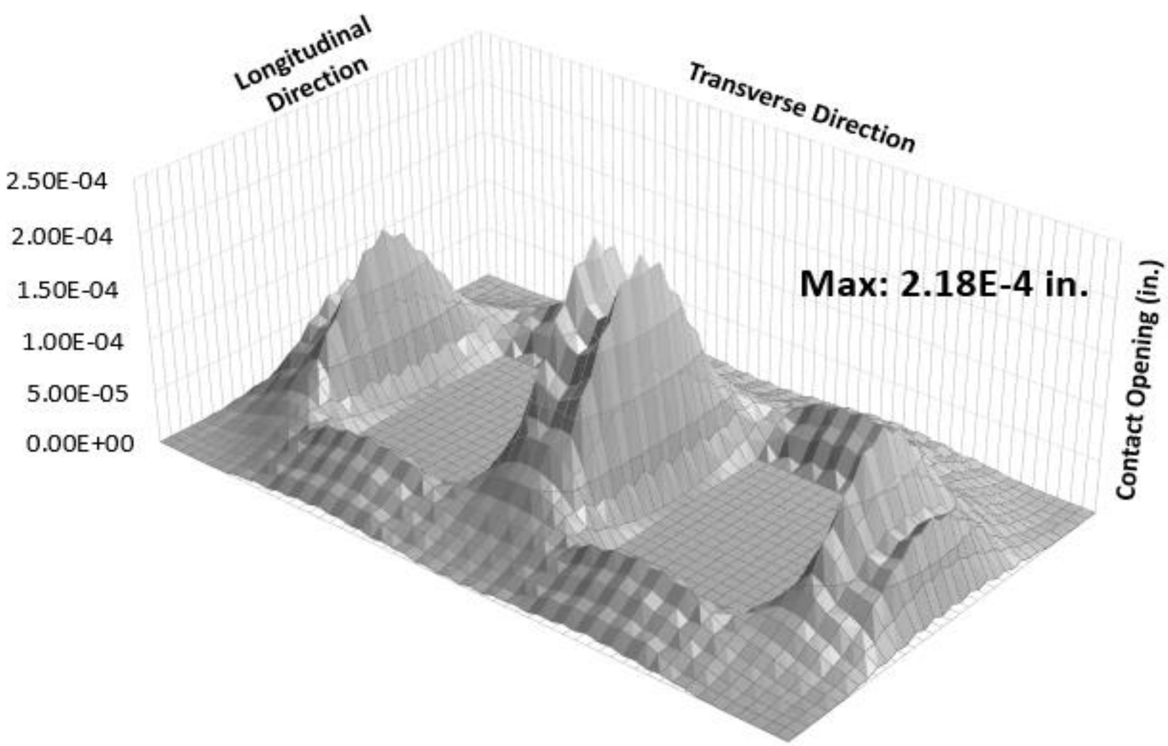


Figure 38 Contact Opening for Pavement with 4+0.5 in. of Asphaltic Materials and K=965 lbf/in^3

Table 18 Maximum Contact Opening between Overlay and Asphalt Layer under a Passing Vehicle for Pavement with 4+2 in. of Asphaltic Materials

Simulation Results	**K=965 lbf/in^3**	**K=1930 lbf/in^3**	**K=3860 lbf/in^3**	**K=5790 lbf/in^3**	**K=7720 lbf/in^3**
Maximum Contact Opening (in.)	2.32E-05	2.10E-05	1.80E-05	1.51E-05	1.32E-05

Table 19 Maximum Contact Opening between Overlay and Asphalt Layer under a Passing Vehicle for Pavement with 4+1 in. of Asphaltic Materials

Simulation Results	**K=965 lbf/in^3**	**K=1930 lbf/in^3**	**K=3860 lbf/in^3**	**K=5790 lbf/in^3**	**K=7720 lbf/in^3**
Maximum Contact Opening (in.)	2.06E-04	1.74E-04	1.30E-04	1.09E-04	9.27E-05

Table 20 Maximum Contact Opening between Overlay and Asphalt Layer under a Passing Vehicle for Pavement with 4+0.5 in. of Asphaltic Materials

Simulation Results	**K=965 lbf/in^3**	**K=1930 lbf/in^3**	**K=3860 lbf/in^3**	**K=5790 lbf/in^3**	**K=7720 lbf/in^3**
Maximum Contact Opening (in.)	2.18E-04	1.81E-4	1.34E-04	1.150E-04	9.30E-05

Table 21 Maximum Contact Opening between Overlay and Asphalt Layer under a Passing Vehicle for Pavement with 5+1 in. of Asphaltic Materials

Simulation Results	**K=965 lbf/in^3**	**K=1930 lbf/in^3**	**K=3860 lbf/in^3**	**K=5790 lbf/in^3**	**K=7720 lbf/in^3**
Maximum Contact Opening (in.)	1.94E-04	1.66E-04	1.28E-04	1.06E-04	8.9E-05

Table 22 Maximum Contact Opening between Overlay and Asphalt Layer under a Passing Vehicle for Pavement with 5+0.5 in. of Asphaltic Materials

