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ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

Finite Element Analysis of Permanent Deformation and Responses under Different Vehicular Load Speeds

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A Thesis in Road and Transport Engineering

By

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A Thesis

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I certify that research work titled "**Finite Element Analysis of Pavement Deformation and Responses under Different Vehicular Load Speeds**" is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged /referred.

ABSTRACT

The increase of dynamic loads exerted on the pavement is one of the major causes that shorten the pavement service life. The current pavement design procedure which incorporates static loads in the structural design of pavement makes the situation critical. Hence, decreased riding quality, discomfort and increased vehicle operating cost that influences overall transportation costs are seen. Thus, a vehicle loading speed must be given attention in dynamic analysis due to its effect on tire-pavement interaction and pavement response values.

In the study, three-dimensional finite element analysis used to simulate the deformation of the pavement surface and sub-grade by different vehicular speeds. ABAQUS software is employed to develop total of five three-dimensional finite element models. Each pavement models represent selected vehicular speeds by considering similar material characterization, single axle single tire load configuration and necessary boundary conditions. The vehicle speed along the wheel path is simulated by progressive shift of the tires over the pavement loading area.

From the analysis of the pavement models, it was found that lower speeds have longer contact time with flexible pavement than higher speeds. This is due to time of loading is the function of tire imprint length and speed. Also, asphalt concrete behavior as viscoelastic material plays an important role. Moreover, the greater static effect of loading makes the reduction in lower speeds is more than higher speeds. Though increasing velocities make the dynamic's effects of loading more than static's effect of that, it cannot higher than load's static's effect at low speeds. Hence, accumulated strain increases with an increase in loading time.

In addition, vertical strain and stress distribution increase and decrease linearly along the wheel path as loading amplitude varies in each step time. As a result, maximum stress magnitude under load center for single axle configuration is higher in 20Km/hr than 100Km/hr speed. It is also worthy to mention, load's dynamic effect is less considerable at the top of subgrade. This is due to deeper position of extracted data and the effect of layers' weight. Hence when speed increases higher than 60Km/hr, a low decrease in strain magnitude is observed.

Keywords: Dynamic analysis, ABAQUS, Finite Element Analysis, HMA, Vertical Strain

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ABBREVIATIONS AND ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ABAQUS	Application software for Finite element analysis of pavement structures
E	Modulus of Elasticity
FEA	Finite Element Analysis
KENLAYER	Well known program in field of pavement analysis and design in which has the capability of linear, nonlinear and viscoelastic analysis of flexible pavements under multiple loading
KN	Kilo Newton
HMA	Hot Mix Asphalt
H	Layer Thickness
MPa	Mega Pascal
Sec	Second
3D	Three Dimensional
V	Poisson Ratio
VMA	Voids in Mineral Aggregate
VOC	Vehicle Operating Cost

CHAPTER 1 INTRODUCTION

Pavement deterioration in Addis Ababa is characterized by frequent pavement damages near bus stations, locations at a steep gradient, at signalized intersections and roundabouts. Though maintenance activities are undertaken recurrently or periodically pavements deteriorate due to excess load, climatic changes, poor drainage, and low-quality pavement materials.

One of the main distresses of asphalt pavements is rutting. Rutting is usually caused by the densification and shearing of the different pavement layers. It is visually identified by the depression in the pavement surface along the wheel paths. In addition to the pavement surface, rutting may occur on any of the layers.

Rutting is a serious issue for pavement. It creates suitable environment for water to seep into the pavement than draining off on the surface. Water accumulated in the pavement creates serious deterioration issues by reducing the strength of subgrade layer. This is characterized by non-uniform longitudinal rutting along wheel path and further encourages failure of asphalt layer. Also, water soak in the ruts is a potential for hydroplaning. The hydroplaning phenomenon consists of the buildup of a thin layer of water between the pavement and the tire and results in the tire losing contact with the surface and consequently loss of steering control.

Not only for the pavement, is rutting undesirable for users directly and indirectly in number of ways. High fuel consumption, early tire wear and losing skid resistance are ill effects of rutting which gradually increase vehicle operating, transportation and pavement maintenance costs.

Rutting is influenced by various factors including material properties of pavement layers, environment conditions, traffic loading, and construction practices. From all the main causes of rutting is traffic loading which contains vehicle characteristics, axle load and wheel configuration. The primary response parameter of the pavement depends on vehicle speed. Moving dynamic loads induces critical wheel load stresses and deflections that vary with depth and horizontal distance from the loading center of the tire-pavement contact area. This implies pavement deformation’s close relationship with dynamic loads.

Accordingly, it is important to evaluate the deformation pavement layers considering the effect of heavy vehicular loads to which it is subjected by considering the effect of dynamic characteristics or time-dependent environments.

1.1 Problem Statement

The performance of flexible pavements is directly dependent on the magnitude and frequency of the applied wheel loads. Most studies on pavement response to a vehicular loading have been conducted with a multilayered elastic approach utilizing stationary wheel loads in normal direction only. However, pavements are actually subjected to three-dimensional dynamic wheel loads which make linear elastic numerical solution under static loading questionable. For pavement responses under moving wheel loads, vehicular speeds must be considered. This is one of the current problems on pavement design procedure and most studies for not incorporating the impact of vehicle speeds in the structural design of pavement.

The problem is highly related to design agencies' common practice of referring hardcopy of design guide manuals and calculation to design flexible pavements. For instance in our country, AASHTO and ERA manuals practiced by design agencies than software based approach. This manual design method has a problem in doing many alternatives for comparison as flexible pavement design involves different nomographs, charts, tables and formulas. Mistakes mostly occur or error cannot be fully avoided in the design procedures that eventually influence the quality of the design and development of science. (Garoma et al, 2017)Therefore it is complex and time taking practice which may result in unsafe or uneconomical design for many design variables including different vehicular load speeds. Possible causes might be lack of proper understanding of the problem and missing solutions to improve the pavement performance.

The other critical issue is the deterioration of the pavement during the very early life of the road. On theory, it is possible for rutting deformation to continue under traffic loading up to a stage of structural failure. However, in the practical case, before structural failure reached, functional service requirements of the pavement would be violated and traffic operations would be severely affected. Especially rutting throughout the entire asphalt pavement structure induced by slow-moving or standing loads plays a significant role in the premature failure of some pavements.

Hence, there is a need to address the mentioned and other related problems for better design and construction of pavements. to minimize the impacts and damages on the pavement. Due to the above two key reasons, the study will investigate the pavement structural responses due to different vehicle load speeds to study the dynamic aspects of vehicle-road interaction.

1.2 Objective of Study

The main objective of the thesis is to investigate pavement deformation under different speed of vehicular loads using three-dimensional finite element analyses. The specific objectives of the thesis paper are

1. Develop pavement models that simulate basic influencing factors and conditions to investigate the effect of speed.
2. Develop stress and strain patterns in pavement models by applying different vehicular load speeds.
3. Extract and relate vehicle speeds and critical strains on pavement layers to find the impact of vehicular speeds.

1.3 Scope and Limitation of Study

In the study, five vehicular speed namely 20Km/hr,40Km/hr,60Km/hr,80Km/hr and 100 Km/hr and single axle single tire configuration were input to develop pavement model. These representative vehicular speeds and single tire configuration were selected based on similar studies approaches. Each pavement model consists of 4 pavement layers and subjected to uniform tire pressure. Critical pavement responses under wheel load center were determined for the bottom of asphalt layer, on surface layer and top of subgrade. Finally, validation of the 3D pavement model was checked and compared with other results of similar material property and characterization model computed by Kenlayer. Kenlayer is very important in pavement design industries as the design by using software is less time consuming, accurate and easy.

The study is limited to developing a pavement structural model that can estimate deformations applicable within the linear elastic material domain for base and subgrade and viscoelastic material behavior for HMA. Hence more realistic characterization of nonlinear and inelastic behaviors for base and subgrade materials as well as viscoplastic property of HMA was not covered.

Though three-dimensional finite element analyses viewed as the best approach to answer fundamental questions about pavement performance, it is tedious, time-consuming and requires high computational efficiency computers to accurately model pavement system. Unavailability of research papers regarding pavement deformation under different vehicular loads in the country and inadequacy of experimental data for viscoelastic HMA makes the modeling process hard. Thus many simplifications and assumptions in the study are made including prony series for viscoelastic HMA layer, repetition and axle load configuration, tire contact area as well as uniform contact pressure.

In addition to this major limitation, simulation results were not compared with experimental data to draw more accurate conclusions. Instead, the pavement model is compared with outputs of similar material characterization and model computed by KENLAYER program.

1.4 Presentation of the Thesis

This thesis work comprises of five Chapters. The first chapter introduces the main issues that are covered by this paper. The basic objectives and the scope of the research are also presented. The second chapter is dedicated to literature review. In this portion, highlights are given concerning previous works conducted under the topic of rutting.

The third chapter is dedicated to the methodology which is discussion of the software development procedures taken. Here, the basic programming modules incorporated in the software and basic concept of finite element analysis are covered.

The analysis and discussion section consists of the fourth Chapter. Here, the output of the finite element software is briefly discussed and compared with output from other software.

On the final Chapter, conclusion and recommendation are forwarded based on lessons taken from the thesis.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

Rutting originating in the asphalt concrete layers ranked as the most relevant distress mechanism to consider, followed by surface cracking, longitudinal unevenness, loss of skid resistance, longitudinal cracking, and bottom-up cracking among others. Therefore the extent and growth of rutting in flexible pavement is given prior consideration in pavement design process. In the literature review, definition, types, and impacts of rutting, studies on the relationship between vehicular speed and rutting are reviewed.

2.2 Definition of Rutting

Rutting is the result of the accumulation of plastic strains or permanent deformation which occurs in the different layers of the pavement structure due to the action of repeated traffic loads. Rutting along wheel path is influenced by property of component materials and mixes as well its structural design. (Dallas et al, 2018)

According to studies, improper aggregate gradation and excess binder content are main causes of rutting. Due to excess binder content in the pavement, the air void and friction between aggregate reduce and result high plastic flow of bitumen in pavement (Mahrez, 2008). In addition to above factors, important causes of rutting include vehicular speed, surface contour, traffic distribution and temperature variation.

Increasing load repetition with dual effect of shear deformation and densification can also be a cause of rutting development. (Wang et al, 2009).Shear deformation due to high shear stress on top of asphalt layer in flexible pavements is considered to be main cause of rutting. Upper layers often contain fine aggregate gradations and high asphalt contents (Katman, 2006).

2.3 Mechanisms of Rutting

Generally, there are two different mechanisms that drive permanent deformation in the asphalt mixture: (Dallas et al, 2018)

Densification, as the name suggests occurs due to an overall change in the volume of the material due to the repeated action of the wheel load. Asphalt mixtures are typically compacted to approximately 92–94% of their maximum density when placed in the field. In other words, after being placed in the field, asphalt mixtures have 6–8% air voids. These air voids typically get compacted due to the repeated action of the traffic wheel loads over the course of time. As such, the density of the asphalt mixture increases to approximately 96% with a corresponding change in the volume of the material. Because of change in volume occurring predominantly along the wheel paths, it reflects in the form of rutting. The rutting type is usually fairly wide and uniform in the longitudinal direction with heaving on the surface occurring seldom. Also, note that for similar rut depth values, the deformation within the pavement may be located within a single weak layer or more evenly distributed through the depth of the pavement (Figure1). However, the contribution of densification to the overall permanent deformation of an asphalt mixture is typically small.

The permanent deformation due to the accumulation of plastic strain has a much more significant contribution to rutting observed in asphalt pavements. The accumulation of permanent deformation in the asphalt mixture is driven by several factors related to the component materials as well as the mixture design. The most significant factors are shape, angularity, gradation, toughness of the aggregate particles, resistance of the asphalt binder to plastic deformation (as a function of temperature and age) and binder content in the asphalt mixture. Plastic flow involves essentially no volume change and gives rise to shear displacements in which both depression and heave are usually manifested. Plastic flow occurs when the shear stresses imposed by traffic exceed the inherent strength of the pavement layers. The rutting, in this case, is usually characterized by heaving on the surface alongside the wheel path (Figure1).

In extreme cases, consolidation and shear deformation may occur concurrently leading to severe distortion of the layer

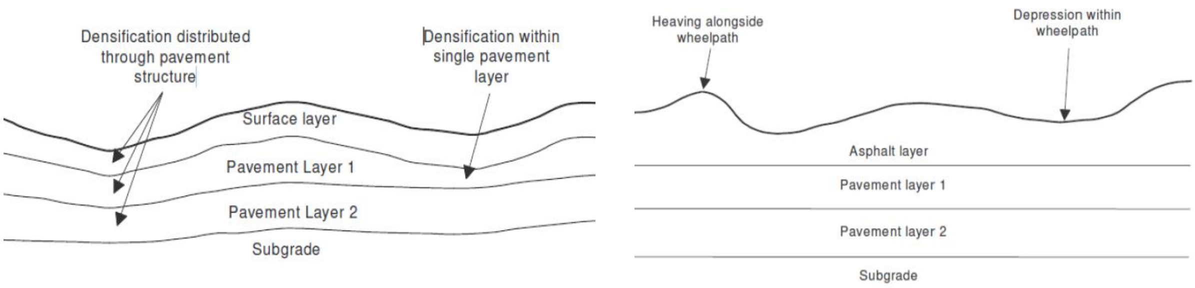

Figure 1: Typical rut profile as a result of densification and Plastic Flow respectively.

2.4 Types and Critical stages of Rutting

According to Eduardo and Liu Gan (2009), rutting is categorized in to three groups. They are:-

a. Wear rutting: Wear rutting is the consolidation in the wheel paths of the HMA layer due to insufficient compaction effort caused by not achieving the target density. Consequently, additional compaction to the asphalt layer is generated by vehicle loading without any base/subbase yielding or the formation of HMA humps. Insufficient compacting effort within the lower base layers, not enough roller passes while paving, weight of roller and way of compact, HMA cooling before target density, asphalt moisture or dust, low asphalt content in the mix, lack of cohesion in the mix (tender mix, gradation problem)and other mix design problem contribute to this type of rutting. Not only has the applied load by the vehicle, the nature and types of tires also induced wear rutting on the pavement. Frequent movements of tires on pavement reduce surface friction of pavement.
b. Flow rutting (instability rutting): It is type of rutting on pavement surface due to visco plastic behavior of asphalt layers. The shear deformation, rather than densification, is the primary rutting mechanism in HMA surface mixtures when the supporting layers are reasonably stiff. This kind of rutting is visually recognized by the humps formed on the sides of the rut and more visible in slow trafficked area of the pavement such as intersections that represent variance in the loading conditions applied to the pavement. Braking, accelerating, turning, standing and slow-moving stresses at intersections induce instability rutting. It may also be contributed to

factors high pavement temperatures, improper materials, rounded aggregates, too much binder and/or filler and insufficient or too high air voids.

c. Structural rutting: Unlike of flow rutting, structural rutting occur underneath asphalt layers. As it name indicates, it is caused by loads on structure of pavement and usually identified on sides of road by wide ruts and no humps. The surface deformation is dependent on which of the layers is failing to support the load. When the base is failing, a small hump will be visible at the surface in the middle of the two-wheel paths, while the deformation due to subgrade failure will have no humps at all with a wider wheel path depression. Inadequate design, poor construction and improper material specification in asphalt pavement systems generally cause structural rutting. Traffic conditions, weak substructure or even poor drainage are essential parameters in pavement design. Miss-estimation of these parameters leads to inadequate design and affects the pavement system which could induce structural rutting.

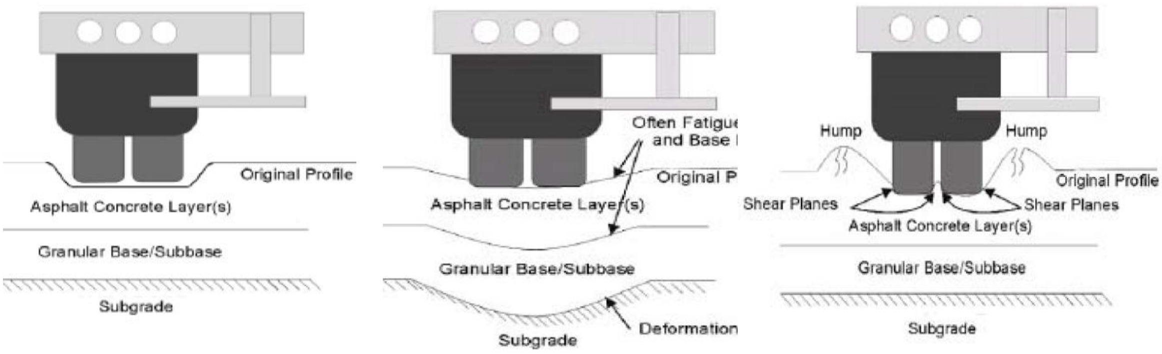

Figure 2: Wear Rutting, Instability Rutting and Structural Rutting.

The three permanent deformation stages indicated are called the primary, secondary and tertiary stages. Three stages have been observed in repeated load permanent deformation tests using specimens (Zhou et al., 2004) and by means of full-scale accelerated pavement testing. The primary stage develops fast due to the initial densification. The secondary stage is recognized by constant rate rutting which develops through most of the pavement life. Flow rutting caused by shear stress is the main contributor, although some densification may also remain. The tertiary stage is characterized by accelerating rutting. The three permanent deformation stages may be difficult to observe on the pavement surface due to the effects of wear and structural rutting. Furthermore, significant temperature effects may also complicate the interpretation of rutting growth (Zhou et al., 2004).

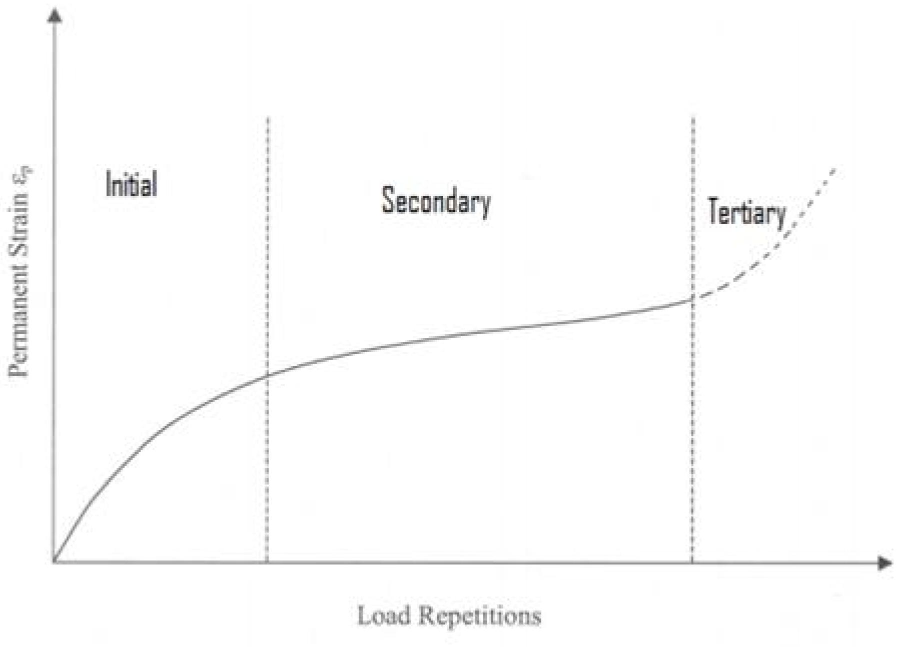

Figure 3: Stages of rutting

2.5 Factors of Rutting

To predict permanent deformation on pavement structure, every constitute materials characteristics and its mixtures has huge influence. Characteristics of asphalt mixtures, test field conditions and the loading distribution affecting rutting are summarized in the table. (Eduardo and Liu Gan, 2009)

2.5.1 **Material Properties Effect**

In pavement design and construction it is quite important to study each material properties and proportions. Stiffness and elasticity are the ultimate goal that should be considered in designing of pavement structure. The asphalt mix should be stiffer and highly elastic so that the pavement will undergo recoverable low strains levels. (Eduardo and Liu Gan, 2009) The effect of each pavement constituent properties on rutting are explained in detail and summarized by table on the following sections.

