EFFECT OF HORIZONTAL SHEAR LOAD ON PAVEMENT PERFORMANCE OF ISLAMABAD–LAHORE MOTORWAY (M-2)

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

In

Transportation Engineering

Submitted By

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DISCLAIMER

The contents of this thesis report simply reveal perspectives and observations of the researcher, and their outcomes and conclusions on the basis of analysis of data. This research report does not constitute any standard, direction, guideline, reference or measure.

Every exertion has been made to make this research accurate, and complete in every aspect. However, there might be errors or mistakes in the thesis. Therefore, this research work ought to be utilized just as guidelines or source of information but in no way as an extreme and ultimate source of standards, guidelines, and information.

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To

My Best Friend Dr. Nayab

ACKNOWLEDGEMENT

I am grateful to Almighty Allah who granted me perseverance and determination to complete my research work.

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ABSTRACT

Road transportation sector contributes as a backbone to Pakistan's transportation system and to the socio-economic development of the country. The complete network of roadways connects cities and villages, and comprised of motorways, national highways, provincial highways, and regional and local roads. Excessive use of road network compared to other transportation facilities is the key factor for rapid road deterioration which results in failure of highways much before the expected service life. Pavement structure is made up of several material layers including wearing course, base course, sub-base course and subgrade. The interfaces of these material layers are bonded together which assume an imperative part in the performance of the pavement structure. One of the major problems associated with flexible pavement is the extensive pavement damage, rutting and slippage cracking in the areas where vehicles accelerate, decelerate, or brake. The aim of this study is to evaluate the effects of horizontal shear load and layer interface bonding condition on pavement performance. The 3D-FE Abaqus software package was used for the mechanistic response analysis of the flexible pavement structure. Two different loading conditions and interlayer bonding conditions were considered in this analysis. Results showed that critical tensile strains are influenced by the application of horizontal shear load. Also, it is found that interface bonding has an impact on pavement strains and horizontal displacements of pavement layers. The research concluded that horizontal shear load has an impact on pavement performance and recommends incorporating the horizontal shear load in pavement design for specific areas.

Chapter 1

INTRODUCTION

1.1 GENERAL

Transportation and Communication plays a significant role in the prosperity and development of Pakistan. This is a globally acknowledged that socio-economic development of a country is closely linked to the efficiency of its transportation system. Transportation sector especially road infrastructure have a humongous effect on the economic development of Pakistan. In this modern era, development of any country can be analyzed by its efficient road infrastructure. Efficient and sustainable road infrastructure assures healthy, safe, and sustainable environment which adds to the overall prosperity of the nation.

Road transportation sector contributes as a backbone to Pakistan’s transportation system which is serving a population of over 180 million people. Road transport is highly preferred than other modes of communication, both for freight and passenger transportation. Road transportation parts about 10% of the GDP. In Pakistan, total roadway network comprises of about 260,000 km, which includes 156,000 km (60%) paved while the remaining about 104,000 km (40%) of the total is unpaved. This complete network connects cities and villages, and comprised of motorways, national highways, provincial highways, and regional and local roads.

Motorways and National highways carry the maximum traffic load of the country, comprise of only 9000 km out of 260,000 km road length. Substantial development and advancement are required to make our transportation system in alignment to the world’s leading standards.

Extended urbanization and economic activities in the country have increased remarkable pressure on travel demands. Also, excessive use of road network compared to other transportation facilities is the key factor for rapid road deterioration in Pakistan which results in failure of highways much before the expected service life.

A modern transportation system is a crucial element of the infrastructure of a modern society. Thus, it is important to base decisions on a well-developed, thorough design methods. Secondly, it is important to understand the maintenance needed so that construction and maintenance costs can be minimized. Pavement structures wear down and deteriorate under different load conditions and exposure to climate conditions such as hot and cold temperature extremes, freezing, thawing, and precipitation. Therefore, the initial design of pavements is of paramount importance and the service life should be maintained and improved on a regular basis.

Developing countries, in particular, suffer from and have an abundance of poor pavement structures. Also, developing countries experience inadequate resource scenarios, poor quality of infrastructure, lack of planning, outdated or malfunctioning technology, and more importantly, design and implementation problems during physical achievement of planned targets. If identified at the initial stage, such problems can provide great insight regarding how to make the pavement structures more effective during execution and construction of the road infrastructure. Eliminating these issues and problems require serious efforts in prioritization and scrutiny of various levels of goals along with appropriate, comprehensive and well thought-out strategies and solutions for the success of the pavement design, and its subsequent construction and maintenance.

1.2 BACKGROUND

Pavement structure comprises of material layers including wearing course, base course, sub-base course and subgrade as shown in Figure 1. The interfaces of these material layers are bonded together which assume an imperative part in the performance of the pavement structure. Traffic loading is an important factor in the pavement design. The depth of the pavement structure, required to distribute the wheel load efficiently and to avoid the subgrade failure, depends on the magnitude of the wheel load. Stress distribution and deflection within pavement structure are affected by wheels configuration. Wheels apply vertical compressive and tensile load on different pavement layers in normal conditions. Besides vertical load (compressive and tensile), the horizontal shear load is also applied on the pavement surface in the areas where vehicles brake, accelerate or decelerate such as toll-gates/plazas, traffic signals, and police checkpoints etc. The surface layer of the pavement structure slide and deform due to braking or turning of wheels. Low-strength asphalt mix (HMA) or poor bonding between the two layers may be the cause of sliding of top layer over the underlying layer of pavement structure [Hu, Lubinda et. al, 2010]. The top layer absorbs most of the stresses due to slippage and is unable to transfer loads effectively through the entire depth of the pavement structure. Thus pavement deteriorates and fatigue life is reduced due to the horizontal shear load on the pavement surface.

Poor interface bonding can cause a top surface slippage and/or separation of the two layers. This results in pavement distress such as potholes, slippage cracking, rutting, delamination, etc. in the top layer of the pavement. Layer interface debonding or slippage often arises in flexible pavement structures; attributed to other causes such as inadequate construction techniques and/or usage of week bonding materials.

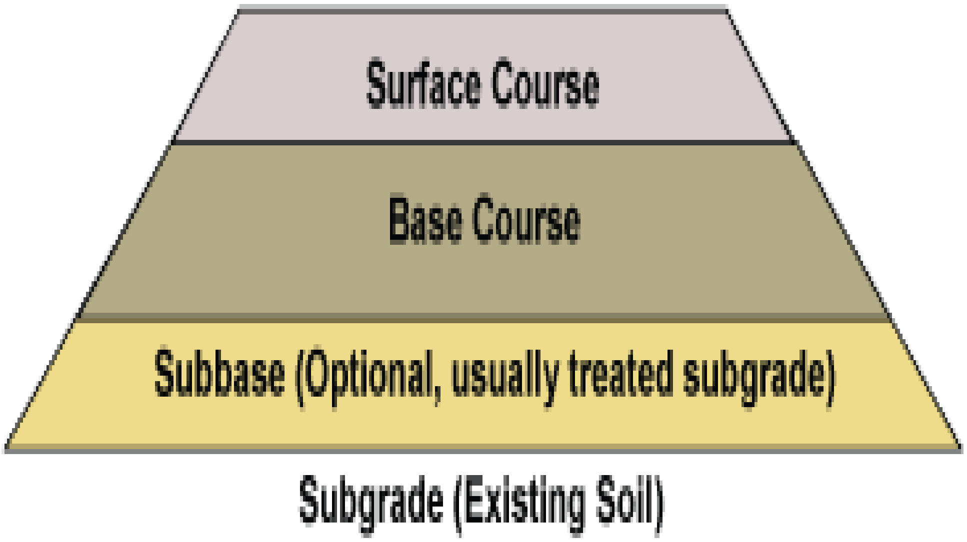

Figure 1: Pavement Structure

1.3 PROBLEM STATEMENT

One of the major problems associated with flexible pavement is the extensive pavement damage, rutting and slippage cracking in the areas where vehicles accelerate, decelerate, or brake as shown in Figure 2. Before we look into improvement in design and maintenance techniques, identification of possible causes of premature failure of flexible pavements in the areas such as airport runways, toll gates (toll plaza), signalized intersections, and police checkpoints is necessary. Slippage cracking and rutting are the main distresses observed in these areas.

These regions of the pavement are mostly under excessive horizontal shear load when the vehicle stops, or turn. Due to horizontal loading, the pavement surface slides and deforms. This sliding of the top surface is mainly due to poor bonding between the two layers or inappropriate construction techniques.

Figure 2: Slippage Crack in Turning Area

1.4 OBJECTIVES

Based on the above background and problem statement, this research has the following objectives:

- Evaluate the effects of horizontal shear load on pavement performance on Islamabad-Lahore Motorway (M-2).
- To determine the sensitivity of layer interface bonding in pavement design.
- Examine the influence of pavement thicknesses and material properties on pavement performance.
- Evaluate the effects of overloading on pavement performacne.