Simulation Results	**K=965 lbf/in^3**	**K=1930 lbf/in^3**	**K=3860 lbf/in^3**	**K=5790 lbf/in^3**	**K=7720 lbf/in^3**
Maximum Contact Opening (in.)	2.15E-04	1.76E-04	1.32E-04	1.12E-04	9.0E-5

Table 23 Maximum Contact Opening between Overlay and Asphalt Layer under a Passing Vehicle for Pavement with 5.5+0.5 in. of Asphaltic Materials

Simulation Results	**K=965 lbf/in^3**	**K=1930 lbf/in^3**	**K=3860 lbf/in^3**	**K=5790 lbf/in^3**	**K=7720 lbf/in^3**
Maximum Contact Opening (in.)	2.12E-04	1.71E-04	1.26E-04	1.02E-04	8.70E-05

5.4 Overlaid Pavement under Braking Vehicles

Braking situation of vehicles puts a major horizontal load over the pavement surface. This horizontal load would be transferred to the depth of the pavement and puts a major impact on interface between overlay and existing asphalt layer. The horizontal load resulted from vehicles braking causes separation between layers. As it is shown in Figure 40 [18], crack initiation and propagation and, eventually, slippage of the overlay over the existing asphalt layer is the main distress that can happen for overlaid pavements.

The durability of the overlay under vehicle's braking load depends on two major criteria. As it is obvious, thickness of the overlay has major impact on its durability. In fact, by increasing the thickness of the overlay, the amount of the horizontal load transferred to the depth of the interface decreases and results in less opening between overlay and existing asphalt layer. The bonding strength between overlay and existing asphalt layer is the second criteria which has a major impact on durability of overlay. The higher interface bonding strength reduces the contact opening between two layers.

Figure 41 shows the ABAQUS visualization of the finite element simulation for contact opening between overlay and existing asphalt layer under the vehicle's braking loading. As it can be seen, the simulation results shows the crescent shape of the slippage between layers, which is similar to what would happens in real overlaid pavement (Figure 40).

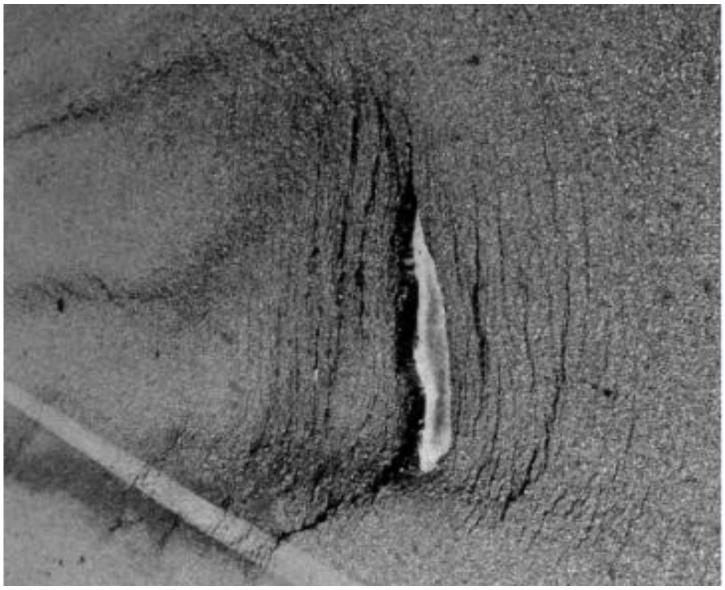


Figure 40 Crescent Shape Slippage between Different Asphalt Layers in Pavement [29]