Table 1: Rutting and material characteristics in HMA

Factors to consider	Rutting Effects	Factors to consider	Rutting Effects
Aggregate		**Test Conditions**	
Shape(Round to Angular)	Increase	Increase in Temperature	Decrease
Gradation(Gap to Continuous)		Stress/Strain(Contact pressure increase)	
Texture(Smooth to Rough)		Water(Dry to Wet)	
Increase in maximum Size		Increase in load repetition	
Mix		**Binder**	
Increase in Air void content	Decrease	Stiffness increase	Decrease
Increase in Voids in Mineral Aggregate			
Binder Content increase			
Compaction method	Depends on the method used		

- **Aggregates**

Mineral aggregate is important part of flexible pavement which composes 90-95% of asphalt mix. Each characteristic of aggregate including gradation, maximum aggregate size, shape and texture has impact on pavement mix.

Maximum size of aggregate is beneficial to resist rutting by high pressure tire loads. But nominal maximum be less proportional to layer thickness 2/3 size. (Oscarsson, 2007)

The other characteristic of aggregate is gradation which has influencing factor than binder content and grade change. The aggregate gradation is either labeled continuations or gap graded. Thus to achieve good asphalt mix the gradation must be continuously graded to resist the application of traffic loads. In continuously graded aggregates, maximum contact between aggregates is attained and unnecessary voids are avoided.(Eduardo and Liu Gan 2009) If dense asphalt mixes are used in super pave mix design, fine natural sands are best fit to avoid rutting.

Shape of aggregate is another critical characteristic of pavement mix. Irregular shaped aggregate has more interlocking and stiffening effect than round shape aggregate. That is why course mixes are prone to rutting due to reduced contact locations. (Guler et al., 2000)

The last but not least characteristic is roughness of aggregate which has strong relationship with shape of aggregate. Asphalt mix composed of smooth aggregates is susceptible to rutting than rough aggregates. Therefore, finer or crushed aggregate must be used. (Eduardo and Liu Gan, 2009)

- **Binder Content**

Comparing to aggregate, bitumen constituent small portion in the mix but it is vital to to carry the loading and determine the connection in between aggregates of the pavement structure. Bitumen has strong connection with durability, cohesion and adhesion properties of aggregate.

Due to visco elastic nature of bitumen, temperature and load repetition determine the stiffness of the binder. Therefore to obtain stiffer mix, low temperature and high load frequency is needed. (Eduardo and Liu Gan 2009)

Although, low temperature is essential for stiff mix, extreme temperatures undermine the elastic property of the binder and make the property of mix dominant by aggregate. This intern make room for additional plastic properties which leads to unrecoverable strains under application of load. Thus workability should be considered while mixing the asphalt, aggregates and any other additives. (Edurardo and Liu Gan 2009)

- **Composition of mix**

As hot mix asphalt is composition of aggregates and bitumen, their proportion and properties must meet the optimal criteria to withstand the deterioration. Therefore, proper amount of compaction (in laboratory or field), and air void are necessary to compose stiffer pavement structure. (Eduardo and Liu Gan 2009)

2.5.2 **Traffic Load**

From all causes of rutting, traffic loading takes the leading role. Since it is changing magnitude over time by nature, it has major effect on asphalt binder. This is due to time and temperature dependent properties of binder content. Some of traffic loading factors that contribute directly or indirectly to rutting are vehicle speed, tire pressure, axle load and configuration can be mentioned.

- **Tire pressure**

Throughout the pavement, the impact of tire contact pressure and axe load are not uniform. In fact, they have higher impact close to surface and lower impact to the pavement as the depth increase from surface. Also in many analysis procedures, contact pressure and inflation pressure assumed to be equal while most prefer uniform tire contact pressure than non-uniform ones due to higher strains values by uniform tire pressure. Even though, for simplicity uniform contact pressure is used, unbalanced the field-calibrated models are created because of overestimated strains. This research area still needs further investigation. (Eduardo and Liu Gan, 2009)

- **Axle configuration**

The numbers of tires that support the axle configuration determine the effect of rutting on the pavement. According to many studies single wide base tires are used for analysis due to their lower vehicle weights and rolling resistance. In addition to this, they produce faster ruts than dual tires which have been used for several years. (Eduardo and Liu Gan, 2009)

2.5.3 Temperature Effects

Temperature is crucial factor to be considered in flexible pavement design especially for asphalt concretes. The asphalt properties such as resilient modulus, rutting and fatigue deterioration are affected by temperature. Asphalt concrete exhibits elastic and stiffer characteristics at low temperature and soft and plastic properties at higher ones.

According to Haung (2004), frequent changes of temperature or freeze and thaw cycles on unstablized material are source of pavement deterioration. Hence many tests are conducted on fatigue deterioration, such that the effect of temperature is different for stress and strain controlled environments. Longer fatigue life is seen at high temperatures than low temperatures in stain controlled tests while the reverse happens at stress controlled tests. (Lundstrom, 2002)

Therefore in pavement deterioration modeling, temperature profiles are predicted by climate models by considering various factors such as short wave, condensation, evaporation, surface icing and infiltration. (Hermansson, 2004)

2.6 Loading Speed

Pavements are actually subjected to three-dimensional dynamic wheel loads. Dynamic load is wheel load moving as well as changing its magnitude by time. Evidence shows that a linear ramp-pulse dynamic wheel load within a tire-pavement contact area (imprint) may cause greater pavement damage than the static would; suggesting a reduction in pavement service life compared to design life. Cebon (1986) suggested that the dynamic component of wheel loads, which is a loading time or frequency-dependent amplitude, may reduce the service life of flexible pavements. In fact, dynamic wheel loads may increase the fatigue damages of HMA by a factor of four. (Al-Qadi et al., 2008)

One of the most important traffic loading factors to be included in the structural design of pavement design is the speed of loading. The loading speed simultaneously has a two-way effect: the permanent response of the unbound material itself and the change in the stress state depending on the resilient properties of the upper bound layers. (Korkiala-Tanttu, 2005)

If the viscoelastic theory is used, speed is directly related to the duration of loading. It was observed that with the increase in loading time the resilient modulus decreases, accumulated strain increases while the stiffness of the asphalt decrease. Thus asphalt concrete behaves like the elastic material at fast-moving loads and then behaves like viscous material at slow-moving loads. Hence increment in vehicle speed causes the pre mature pavement failure while rutting is caused by lower speed. These effects are noticed in different parts of road segments like bus stops, roundabouts, and steep uphill areas. (Imran et al., 2015)

If the elastic theory is used, the resilient modulus of each paving material should be properly selected to be commensurate with the vehicle speed. So, if pavement performs as an elastic system, an increase in vehicle speed would tend to linearly decrease the stress pulse time and a decrease in speed would linearly increase the stress pulse time. Generally, the greater the speed will result in the larger the modulus and the smaller the strains in the pavement (Huang, 1995).

2.6.1 Studies on vehicular load speed

In many current and previous studies, vehicular speed simulation on flexible pavement follows certain common procedures and techniques. Though vehicle speed has dynamic nature, for simplicity and ease of calculation it is either assumed to be moving with certain amplitude or static. However, vehicle speed must be properly modeled to present its direct and indirect effects on the pavement structure. (Perret and Dumont, 2004)

The speed of vehicle loading influences the magnitude of stresses and strains in the pavement due to the viscoelastic characteristics of the bituminous mix. The magnitude of stresses and strains varies with both depth and horizontal distance from the loading center of the tire-pavement contact area. These parameters have a substantial effect on the precision of rut depth prediction on the pavement surface. (Said et al., 2016)

The effect of loading speed greatly depends on the structure and its temperature. According to modeling and loading test results, decreasing the loading speed from 80 km/h to 12 km/h will increase the rutting of unbound layers in warm conditions (+25 °C) by about 20 %...25 % and in colder conditions (+10 ºC) about 10 %...15 %. According to the modeling calculations, the effect is stronger nearer to the road surface. The speed effect also depends on the structure. The study demonstrates that the visco-plastic behavior of bituminous materials is much more important for loading speed effect than the visco-plastic behavior of the unbound materials itself. (Korkiala-Tanttu, 2005)

The pulse duration increases with decreasing the vehicle speed and the magnitude of the pulse gets smaller when the depth increases since the load is distributed over larger areas. This is in fact good example of effect of lower vehicular speed on permanent deformation. The pulse shape varies largely when the speed changes. Moreover, the shape of the stress pulse becomes asymmetric when the depth increases, especially at high speeds. With a harmonic variation on the moving axle loads, the maximum deflection and stress increase with increasing load frequency considered without viscous damping. But, with viscous damping, the maximum deflection and stress tend to decrease with increasing load frequency. (Abd Alla, 2006)

Based on research done by Cebon (1986), the effect of vehicular speed for higher speeds (above 108km/s) result less damage on road surface while for speeds lower than 108km/s, static effect dominates the dynamic effects of moving load.

Cheung (1994) has studied the effect of the loading waveform and frequency on permanent deformation in a couple of repeated loading tests. He found that on average a square waveform resulted in 10 % greater permanent strains than sinusoidal or ramp waves. He also observed lower loading speed produced larger permanent deformations than higher frequencies (1 Hz). He asserted the permanent deformation of granular materials was slightly dependent on the loading speed.

Based on Lourens (1992) research, vehicular loading speed effect extends to beneath layers and pavement stress magnitude. In fact it is completely different for dynamic and static loading conditions.

Mikhail and Mamlouk (1997) research by finite element analysis (FEA) results showed that permanent strain for lower speed of 20km/hr is 10 times larger than higher speed of 130km/hr

It is therefore quite important to consider vehicular load speeds in pavement and design analysis since its effect on pavement responses are significant. (Siddharthan et al., 2002)

2.7 Current Practices to Minimize Rutting Effects

Pavement rutting problems extensively impacts society by damaging road pavement assets, increasing vehicle operation costs (VOC) and reducing road level of service. (Thao Dinh and Luu Xuan, 2016)

The majority of rutting impact is related to road traffic safety. Due to deteriorated pavement, vehicles frequently change lanes which lead to loss of control and longer braking distance. Also, water concentrated in the wheel paths is good source for ice formation and hydroplaning and eventually reduce skidding resistance of tires. In addition, rut influences comfort of road users by raising, fuel consumption, vehicle maintenance, and travel time costs.

Corrective or preventive measures for rutting are costly which makes them critical concern for road operators and tax payers. This is due to many pavements deteriorate before design life and measures taken are quite difficult to manage with in allocated budget.

Current practices to minimize rutting depend on loading or traffic data, site investigation, structural analysis, materials, and construction. (Hansen, 2001).Regarding material and construction, extra care is taken for HMA's aggregate, binder, and air. Use of rough textured cubical-shaped aggregate, sufficient compaction during construction, properly designed mixture with a stiffer asphalt binder and strong aggregate structure will resist plastic deformation of the hot mix asphalt pavement.

In addition to constitute materials, adding polymers to asphalt mix improve design life and rutting resistance. Polymers have tendency to change elastic and viscous components balance by elevating the elastic portion. Besides in order to achieve desirable mix stiffness, polymers increase bitumen stiffness These two approaches are followed to achieve modified and better asphalt mix with required viscosity at nominal pavement temperatures. (Oscarsson, 2007)

In general, for low and medium severe rutting, controlling vehicle overloading by traffic signs measures, filling rut path by bitumen and routine maintenance along the road are good measures to minimize rutting. In addition, techniques like improving the aggregate by compaction (within limits), stabilization using a geosynthetic reinforcement or improving the conditions of aggregate which control behavior especially in drainage condition are used. (Thao Dinh and Luu Xuan, 2016)

Cutting and resurfacing is one of rehabilitation methods commonly used for severe rutting. The depth of cut depends on structural capacity of pavement and traffic safety measures. Careful procedures must be taken while cutting and replacing of new asphalt mixtures to attain rut resistant pavements. If better performance is needed, polymers are used to modify the asphalt mixtures. Besides modified hot mix asphalt, thickening the aggregate spread wheel loads better to the pavement structure. In addition to above measures, restricting traffic or axle load on pavement can minimize rutting effects on the pavement. (Thao Dinh and Luu Xuan, 2016)

2.8 Finite Element Analysis

2.8.1 Background

The finite element analysis is a systematic approximate computational methodology for predicting the stresses, strains, and displacements as functions of both time and spatial coordinates in an object of arbitrary shape subjected to external loads and environmental effects. (Dallas et al., 2018)

The finite element analysis offers a means of solving practical problems by numerical techniques. An analytical procedure of this type provides a very powerful tool for determining the mechanical behavior of a pavement structure because of modeling flexibility. With sufficient attention devoted to determination of appropriate physical property values and simulation of actual boundary and loading conditions, the finite element analysis promises to afford an improved understanding of the behavior of pavement structures under load. (Eduardo and Liu Gan, 2009)

In engineering problems to predict the structure under analysis, not all terms are known. In fact these unknown terms are basic and can be further categorized to finite or infinite variables. The procedures to solve finite elements are quite easy comparing to infinite one. In order to solve infinite elements, finite element procedure is necessary to reduce infinite unknowns to finite unknown variables and express in approximating functions. These equations are defined by nodal points which later used to find other points by interpolating. Then the next step in finite element analysis is to assemble element properties for each element. Then the boundary conditions are imposed. The solutions to these simultaneous equations give the nodal unknowns. Using these nodal values additional calculations are made to get the required values. (Bhavikatti,2005)

Some advantages of finite element analysis include

a) Dynamic analysis of pavement structures and practical boundary conditions can be modeled.
b) Model irregularly shaped bodies and bodies composed of several different materials. Non-linear elastic or any other material behavior such as viscoelastic, viscoplastic or elasto-plastic can be incorporated.
c) Handle general load conditions without difficulty: Types of applied surface loadings may be varied to include vertical, horizontal, flexible and rigid loading

d) Vary the size of the elements to make it possible to use small elements where necessary
e) Alter the finite element model relatively easily and cheaply
f) Handle nonlinear behavior existing with large deformations and nonlinear materials

2.8.2 Application of Finite Element Analysis in engineering problems

The finite element analysis has been successfully applied to many engineering problems. Helwany et al. (1998) in their study illustrates the usefulness of finite element analysis in the analysis of three-layer pavement systems subjected to different types of loading. The method is capable of simulating the responses of pavement under different tire pressures of axle. The pavement materials are considered as linear, elastic, nonlinear elastic, and viscoelastic.

Hadi (2003) study the effects of material properties and traffic loading on flexible pavements using finite element analysis. First, a sample of pavement structure is taken and subjected to repetitive loading. Then it is analyzed by ABACUS which is one of finite element analysis software. In order to obtain accurate result, materials with different property compose the representative model and it is subjected to both static and dynamic loading. Finally the comparison between analysis and field condition indicate that the displacements due to cyclic loading under presence of nonlinear materials show close results.

Ameri et al. (2012) has used finite element analysis to design and analyses pavements by means of two techniques: Finite element method and theory of multilayer system. Eventually, from a statistical viewpoint, the results of the analysis of these two techniques have been compared by significance parameter and correlation coefficient. The results of this study indicate that the results of the analysis on finite elements are most appropriately compiled with results came from the theory of multilayer system and there is no significant difference among the mean values in both techniques.

Hence Finite Element Analysis is quite important procedure and technique that can be used for analysis and design of simple to complex pavement structures. (Mujtaba et al., 2011)

CHAPTER 3 METHODOLOGY

In this section, background information regarding ABAQUS software and methods used to investigate pavement deformation under different speeds is presented. Version 6.14 of ABAQUS software is employed to develop a structural model with accurate boundary conditions and meshing to perform dynamic analysis of the pavement. In addition KENLAYER software approaches and methods are presented in detail which will be later used for result verification.

3.1 ABAQUS as Finite Element Software

Abaqus is one of finite element analysis program that have been used by researchers for analysis of pavement structures. Zaghaloul and White simulated the pavement responses under Falling Weight deflecto meter loading for flexible pavements using three-dimensional dynamic analysis using the software**.** (Rahman et al., 2011)

Abaqus includes many material modes such as linear elastic, viscoelastic, hypo elastic and elasto-plastic models. Accordingly Haung (1995), study the effect of dynamic loads on pavement structure by assuming three layers of all pavement materials properties and most of them deform elastically and linearly.

Abaqus calculates the values of stress and strain in each and every node location. Thus model dimensions are selected keeping element sizes within acceptable limits to reduce any edge effect. Therefore extra care must be taken while selecting elements and meshing the model. (Rahman et al., 2011)

Displacement or rotational constraints are used to simulate the sub grade's support of the pavement structure. These elements act as springs to the ground and provide stiffening effect to subgrade.

3.1.1 **Model Geometry**

Three-dimensional finite element analysis tools appeared to the best approach to respond to significant fundamental issues in pavement implementation. Thus 3-D finite element models with appropriate dimensions are developed for four layers flexible pavement.

In this study, HMA surface with an unbound granular road base of S3 subgrade class and T8 traffic class with an assumption of 20 million traffic on pavement model depth of 11250 mm is considered. The dimensions of the model are 16m (along traffic side) and 8m (transverse side). A width of 8m was used considering full lane standard width of pavement and length of 16 m taken considering one full passage of standard truck. The configuration of pavement structure is shown in table 2.1.