1.5 SCOPE OF THE STUDY

This study analyzes different sections of Islamabad - Lahore Motorway (M-2). Figure 3 shows the Islamabad – Lahore Motorway (M-2) route. Data was collected from National Highway Authority (NHA) and Frontier Works Organization (FWO), Pakistan. 3D-FE Abaqus software package was used to analyze the mechanical responses of the pavement structure under different load applications and different interlayers bonding condition. This analysis includes standard dual wheel loading condition and two different layer bonding conditions. Two different layer bonding conditions are: fully bonded, and debonded (full slip) conditions.

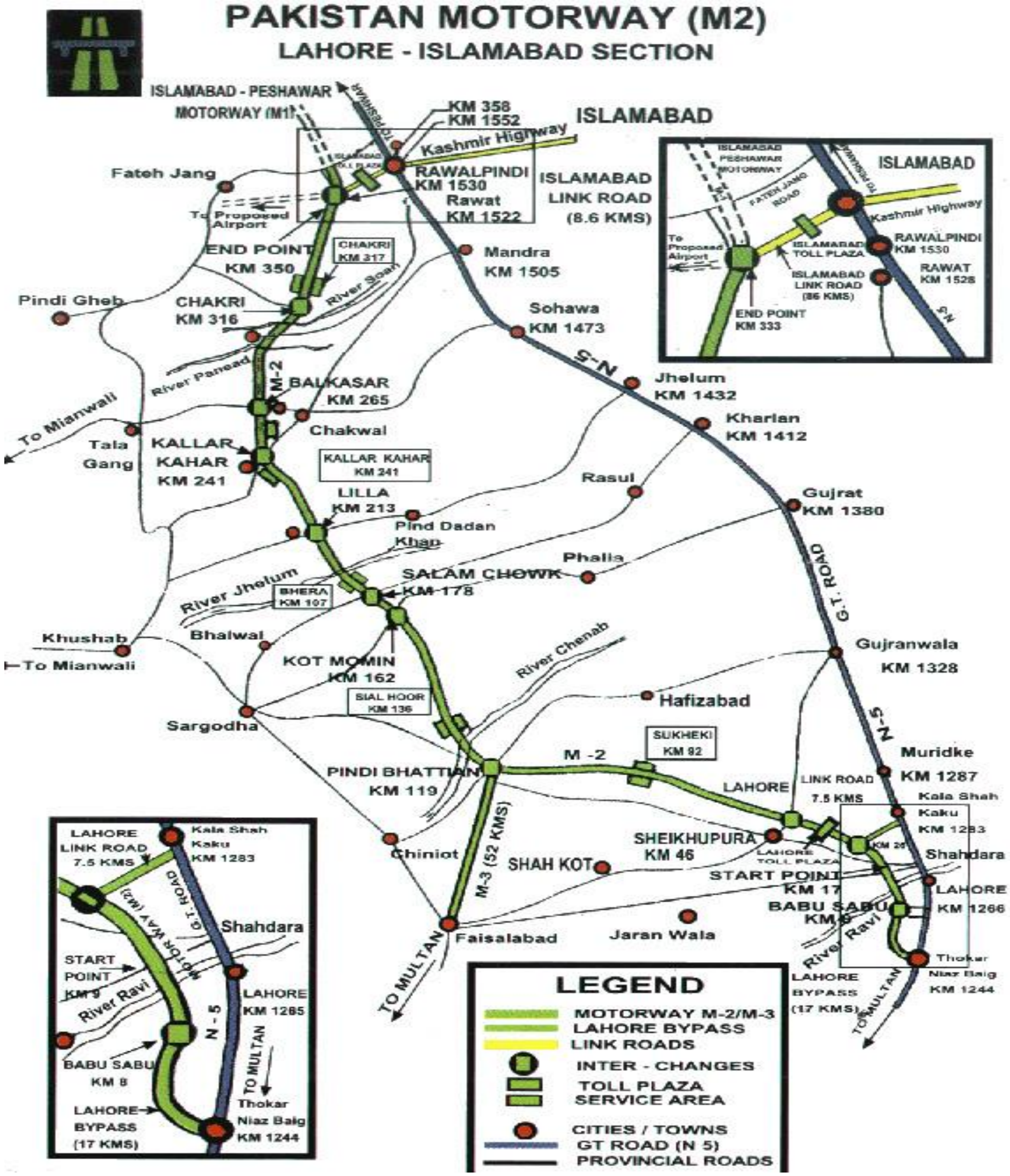

Figure 3: Map of Islamabad - Lahore Motorway (M-2)

1.6 THESIS OUTLINE

This research is organized in five chapters.

The first chapter presents an introduction which includes the background of the study, a problem that motivates the researcher for this study, the objectives of the research, and the description of the chapters.

The second chapter is devoted to the literature review. It provides the most relevant past research, pavement design methods, and explains about 3D-FE Abaqus software.

The third chapter is concerned with the research methodology employed in the study. The data requirement for the analysis, use of the software package, required assumptions, and steps of analysis are presented in this chapter.

The fourth chapter describes the results obtained from comprehensive analysis and discussion. This chapter presents the analysis of pavement mechanical responses for different bonding conditions. It also includes the results in the form of strains and displacements. The results are discussed in this chapter.

The fifth chapter is concerned with the conclusions and future recommendations. Conclusions and recommendations are drawn from key research findings.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Flexible pavements are constructed of material layers. Each layer is composed of different materials, hence, different strength. These material layers are mainly wearing course, base course, subbase course and sub-grade. All the flexible pavement layers are bonded with each other which influence the performance of flexible pavement significantly and extend the service life of the flexible pavement. Poor bonding between the pavement layers can cause a slippage and/or separation of the HMA layer and base course layer. Due to this slippage of asphalt layer, distresses may create in the surface layer such as rutting, slippage cracking, or potholes etc. Unfortunately, the debonding of pavement material layers are mostly occurs in the flexible pavement. The reason behind the debonding of layers may not only include low-quality bonding material (tack coat) but also extend to poor HMA mix or inappropriate construction techniques.

On Islamabad--Lahore Motorway (M-2), significant distresses and premature failures are reported at Toll Plazas and the areas where vehicles accelerate or decelerate. This premature failure is due to the slippage of asphalt layer, which causes rutting and slippage cracking in the pavement surface.

Vehicle loads are transmitted to the pavement surface by tires. These loads are distributed through the pavement structure to subgrade. In this load transferring and tire-pavement interaction, tire rotation and inflation play an important role. Tire rotation deals with the load direction while tire inflation affects the magnitude of the load. When the vehicle is moving with constant speed i.e. constant rotation, then the load applied on the pavement is only vertical load;

otherwise, a horizontal shear load is also applied on the pavement surface due to acceleration or deceleration.

2.2 PAST RESEARCH

Past studies corroborate the remarkable effect of interlayer bonding on the mechanistic responses i.e., stresses and strains, which directly impacts the service life and overall performance of the flexible pavements. However, the interlayer bonding condition must be known for the precise prediction of the mechanistic responses and service life of a pavement. Lushinga and Xin (2015) used BISAR 3.0 software to replicate the braking effect whilst investigating the influence of horizontal shear load on pavement performance, using conditions of zero and full friction between the layers. It was deduced that braking or horizontal shear load could cause slippage in the pavement layers; however, slippage was not observed when only normal vertical load was applied.

Su et. el. (2008) concluded that shear stress depends on the tire inflation pressure, load and the interface condition between base course and the asphalt layer, using the finite element method (FEM). Additionally, it was showed that maximum shear stress occurs at 60mm below the tire edge in the pavement structure. Furthermore, Xiaodi and Lubinda (2010) investigated that the impact of bonding condition was not observed in the absence of horizontal shear stress (i.e. acceleration, deceleration or braking), on the mechanistic responses of the pavement. They also suggested that bonding conditions should be considered during mechanistic-empirical pavement design method.

Shahin et al. (1986) investigated that in the case of fully bonded interface, the maximum tensile strain occurs at the interface. Whereas in case of lack of bonding, researchers analyzed that overlay and underneath layers will respond distinctively, which causes high stresses at the interface (Buchanan and Woods 2004; Ziari and Khabiri 2007), whilst also dominate the tensile stresses at the bottom of the overlay (Shahin et al. 1986; Hu et al. 2010), and thus also moves the critical stresses to the overlay bottom and bring about an increase in the magnitude of critical stresses as compare to full bonding (Ameri et al. 1990). Similarly, this could also trigger the relative movement of the two layers at the interface, due to additional compressive strain, which affects the structural integrity of the interface (Shahin et al. 1986). Researchers also examined that this additional compressive strain would further augment the occurrence of permanent deformation in the pavements (Shahin et al. (1986), Willis and Timm (2006), Ziari and Khabiri (2007), and Hu et al. (2010)). Additionally, Al-Qadi and Leng et al. (2009) observed lower strength values of HMA overlay in the test sections with high interface shear strength.