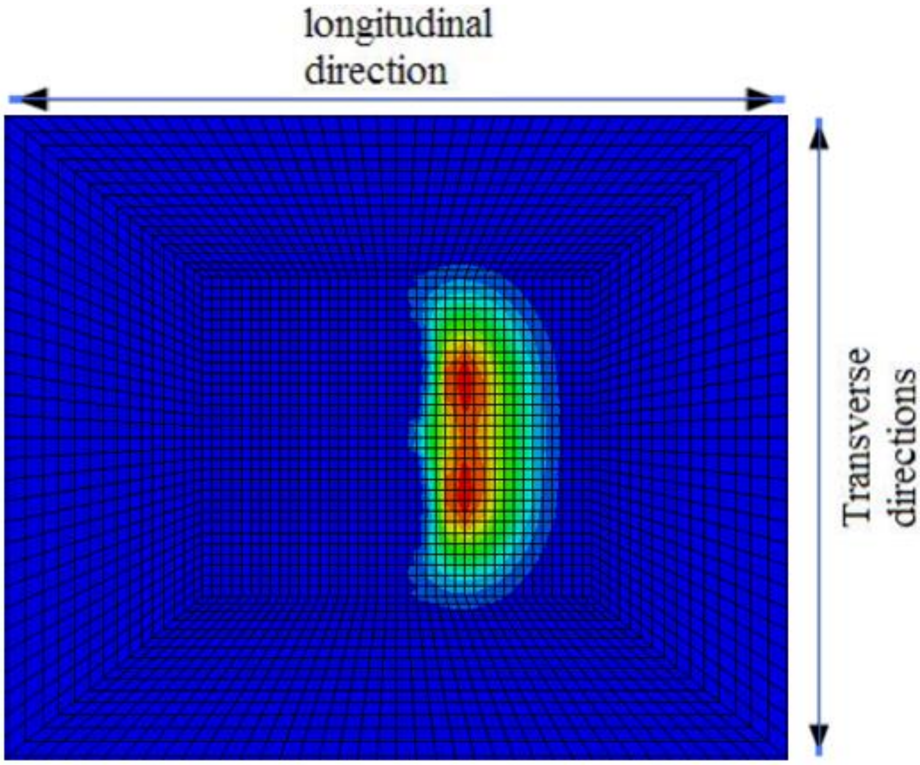


Figure 41 Contact Opening between Overlay and Existing Asphalt Layer under Vehicle's Braking Load

5.4.1 Impact of the Overlay Thickness on Overlay Durability

Increasing the overlay thickness decreases the amount of the load transferred to the interface layer which results in smaller contact opening between overlay and existing asphalt layer. The very thin or ultra-thin overlay, especially under vehicles braking load, the horizontal load can separate overlay and existing asphalt layer at the interface layer. The overlay with thicknesses of 2, 1, and 0.5 in. was evaluated and results discussed in the following paragraphs are based on K=3860 lbf/in^3 for all simulations.

As it can be seen in Figures 42, 43, and 44, the maximum contact opening for pavement with 4+0.5 in., 4+1 in., and 4+2 in. of overlay are 2.29 x 10 $^{-4}$ in., 2.26 x 10 $^{-4}$ in., and 1.56 x 10 $^{-4}$ in.. The difference between results for pavement with 1 in. and 0.5 in. of overlay is very small, but the maximum contact opening of pavement with 2 in. of overlays is less than 70 percent of the maximum contact opening in pavement with 0.5 in. overlay.

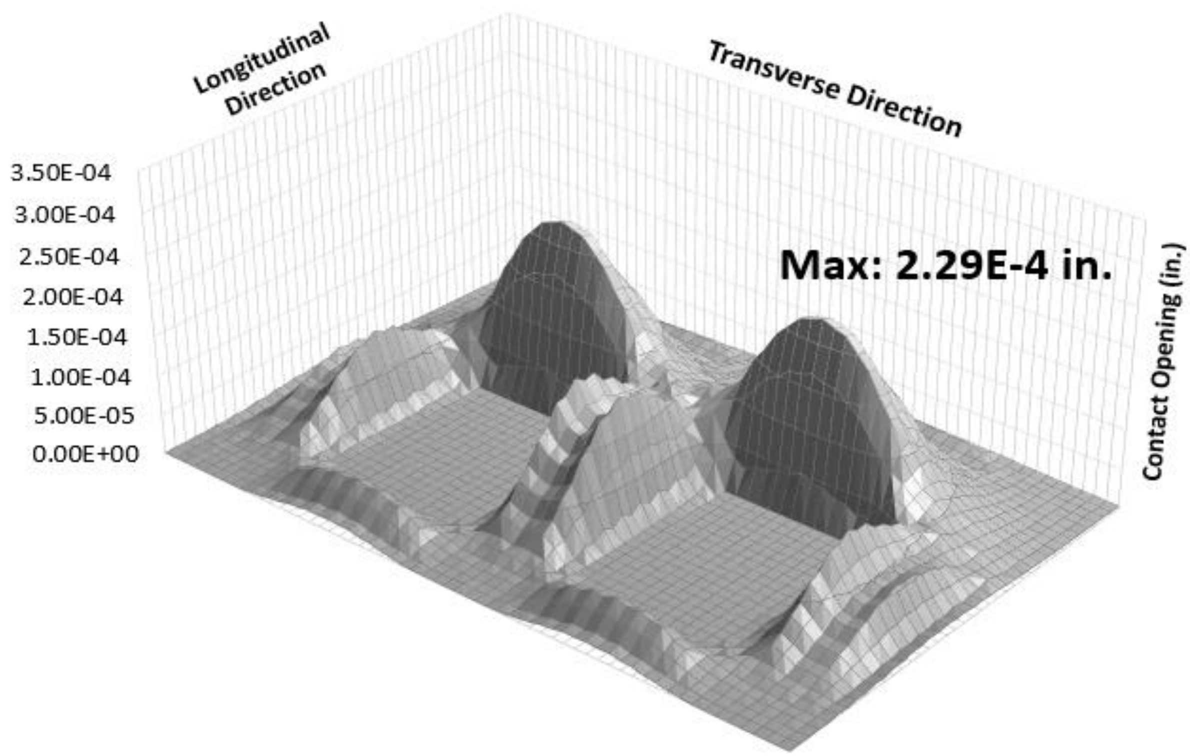


Figure 42 Contact Opening for Pavement with 4+0.5 in. of Asphaltic Materials (K=3860 lbf/in^3)