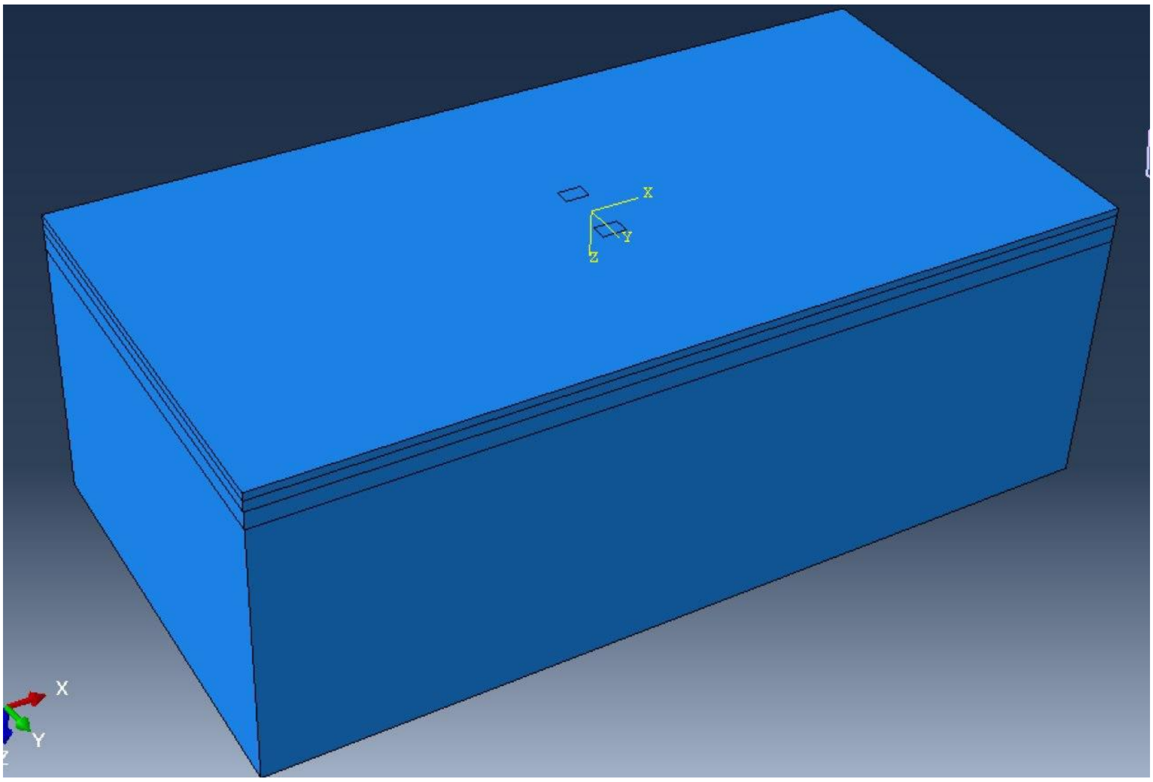

Figure 4: Geometric Model of the Pavement Structure

3.1.2 **Material Characterization**

For simplicity, the material properties of the base, sub base and sub grade layers are assumed to be granular, time independent and linear elastic, whereas viscoelastic behavior is used to represent the asphalt layer. However in reality base and sub base soils are inelastic and respond non linearly to applied traffic load. But it is reasonable to consider both layers elastic under application of repetitive loads due to recoverable deformation observed. (Haung, 2004)

To characterize the linear viscoelastic properties of HMA, the generalized maxwell solid model that was performed by Al-Qadi and colleagues was used. The model parameters are regressed dimensionless shear modulus (G), bulk modulus (K), and reduced relaxation times (τ) in terms of a Prony series (Appendix A). They used creep compliance test results to fit on the data set to get the prony series parameters. (Al-Qadi et al, 2010)

$G_{(t)}= G_0(1-\sum_{i=1}^{n} Gi\,(1-e^{-\left(\frac{t}{\tau i}\right)})$

$K_{(t)}= K_0(1-\sum_{i=1}^{n} ki\,(1-e^{-\left(\frac{t}{\tau i}\right)})$

Where

G and K:-Shear and bulk modulus respectively

Go and Ko:-Instantaneous elastic modulus

Gi, Ki and τi:-Prony series parameters

N:-Number of terms

Table 2 : Pavement configuration for pavement model (Source: ERA ,2013)

Layer Name	H	E	V
	Mm	MPa	-
Asphalt	150	9840	0.35
Base	200	300	0.3
Sub Base	325	175	0.3
Sub Grade	5000	53	0.4

Table 3: Prony series parameters of HMA at 25°C (Source:Al-Qadi et al., 2010)

	Prony Series Parameters	
N	G_i or K_i	τ_i
1	0.631	0.0206
2	0.251	0.173
3	0.0847	1.29
4	0.0267	5.35
5	0.00666	106

3.1.3 Boundary Condition and Contact Modeling

Boundary conditions for finite element analysis highly affect pavement responses by directly affecting the accuracy of models (Bayat and Knight, 2010). Boundary conditions of the asphalt pavement are clamped or fixed at the bottom and roller supports in two directions which restricts movement in horizontal direction. Interaction properties between two adjacent layers were assumed as perfectly bonded so friction less contact was given.

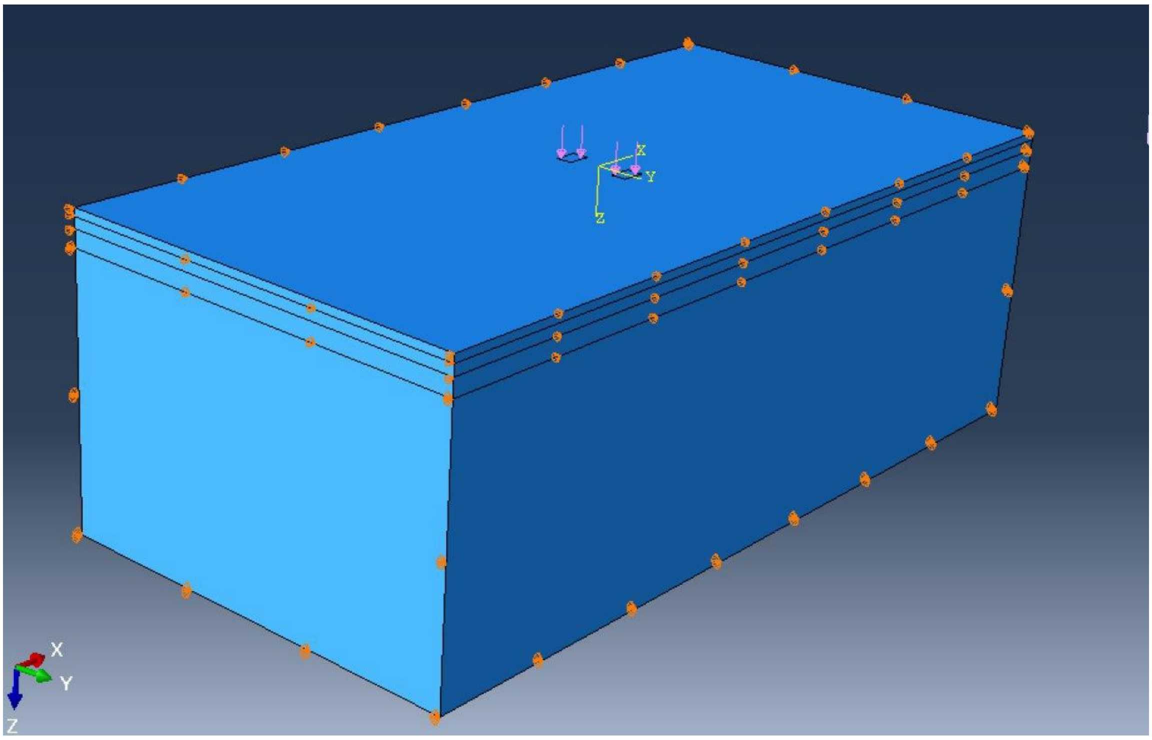

Figure 5: Boundary Conditions of the Pavement Structure

3.1.4 **Mesh**

Meshing should be designed in a way to provide good accuracy. All layers meshed in a way to maintain consistency between the layers. Therefore Eight-node brick element type with reduced integration (C3D8R) is selected. Besides element type selection, mesh size is important factor such that the finer size of the mesh has influence on computer running time as well as on the results. For this reason, reasonable mesh dimensions of 200mm in the longitudinal and transverse direction are selected. This pavement model consisted of 15664 elements and 17680 nodes.

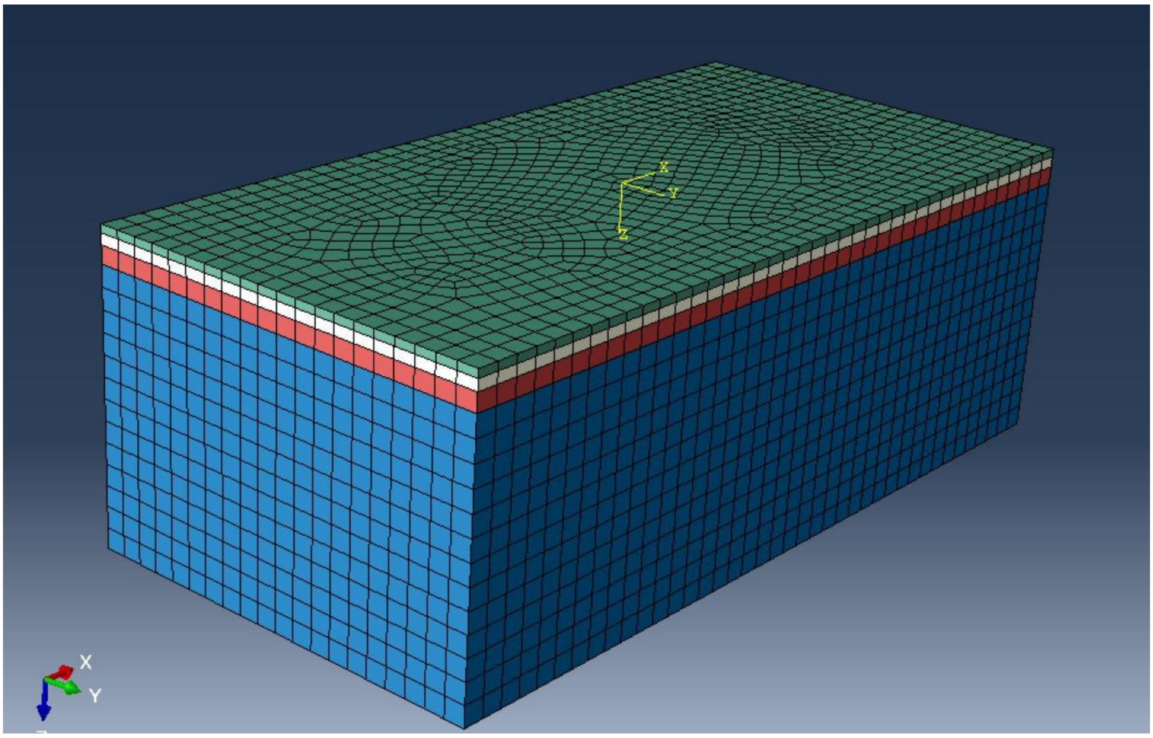

Figure 6: Mesh of the Pavement Structure

3.1.5 **Contact Area(Tire-Pavement)**

Determination of tire contact area and stress are important factors of pavement modeling and simulation.In the study,single truck tire with rectangular shape is considered.According to Hadi (2003), the shape of tire is more of rectangular than circular such that total area of tire is composed of two semicircles and a rectangle.For evaluation of rut susceptibility and ease of computation, the tire contact area is calculated from axle load by assuming rigid single tire is a rectangle of 306mm by 210 mm.

Here,

A_c=40KN/621KPa=644.12cm^2,

L= (644.12/0.5227)$^{0.5}$=35.10 cm,

→Width(0.6L) = 210mm and

→Length(0.8712L) = 306mm

In addition, 0.621MPa evenly distributed maximum pressure inflation pressure and 80 KN single axle load with a spacing of 1.2m was given. (Haung, 2004).Every single tire of single axle load carries a 40KN load.

Figure 7: Contact area between tire and pavement surface and equivalent contact area respectively

3.1.6 **Dynamic loading method**

The wheel load applied to the pavement system is not only static or dynamic rather it is the summation of both loads. Hence, the dynamic loads would be simplified by the continuous changing of the loading amplitude within the tire–pavement contact area.

Abaqus manual (2010) state the movement of body due to dynamic load as:

$$[M][\ddot{u}]+[C]\,[\hat{u}]+[K]\,[u]=[P]$$

Where

M,C, K: Matrices of mass, damping and stiffness respectively

Û, ü ,u, P:Vectors of acceleration, velocity, displacement and external force respectively

Unlike of static loading, two important factors needed to be considered in dynamic transient analysis are mass inertia and damping effects. Therefore, maximum damping ratio of 5% was used for base, sub base and sub grade. (Chopra, 2001).However mass damping ratio is not needed for asphalt layer.

Here, dynamic responses caused by a moving load speed on a smooth pavement were considered and solved by a direct integration method of implicit modes. Continuous loading approach is used to define the wheel path of individual tires such that the tire imprint loading is progressively shifted on the pavement surface.

From three categories of continuous loading, trapezoidal loading step is used to define amplitude of moving load with time. In trapezoidal loading approach, the wheel moves longitudinally over the element sets until a single wheel way is finished. (Table 4 and Figure 8)

0.621MPa uniform contact pressure and five vehicle speeds of 20, 40, 60, 80 and 100 km/hr applied over the contact area of 306 mm length and 210 mm width of each tire.

Table 4: Amplitude of loading with time

Step time	Amplitude
T_0	0
T_1	1
T_2	1
T_3	1
T_4	0

* Length of time from T_0-T_1, T_1-T_2, T_2-T_3, T_3-T_4 is the function of speed.

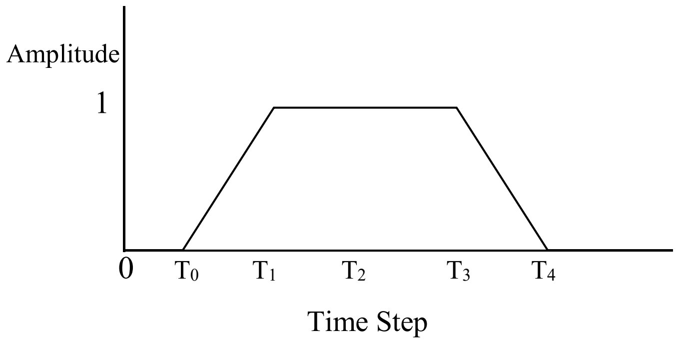

Figure 8: Definition of the trapezoidal repeated loading

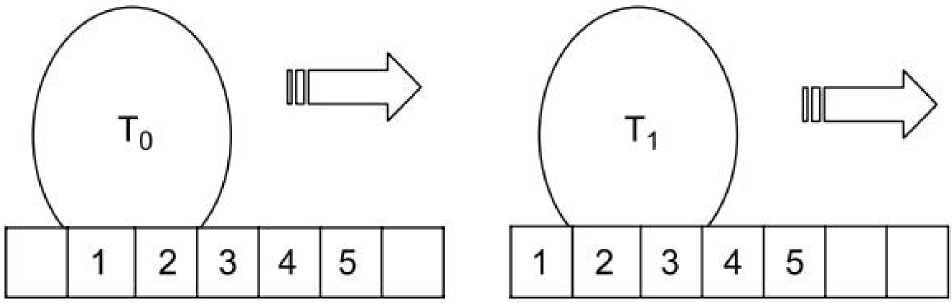

Figure 9: Loading step

3.1.7 **Run and Generating results**

Here, the analysis program executes the main finite element method procedures so that elemental strains or deformation and stresses are calculated. Then after few minutes calculation results will be generated. The evaluation is generally done interactively using the visualization module of Abaqus /CAE or another post processor. By default, Abaqus displays a contour plot using 12 equal intervals between the maximum and minimum value of stress or strain. Abaqus updates the maximum and minimum values and computes new contour intervals for every frame. The legend indicates the calculated intervals and the color corresponding to each interval. When the contour limits are set, Abaqus uses the values supplied in every contour plot to display regardless of the frame and which variable is being contoured.

Along with the contour plot, Abaqus displays X–Y plots of data read from ASCII file, data entered at the keyboard and existing data either combined with other data or arithmetically manipulated. Furthermore, X–Y data can be generated for a specfic path through pavement model. This is especially used to collect strain data on surface of pavement, bottom layer of HMA and top layer of subgrade.

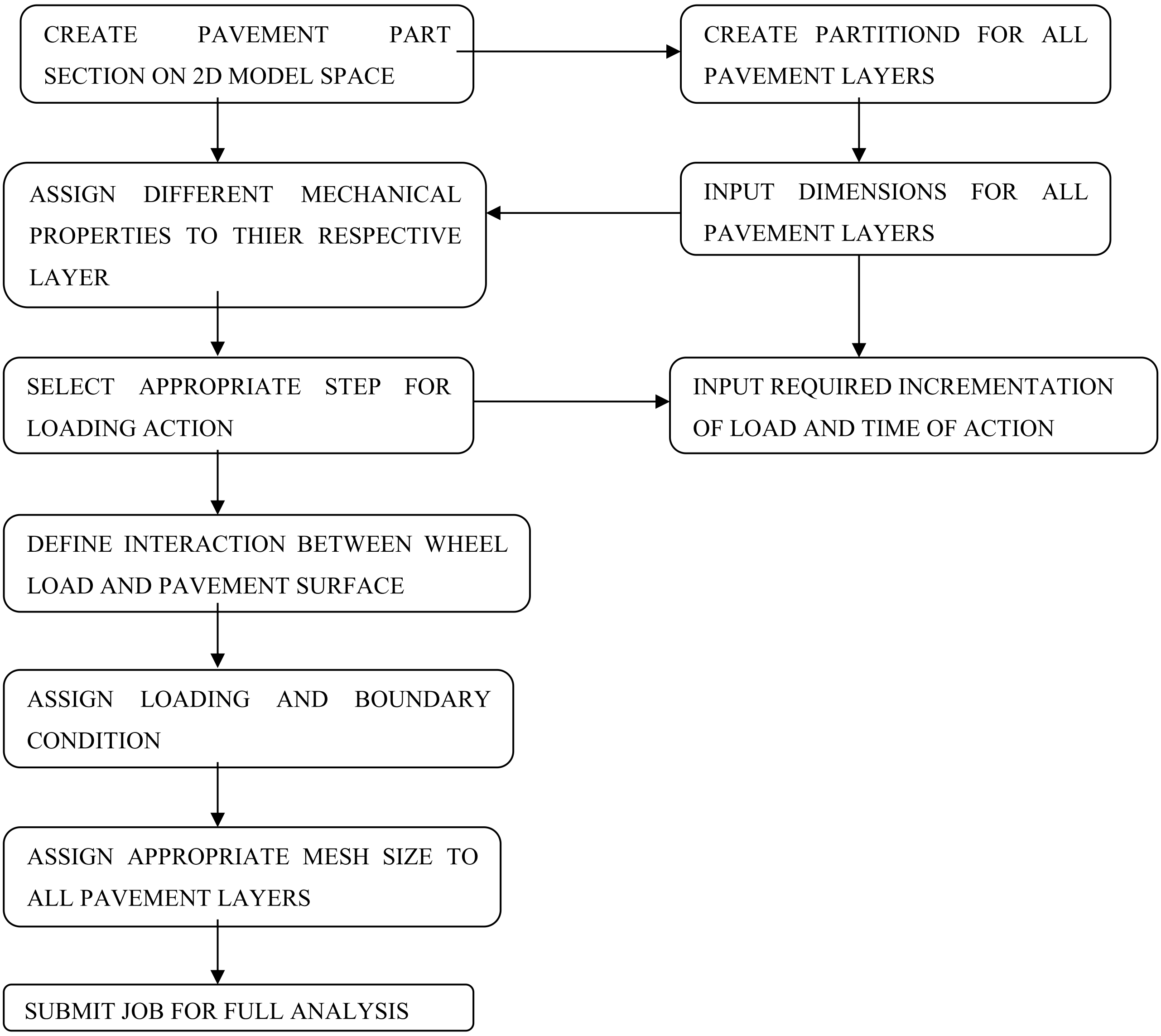

Figure 10: Flowchart for modeling on Abaqus

3.2 KENPAVE Software

Kenpave is one of oldest engineering soft wares for analysis and design of flexible and rigid pavements. It is used to find out stress, strains, deformation and damage ratio by using distress models. Kenpave Software is composed of LAYERINP, KENLAYER, SLABSINP and KENSLABS packages.