Rigorous analysis showed that acceleration, deceleration or braking cause horizontal force which could increase the shear stress at the interface (Shahin et al. 1986; Ameri et al. 1990; Hachiya and Sato 1997). A study shows that deceleration was observed to be more significant as compared to acceleration in producing the shear strains at the interface, For example it was noticed that acceleration less than $1.5 m/s^2$ did not impact the mechanistic response of the layers significantly, whereas the deceleration of $1.5 m/s^2$ was causing significant changes in the shear strain at the AC surface (Hu et al. 2010). The significance of interface bonding was noticed when a pavement failed prematurely which was opened to the traffic on its first day and was thought to be occurred due to loss of interface bonding (Chen 2010). Moreover, researchers also concluded that the interface strains in the case of the fully-bonded interface are also remarkably affected by the horizontal shear stresses (Al Qadi et al. 2006; Romanoschi et al. 2001; Drescher et. al. 2003).

Similarly, Al-Qadi and Yoo analyzed the vertical and horizontal contact stresses using three-dimensional (3D) finite element (FE) model for moving load using different tire configurations. They concluded that pavement responses can be affected by the tangential stresses, whereas, they also added that horizontal tangential stresses should be incorporated in the flexible pavement design because it can go up to 52% of the vertical compressive stresses.

2.3 PAVEMENT DESIGN METHODS

Pavement design techniques mainly deal with structural features of pavement system such as the appropriate materials required for each layer, load-bearing capacity of the structure, and appropriate thickness of each material layer based upon the quality of materials. Currently, most of the pavement design practices around the globe are typically based on empirical relations with the previous pavement performance, physical properties of the materials such as drainage coefficient, CBR value or resilient modulus and engineering judgment to select a specific design technique. Ample research has been done to rationalize the engineering judgments and numerous changes have been made in the design procedures of the flexible pavement structure. These pavement design techniques were relied on empirical performance equations, developed utilizing the 1950's AASHO Road Test data (Haung, 1993). Moreover, it is challenging to incorporative diverse climatic condition into the models as the AASHO Road Test was executed at just a single geographic location. Only one type of subgrade material and very few types of base course and surface course materials were used in the tests. These limitations and several other factors, for example, construction practices, various drainage conditions, and continuous long-term impact of climatic conditions and deterioration of pavement structure make the empirical design technique unclear and difficult to apply. Figure 4 shows the pavement design methods.

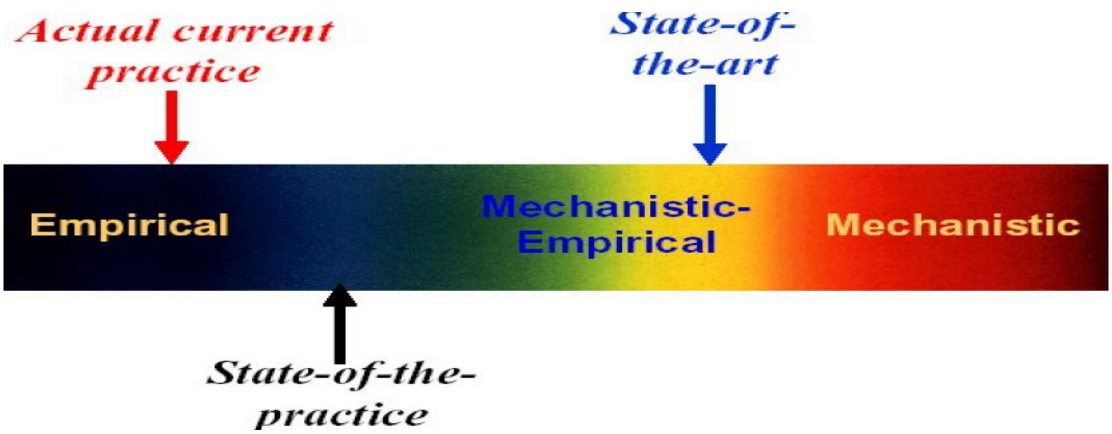

Figure 4: Pavement Design Methods

2.3.1 Empirical Design Method

An empirical pavement design technique is completely based on the experimental results or past experiences. Engineering judgments are employed to develop an association between the inputs and the results of the process such as the performance of the pavement and pavement design. These relationships solely based upon engineering judgments have to fulfill the required tests of reasonableness e.g. true behavior for limiting cases, trends of properties in the right direction, etc. Empirical methods are generally used as an efficient and convenient alternative when it is hard to delineate theoretically specific cause-and-effect association of a phenomenon. In the mid-1920s, empirical pavement design approach was used when the first soil classifications were developed. Public Road (PR) soil classification system was among the first published work in this area (Hogentogler & Terzaghi, 1929, after Huang, 2004). In 1929, the California Bearing Ratio (CBR) test was developed by the California Highway Department (Porter, 1950, after Huang, 2004). The CBR value of pavement material strength provides information for required thickness of the layer to avoid the shear failure of the subgrade. The computed thickness was the only result for the specific standard crushed aggregates which were used in the development of CBR test. Later on, U.S. Corps of Engineers (USCE) improved the CBR method for the period of the World War II and it turns out to be the most widespread pavement design technique. In 1945, the Highway Research Board (RHB) made some modifications in the PR soil classification system. Soils were classified in seven groups from A-1 to A-7 included indexes to distinguish soils within each group. This soil classification was used to figure out the quality of sub-base and to compute the thickness of the total pavement. Several pavement design methods, integrating subgrade shear failure criteria were developed after the CBR pavement design approach. Barber (1947, after Huang 2004) computed flexible pavement thickness using Terzaghi bearing capacity formula. After that McLeod (1953, after Huang 2004) computed bearing capacity for pavement structure using logarithmic spirals. With high increase in traffic volume, and vehicle speed, the criterion for pavement design was changed from subgrade shear failure. New pavement materials were introduced to improve pavement performance and smoothness. Surface vertical deflection was used when for the first time the structural response was considered as a quantitative measure of pavement structure capacity. Later on, based on the elastic theory of the soil mass, several design methods were developed. In these design methods, the thickness of the pavement layers was computed based on the certain limits for vertical deflection of the pavement surface. In 1947 Kansas State Highway Commission developed the first design method and published, which included Boussinesq's equation, and limit of the subgrade deflection was kept 2.55 mm.

After 1950, pavement performance data collection and evaluation started and regression models were used to develop relations between the pavement performance data and design inputs. Today most widely used pavement design method is from the late 1950s, the empirical AASHTO design method (Haung, 1993). The AASHTO pavement design model is based on regression equation which includes load repetitions, structural capacity of the road, and performance of the pavement in term of serviceability. The prime drawback of the regression models is their limited application. Regression models are applicable only if the conditions and situations for which the model will be applied are similar to those conditions and situations for which the models were developed. That is the reason the AASHTO pavement design method has been calibrated and modified numerous times to integrate different conditions based on principles, theory, and observations.

2.3.2 Mechanistic-Empirical Method

A mechanistic - empirical pavement design method is the modern form of empirical method – as it includes the principles of engineering mechanics along with performance observations from past experiences. Pavement response to loading conditions can easily understand using this method, based on the principles of engineering mechanics. This new approach also incorporates the flexibility needed to consider the conditions such as virgin materials properties and different loading conditions. The laboratory set-ups and testing equipment are needed to be used to simulate effectively the actual behavior of pavement while implementing a mechanistic--empirical design method. Otherwise, we can't expect actual results or predict real-world pavement performance. This modern technique would terminate some of the old tests which were the part of the structural design of pavements for a long time, such as the California bearing ratio test. It would replace the classical tests with the tests that would give more efficient and consistent results, which would lead to making a more reliable decision about the pavement design and construction.

Major factors affecting the performance of flexible pavement and causing the distresses in the structure are: i) the vehicle load condition on the pavement, ii) cross-section of the pavement structure, iii) the climatic condition iv) material properties of the pavement layers. The primary factors affecting the performance of flexible pavement and causing the distresses in pavement structures are: *i*) the cross section of the pavement structure, *ii*) the traffic (axle) load condition on the pavement structure, *iii*) the climatic conditions the pavement will be exposed to during its entire service life, and *iv*) the material properties of the different layers in the pavement structure. It is required to thoroughly understand these factors to have the ability to anticipate, predict or estimate the structural and functional condition of the flexible pavement structure. Moreover, the important thing is to understand how these factors are associated mechanistically to pavement performance and distress development. Figure 5 explains the components of the mechanistic-empirical design method.

Advantages of the mechanistic--empirical design method over the empirical design methods are following:

- Intrinsically well developed to incorporate the actual environmental effects and wheel loading conditions.
- Evaluation and estimation of different loading conditions such as multiple axles, high tire pressure, and the detrimental effects of overloading on pavement structure.
- Enhance the utilization of available materials.
- Seasonal variations and its impact on pavement can be incorporated in the pavement design method.
- Better drainage systems in the design.

Besides, an extra critical advantage of the mechanistic–empirical technique incorporates simplicity in executing future upgraded or enhanced knowledge.