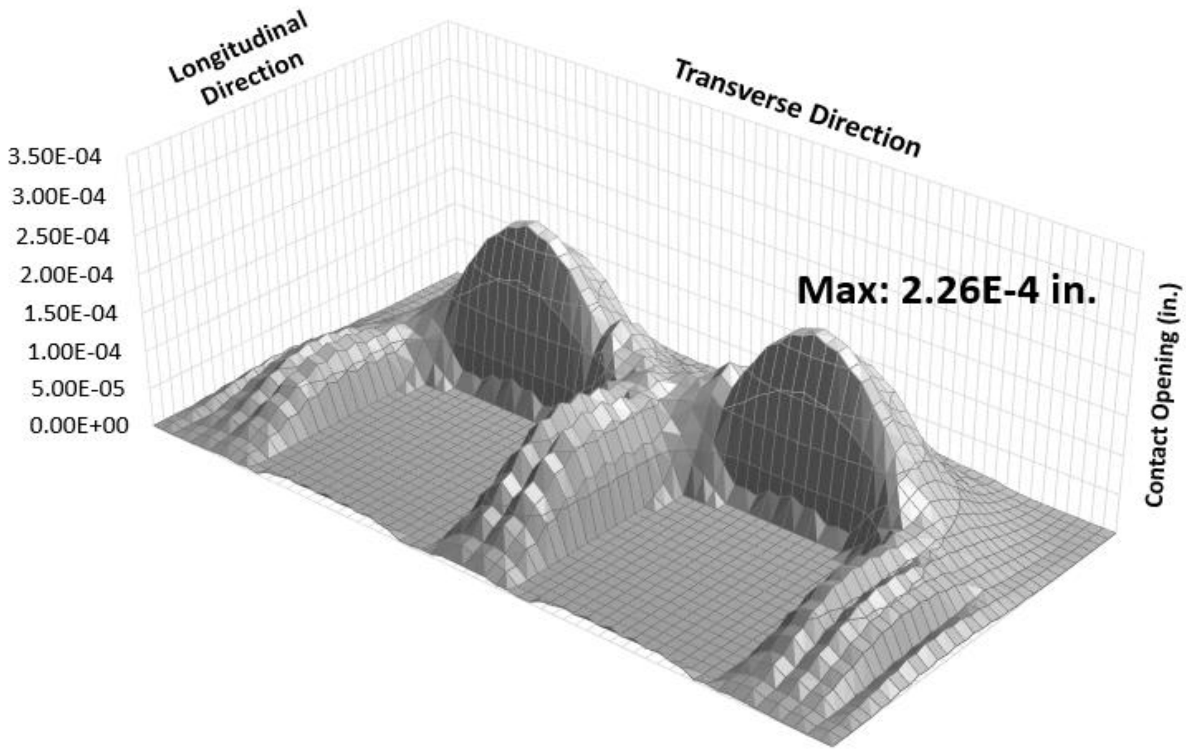


Figure 44 Contact Opening for Pavement with 4+1 In.es of Asphaltic Materials (K=3860 lbf/in^3)