Kenlayer is a part of Kenpave software that is utilized to accurately calculate stresses and strains in asphalt pavement and the results obtained will be used to calculate allowance for rutting. Elastic multilayer pavement under influence of circular loading is the basic principle behind kenlayer software design. For other cases such as for multiple axles, visco elastic or nonlinear layers, superimposing or iterative solutions are necessary.

Input parameters in Kenpave software tool are generally layer thicknesses, material properties (modulus of elasticity and poisons ratios), load group, tire pressure and number of stress points for analysis of pavement. KENPAVE gives output in the form of "output as a text".

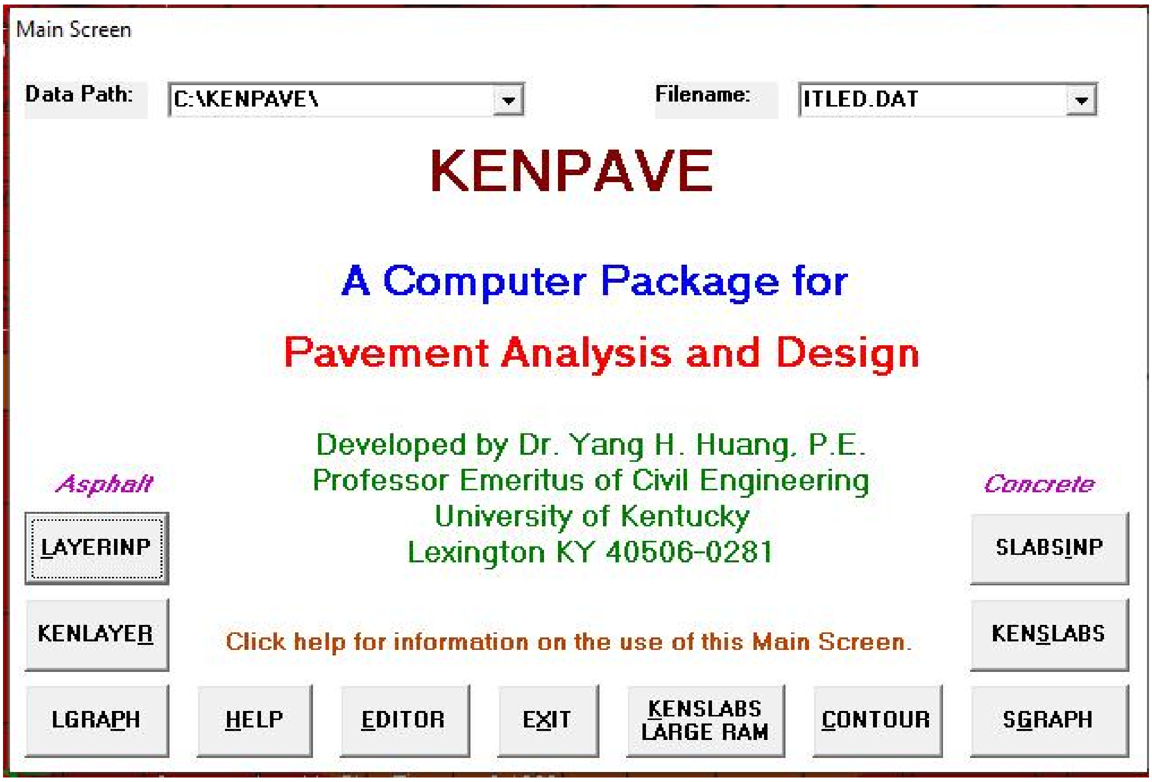

Figure 11: Main Screen of KENPAVE software

3.2.1 General Information

Most input parameters such as type of material, number of load groups, number of layers and number of Z coordinates are similar to Abaqus input parameters. Default inputs are used whenever recommended.

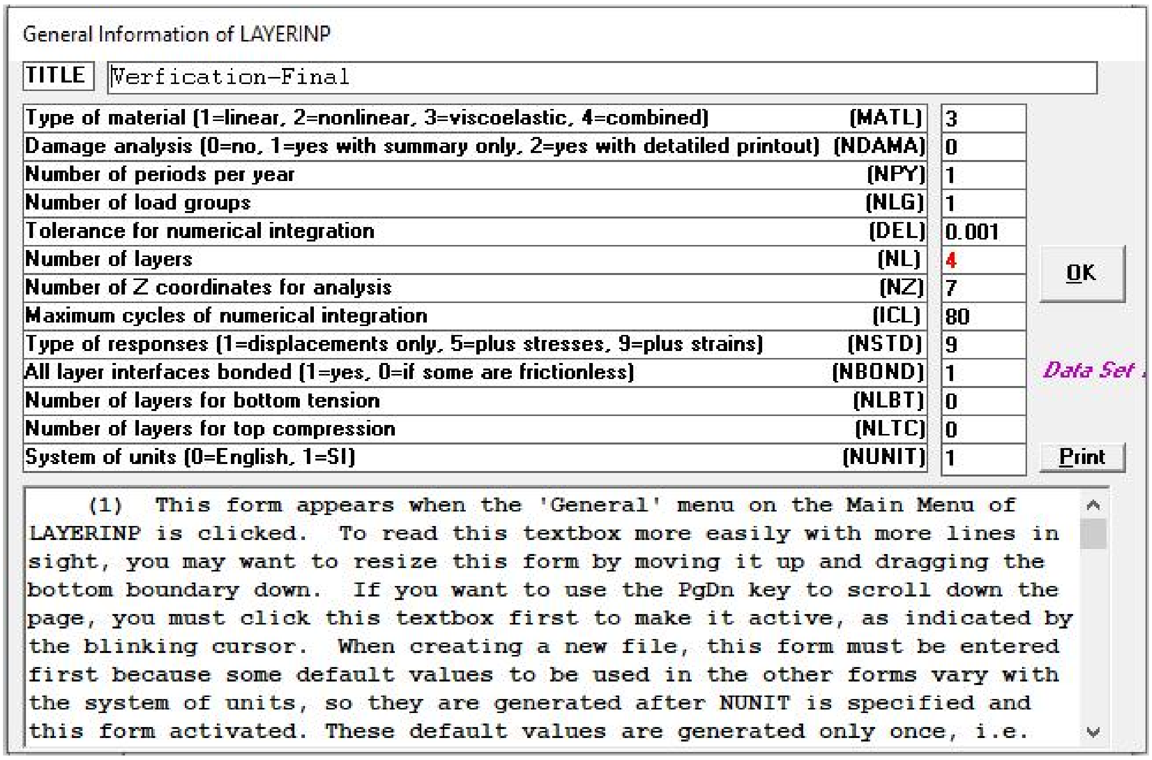

Figure 12: General Screen Capture

3.2.2 Vertical Distance of each Response Points

In order to find the response on each pavement layers, seven response points (0, 15, 15.001, 35, 35.001, 67.5, and 67.501) are taken. Point 0 represents the surface part of pavement or top layer of asphalt and point 15 bottom layer of asphalt. Top and bottom layers' of base are represented by points 15.001 and 35 respectively. Similarly top and bottom layers' of sub base are represented by 35.001 and 67.5 points respectively. Finally the top layer of sub grade is represented by 67.501 response point.

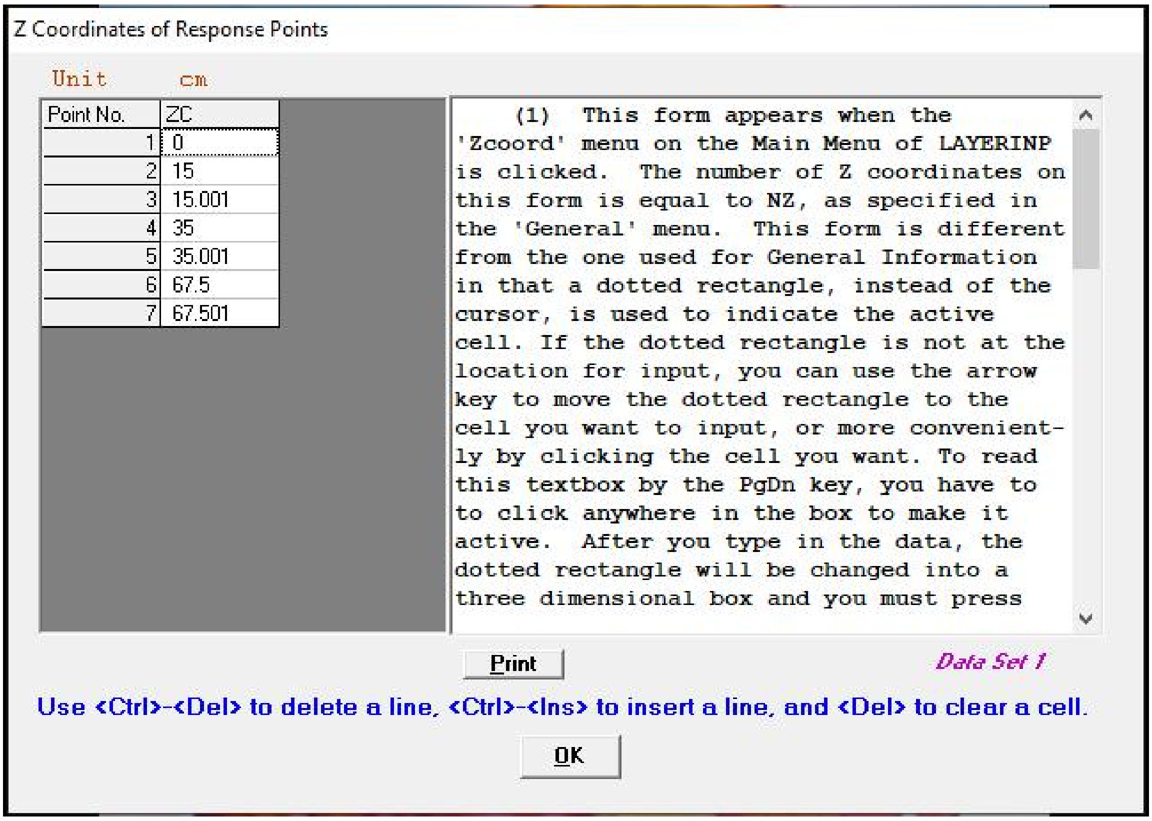

Figure 13: Z Coordinates of Response Points

3.2.3 Layer Menu

Similar to Abaqus input values in Table 2, layer thickness, poisson's, Young's modulus are inserted respectively in layer screen and in layer moduli for period screen.

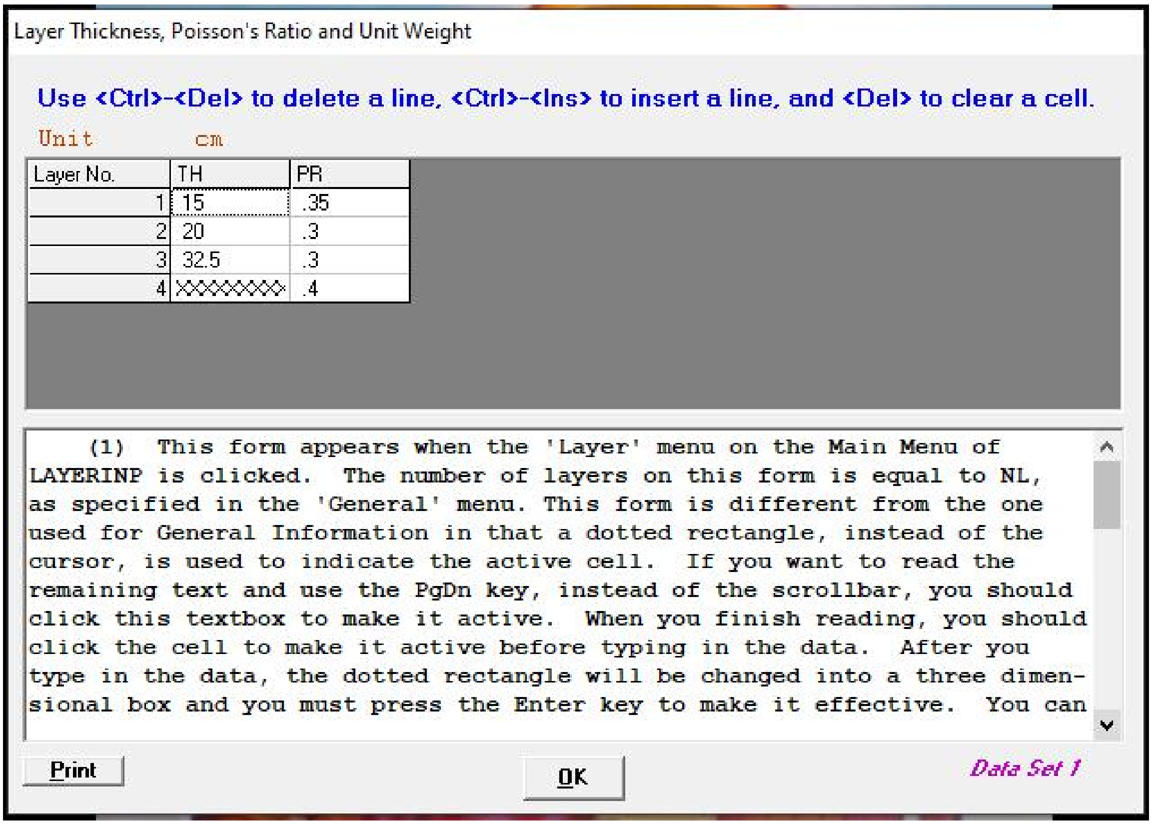

Figure 14: Layer Screen

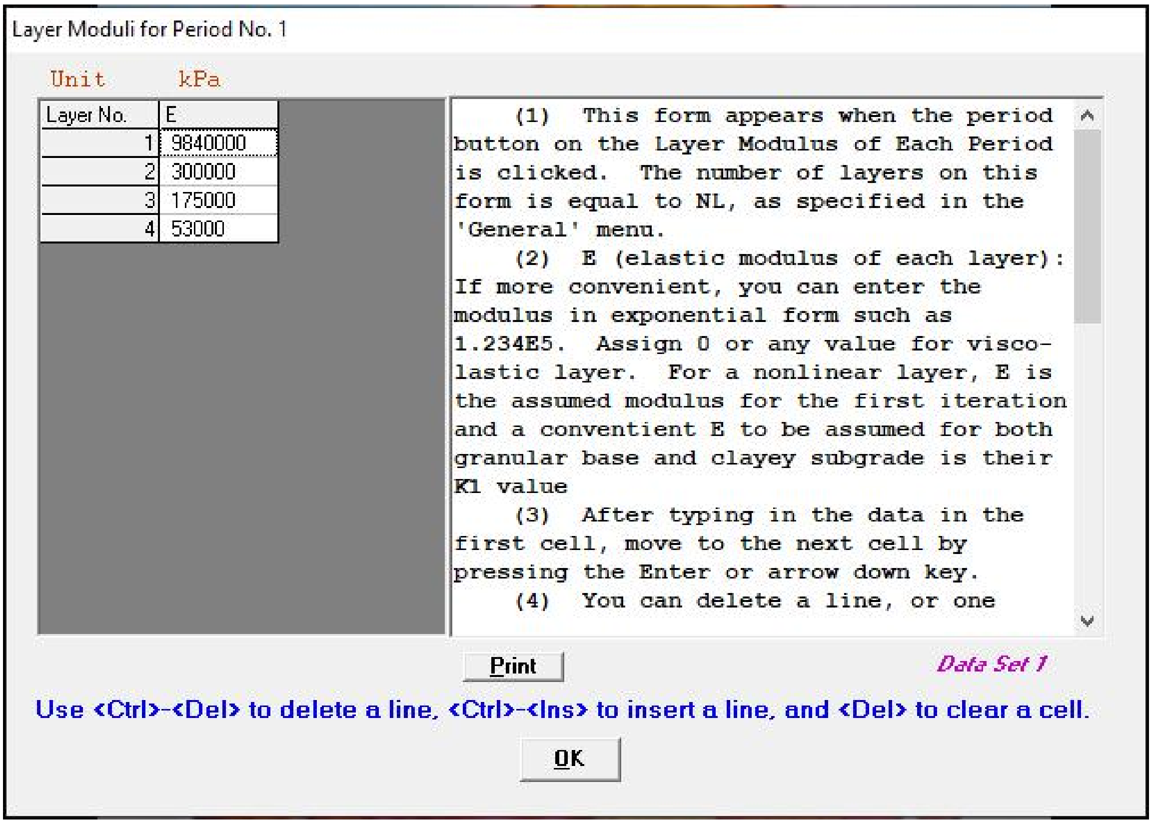

Figure 15: Layer Moduli Screen

3.2.4 **Load Information**

The load information box includes type of loading, contact radius, contact pressure, center to center spacing and number of radial points to be analyzed. Here similar to Abaqus software, single axle with single tire type of loading and contact pressure of 621Kpa are used. Unlike to rectangular contact area used in Abaqus, circular contact area is used in Kenlayer program. Accordingly the contact radius is 14.32 cm which is obtained from pressure definition(A_c=40KN/621KPa=644.12cm^2) and A_c=Πr^2.