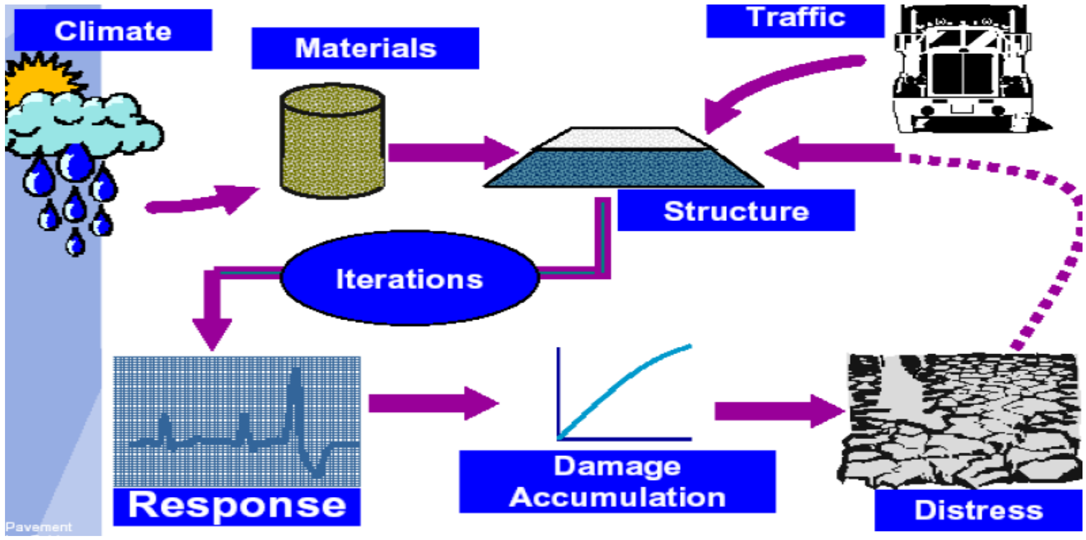

Figure 5: Mechanistic – Empirical Design Method

2.3.3 Mechanistic Design Approach

Rather than the empirical approach, it is a totally scientific approach which is based on the mechanical analysis of pavement structural layers. It analyzes mechanically the pavement response under different loading conditions and evaluates the environmental impact mechanically. In the 1920s, when Harold Malcom Westergaard (1888-1950) was developing slab on subgrade design and theories of thermal curling stresses to calculate the stresses and deflection for rigid pavement, a Mechanistic approach for rigid pavement was evolved. For flexible pavement, this approach was evolved in the 1940s when Burmister was developing multilayer elastic theory to calculate various stresses, strains, and deflection in the pavement structure. Mechanistic approach mathematically models the pavement response. Various models are available today to measure the pavement response e.g. dynamic models, viscoelastic models etc.

One of the most important advantages of this approach is that it predicts the pavement material response and response of pavement itself very accurately. Solutions gave by Boussinesq, Burmister, and Westergaard based on elastic behavior were important steps toward the development of a theoretical description of pavement response under load. However, it was assumed in these solutions that material behavior is linear elastic; it means that these solutions they will be unable to predict the nonlinear behavior of the material and thus unable to predict inelastic cracking, permanent deformation, and other distresses in the pavement structure. A lot of work has been done in recent years on performance prediction model but the problem is very complex and a true mechanistic approach does not exist yet.

2.4 LINEAR ELASTIC ANALYSIS

Linear elastic analysis is based on layered elastic theory. It is very simple to use, so it is being used by engineers since 1940s. Because of its simple nature and low computation time and cost, it is mostly used for the study of pavement behavior under traffic loading. In 1943, Burmister developed two layers linear elastic model which is then upgraded to three layers model. This development process of models continues to deals with a multilayered elastic system and thus results in the development of various software (Amara et al, 2006).

Chevron Research Company developed the earliest program CHEV to deal with only linear elastic materials (Huang, 1993). Then with further development, on later stages various other software like DAMA, BISAR, ELSYM5, PDMAP, DIPLOMAT, were developed.

Important assumptions that were made in layered theory are as follow (Amara et al, 2006):

- Each material layer is homogeneous, with the same properties throughout the layer.
- Materials are weightless, so no inertia effects are considered.
- Layers are infinite in the lateral direction.
- Pavement structures are loaded statically, so no moving loads are considered.

- Loading areas are circular.
- The layers are fully bonded.

2.5 VISCO-ELASTIC ANALYSIS

Because of the physical properties – from elastic solid to viscous liquid at the same time, HMA is considered as visco-elastic material. When HMA is subjected to high temperature or slow-moving load, it behaves like a viscous liquid, and when it subjected to very low temperature or fast moving load it shows elastic behavior (Elseifi et al., 2006). Work done in early stages to study the behavior of HMA mix, linear elastic pavement response models were used, but this linear elastic approach does not consider the dependency of HMA on time and temperature. Concepts of visco-elastic theory based on elastic-viscoelastic correspondence principle, which transform a visco-elastic problem to an associated elastic problem through Laplace transform application (Huang, 1993).

2.6 FINITE ELEMENTS MODEL

Numerical analysis technique used for solving a wide variety of engineering problems is called as finite element method (FEM). Although originally developed to study stresses in complex airframe structures, it has since been extended and applied to the broad field of continuum mechanics (Huebner et al., 2001). Variables of interest in a continuum problem have values as they are functions of each generic point in the continuum. For example, one simple equation cannot solve stresses in particular elements of pavement as the functions describing the stresses are particular to a specific location. Although, in finite element method an approximate numerical solution can be obtained by dividing a continuum into a number of small discrete volumes for each individual volume instead of the complete pavement volume. All of these tedious calculations can be done using a computer.

In FEM analysis of flexible pavement, the wheel loads are distributed at the top of the region of interest while dividing the region of interest into a discrete number of elements. All areas of interest are included within the influence of the wheel as the finite elements extend vertically and horizontally from the wheel.

2.6.1 Inputs

Following steps are involved in a typical finite element method approach.

1. Distribute the region of interest into small discrete shapes.
2. Assign a node to each element and then interpolate the variation of a variable over the discrete element by choosing a function.
3. Determine the matrix equations which reflect the properties of individual elements by using the established finite element model.
4. Obtain the matrix equation expressing the behavior of the entire system by combining individual matrix equations expressing the behavior of elements.
5. Set the values for certain variables occurring at key boundary positions.
6. The above procedure generates an equation which can be solved.
7. Calculate the elements stresses and strains from the unknown displacement components.

2.6.2 Outputs

The outputs of a FEM analysis are similar to that of a layered elastic model.

1. Stress: Stress is the force per unit area measured in N/m2 or psi. Pavement structure experiencing internally distributed force is called as stress.
2. Strain: The unit displacement occurring in a pavement due to stress is called strain. It is more often expressed as the ratio of change in dimension to the original dimension. It is measured in (mm/mm or in/in)
3. Deflection: The linear change in dimension measured in the units of length is called deflection.

2.7 ABAQUS SOFTWARE

ABAQUS is a very powerful finite element modeling software that can solve problems implementing linear and nonlinear analysis. It is able to model virtually any geometry and the properties or characteristics of most of the engineering materials using its extensive library of elements and material models (ABAQUS, 2007). Some of the materials that can be modeled with ABAQUS are:

- Asphalt concrete
- Reinforced concrete
- Metals
- Wood
- Crushed stones
- Rubber
- Composite materials
- Geotechnical materials like rocks and soils

FEM in the research environment is nothing new and was used as far back as 1970's by Pretorius in his Ph.D. study (Pretorius, 1970), as well as Otte (1987), and Maree (1980). A major drawback of FEM and associated dynamic analysis of pavements since then was Deflectometer (IDM) (Horak 1988, and LaCante 1992) and still is; that it is time-consuming and needs relatively large computing memory which adversely affects its everyday use. This type of analysis was only available to large consulting firms. As mentioned earlier, that finite element modeling approach can be used to model the multi-layered pavement structure having non-linear material properties, various loading distribution (1-D to 3-D), and dynamic or moving load application on pavement surface (Lourens, 1991). It is not necessary to assume circular uniformly distributed load in modeling finite element model. In FEM, the equilibrium equations for each nodal point in the structural system are derived in terms of unknown nodal displacements and a solution set of the equilibrium equations constitutes a solution to the structural system. With the aid of experimental data, material properties for each element can be approximated fairly accurately and the element assemblage can represent complex bodies containing many different layers and material properties. Moreover, boundary conditions related to displacements and stresses may be specified at any point within the finite element system. Equilibrium equations for FEM result in a symmetric positive definite matrix that may be stored in a banded form and solved with minimum computer storage and time.

Chapter No. 3

METHODOLOGY

3.1 INTRODUCTION

The purpose of this chapter is to discuss the methodology used in this study to analyze the pavement structure, to achieve the research objectives. The collection and reduction of data is a part of the chapter. The selection of specific sections of M-2 and properties related to pavement structure are discussed in details. The interface bonding condition is explained in this chapter. The 3D-FE Abaqus 6.9 software package was used for the mechanistic response analysis of the flexible pavement structure presented in this research. Pavement structure response analysis steps and inputs required for the analysis in FE Abaqus are included in details.