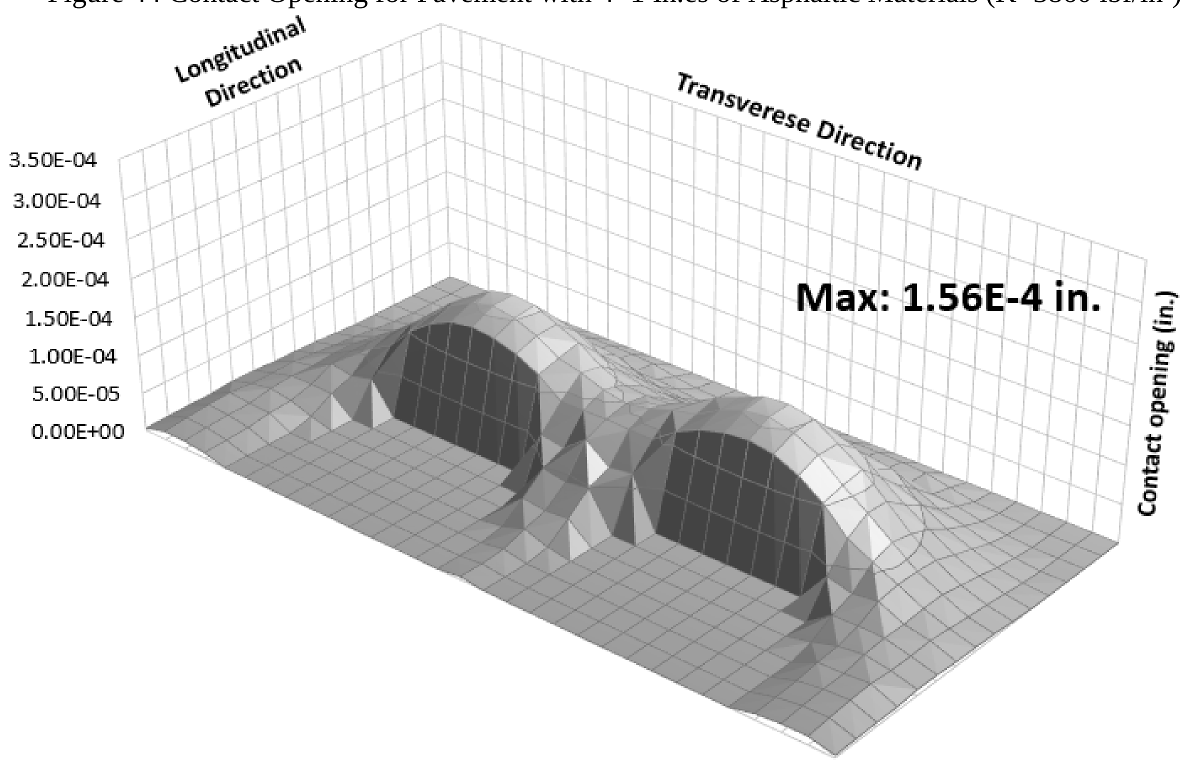


Figure 43 Contact Opening for Pavement with 4+2 in. of Asphaltic Materials (K=3860 lbf/in^3)

Table 24 shows the contact opening for different pavement designs with different thicknesses of existing asphalt layer and overlay. As it can be seen, the contact opening for all pavement with 0.5 in. of overlay are almost equal. It shows that the impact of thickness of existing asphalt layer on durability of overlay is negligible and the durability of overlay is majorly impacted by its thickness.

Table 24 Contact Opening between Overlay and Existing Asphalt Layer Resulted by Braking Vehicle

Simulation Results	**4+2 in. of asphaltic materials**	**4+1 in. of asphaltic materials**	**4+0.5 in. of asphaltic materials**	**5+1 in. of asphaltic materials**	**5+0.5 in. of asphaltic materials**	**5.5+0.5 in. of asphaltic materials**
Maximum Contact Opening (in.)	1.56E-04	2.26E-04	2.29E-04	2.26E-04	2.27E-4	2.24 E-05

5.4.2 Impact of the Interface Bonding Strength on Durability of the Overlay Itself

Increasing the interface bonding strength between overlay and existing asphalt layer, the effect of vehicle's braking load on overlay durability decreases as shown in Figures 45, 46, and 47. The contact opening in a pavement with 4+0.5 in. of asphaltic materials are 1.7 x 10^{-4} in., 2.29 x 10^{-4} in., and 3.41 x 10^{-4} in. for K=7,720 lbf/in^3, K= 3,860 lbf/in^3, and K= 965 lbf/in^3, respectively. Tables 25 to 29 includes the results for contact opening of different pavements with different design and different interface bonding.

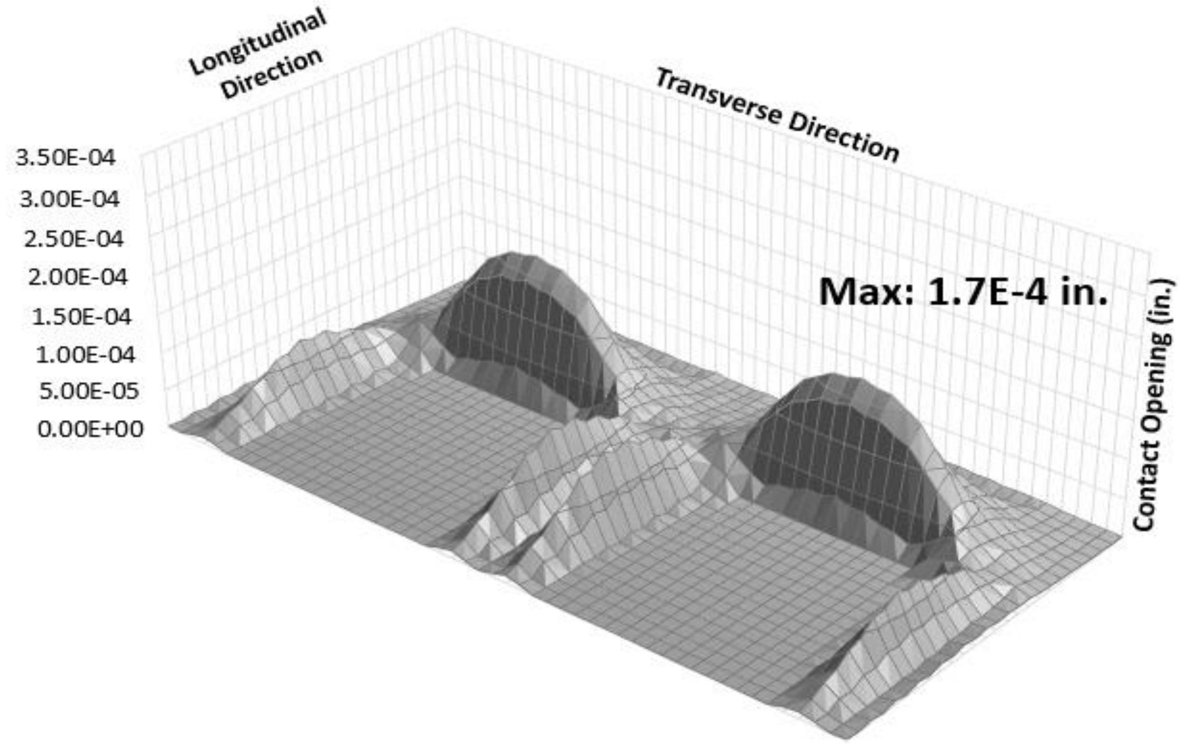


Figure 46 Contact Opening for Pavement with 4+0.5 In.es of Asphaltic Materials and K=7720 lbf/in3