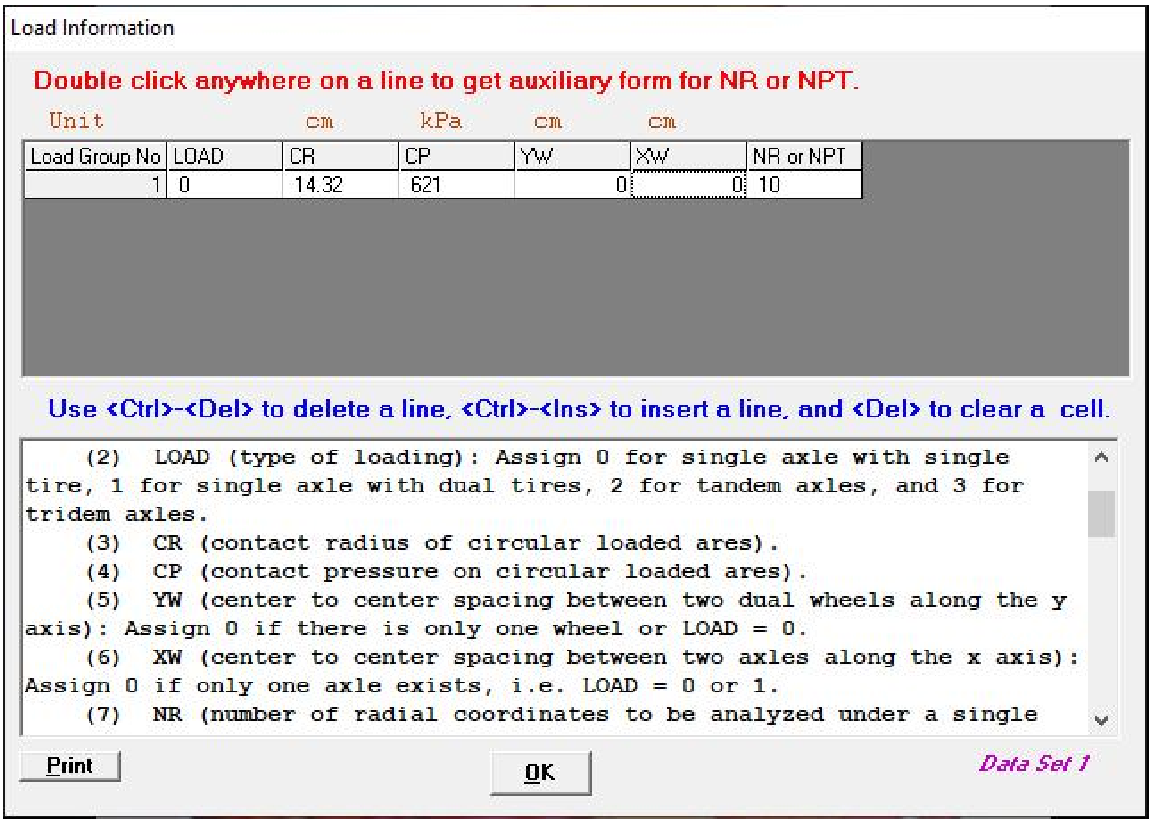

Figure 16: Load Screen

3.2.5 **Viscoelastic Information**

As stated previously HMA is characterized by linear viscoelastic properties. In order to represent its viscoelastic properties, the generalized Kelvin-Vogit model is used. In Kenlayer software, creep compliance is presented by a generalized Kelvin-Voigt model that can be written as (Huang, 2004):

$$D_{(t)}=\frac{1}{E_o}+\sum_{i=1}^{n}\frac{1}{E_i}\left[1-e^{(-t/Ti)}\right]$$

This is similar to generalized Maxwell model Equation presented earlier. This implies Maxwell model and generalized Kelvin-Voigt model are equivalent. (Koohmishi, 2013)

Table 5: Viscoelastic properties of HMA layer for the Voigt model. (Koohmishi, 2013)

i	Di (1/kPa)(E-9)	τ_i
infinite	0.0689	-
1	0.0841	0.00005
2	0.12	0.0005
3	1.5	0.005
4	2.69	0.05
5	4.3	0.5
6	5.56	5
7	14.3	50
8	48.5	500
9	352	5000
10	421	50000
11	539	500000

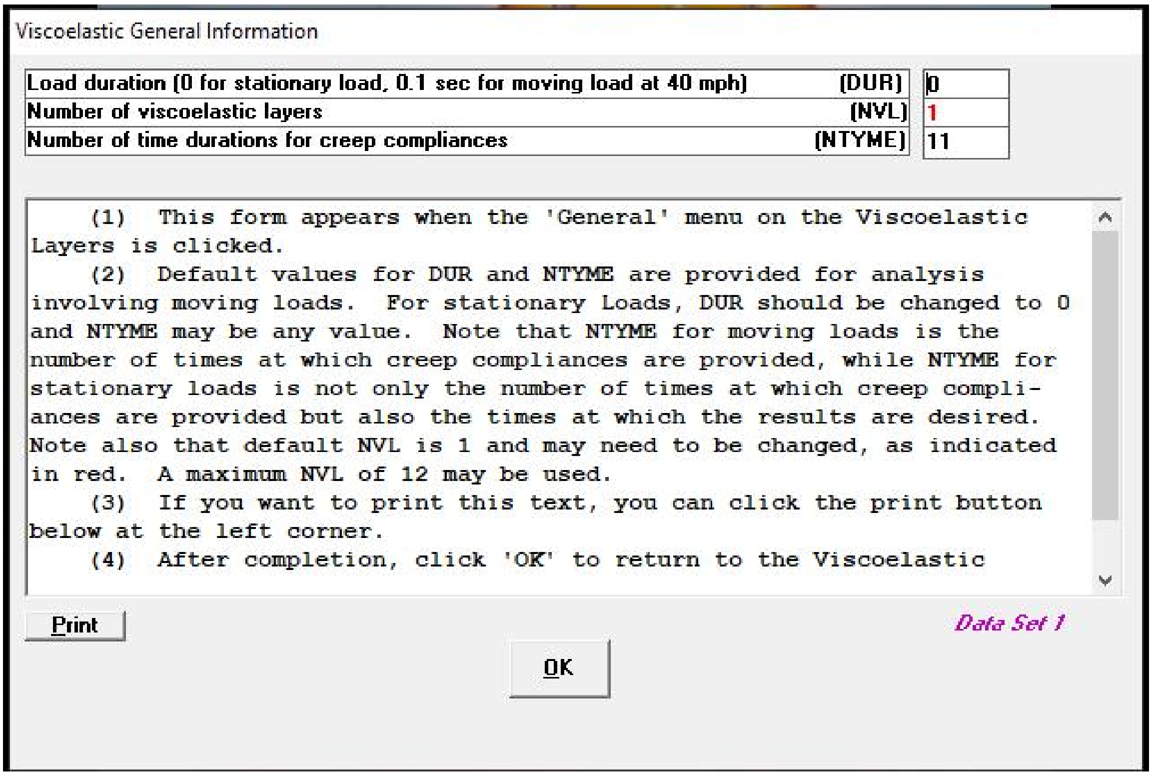

Figure 17: Viscoelastic General Information

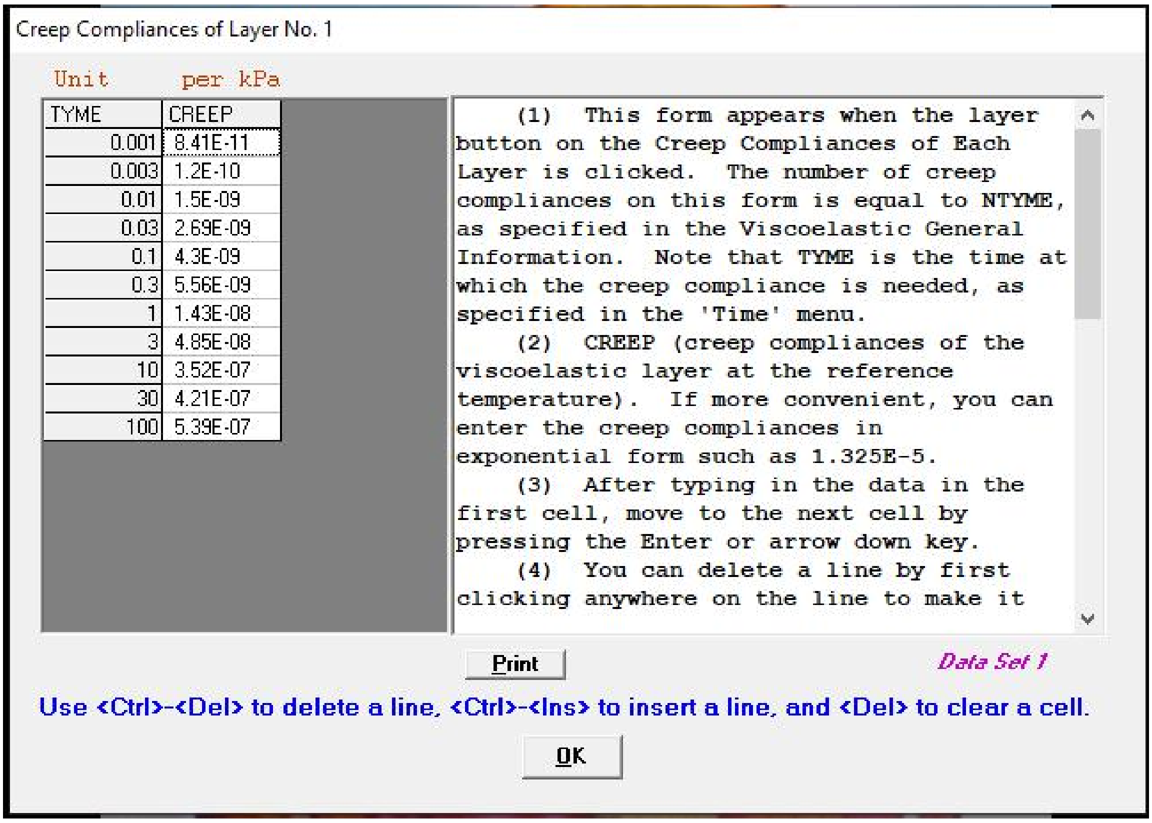

Figure 18: Creep Compliance of HMA Layer

3.2.6 **Run and Generating Results**

After inserting the input parameters, save and click on kenlayer to perform calculations. The output file is viewed in Editor menu.

CHAPTER 4 DATA ANALYSIS, RESULT AND DISCUSSION

In this chapter, 5 models' data analysis and results were generated under different vehicular load speeds of 20km/hr, 40km/hr, 60km/hr, 80km/hr, and 100km/hr. The dynamic effects of these moving loads on a single axle single tire configuration were applied on the pavement. Hence, the investigation was done throughout the pavement model and critical responses at the bottom and surface of asphalt layer as well as on top of subgrade were obtained.

In order to check model validity, the results of Abaqus will be compared with output from Kenlayer program (Huang 2004, Al-Qadiet al. 2010) under similar material characterization and loading conditions.

4.1 Effect of Different Vehicular Load Speeds throughout the Pavement

A portion of compressive stresses may convert its phase into tensile stresses inside a pavement system, and this localized phenomenon may result in deformation (stretching, shearing, or bending) of that layer. Using Abaqus, thickness of 150mm HMA, 200mm base, 325mm Sub base and 5000 mm subgrade are subjected to tire compressive stress of 0.621 MPa. In addition, 80KN single axle load moving with 20km/hr, 40 km/hr, 60km/hr, 80km/hr, and 100km/hr applied symmetrically on the center of 8m width and 16m long pavement. As a result maximum stress and strain induced throughout the whole model for each pavement layers were presented on the following subsections.

4.1.1 **Maximum Stress Distribution**

Maximum principal stress distribution for flexible asphalt pavement for 5 vehicular speeds is presented below. The loading time for 20km/hr is 20% larger than loading time of 100km/hr. This is indeed a good explanation of loading time as a function of tire imprint length and vehicular speed. As a result, maximum stress magnitude under load center for single axle configuration is higher in 20Km/hr speed than 100Km/hr speed. In addition to this, the loading's amplitude and pressure distribution of each model varies despite the assignment of same specific speed and step time. This concave like pattern increases and then decreases linearly as wheel load passes the tire imprint areas. Moreover, the contour shape varies largely when the speed changes. The magnitude of the stress gets smaller when the depth increases since the load is distributed over larger areas. It should be noted that with higher load repetition, the distribution and magnitude increases.

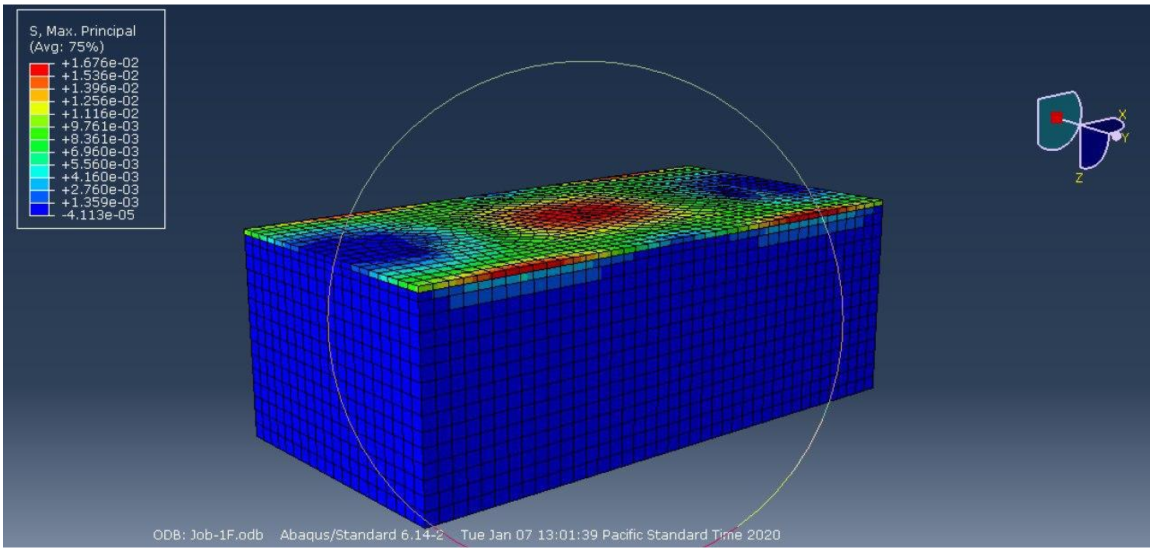

Figure 19: Maximum Principal Stress Contour for 20Km/hr speed

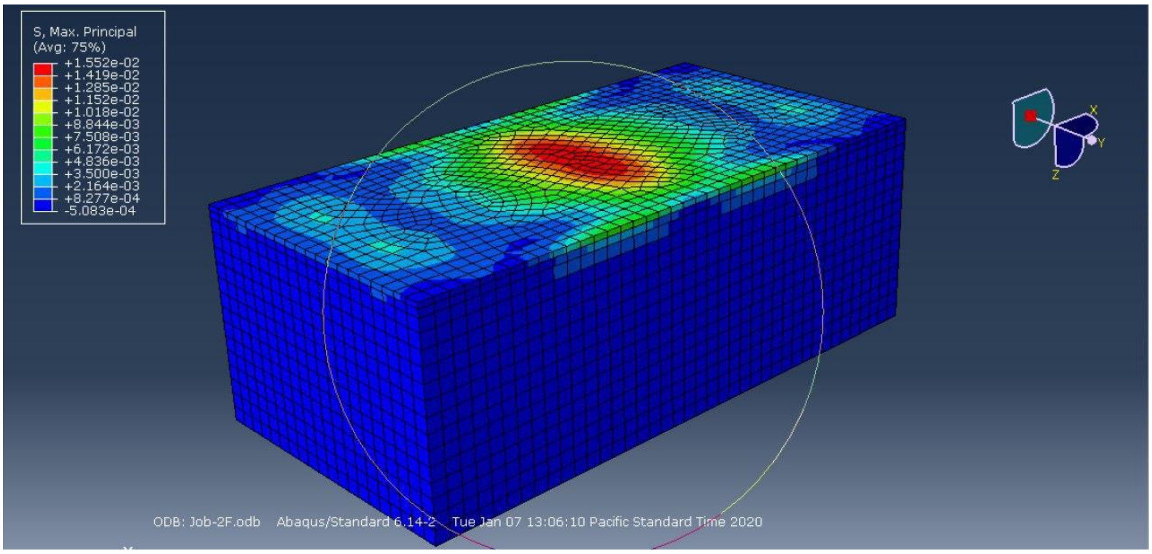

Figure 20: Maximum Principal Stress Contour for 40Km/hr speed

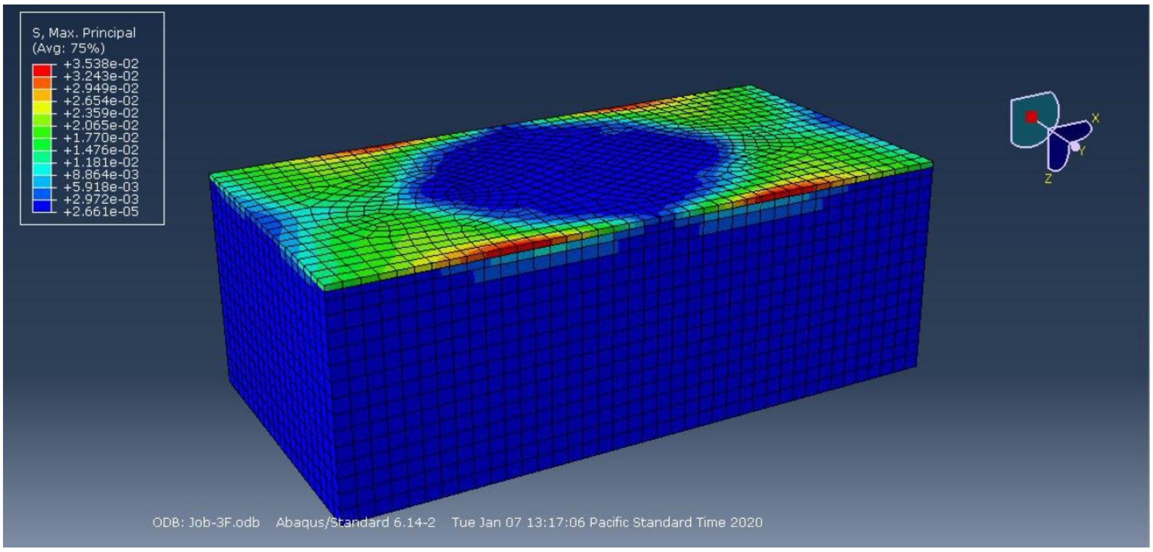

Figure 21: Maximum Principal Stress Contour for 60 Km/hr speed

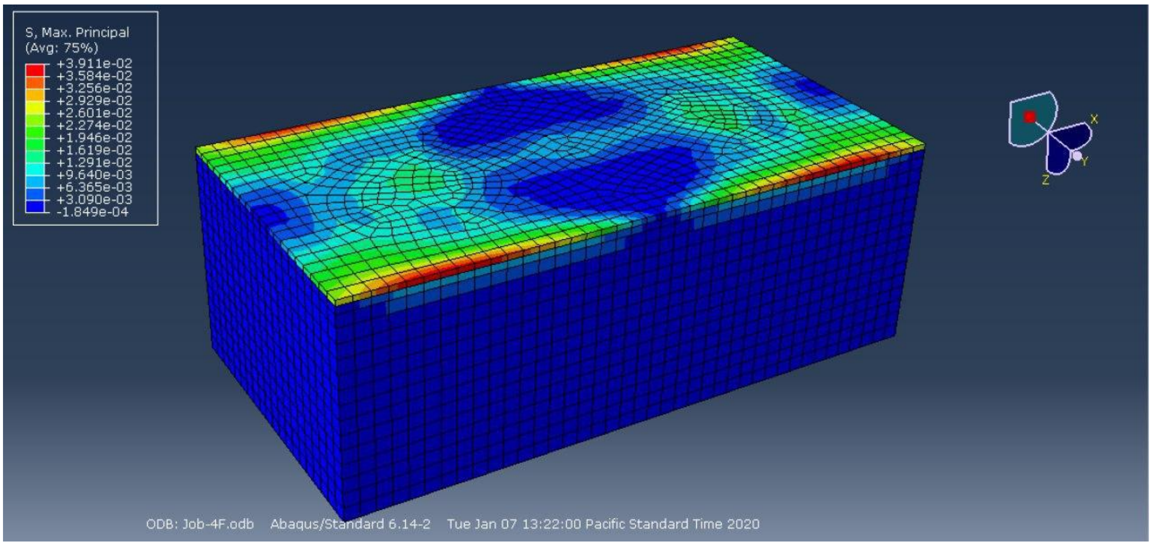

Figure 22: Maximum Principal Stress Contour for 80 Km/hr speed

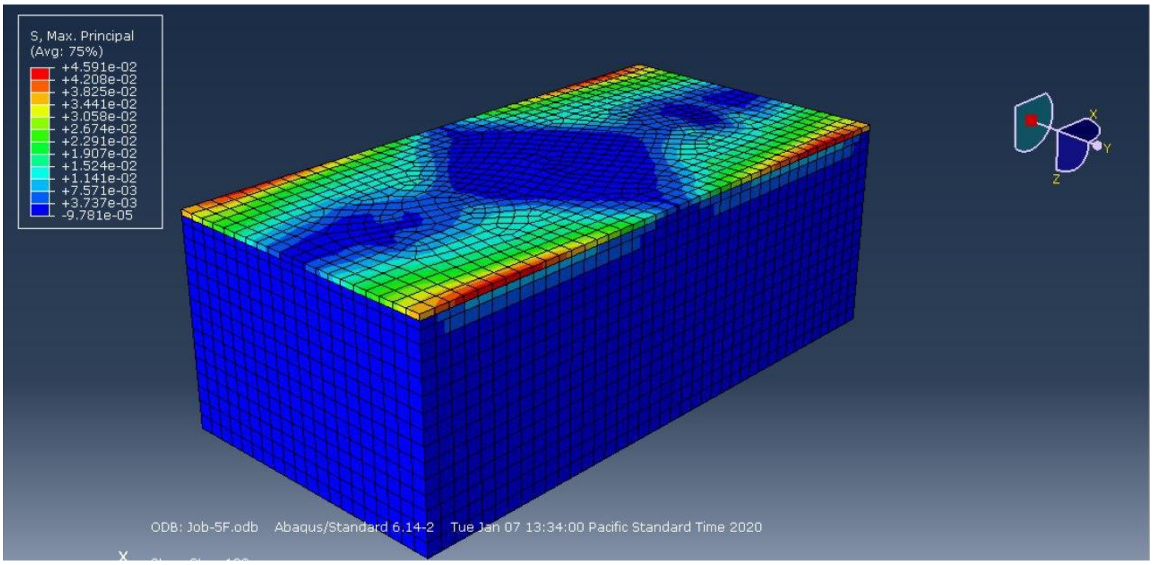

Figure 23: Maximum Principal Stress Contour for 100 Km/hr speed

4.1.2 **Maximum Strain Distribution**

Here, maximum strain distribution for flexible asphalt pavement for 5 vehicular speeds is presented below. As shown in each models', vertical strain distribution and magnitude of the last three layers are comparatively larger than asphalt layer. The elastic nature of base, subbase and subgrade makes the layers more susceptible to deformation than viscoelastic asphalt layer. This also can be easily justified because of the arrangement of successive weaker material from top to bottom of the pavement layer. Usually vertical strain component (compressive) is found to be maximum just beneath the top layer.