3.2 DATA COLLECTION AND REDUCTION

Islamabad – Lahore Motorway (M-2) is selected for pavement mechanistic response analysis in this research. M-2 flexible pavement data were collected from Frontier Works Organization (FWO). The complete 354 km length of M-2 was divided into multiple sections on the basis of pavement layers thicknesses and material properties of the layers. Two sections, one close to Lahore having lowest characteristics values, and the second close to Islamabad having largest characteristics values were considered in this study.

3.3 PAVEMENT STRUCTURE AND PROPERTIES

Two sections of M-2 as mentioned above were considered in this study. Flexible pavement structure model under consideration consisted of five layers and had the following material properties presented in Tables 1 and 2.

Table 1: Pavement Layers Properties (Section – I)

Layer	Thickness cm (inches)	Elasticity Modulus ksi	Poisson ratio
ACWC	5 (2)	237	0.35
ACBC	8 (3)	237	0.35
Base (GB)	30 (12)	57	0.40
Subbase (GSB)	15 (6)	57	0.40
Subgrade	∞	50	0.45

ACWC= Asphalt Concrete wearing course ACBC = Asphalt concrete base course
GB = Granular base course GSB = Granular subbase course

Table 2: Pavement Layers Properties (Section – II)

Layer	Thickness cm (inches)	Elasticity Modulus ksi	Poisson ratio
ACWC	5 (2)	931	0.35
ACBC	8 (3)	931	0.35
Base (GB)	36 (14)	237	0.40
Sub-base (GSB)	15 (6)	237	0.40
Subgrade	∞	76	0.45

ACWC= Asphalt Concrete wearing course ACBC = Asphalt concrete base course
GB = Granular base course GSB = Granular sub-base course

3.4 FINITE ELEMENT ANALYSIS

In this research work, three-dimensional finite element (3D-FE) ABAQUS software is used to analyze the mechanistic response of flexible pavement under applied load. Three-dimensional finite element models were developed to simulate the behavior of the Islamabad-Lahore motorway (M-2) pavement structure under static standard dual wheel loading conditions. Critical strains and stresses tend to develop around the loading areas; they are small and sometimes negligible in the far field areas. In order to optimize the model, an analysis was carried out using a coarser mesh first, and then the areas of interest were refined with a finer mesh. This procedure was done to decrease the computational time without affecting the accuracy of the results. The flexible pavement structure was considered as a linear elastic multilayered system with different layer interface conditions. Moreover, a horizontal shear load was considered using friction force between tires and road surface combined with a standard dual load (Lushinga and Xin, 2015). The model is presented in Figure 6.

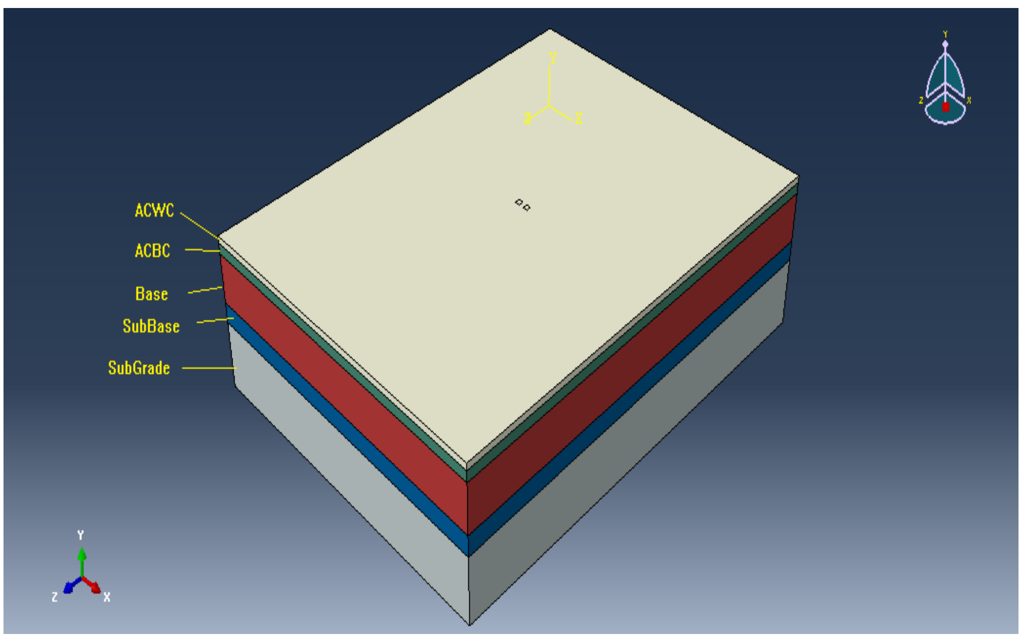

Figure 6: 3D-FE Flexible Pavement Model

3.5 MODEL GEOMETRY

3.5.1 Dimensions and boundary conditions

Appropriate dimensions are required to be assigned for modeling the pavement structure in Abaqus 3D-FE software. The software will take longer time for computation if the dimensions of the model are too large. On the other hand, if the dimensions of the model are too short the results of the calculation will be inaccurate. Based on the literature review and also after conducting a brief sensitivity analysis of the pavement models, it was confirmed to design the model 400 inches long, and 300 inches wide. These dimensions made the pavement models long and wide enough and took large time for computation, but it yielded reliable and accurate results.

The boundaries of the model are only restricted from displacement. The bottom of the subgrade is modeled as fixed support and restrained against translation in all three directions, while the sides of the model are modeled as roller supports and restrained the displacement in the direction perpendicular to the plane of the boundary.

3.5.2 Element Type

To yield correct results and to reduce the computation time, selection of element type is critical for any finite element analysis. Finite elements normally used in stress analyses follow a mathematical theory that defines how they work. Quadratic elements take more computational time, but they produce more accurate results. After reviewing past research on finite element analysis of flexible pavements, the C3D8R and CIN3D8 elements were selected to use in this study. C3D8R elements have eight-node linear brick structure with reduced integration. These elements have only one integration point, lies in the center of the element. The advantage of using this element is to reduce the computational time without affecting the results accuracy highly (Yoo, 2007). As there is only one integration point, small size elements are desired to account for stresses and strains at the edge of a structure.

3.6 LOAD CONFIGURATION

The elastic effect of an asphalt layer in flexible pavement system is a critical factor in determining the mechanistic responses. Therefore, load configuration in pavement response analysis is a significant factor affecting the critical stresses magnitude and nature. In this research, standard dual wheel load of 9000 lb. configuration was used. The coefficient of friction between tire and pavement surface, from past literature review, was assumed 0 and 0.5. To compute horizontal shear load for the wheel, the coefficient of friction multiplied by the vertical normal load. The horizontal shear load was 0 lb. and 2250 lb. Vehicle braking generates horizontal shear loads due to friction which makes the association with the vertical load as presented:

$$F = f \times P \tag{3.1}$$

where, *F = horizontal shear load due to vehicle braking (single wheel) lb.*

P = vertical normal load (single wheel) lb.

f = coefficient of friction, (ranges from 0 - 0.5).

Standard dual wheel load of 9000 lb. was used in this study, while the contact pressure of the tire was considered 80 psi. The circular static load was considered. The radius of contact area was taken to be 6 inches. Center to center distance between two tires was considered 13.5 inches. F = horizontal shear load was computed using equation 3.1.

3.7 LAYERS INTERFACE CONDITION

Several factors affecting layer interface bond strength including temperature, normal pressure, tack coat type, dilution, surface roughness, and material mix type. The pavement layers slip due to weak bond strength between layers; hence produce slippage cracking. Research conducted using mechanistic models usually considered a layered elastic model (e.g., BISAR, Everstress) and varying the interface slip parameter. In general, studies conducted by Shahin et al. (1986), and Willis and Timm (2007) suggest that loss of layers bond results in reduced pavement fatigue life. Two interface conditions, full friction (i.e. fully bonded), and frictionless/de-bonded (i.e. full slip), were considered in this study.

Contact interaction feature in ABAQUS is used to model the interface between layers. This feature is generally used to design friction between the surfaces of two elastic or rigid objects that slide over each other. Two surfaces, a master surface, and a slave surface are defined in the contact interaction feature. The slave surface (upper layer) slides over the master surface (bottom layer) during the analysis of the model. To model the interface between the pavement layers, the contact interaction feature is generally adapted.

The two interface conditions were modeled as follow:

- **‘Tied’ condition** is the case in which each single node of the slave surface is bonded to the nearby node on the master surface.
- **Simple friction** condition is totally characterized by a friction coefficient, mu. The resistance to movement is proportional to the normal pressure at the interface.

Here mu= 0 is used for the de-bonded or full-slip condition.

3.8 POISSON RATIO

It is defined as “the ratio of transverse strain to longitudinal strain of a loaded specimen”. Poisson ratio generally varies from 0.0 to 0.5. In general, “stiffer” object have lower Poisson ratio than a “softer” object.