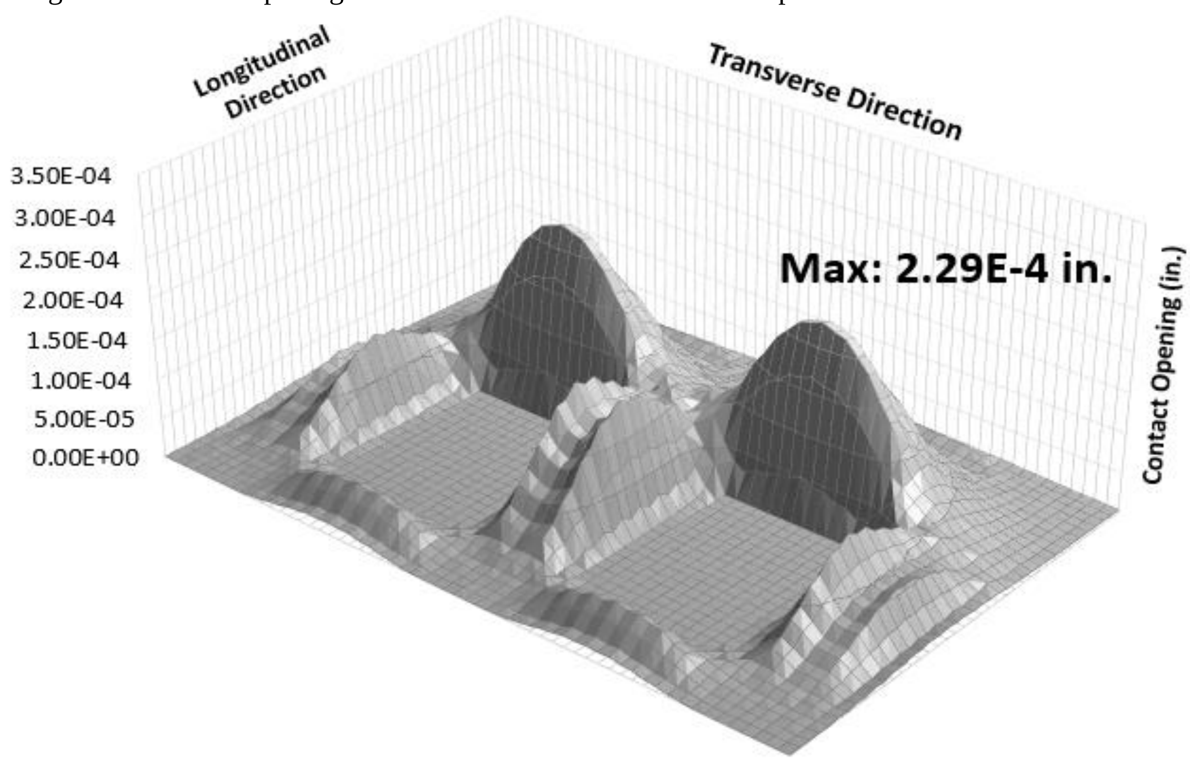


Figure 45 Contact Opening for Pavement with 4+0.5 in. of Asphaltic Materials and K=3860 lbf/in^3