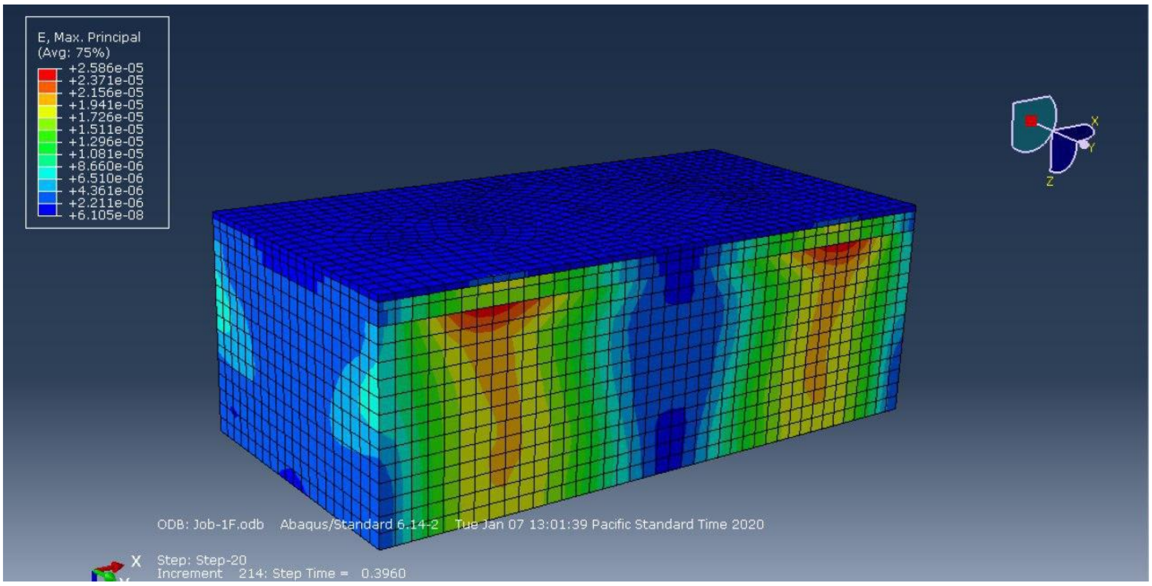

Figure 24: Maximum Vertical Strain Contour for 20 Km/hr speed

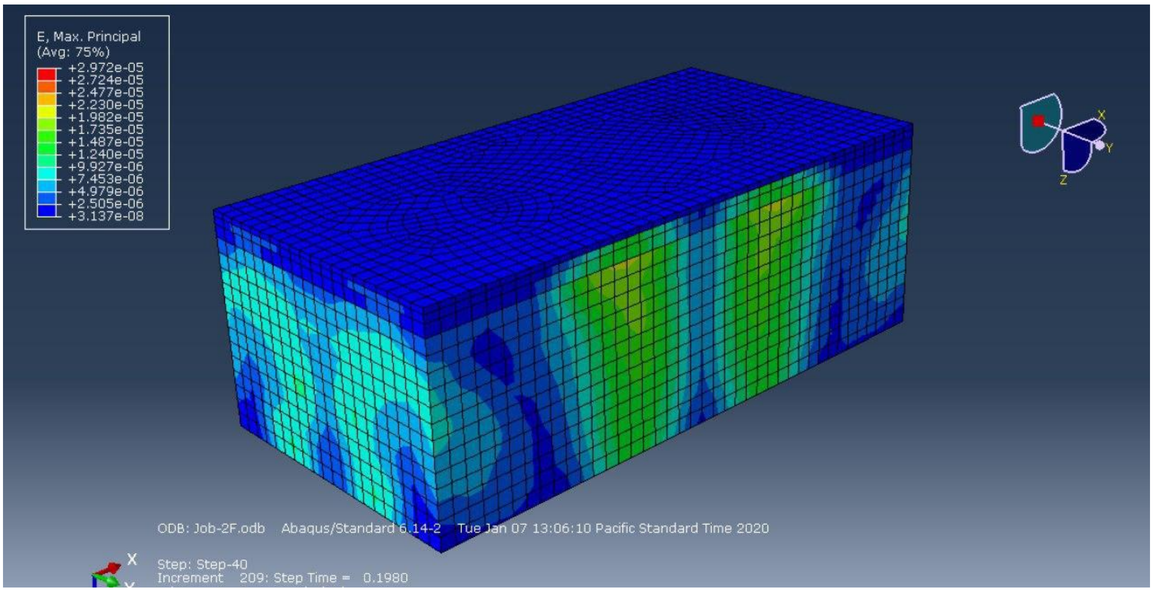

Figure 25: Maximum Vertical Strain Contour for 40 Km/hr speed

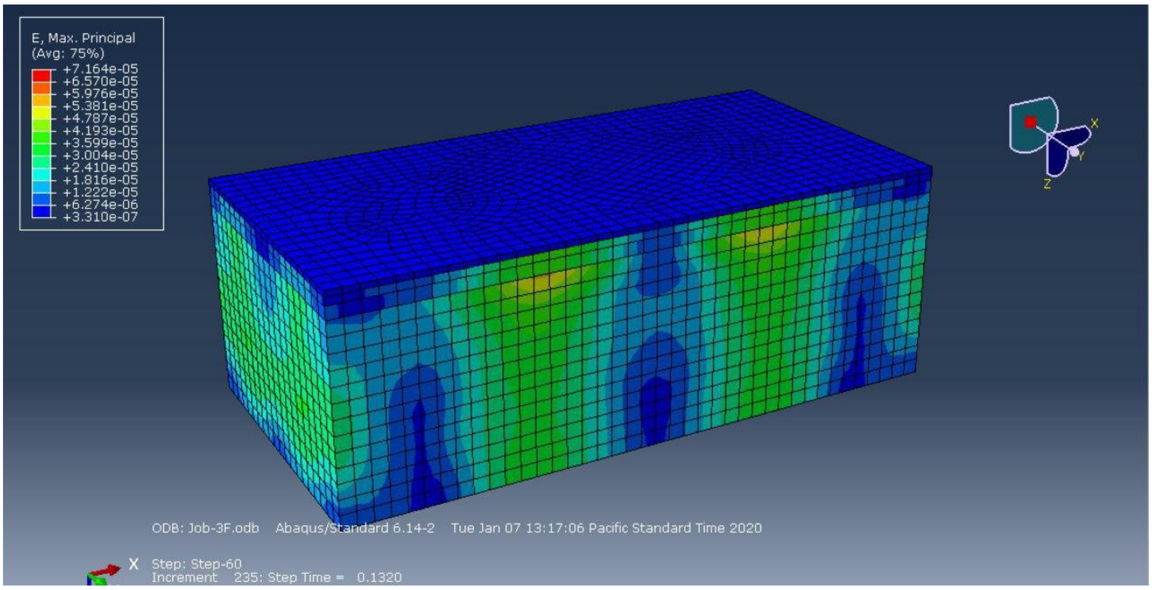

Figure 26: Maximum Vertical Strain Contour for 60 Km/hr speed

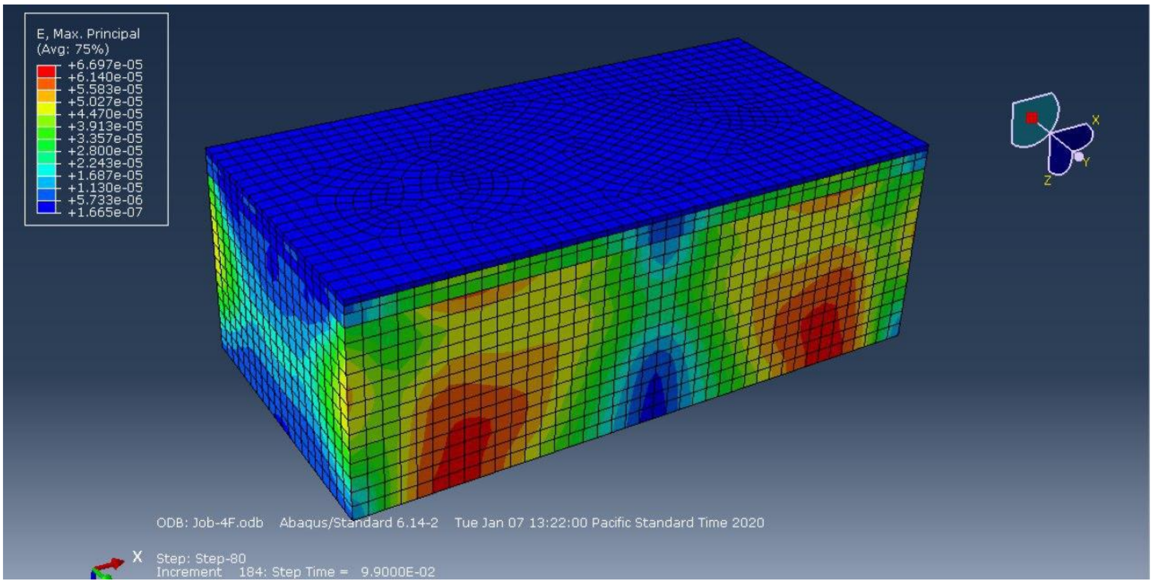

Figure 27: Maximum Vertical Strain Contour for 80 Km/hr speed

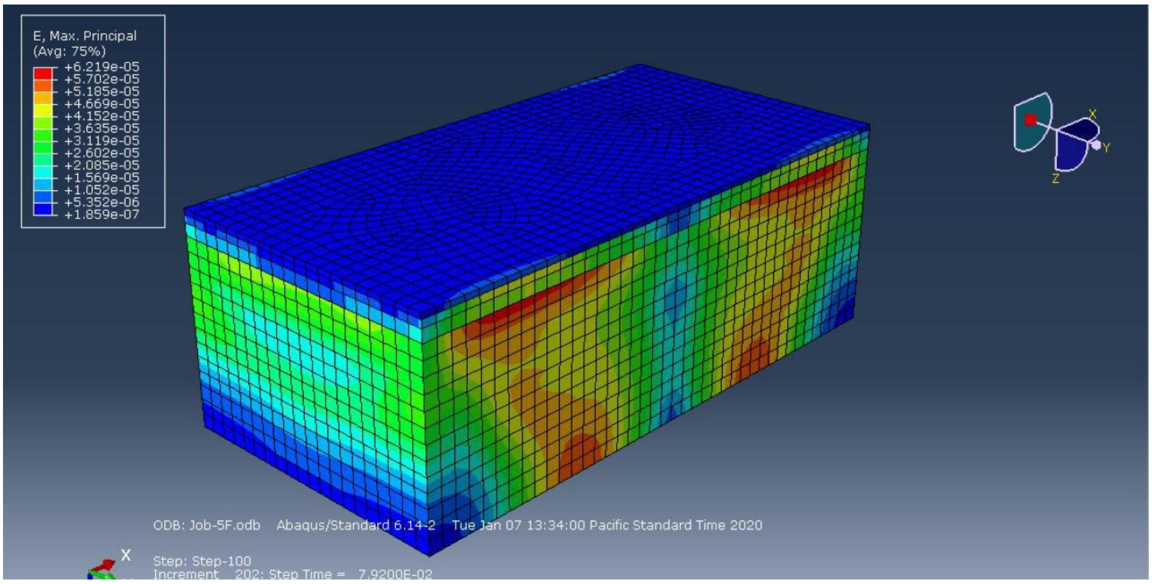

Figure 28: Maximum Vertical Strain Contour for 100 Km/hr speed

4.2 Effect of Different Vehicular Load Speeds on Critical Locations

In this analysis of flexible pavement, axle loads on the surface of the pavement produce three different types of strains, which are believed to be most critical for pavement design purposes. The horizontal strain on surface of asphalt layer and top of subgrade as well as vertical strain at the bottom of asphalt layer are crucial values to determine design life of pavement. Specific nodes locations beneath the load center were taken to analyze critical responses.

4.2.1 **Response at the bottom of asphalt layer**

The speed of 20Km/hr and 40 km/hr have higher magnitude of horizontal strain than other vehicular speeds. Because of the dominant static effect of loading at low speeds, the horizontal strain value decreases as the speed goes higher. This implies, lower vehicular speeds produce larger deformation than higher vehicular speeds.

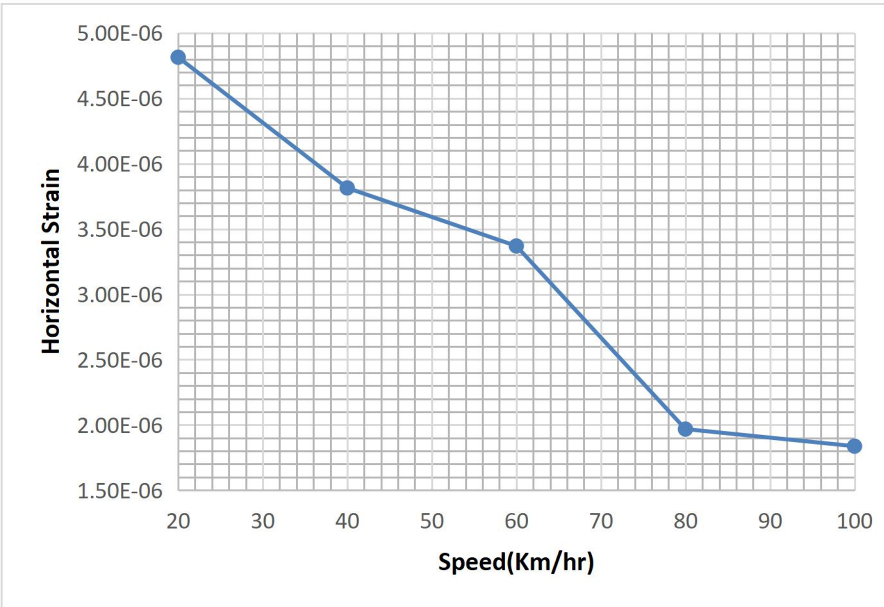

Figure 29: Response at the bottom of asphalt layer

4.2.2 **Response on the top of Subgrade**

One of critical responses for pavement design process is vertical compressive strain at the top of subgrade. If the vertical compressive strain is excessive, permanent deformations are observed at the surface of pavement structure and pavement fails due to rutting. Similar to the horizontal strain, compressive strain magnitude decreases as the speed goes higher. Because of the deeper position of extracted data and the effect of layers' weight, the load's dynamic effect is less considerable than its effect under HMA. Hence, when speed increases higher than 60kmhr, low decrease in strain responses is observed.

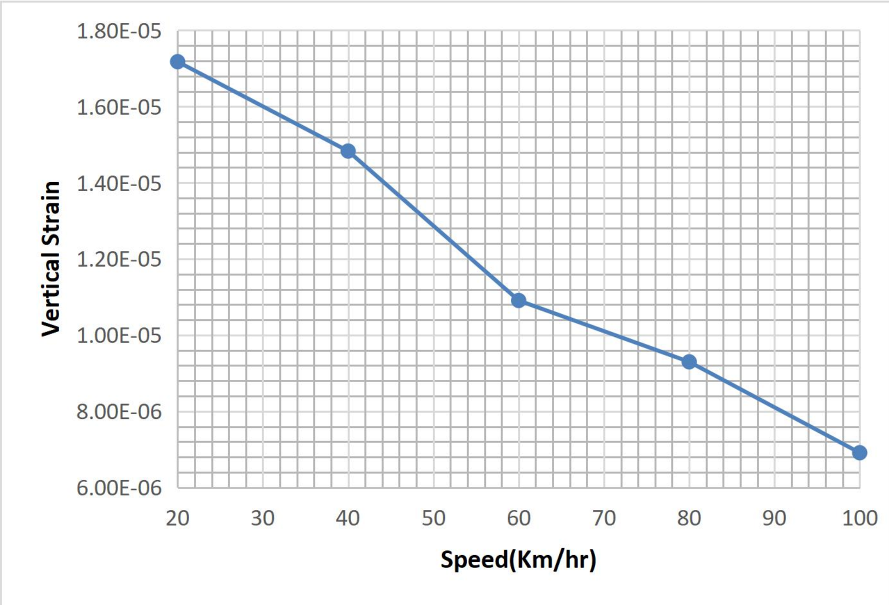

Figure 30: Response on the top of Subgrade

4.2.3 Vertical strain on the surface of pavement

Analysis and response on surface of the pavement indicate that increasing vehicular speed will result less vertical strain on surface of the pavement layer. Reasonable justification for this finding is greater static's effect of loading at lower speeds than higher speeds. Though increasing speed increases dynamic effect of loading, it cannot be higher than the load's static effect at low speeds.