Mathematically, Poisson ratio can be expressed as:

$$\mu = - \varepsilon_t / \varepsilon_l \qquad (3.2)$$

where; μ = poisson ratio

ε_t = transverse strain

ε_l = longitudinal or axial strain

Table 3: Typical Values of Poison Ratio

Material	Poison Ratio
Asphalt concrete	0.35
Crushed stone	0.40
Soils (fine grained)	0.45

3.9 DIFFERENT CASES FOR ANALYSIS

This study of pavement response analysis was conducted under different loading conditions and different interlayer (interface) bonding condition. On the basis of types of the applied load and types of the layers interface condition, two different cases: Case – I and Case – II having two sub-parts of each case were established for the analysis. The two cases analysis are given below.

Case - I

a. ***All the layers are fully bonded (Full bond interface):***

   i. Normal load with horizontal shear load

   ii. Normal load without horizontal shear load

Case - II

b. ***Layer interface between surface layer (ACWC) and a second layer (ACBC) is de-bonded (full-slip/frictionless):***

   i. Normal load with horizontal shear load

   ii. Normal load without horizontal shear load

Chapter 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter mainly discusses the results obtained from the detailed analysis of pavement structure using the 3D-FE software. Both the sections were analyzed for all the different cases mentioned in Chapter 3. The effects of horizontal shear load on critical strains and horizontal displacements of pavement layers are evaluated in detail. The critical responses considered in this study included the tensile strain at the bottom of the HMA layers that is responsible for the bottom-up fatigue cracking and compressive strains at the top of subgrade layer that are responsible for rutting and near-surface cracking.

4.2 INFLUENCE OF HORIZONTAL LOAD ON PAVEMENT RESPONSE

Generally, flexible pavement structural design methods are based on response models, which consider only vertical loads on the pavement surface. If horizontal loads apply along with the vertical loads, significant horizontal shear stress between the top layers is expected to develop. This case is the most critical one not only in the bonding between layers, but it has also a substantial influence on the tensile stresses on the top and bottom surfaces of the HMA layers. The tensile stresses may develop in those locations of the pavement layers where they are not induced when only the normal vertical loads are acting. To analyze these issues, two separate conditions were considered. In the first case, the only vertical load was applied on the surface of the pavement on the circular area. In the second case, a horizontal load was applied along with the vertical load on the same circular area.

4.2.1 Effect on Critical Strains in Pavement Structure

The horizontal load along with normal load was used to study the effect on pavement response. Table 4 and Table 5 show that the critical tensile strains are influenced by the application of horizontal shear load, as shown in past research (Su et. al. 2008). The increase in critical tensile strain at the bottom of the surface layer (ACWC) is 31.5 %, while in the other layers is about10 %.

Table 4: Pavement Mechanistic Response (Section – I)

Pavement Layer	Bonding Condition	Critical Strains	Normal Load	Normal Load with Horizontal Load
			Strain (Ɛ)	Strain (Ɛ)
ACWC	Full Bond	ε_{t1}	1.81E-04	2.38E-04
ACBC	Full Bond	ε_{t2}	7.31E-05	8.05E-05
Base (GB)	Full Bond	ε_{t3}	8.53E-05	9.32E-05
Sub-base (GB)	-----	-----	-----	-----
Subgrade	Full Bond	ε_{c}	1.82E-05	1.82E-05

Table 5: Pavement Mechanistic Response (Section – II)

Pavement Layer	Bonding Condition	Critical Strains	Normal Load	Normal Load with Horizontal Load
			Strain (Ɛ)	Strain (Ɛ)
ACWC	Full Bond	ε_{t1}	4.56E-05	6.04E-05
ACBC	Full Bond	ε_{t2}	1.79E-05	2.01E-05
Base (GB)	Full Bond	ε_{t3}	2.07E-05	2.29E-05
Sub-base (GB)	-----	-----	-----	-----
Subgrade	Full Bond	ε_{c}	6.54E-06	6.55E-06

4.2.2 Effect on Horizontal Displacement in Pavement Structure

As it can be seen from Table 6 and Table 7, when the normal load was applied without horizontal shear load, the horizontal displacement on the layer interface was zero inches (0 in.). When the normal load was applied with a horizontal shear load, horizontal displacement occurred at the interface of the asphalt layers. This indicates that the horizontal shear load has an effect on the horizontal displacement between pavement layers. Horizontal shear stress induced by traffic deceleration or braking effect cause the horizontal displacement at the asphalt layers interface. This results in the slip of pavement layers due to high shear stress concentration in the top layers; hence causes the slippage cracking in the pavement surface. These results are in agreement with past research (Nonde 2015, Xiaodi 2011).

Table 6: Pavement Mechanistic Response (Section - I)

Pavement Layer	**Bonding Condition**	**Normal Load**	**Normal Load with Horizontal Load**
		Horizontal Displacement (in)	**Horizontal Displacement (in)**
ACWC	Full Bond	0.00E+00	3.61E-03
ACBC	Full Bond	0.00E+00	1.19E-03
Base (GB)	Full Bond	0.00E+00	1.19E-03
Sub-base (GB)	-----	-----	-----
Subgrade	Full Bond	-----	-----

Table 7: Pavement Mechanistic Response (Section - II)

Pavement Layer	Bonding Condition	Normal Load	Normal Load with Horizontal Load
		Horizontal Displacement (in)	Horizontal Displacement (in)
ACWC	Full Bond	0.00E+00	9.11E-04
ACBC	Full Bond	0.00E+00	2.87E-04
Base (GB)	Full Bond	0.00E+00	2.87E-04
Sub-base (GB)	-----	-----	----
Subgrade	Full Bond	-----	----

Figure 7 and Figure 8 show the contours of horizontal displacement under vertical load with a horizontal load in full bonding layers interface condition for both the sections under consideration.

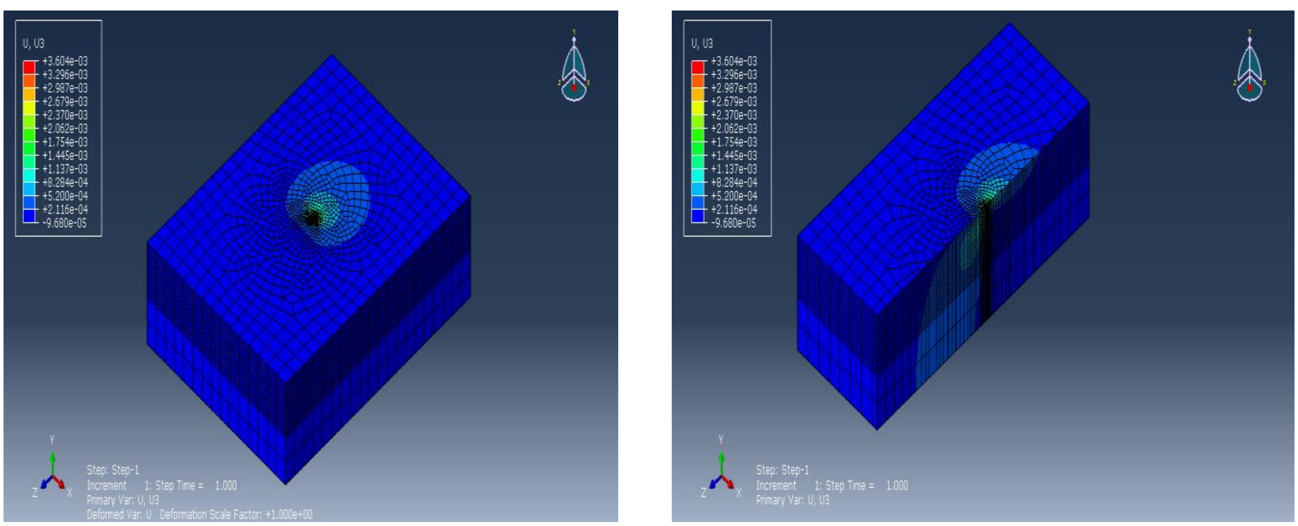

Figure 7: Horizontal Displacement under Normal Load with Horizontal Load in Full Bond Condition (Section-I)