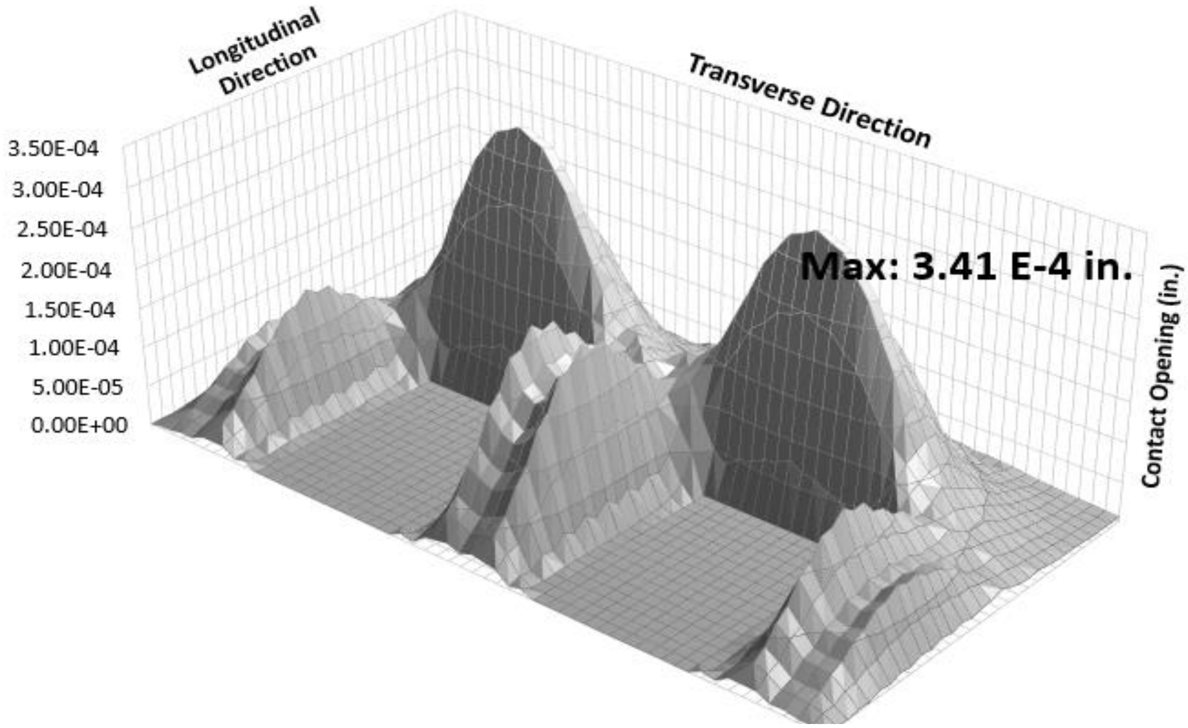


Figure 47 Contact Opening for Pavement with 4+0.5 in. of Asphaltic Materials and K=965 lbf/in^3

Table 25Maximum Contact Opening between Overlay and Asphalt Layer under a Braking Vehicle for Pavement with 4+2 in. of Asphaltic Materials

Simulation Results	**K=965 lbf/in^3**	**K=1930 lbf/in^3**	**K=3860 lbf/in^3**	**K=5790 lbf/in^3**	**K=7720 lbf/in^3**
Maximum Contact Opening (in.)	2.18E-4	1.93E-4	1.56E-4	1.39E-4	1.26E-4

Table 26 Maximum Contact Opening between Overlay and Asphalt Layer under a Braking Vehicle for Pavement with 4+1 in. of Asphaltic Materials

Simulation Results	**K=965 lbf/in^3**	**K=1930 lbf/in^3**	**K=3860 lbf/in^3**	**K=5790 lbf/in^3**	**K=7720 lbf/in^3**
Maximum Contact Opening (in.)	3.24E-4	2.86E-4	2.26E-4	2.01E-4	1.59E-4

Table 27 Maximum Contact Opening between Overlay and Asphalt Layer under a Braking Vehicle for Pavement with 4+0.5 in. of Asphaltic Materials

Simulation Results	**K=965 lbf/in^3**	**K=1930 lbf/in^3**	**K=3860 lbf/in^3**	**K=5790 lbf/in^3**	**K=7720 lbf/in^3**
Maximum Contact Opening (in.)	3.41E-4	3.01E-4	2.29E-4	2.1E-4	1.7E-4

Table 28 Maximum Contact Opening between Overlay and Asphalt Layer under a Braking Vehicle for Pavement with 5+0.5 in. of Asphaltic Materials

Simulation Results	**K=965 lbf/in^3**	**K=1930 lbf/in^3**	**K=3860 lbf/in^3**	**K=5790 lbf/in^3**	**K=7720 lbf/in^3**
Maximum Contact Opening (in.)	3.40E-4	2.92E-4	2.27E-4	2.02E-4	1.7E-4

Table 29 Maximum Contact Opening between Overlay and Asphalt Layer under a Braking Vehicle for Pavement with 5.5+0.5 in. of Asphaltic Materials

Simulation Results	**K=965 lbf/in^3**	**K=1930 lbf/in^3**	**K=3860 lbf/in^3**	**K=5790 lbf/in^3**	**K=7720 lbf/in^3**
Maximum Contact Opening (in.)	3.40E-4	2.86E-4	2.24E-4	1.93E-4	1.7E-4

5.5. Pavement with Different Ultra-thin Overlay Mix Designs under Braking Vehicles

Five different mix designs have been used to observe how using different asphalt mix designs for the 0.5 in. ultra-thin overlay impacts the surface deformation and contact opening between overlay and existing asphalt layers. Mix designs offered for the ultra-thin overlay in Interim Report by Haj et al. [30] has been used for this part of the study. The list of the five different mix designs can be seen in table 30.

Table 30 Different Mix Designs for 0.5 in. of Overlay

Mix Design Number	Mix Design Gradation
Mix 1	4.75 SMA Gap Graded
Mix 2	4.75 Fine Dense Graded
Mix 2	9.5 Fine Dense Graded
Mix 2	9.5 Coarse Dense Graded
Mix 2	4.75 Gap Graded/Open Graded

Table 31 shows the maximum deformation at the pavement surface, maximum tensile strain at the bottom of the asphalt layer and contact opening for pavements with five different overlay mix designs. As it can be seen, and as it was expected, the difference in results is minimal. It may be due to the very small thickness of the overlay which makes its properties lees important in compare to 4 in. of existing asphalt layer. It should be mentioned that the results at this part should not be compared to what is presented in previous sub-sections because material that have been used for the 4 in. of existing HMA layer in these 5 runs is different.