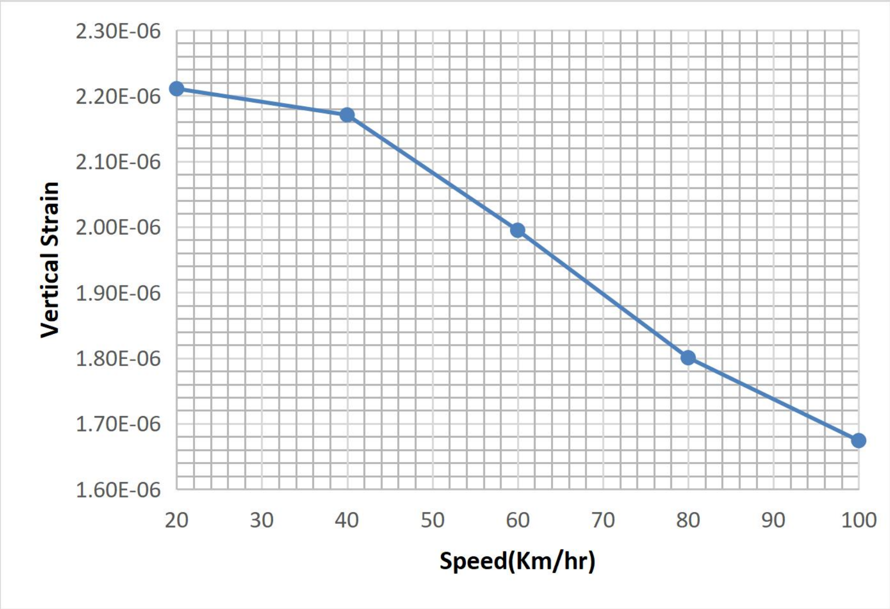

Figure 31: Vertical Tensile strain on the surface of pavement

Overall, Deformation of HMA, Base, Sub base and Subgrade for Pavement model

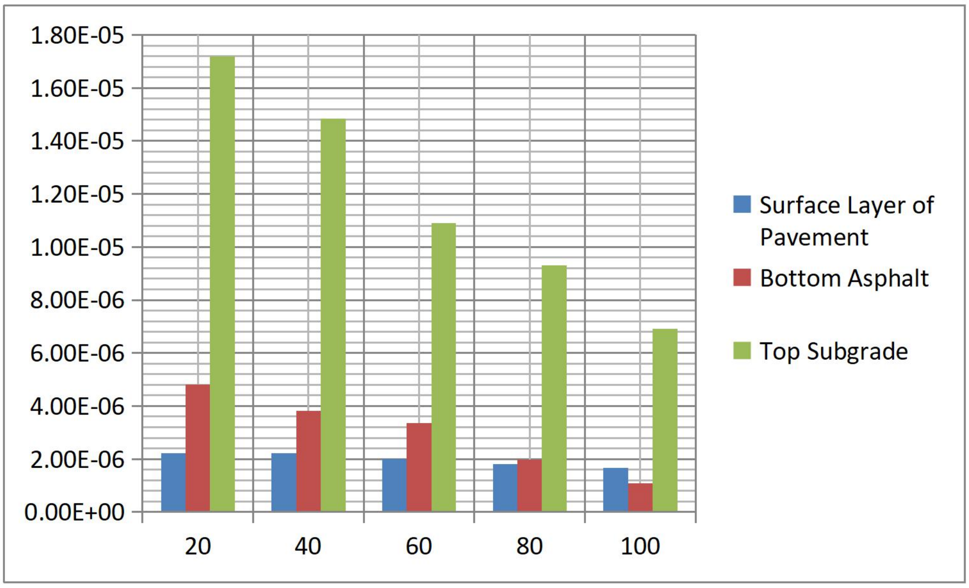

Figure 32: Deformation of the whole pavement model

Due to the viscoelastic nature of asphalt layer, the vulnerability of deformation of asphalt top surface is less compared to the other three elastic layers. Hence, transfer of load to the underneath layers will incur considerable higher compressive strain to subgrade layer.

4.2.4 Estimating Equations to Simulate Other Speeds Considering Critical Responses in the Pavement

According to results of critical response on asphalt and subgrade plots, the curve is fitted with the greatest precision in figures below to present new relationship between speed and strain.

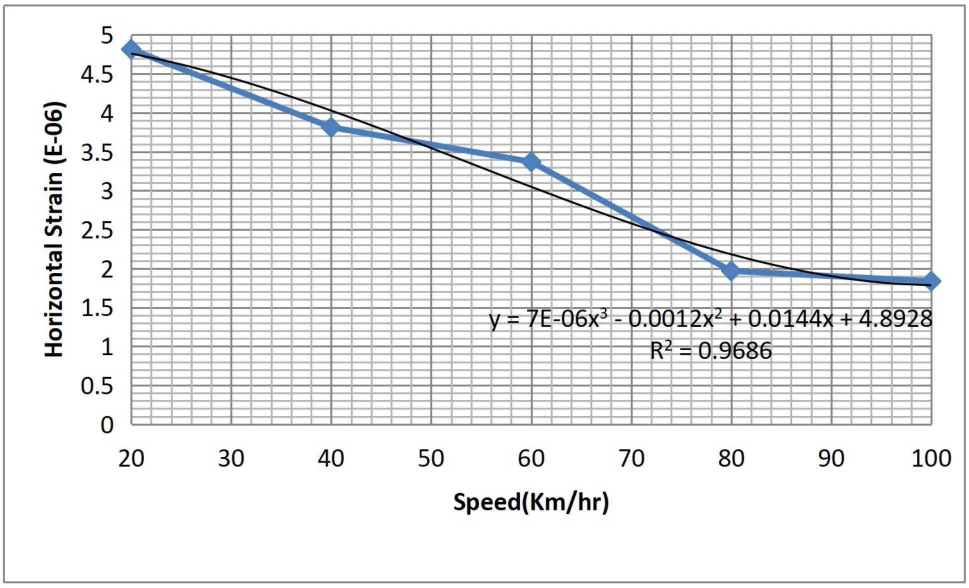

Figure 33: Speed-Horizontal strain curve at the bottom of asphalt Layer

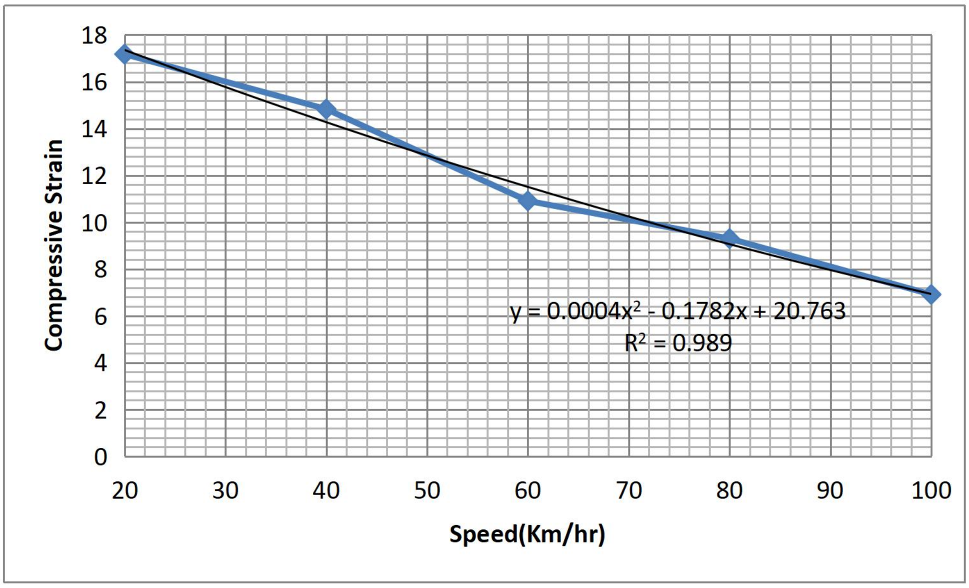

Figure 34: Speed-compressive strain curve on the top of subgrade

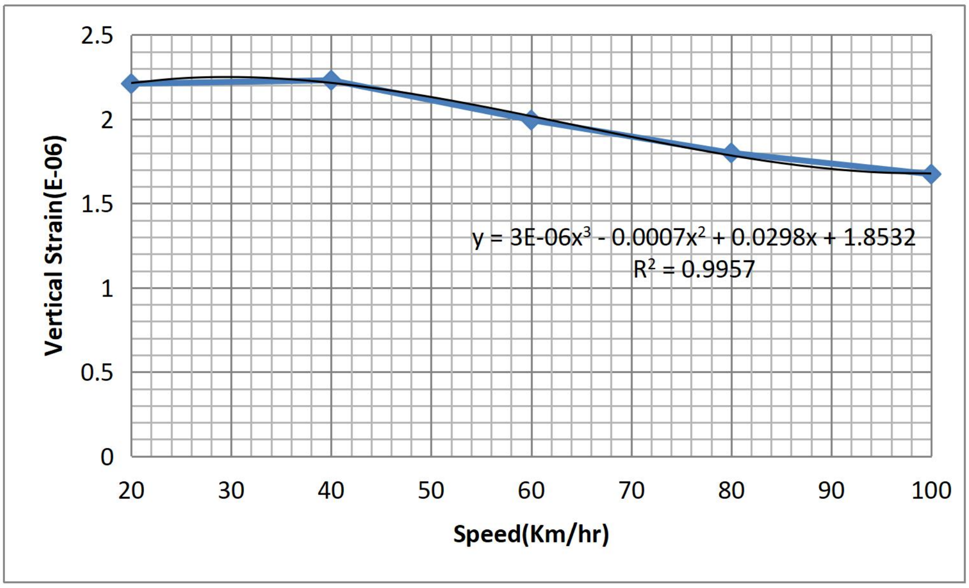

Figure 35: Speed-vertical strain curve on the surface of pavement

Hence the following polynomial equation are presented

ε_h=3E-06 V^3+0.029V+1.853

ε_{cv}=-0.178V+20.76

ε_v=7E-06 V^3- 0.001V^2+0.014V+4.892

Where as ε_h: Horizontal Strain at the bottom of asphalt layer (µϵ)

ε_{cv}: Compressive Vertical Strain on the top of subgrade (µϵ)

ε_v: Vertical Strain on the pavement surface (µϵ)

V: Vehicular Load Speed (Km/hr)

4.3 Finite Element Analysis Model Validation

To validate the obtained result, response values on critical locations are compared with similar locations result values of KENLAYER program. In KENLAYER analysis, static analysis with similar procedures such as model composition, material property and procedures is used. The detail results of Kenlayer are presented in detail in Appendex B.

Table 6: Validation of Finite element analysis model

Response	ABAQUS	KENLAYER	Difference (%)
Deflection on Surface(mm)	0.232	0.303	23.43
Tensile Strain at the bottom of AC layer(με)	62.17	65.10	4.50
Vertical Strain above Subgrade (με)	149.45	168.6	11.36

The close results extracted from both programs indicate that the analysis and procedure to model in both programs are compatible. With all constraints and limitations, result of Abacus indicates that the developed FE model is applicable for predicting the pavement response under various speeds of vehicular loading conditions.

CHAPTER 5 CONCLUSION

5.1 Conclusions

The pavement structural responses due to different vehicular speeds induced by moving single axle on flexible pavements were investigated using the 3D Finite Element Analysis. The findings on dynamic analysis of wheel loads on pavement structure are great inputs for design and construction of pavement structures.

In simulating the study, simplifications are made due to software constraints and unnecessary calculations. Some of the simplifications in modeling are rectangular shape the loading area, material characterization of each pavement layers, steering and braking maneuvers and fewer load repetition. Hence only the comparison between results is used for conclusion.

The following conclusions were drawn from this study:

1. As wheel load gradually passes the tire imprint areas, lower speeds have longer contact time with the flexible pavement than higher speeds. This contributes to pavement susceptible to permanent deformation (rutting) as the time of loading increases. The suggested reason is due to asphalt concrete behavior as the visco-elastic material: which behaves like elastic material at the fast-moving loads and then behaves like the viscous material at slow-moving loads. Hence, accumulated strain increases with increase in loading time.
2. Since trapezoidal loading amplitude is used, vertical strain and stress distribution is like concave like pattern such that the magnitude increases and decreases linearly as wheel load passes the tire imprint areas. In each model, the loading's amplitude and pressure distribution varies despite the assignment of same specific speed and step time. As a result, maximum stress magnitude under load center for single axle configuration is higher in 20Km/hr than 100Km/hr speed.

3. Increasing velocities up to 100Km/hr caused a reduction in critical responses. Because of the greater static effect of loading, the reduction in lower speeds is more than higher speeds. Increasing velocities make the dynamic's effects of loading more

than static's effect of that, although it cannot higher than load's static's effect at low speeds.

4. It is worthy to mention, load's dynamic effect is less considerable at the top of subgrade. This is due to deeper position of extracted data and the effect of layers' weight. Hence when speed increases higher than 60Km/hr, low decrease in strain magnitude is observed.

5. Speed has great impact on permanent deformation of pavement such that, strain versus speed curve is plotted and a regression coefficient of 0.968, 0.989 and 0.995 obtained for polynomial equations of ε_h=3E-06 V^3+0.029V+1.853 , ε_{cv}=-0.178V+20.76 and ε_{tv}=7E-06 V^3- 0.001V^2+0.014V+4.892 , where V is speed in terms of kilometer per hour and ε_h ,ε_{cv} and ε_v are strains induced by vehicular speeds. This equation is valid only for this specific model such that it only describes material composition, loading, thickness and assumptions used in the model.

In general, it can be concluded that one of the causes of stress, strain and deflection of flexible pavement is vehicle load speed. In order to determine critical response on the flexible pavement, finite element analysis software is used. Better results can be obtained if modeling is close to real conditions.

5.2 Recommendations

1. The analysis result indicates the importance of viscoelastic nature of the asphalt layer and the moving load speed to describe true characteristics in the mechanistic pavement model. For further study considering the true nature of asphalt, base and subgrade characteristics will capture accurately natural phenomena.
2. For future study, instead of applying load in one position and simulating moving nature by time steps, moving load perfectly simulate the actual loading in the field. Moreover, in comparison with the laboratory or field pavement performance data should be conducted.
3. Considering other factors such as different axle loads and temperature which are equally important as that of different vehicle speeds. Also, in order to arrive at

precise conclusion, numerous sample models should be taken. This will make generalizations accurate for real problem-solving applications.

4. Software is very important for the design and analysis of new highway and existing highway without error. So every institution in Ethiopia has to use software in addition to hard copy manual.

REFERENCES

ABAQUS.(2010).User's Manual Version 6.10.Dassault Systemes Simulia.Inc.

AbdAlla, E. M. (2006). The rational use of finite element method in the analysis of flexible pavements, *Journal of Engineering Sciences*, Assiut University, *34(4),* 1185-1211

Al-Qadi, I.,Wang, H.,Yoo, P., & Dessouky, S.(2008).Dynamic analysis and perpetual pavement response to vehicular loading, *Transportation Research Record,*2087,29-39

Al-Qadi,I.,Wang, H., & Tutumluer, E.(2010).Dynamic analysis of thin asphalt pavements by using cross-anisotropic stress-dependent properties of granular layer. *Transportation Research Record* , 2154,156-163

Ameri, M., Salehabadi, E.G., Nejad, F.M., & Rostami, T. (2012), Assessment of analytical techniques of flexible pavements by Finite Element Method and Theory of multi-layer System, *Journal Basic Applied Science Research*

Bayat, A. & Knight, M. (2010). Investigation of flexible pavement structural response for the Centre for Pavement and Transportation Technology (CPATT) test road. *Transportation Research Board,* 89th Annual Meeting

Cebon, D. (1986). Road damaging effects of dynamic axle loads. In*ternational Symposium on Heavy Vehicle Weights and Dimensions,(*i),37-53

Chopra, A.K. (2001). Dynamics of structures. (2nd ed.).Upper saddle River, NJ: Prentice Hall.

Cheung, L.W.(1994). Laboratory Assessment of Pavement Foundation Materials [Ph.D. thesis].University of Nottingham.

Dallas, N.L., Daid, H.A. & Amit, B.(2018). *Modeling and design of flexible pavements and materials.,*NY,USA:Spring International Publishing.

Eduardo, G.E ,& Liu,G. (2009).Validation of a pavement performance model for flexible pavements bases on test results in MnRoad [M.Sc. Thesis]. Chalmers University of Technology.

Ethiopian Roads Authority, Pavement Design Manual, Volume I, Flexible Pavements - 2013

Guler, M., Bahia,H.U. ,& Bosscher, B.j. (2000).Development of a device for measuring shear resistance of HMA in the Gyratory compactor.*Journal of the Transportation Research Board*,1723(1),116-124

Hadi ,M.N.S. (2003).Non-linear Finite Element Analysis of flexible pavements. *Advance Engineering Software*, *34(11-12)*, 657-662

Hermansson, A.(2004). Mathematical model for paved surface summer and winter temperature: Comparison of calculated and measured temperatures,*Cold Regions Science and Technology,40,1-17*

Haung, H. (2004). *Pavement analysis and desi*gn. (2nd ed.).Upper Saddle River,NJ: Prentice Hall.

Haung, H.,(1995).Analysis of accelerated pavement tests and finite element modeling of rutting phenomenon[Ph.D. Thesis]. Purdue University

Helwany, S.,Dyer, J., & Leidy, J.(1998).Finite element analysis of flexible pavements.*Journal of pavement Engineering*.124(5)

Katman, H.Y. (2006).Effects of rubberized bitumen on properties of porous mixes [M.Sc. Thesis].University of Malaya.

Imran,M.,Khan,K.,Ullah, H.,& Khan,K. (2015).Evaluation of speed effect of vehicles on asphalt pavement:The Eighth International Structural Engineering and Construction Conference,Sydney,Australia.

Hansen, K.(2001), Rutting-leave into the deer, Hot Mix Asphalt Technology.

Korkiala-Tanttu, L. (2005). Speed and reloading effects on pavement Research Scientist, VTT Building and Transport

Lourens,J.P.(1992).Non linear dynamic analysis and design of road pavements.Department of Transport.Pretoria,South Africa.

Lundstorm,R.(2002).Rheological and fatigue characterization of asphalt concrete mixtures using uniaxial testing[Licentiate Thesis].Royal Institute of Technology.

Mahrez,A.(2008).Properties and performance of stone asphalt reinforced with glass fiber[Ph.D. Thesis].University of Malaya.

Koohmishi, M.(2013).Comparison of pavement layers response with considering different models of asphalt concrete viscoelastic properties. *XXI(2)*, 15 – 20. doi: 10.2478/sjce-2013-0008

Mikhail,M.Y.,& Mamlouk, M.S.(1997).Effect of vehicle pavement interaction on pavement response.*Journal of the Transportation Research Board.1570,*78-88

Mujtaba A., Hassan and Abdulfatai A.(2011).Development of finite element response model for mechanistic-empirical design of flexible pavement.*Leonardo Electronic Journal of Practices and Technologies.10(19)*,69-84

Oscarsson,E.(2007).Predication of permanent deformation in asphalt concrete using the mechanistic empirical pavement design guide[Licentiate Thesis].Lund University.

Perret, J.,& Dumont, A.G. (2004). Strain and stress distributions in flexible pavements under moving loads. *Road material and pavement Design,1(1)*,203-225

Pyeng,J.Y. & Al Qadi,I.(2008).The truth and myth of fatigue cracking potential in Hot Mix Asphalt:Numerical analysis and validation,*Journal of Association of Asphalt Technologies,77*

Rahman, M.,& Ahsan, S.(2011).Stress-strain characteristics of flexible pavements using Finite Element Analysis.*International Journal for Computation of Civil and Structural Engineering.2(1)*,233-240

Siddharthan,R.V.,Krishnamenon, N.,Mohey, M.,&Peter, E.Validation of a pavement response model using full-scale field test.*International Journal of Pavement Engineering.3(2)*,85-93

Garoma, S.,Quezon E., & Kumela,T.(2017). Analysis of stress- strain and deflection of flexible pavements using finite element method case study on Bako-Nekemte Road.,*Journal of Civil, Construction and Environmental Engineering,2(4)*,100-111. doi: 10.11648/j.jccee.20170204.11

Said, S.F., Ahmed, A.W., Carlsson, H. (2016). Evaluation of rutting of asphalt concrete pavement under field like conditions. E&E Congress ,doi:10.14311/EE.2016.67

Bhavikatti, S.S.(2005).Finite Element Analysis, New Age International (P) Ltd. Publishers

Thao Dinh,N.,& Luu Xuan,L.(2016).Research of asphalt pavement rutting on national roads in Vietnam.