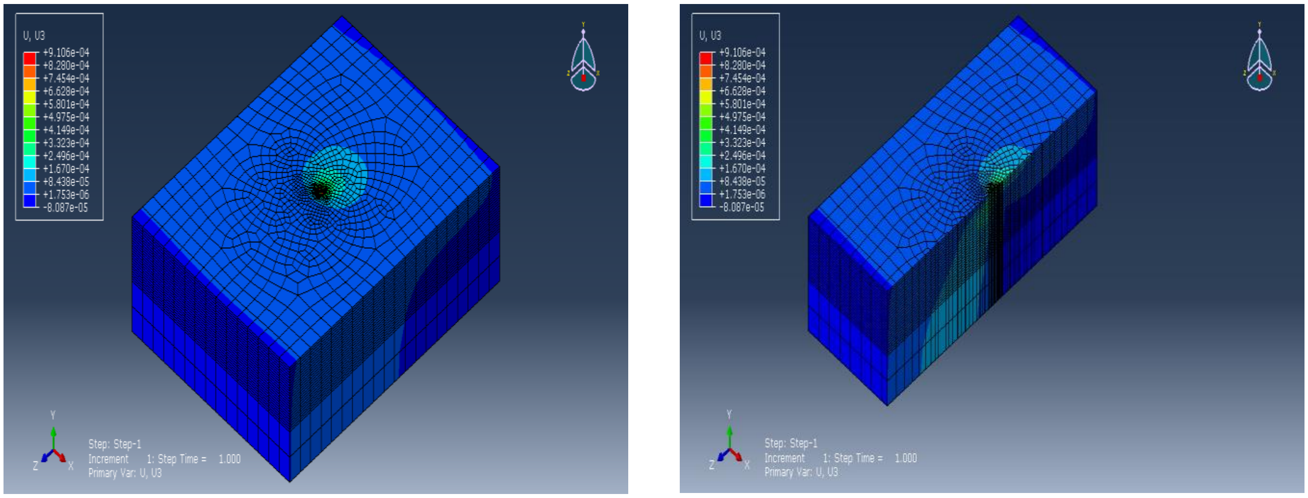

Figure 8: Horizontal Displacement under Normal Load with Horizontal Load in Full Bond Condition (Section-II)

4.3 INFLUENCE OF INTERFACE BONDING ON PAVEMENT RESPONSE

The behavior of flexible pavements shows that the bonding between pavement layers has a significant impact on the performance of the pavement structures. The interlayers bonding condition between the asphalt course and the base course can lower the service life of the flexible pavement up to 80%, and the surface layer and binder layer were found to be highly responsive to a horizontal shear load of the traffic (Kruntcheve, 2005). Premature failure of the pavement sections occurs mostly due to layer separation, which leads to the relocation of stresses and strains in the flexible pavement structure, especially in regions where vehicles decelerate or accelerate --- such as intersections, toll plaza, and bus-stops etc. In order to study the influence of layers interface condition on pavement response, two bonding conditions: (i) full bond, (ii) full slip, were considered in this research.

4.3.1 Effect on Critical Strain in Pavement Structure

In a multi-layered pavement structure, the layer interface bonding condition plays a significant impact on pavement performance. Here, the effect of interface condition on critical strain is evaluated, concentrating on the cases of full bonding and no bonding (full slip) between the asphalt concrete wearing course (ACWC) layer and the asphalt concrete base course (ACBC) layer. For these two conditions, the results of critical strain are presented in Tables 8, 9, 10 and 11. The results indicate that the magnitude of critical strain at the bottom of the wearing course is higher in full slip (no bonding) condition than in the full bonding condition. The increase in critical strain at the bottom of ACWC layer is from 40 - 77 % due to full slip (no bonding) condition between two layers. These results corroborate the past research findings regarding the impact of interlayers bonding condition on pavement performance and service life. Consequently, inadequate bonding at the interface would result in higher shear stress at layer interface than the full bonding case. That is, poor bonding between the asphalt wearing course and the asphalt base course is damaging and may not only induce the slippage cracking, but also can develop rutting and top-down cracking (TDC).

Table 8: Full Bond and Full Slip Conditions under Normal Load (Section - I)

Pavement Layer	Critical Strains	Bonding Condition	Strain (ε)	Bonding Condition	Strain (ε)
ACWC	ε_{t1}	Full Bond	1.81E-04	Full Slip	3.21E-04
ACBC	ε_{t2}	Full Bond	7.31E-05	Full Bond	4.72E-05
Base (GB)	ε_{t3}	Full Bond	8.53E-05	Full Bond	3.33E-05
Sub-base (GB)	----	----	----	----	----
Subgrade	ε_{c}	Full Bond	1.82E-05	Full Bond	1.76E-05

Table 9: Full Bond and Full Slip Conditions under Normal Load (Section - II)

Pavement Layer	Critical Strains	Bonding Condition	Strain (ε)	Bonding Condition	Strain (ε)
ACWC	ε_{t1}	Full Bond	4.56E-05	Full Slip	8.16E-05
ACBC	ε_{t2}	Full Bond	1.79E-05	Full Bond	1.15E-05
Base (GB)	ε_{t3}	Full Bond	2.07E-05	Full Bond	7.938E-06
Sub-base (GB)	----	----	-----	----	----
Subgrade	ε_{c}	Full Bond	6.54E-06	Full Bond	6.71E-06

Table 10: Full Bonded and Full Slip Conditions under Normal Load with Horizontal Load (Section - 1)

Pavement Layer	Critical Strains	Bonding Condition	Strain (Ɛ)	Bonding Condition	Strain (Ɛ)
ACWC	Ɛt1	Full Bond	2.38E-04	Full Slip	3.36E-04
ACBC	Ɛt2	Full Bond	8.05E-05	Full Bond	2.05E-04
Base (GB)	Ɛt3	Full Bond	9.32E-05	Full Bond	2.80E-05
Sub-base (GB)	----	----	-----	----	----
Subgrade	Ɛc	Full Bond	1.82E-05	Full Bond	1.72E-05

Table 11: Full Bonded and Full Slip Conditions under Normal Load with Horizontal Load (Section - II)

Pavement Layer	Critical Strains	Bonding Condition	Strain (Ɛ)	Bonding Condition	Strain (Ɛ)
ACWC	Ɛt1	Full Bond	6.04E-05	Full Slip	8.47E-05
ACBC	Ɛt2	Full Bond	2.01E-05	Full Bond	1.04E-05
Base (GB)	Ɛt3	Full Bond	2.29E-05	Full Bond	7.38E-06
Sub-base (GB)	----	----	----	----	----
Subgrade	Ɛc	Full Bond	6.61E-06	Full Bond	6.58E-06

4.3.2 Effect on Horizontal Displacement in Pavement Structure

Pavement layers interface bonding condition plays an important role in flexible pavement performance. Top layers displace horizontally due to debonded interface between the layers as investigated by past researchers (Khweir, 2003) . Tables 12 and 13 present the results of the impact of the interface bonding condition on horizontal displacement for Section-I and Section-II. The results show that the horizontal displacement of the top surface layer increases due to full slip on the interface between the ACWC and ACBC layers. These results are in agreement with the past results.

Table 12: Influence of Layers Bonding on Horizontal Displacement (Section-I)

Pavement Layer	Bonding Condition	Horizontal Displacement (in)	Bonding Condition	Horizontal Displacement (in)
ACWC	Full Bond	3.61E-03	Full Slip	6.088e-3
ACBC	Full Bond	1.19E-03	Full Bond	4.104e-4
Base (GB)	Full Bond	1.19E-03	Full Bond	4.104e-4
Sub-base (GB)	----	-----	----	----
Subgrade	Full Bond	-----	Full Bond	----

Table 13: Influence of Layers Bonding on Horizontal Displacement (Section-II)

Pavement Layer	Bonding Condition	Horizontal Displacement (in)	Bonding Condition	Horizontal Displacement (in)
ACWC	Full Bond	9.11E-04	Full Slip	9.26E-04
ACBC	Full Bond	2.87E-04	Full Bond	1.88E-04
Base (GB)	Full Bond	2.87E-04	Full Bond	1.88E-04
Sub-base (GB)	----	----	----	----
Subgrade	Full Bond	----	Full Bond	----

Figures 9 and 10 present the contours of horizontal displacement under vertical load with horizontal load in full-slip layer interface condition for both the sections under consideration.

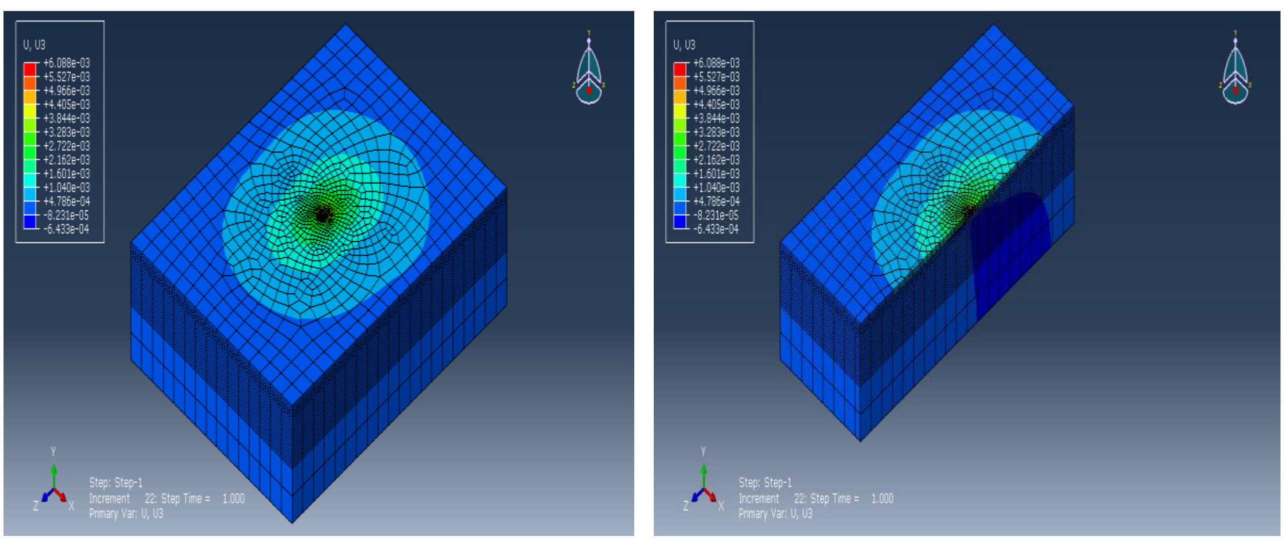

Figure 9: Horizontal Displacement under Normal Load with Horizontal in Full Slip Condition (SB-I)