Table 31 Maximum Surface Deformation for Pavements with Five Different Overlay Mix Designs (4+0.5 in. of Asphaltic Material with K=7720 lbf/in^3)

Simulation Results	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
Contact Opening (in.)	1.176E-4	1.158E-4	1.157E-4	1.161 E-4	1.162E-4
Maximum Surface Deformation (in.)	11.6E-3	11.7E-3	11.7E-3	11.9E-3	11.8E-3
Longitudinal tensile strain(με)	2.31E-4	2.30E-4	2.30E-4	2.31E-4	2.31E-4
Transverse tensile strain(με)	1.60E-4	1.60E-4	1.60E-4	1.60E-4	1.6E-4

6. Closure

A composite pavement system was evaluated in this study to identify the influence of ultra-thin overlays using ABAQUS software. The following conclusions can be drawn from the evaluation:

- The ability of implementing viscoelastic and linear elastic-perfectly plastic materials, and also defining frictional and cohesive contact between layers makes ABAQUS a suitable candidate to model different pavement systems (with or without overlay)
- Relationship between HMA layer thickness and pavement structural characteristics is nonlinear. This means that removing the same thickness of the HMA layer would have more critical structural impact on the pavement with thinner original HMA layer.
- Overlaying cannot fully recover the structural characteristics of the pavement to its original shape at the initial construction time. In other words, pavements with the same properties of the materials, 6 in. of original consistent HMA layer, is stronger than 4+2 in. of overlaid HMA layer. So, even removing the 2 in. of deteriorated HMA surface and putting 2 in. of overlay reduces structural strength in comparison to 6 in. of single pavement layer.
- The relationship between overlay thickness and structural characteristics of the pavement (surface deformation and strain at the bottom of the HMA layer) is almost linear. This means that impact of the 2 in. of the overlay is nearly 4 times bigger than the impact of 0.5 in. overlay.
- Having weak interface bonding (K=965 lbf/in3), the difference between results (surface deformation and strain at the bottom of the HMA layer) for pavements with 2, 1, and 0.5 in. becomes very small. It means that decreasing the interface bonding, the impact of the overlay thickness on the structural characteristics of the pavement decreases.

- Considering durability of the overlay, overlay with 1 or 0.5 in. should be categorized separately in comparison to overlays with 2 in. of thickness. Under moving vehicle load, for pavements with 1 and 0.5 in. overlay, the contact opening between the overlay and existing HMA layer are almost equal. On the other hand, their results are about 7 times bigger than contact opening for a pavement with 2 in. of the overlay.

- According to this study's simulations results, for overlay with less than 1 in. of thickness, the impact of the interface bonding (different tack coats) is more important than the impact of the overlay thickness. In fact, improving the interface bonding impacts more on the contact opening in comparison to increasing the overlay thickness. From the constructional point of view, this could be interpreted in this way: if the interface bonding between the ultra-thin overlay and existing HMA layer is not strong enough, increasing the overlay thickness up to 1 in. does not improve the performance significantly.

- Generally speaking, up to 1 in. of the overlay, interface bonding (tack coating) is the most important factor in the durability of the overlay. But going from 1 in. to 2 in. of the overlay, the thickness of overlay becomes more important and plays the major role (that's another reason that overlays with 1 in. or less should be considered as a composite layer.

- For 1 or 0.5 in. of the overlay, contact opening under the braking vehicles is almost twice of the contact opening under moving loads. This suggests special emphasis needs to be placed where the ultra-thin overlay is placed at the intersections.

- Under braking conditions, the amount of the contact opening between layers for 2 in. of the overlay is almost half of the opening for 0.5 in. of the overlay. This means that, under braking vehicles like near the red lights, slippage and other related distresses could be a concern even for 2 in. of the overlay.

The main limitation of this study would be a lack of experimental results to define interface layer characteristics. For the input, having real values for the reaction modulus based on the different types of tack coats would be of a great benefit. To achieve this, a heavy weight direct shear test machinery would be needed because the total load on the wheel of a vehicle (4,500 lb) should be used as a normal load. For the verification purposes, a whole testing set of a pavement slab and a vehicle simulator would be needed, so the deflections, stresses, and strains could be read and compared to the simulation results.

Although most current research in this area uses a linear viscoelastic model to implement the behavior of HMA materials, adding the nonlinear parts of the HMA behavior could be also another next step for this research.

Recent research shows that wheel load is non-uniform neither in longitudinal or in the transverse direction. Most of the researchers use uniform loading in the transverse direction. Doing the more experimental test to have more result on non-uniformity of the loads in the transverse direction and implementing it in a simulation would be another forward step for this research.

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Vita

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