Wang,H.,Zhang,Q.,& Tan,J.(2009).Investigation of layer contributions to asphalt pavement rutting.Innovative use of materials for highway construction,China.

Zhou,F.,Sculliom,T.,& Sun,L.(2004).Verification and modeling of three stage permanent deformation behavior of asphalt mixes.*Journal of Transportation Engineering.130(4*).486-494.

Zienkiewicz, O.C,& Taylor, R.L.(1989). The Finite Element Method (4^{th} ed.).NY.McGraw-Hill.

APPENDIX

Appendix A: Prony Series and Maxwell model for a Viscoelastic Material (HMA)

In order to determine the time-dependent stress-strain state in a linear viscoelastic material, under an arbitrary loading process, the deformation history must be considered. The time-dependent constitutive equations of a solid viscoelastic material include these history effects. The load (stress) and displacement (strain) history, the loading rate(displacement rate) and time of load application on the specimen are all needed to determine the constants in the constitutive equations. A common form for these constitutive equations employs a Prony series
Creep and relaxation tests are most commonly used to determine the viscoelastic material properties. In ideal relaxation and creep tests, the displacements or loads are applied to the specimen instantly. In the real test, especially for a large structural component, limitations of the testing equipment result in a relatively low strain rate and a long period of loading. The response during the period of loading is typically ignored, and only the data obtained during the period of constant displacement or constant load are used to determine the material properties. Ignoring this long loading period and the strain rate effects in the data reduction introduced additional errors in the determination of the material properties

There are numerous methods for determining the Prony series from creep data. One of the simplest models to describe linear viscoelastic material behavior is the Generalized Maxwell model.

Here, each spring element is assigned a relaxation modulus E_m, and each dashpot is assigned a frictional resistance η_m. When the model is subjected to a constant strain, the force on each spring-dashpot pair relaxes exponentially. Since the stresses are additive in the generalized Maxwell model, the relaxation modulus Em (t) for pair m is given by

$$E_m\,(t)=E_m e^{-\left(\frac{t\mathrm{Em}}{\eta\mathrm{m}}\right)}=E_m e^{-\left(\frac{t}{\tau i}\right)}$$

In which the time constant $\tau_{\,m}$, relaxation constant is defined as an sη_{m}/E_{m}.The Generalized Maxwell model described by relaxation model is given by

$E_{(t)}= E_0(1-\sum_{i=1}^{n} Ei\,(1-e^{-\left(\frac{t}{\tau i}\right)})$

Where

E_0: Inital instantaneous modulus

Ei: Relaxation Strength

τ_i: Relaxation Time

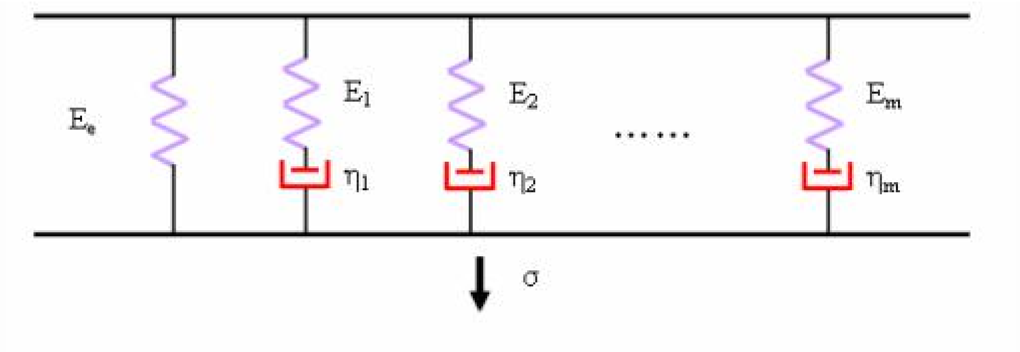

Figure 36: Generalized Maxwell Model

Appendix B: KENLAYER ANALYSIS

INPUT FILE NAME -C:\KENPAVE\ITLED.DAT

NUMBER OF PROBLEMS TO BE SOLVED = 1

TITLE -Verification-Final

MATL = 3 FOR VISCOELASTIC LAYERED SYSTEM

NDAMA = 0, SO DAMAGE ANALYSIS WILL NOT BE PERFORMED

NUMBER OF PERIODS PER YEAR (NPY) = 1

NUMBER OF LOAD GROUPS (NLG) = 1

TOLERANCE FOR INTEGRATION (DEL) -- = 0.001

NUMBER OF LAYERS (NL)------------- = 4

NUMBER OF Z COORDINATES (NZ)------ = 7

LIMIT OF INTEGRATION CYCLES (ICL)- = 80

COMPUTING CODE (NSTD)------------- = 9

SYSTEM OF UNITS (NUNIT)------------= 1

Length and displacement in cm, stress and modulus in kPa

unit weight in kN/m^3, and temperature in C

THICKNESSES OF LAYERS (TH) ARE : 15 20 32.5

POISSON'S RATIOS OF LAYERS (PR) ARE : 0.35 0.3 0.3 0.4

VERTICAL COORDINATES OF POINTS (ZC) ARE: 0 15 15.001 35 35.001 67.5 67.501

ALL INTERFACES ARE FULLY BONDED

FOR PERIOD NO. 1 LAYER NO. AND MODULUS ARE : 1 9.840E+06 2 3.000E+05

3 1.750E+05 4 5.300E+04

LOAD GROUP NO. 1 HAS 1 CONTACT AREA

CONTACT RADIUS (CR)--------------- = 14.32

CONTACT PRESSURE (CP)------------- = 621

RADIAL COORDINATES OF 10 POINT(S) (RC) ARE : 1 2 3 4 5 6 7 8 9 10

DURATION OF MOVING LOAD (DUR) = 0

NUMBER OF VISCOELASTIC LAYER (NVL) = 1

LAYER NUMBERS WHICH ARE VISCOELASTIC (LNV) = 1

CREEP TIMES (TYME) ARE: 0.001 0.003 0.01 0.03 0.1 0.3 1 3 10 30 100

FOR LAYER 1 TIME TEMPERATURE SHIFT FACTOR (BETA) = 0.2034

REFERENCE TEMPERATURE (TEMREF) = 21.1

CREEP COMPLIANCES (CREEP) AT REFERENCE TEMP. (TEMREF) OF 21.1 ARE:

8.410E-11 1.200E-10 1.500E-09 2.690E-09 4.300E-09 5.560E-09 1.430E-08

4.850E-08 3.520E-07 4.210E-07 5.390E-07

PERIOD NO. 1 LOAD GROUP NO. 1

RADIAL COORDINATE	VERTICAL COORDINATE	VERTICAL DISPLACEMENT	VERTICAL STRESS (STRAIN)	RADIAL STRESS (STRAIN)	TANGENTIAL STRESS (STRAIN)	SHEAR STRESS (STRAIN)
1.00000	0.00000	**0.03027**	621.000	1236.634	1236.852	0.000
(STRAIN)			-3.492E-05	3.651E-05	3.652E-05	.494E-13
1.00000	15.00000	0.03108	52.517	-1841.816	-1843.210	1.238
(STRAIN)			**6.510E-05**	-5.893E-05	-5.902E-05	.162E-06

1.00000	15.00100	0.03108	52.515	-2.758	-2.780	1.238
(STRAIN)			1.806E-04	-5.893E-05	-5.902E-05	.107E-04
1.00000	35.00000	0.02840	22.359	-16.585	-16.593	0.381
(STRAIN)			1.077E-04	-6.105E-05	-6.108E-05	.330E-05
1.00000	35.00100	0.02840	22.358	-5.682	-5.687	0.381
(STRAIN)			1.473E-04	-6.105E-05	-6.108E-05	.566E-05
1.00000	67.50000	0.02484	8.841	-13.223	-13.225	0.067
(STRAIN)			9.586E-05	-6.805E-05	-6.806E-05	.989E-06
1.00000	67.50100	0.02484	8.841	-0.117	-0.117	0.067
(STRAIN)			1.686E-04	-6.804E-05	-6.806E-05	.352E-05
2.00000	0.00000	0.03027	621.000	1234.805	1235.679	0.000
(STRAIN)			-3.488E-05	3.644E-05	3.650E-05	.988E-13
2.00000	15.00000	0.03106	52.321	-1831.145	-1836.721	2.470
(STRAIN)			6.480E-05	-5.852E-05	-5.889E-05	.323E-06
2.00000	15.00100	0.03106	52.319	-2.694	-2.778	2.469
(STRAIN)			1.799E-04	-5.852E-05	-5.888E-05	.214E-04
2.00000	35.00000	0.02839	22.323	-16.545	-16.576	0.761
(STRAIN)			1.075E-04	-6.090E-05	-6.103E-05	.660E-05
2.00000	35.00100	0.02839	22.323	-5.665	-5.683	0.761
(STRAIN)			1.470E-04	-6.090E-05	-6.103E-05	.113E-04
2.00000	67.50000	0.02483	8.837	-13.211	-13.219	0.133
(STRAIN)			9.581E-05	-6.798E-05	-6.804E-05	.198E-05

2.00000	67.50100	0.02483	8.837	-0.115	-0.117	0.133
(STRAIN)			1.685E-04	-6.798E-05	-6.804E-05	.703E-05
3.00000	0.00000	0.03025	621.000	1231.762	1233.725	0.000
(STRAIN)			-3.482E-05	3.634E-05	3.646E-05	.148E-12
3.00000	15.00000	0.03104	51.995	-1813.362	-1825.907	3.688
(STRAIN)			6.430E-05	-5.784E-05	-5.866E-05	.483E-06
3.00000	15.00100	0.03104	51.992	-2.585	-2.775	3.687
(STRAIN)			1.787E-04	-5.783E-05	-5.866E-05	.320E-04
3.00000	35.00000	0.02838	22.265	-16.478	-16.548	1.139
(STRAIN)			1.072E-04	-6.064E-05	-6.095E-05	.987E-05
3.00000	35.00100	0.02838	22.264	-5.636	-5.677	1.138
(STRAIN)			1.466E-04	-6.064E-05	-6.095E-05	.169E-04
3.00000	67.50000	0.02483	8.830	-13.192	-13.209	0.199
(STRAIN)			9.572E-05	-6.788E-05	-6.800E-05	.296E-05
3.00000	67.50100	0.02483	8.830	-0.112	-0.117	0.199
(STRAIN)			1.683E-04	-6.787E-05	-6.800E-05	.105E-04
4.00000	0.00000	0.03024	621.000	1227.511	1230.996	0.000
(STRAIN)			-3.473E-05	3.619E-05	3.641E-05	.197E-12
4.00000	15.00000	0.03100	51.539	-1788.476	-1810.771	4.885
(STRAIN)			6.360E-05	-5.688E-05	-5.834E-05	.640E-06
4.00000	15.00100	0.03100	51.537	-2.433	-2.770	4.885
(STRAIN)			1.770E-04	-5.688E-05	-5.834E-05	.423E-04

4.00000	35.00000	0.02836	22.183	-16.384	-16.509	1.512
(STRAIN)			1.068E-04	-6.029E-05	-6.083E-05	.131E-04
4.00000	35.00100	0.02836	22.182	-5.596	-5.669	1.512
(STRAIN)			1.461E-04	-6.029E-05	-6.083E-05	.225E-04
4.00000	67.50000	0.02482	8.820	-13.165	-13.195	0.265
(STRAIN)			9.559E-05	-6.773E-05	-6.795E-05	.394E-05
4.00000	67.50100	0.02482	8.820	-0.108	-0.117	0.265
(STRAIN)			1.681E-04	-6.773E-05	-6.795E-05	.140E-04
5.00000	0.00000	0.03021	621.000	1222.062	1227.495	0.000
(STRAIN)			-3.461E-05	3.599E-05	3.635E-05	.245E-12
5.00000	15.00000	0.03096	50.956	-1756.518	-1791.327	6.054
(STRAIN)			6.270E-05	-5.565E-05	-5.793E-05	.793E-06
5.00000	15.00100	0.03096	50.953	-2.237	-2.763	6.053
(STRAIN)			1.748E-04	-5.565E-05	-5.793E-05	.525E-04
5.00000	35.00000	0.02834	22.079	-16.265	-16.459	1.881
(STRAIN)			1.063E-04	-5.984E-05	-6.068E-05	.163E-04
5.00000	35.00100	0.02834	22.078	-5.545	-5.659	1.881
(STRAIN)			1.454E-04	-5.984E-05	-6.068E-05	.279E-04
5.00000	67.50000	0.02481	8.808	-13.130	-13.177	0.331
(STRAIN)			9.543E-05	-6.754E-05	-6.789E-05	.492E-05
5.00000	67.50100	0.02481	8.808	-0.103	-0.116	0.331
(STRAIN)			1.678E-04	-6.754E-05	-6.789E-05	.175E-04

6.00000	0.00000	0.03018	621.000	1215.425	1223.230	0.000
(STRAIN)			-3.448E-05	3.576E-05	3.627E-05	.293E-12
6.00000	15.00000	0.03091	50.248	-1717.723	-1767.665	7.186
(STRAIN)			6.160E-05	-5.416E-05	-5.743E-05	.941E-06
6.00000	15.00100	0.03091	50.244	-1.998	-2.754	7.186
(STRAIN)			1.722E-04	-5.415E-05	-5.743E-05	.623E-04
6.00000	35.00000	0.02831	21.953	-16.121	-16.399	2.244
(STRAIN)			1.057E-04	-5.929E-05	-6.049E-05	.194E-04
6.00000	35.00100	0.02831	21.952	-5.484	-5.646	2.243
(STRAIN)			1.445E-04	-5.929E-05	-6.049E-05	.333E-04
6.00000	67.50000	0.02479	8.793	-13.087	-13.155	0.397
(STRAIN)			9.523E-05	-6.730E-05	-6.781E-05	.589E-05
6.00000	67.50100	0.02479	8.793	-0.096	-0.115	0.397
(STRAIN)			1.675E-04	-6.730E-05	-6.781E-05	.210E-04
7.00000	0.00000	0.03015	621.000	1207.616	1218.208	0.000
(STRAIN)			-3.431E-05	3.549E-05	3.618E-05	.341E-12
7.00000	15.00000	0.03085	49.416	-1671.882	-1739.747	8.274
(STRAIN)			6.031E-05	-5.239E-05	-5.684E-05	.108E-05
7.00000	15.00100	0.03085	49.412	-1.715	-2.741	8.272
(STRAIN)			1.692E-04	-5.239E-05	-5.683E-05	.717E-04
7.00000	35.00000	0.02828	21.805	-15.954	-16.328	2.599
(STRAIN)			1.050E-04	-5.866E-05	-6.028E-05	.225E-04

7.00000	35.00100	0.02828	21.804	-5.413	-5.631	2.599
(STRAIN)			1.435E-04	-5.866E-05	-6.028E-05	.386E-04
7.00000	67.50000	0.02478	8.775	-13.037	-13.130	0.462
(STRAIN)			9.500E-05	-6.703E-05	-6.772E-05	.686E-05
7.00000	67.50100	0.02478	8.775	-0.089	-0.115	0.462
(STRAIN)			1.671E-04	-6.703E-05	-6.772E-05	.244E-04
8.00000	0.00000	0.03011	621.000	1198.651	1212.439	0.000
(STRAIN)			-3.412E-05	3.517E-05	3.607E-05	.388E-12
8.00000	15.00000	0.03078	48.467	-1619.437	-1707.725	9.306
(STRAIN)			5.883E-05	-5.038E-05	-5.616E-05	.122E-05
8.00000	15.00100	0.03078	48.464	-1.391	-2.725	9.304
(STRAIN)			1.657E-04	-5.037E-05	-5.616E-05	.806E-04
8.00000	35.00000	0.02825	21.638	-15.763	-16.247	2.946
(STRAIN)			1.041E-04	-5.793E-05	-6.003E-05	.255E-04
8.00000	35.00100	0.02825	21.637	-5.332	-5.614	2.946
(STRAIN)			1.424E-04	-5.793E-05	-6.003E-05	.438E-04
8.00000	67.50000	0.02476	8.754	-12.980	-13.100	0.526
(STRAIN)			9.473E-05	-6.672E-05	-6.761E-05	.781E-05
8.00000	67.50100	0.02476	8.754	-0.080	-0.114	0.526
(STRAIN)			1.666E-04	-6.672E-05	-6.761E-05	.278E-04
9.00000	0.00000	0.03007	621.000	1188.550	1205.933	0.000
(STRAIN)			-3.391E-05	3.482E-05	3.595E-05	.434E-12

9.00000	15.00000	0.03070	47.407	-1560.853	-1671.814	10.272
(STRAIN)			5.717E-05	-4.813E-05	-5.539E-05	.135E-05
9.00000	15.00100	0.03070	47.406	-1.028	-2.704	10.270
(STRAIN)			1.618E-04	-4.813E-05	-5.539E-05	.890E-04
9.00000	35.00000	0.02821	21.451	-15.552	-16.157	3.283
(STRAIN)			1.032E-04	-5.713E-05	-5.975E-05	.285E-04
9.00000	35.00100	0.02821	21.450	-5.242	-5.594	3.283
(STRAIN)			1.411E-04	-5.713E-05	-5.975E-05	.488E-04
9.00000	67.50000	0.02474	8.731	-12.915	-13.067	0.590
(STRAIN)			9.443E-05	-6.637E-05	-6.750E-05	.876E-05
9.00000	67.50100	0.02474	8.731	-0.070	-0.113	0.590
(STRAIN)			1.661E-04	-6.637E-05	-6.750E-05	.312E-04
10.00000	0.00000	0.03002	621.000	1177.334	1198.703	0.000
(STRAIN)			-3.367E-05	3.442E-05	3.582E-05	.479E-12
10.00000	15.00000	0.03061	46.249	-1496.797	-1632.320	11.163
(STRAIN)			5.536E-05	-4.567E-05	-5.454E-05	.146E-05
10.00000	15.00100	0.03061	46.248	-0.632	-2.678	11.161
(STRAIN)			1.575E-04	-4.567E-05	-5.454E-05	.967E-04
10.00000	35.00000	0.02817	21.245	-15.320	-16.057	3.611
(STRAIN)			1.022E-04	-5.626E-05	-5.945E-05	.313E-04
10.00000	35.00100	0.02817	21.245	-5.143	-5.573	3.611
(STRAIN)			1.398E-04	-5.626E-05	-5.945E-05	.536E-04

10.00000	67.50000	0.02471	8.705	-12.843	-13.030	0.653
(STRAIN)			9.410E-05	-6.598E-05	-6.736E-05	.970E-05
10.00000	67.50100	0.02471	8.705	-0.059	-0.112	0.653
(STRAIN)			1.655E-04	-6.597E-05	-6.736E-05	.345E-04

The results obtained by KENLAYER shows that the maximum surface deflection is 0.03027cm (0.03027 mm) and occurs at point 1, while the maximum vertical strain at the bottom of HMA layer is 6.510E-05(65.10µm) and also occurs at point 1. Finally vertical strain above subgrade is 1.686E-04(168.6µm) and occurs at point 1.For ease of reference; all results are in bold and underlined.