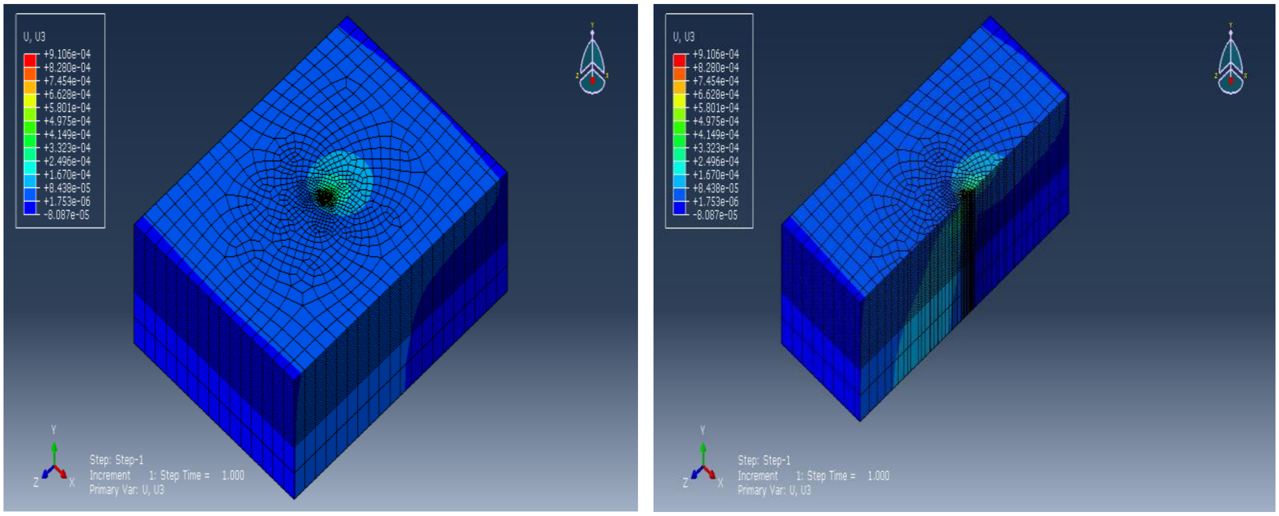

Figure 10: Horizontal Displacement under Normal Load with Horizontal in Full Slip Condition (SB-II)

4.4 INFLUENCE OF PAVEMENT THICKNESSES AND MATERIAL PROPERTIES ON PAVEMENT RESPONSE

Pavement structure is comprised of several layers of pavement materials. These materials vary in physical properties and hence strength such as dynamic modulus and resilient modulus. Also, the material layers have different thicknesses to withstand the applied loads. In this study, one of the objectives was to analyze the effects of pavement layer thicknesses and material properties on pavement performance. Table 14 and Table 15 present the pavement response (critical strains) for Section-I and Section-II, respectively. As the layer thicknesses and material elastic modulus (resilient/dynamic modulus) of the Section–I are lower than those of Section-II, presented in Chapter 3.

Results presented in Table 14 and Table 15 show that strains of Section-I is lower than Section-II as the layers thickness and materials strengths of Section-I is less than Section-II. The results confirm the previous findings of different researchers.

Table 14: Pavement Mechanistic Response (Section – I)

Pavement Layer	Bonding Condition	Critical Strains	Normal Load	Normal Load with Horizontal Load
			Strain (ε)	Strain (ε)
ACWC	Full Bond	ε_{t1}	1.81E-04	2.38E-04
ACBC	Full Bond	ε_{t2}	7.31E-05	8.05E-05
Base (GB)	Full Bond	ε_{t3}	8.53E-05	9.32E-05
Sub-base (GB)	-----	-----	-----	-----
Subgrade	Full Bond	ε_{c}	1.82E-05	1.82E-05

Table 15: Pavement Mechanistic Response (Section – II)

Pavement Layer	Bonding Condition	Critical Strains	Normal Load	Normal Load with Horizontal Load
			Strain (ε)	Strain (ε)
ACWC	Full Bond	ε_{t1}	4.56E-05	6.04E-05
ACBC	Full Bond	ε_{t2}	1.79E-05	2.01E-05
Base (GB)	Full Bond	ε_{t3}	2.07E-05	2.29E-05
Sub-base (GB)	-----	-----	-----	-----
Subgrade	Full Bond	ε_{c}	6.54E-06	6.55E-06

4.5 INFLUENCE OF OVERLOADING ON PAVEMENT RESPONSE

Table 16 presents the results of allowable equivalent single axle loads (ESALs) application based on rut depth. The results show that the ESALs to failure based on rut depth decreases with the increase of load.

Table 16: Effects of Overloading on Pavement Service Life

Section	Load (lb)	Allowable ESALs based on Rutting (Nr)
Section- I	9000	4.104E+04
	18000	3.586E+04
	27000	3.222E+04
Section -II	9000	7.466E+04
	18000	6.996E+04
	27000	6.698E+04

Chapter 05

CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

This research was primarily aimed to evaluate the effects of horizontal shear load on pavement performance. Also, to assess the impact of the pavement layer interface bonding condition on pavement mechanistic response. Mostly the computer programs for pavement design consider only vertical loads and the fully bonded layers interface system as well. But in real conditions, the vehicle apply horizontal load along with vertical load in areas where vehicles accelerate, decelerate or turn such as bus stops, traffic signal, and toll-plaza etc. Sometimes due to poor construction or inappropriate asphalt mix, the asphalt layer and the base layer is not fully bonded and hence can create slippage cracking at the surface of the flexible pavement.

5.2 CONCLUSIONS

A detailed analysis was conducted using the 3D-FE Abaqus software to evaluate the effect of the horizontal shear load on pavement performance and investigate the impact of interlayer bonding conditions on flexible pavement structural response. The findings and conclusions are summarized and presented as follows.

- The results of the analysis show the importance of horizontal shear load in the design of flexible pavement especially in the areas where vehicles brake, accelerate, and decelerate.

- It is concluded that pavement distresses such as slippage cracking and rutting often occurs on signalized intersection, bus stops, toll plaza, and police check posts, due to horizontal shear stress in pavement structure induced by the vehicles braking effect on the road surface.
- The analysis of mechanical response (critical strains) of flexible pavement further revealed that the relative horizontal displacement was zero when the vertical load was applied without horizontal shear load, indicating that vertical load does not cause slippage of pavement layer.
- Based on the results obtained from the analysis, it is concluded that layer interface bonding condition found to be critical in pavement response and critical for pavement structural performance.
- When the two different interlayers bonding conditions were simulated in software, results indicated that high strains induced in the surface layers due to the high concentration of stress within the surface layer.
- It is concluded that slippage cracking is likely to develop on the top surface when the surface layer is unable to withstand the horizontal stresses induced by the horizontal load.
- It is obvious that stresses induced by vertical loads are very critical and hence pavement is designed on the basis of vertical loads without considering the horizontal loads. However, it is worth mentioning that horizontal stresses and strains induced by horizontal loads become critical in the areas where vehicle braking or declaration such as signalized intersection, toll-plaza, bus stops and even airport runway. In that regard, both vertical load and horizontal load should be considered in pavement design to avoid surface cracking and rutting, and to prolong the pavement service life.
- The study also concluded that pavement layer thickness and elastic modulus of the materials have effects on pavement performance.

5.3 FUTURE WORK AND RECOMMENDATIONS

The aim of this study was to evaluate the influence of horizontal shear load and interlayers bonding condition on pavement performance. On the basis of this research, following recommendations are proposed for future work.

- Horizontal shear load should be incorporated in the design of flexible pavement for the areas where vehicles brake, accelerate or decelerate.
- It is suggested to investigate the pavement mechanistic response while considering the visco-elastic properties of hot mixed asphalt instead of elastic properties.
- It is proposed that further research should be conducted to find the effect of dynamic loading condition on pavement response.
- This study should be extended and analyze the effects of overloading on pavement performance under same conditions.
- In future study, the influence of different interface bonding conditions should be evaluated.

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