JIMMA UNIVERSITY

JIMMA INSTITUTE OF TECHNOLOGY

FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING

HIGHWAY ENGINEERING STREAM

Finite Element Modelling for Rutting Prediction of Flexible Pavement Considering the Effects of Sub-grade Material Quality and Gradation of Aggregates

A Thesis Submitted to School of Graduate Studies of Jimma University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Highway Engineering

BY:

GEDAFA TOLERA BELCHA

April 14, 2021

JIMMA, ETHIOPIA

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By
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DECLARATION

I, GEDAFA TOLERA, declare that this thesis entitled “Finite Element Model for Rutting Prediction of Flexible Pavement Considering Effects of Sub-Grade Material Quality & Gradation of Aggregate.” is my original work, and has not been presented by any other person for an award of a degree in this or any other University, and all secondary sources referred to in this work have been duly acknowledged.

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As Master research Advisors, we hereby certify that we have read and evaluated this MSc research prepared under our guidance, by Gedafa Tolera entitled: Finite Element Model for Rutting Prediction of Flexible Pavement Considering Effects of Sub-Grade Material Quality & Gradation of Aggregate

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ABSTRACT

Infrastructure facilities are delivered for economic growth of countries' progress. Road transport is the dominant mode of transport in developing countries like Ethiopia. Major types of distresses observed on major sections of the trunk roads is permanent deformation in the form of rutting. As the roads have experienced deterioration, which has given rise to the need for periodic maintenance and rehabilitation. Pavement deformation or rutting is one of the key distresses that affect the pavement performance. Performance of roads with regards to ride-ability and roughness is known to have a significant cost implication to the road users in terms of operational cost, in addition to affecting their safety and comfort. Aggregates are one of the key building materials used in the construction industry and the largest portion of an asphalt pavement. The general objective of this research is Investigating a modelling tool for rutting prediction of Flexible pavement considering effects of aggregate gradation and quality of sub-grade material.

Hence, in this study, a three-dimensional finite element model was developed, using ABAQUS software, to predict rutting on flexible pavement considering effect of Sub-grade material quality and gradation of aggregate. Flexible pavement modelling was performed using finite element method; a 3-D dimensional finite element model using ABAQUAS (ver.6.14-1) computer program was developed. The material in this model was assumed to be homogenous isotropic linear elastic materials. Natural subgrade materials were modeled in terms of the elastic modulus and Poisson's ratios. The fine finite element mesh used in this study gives the values of stresses and strain in each point. The results of rutting prediction of existing flexible pavement and series of model created are discussed. According, to the modelling results the permanent deformation (rutting) severity are increase as the resilient modulus of the pavement materials is decrease. This thesis presented the static loading response of flexible pavement layers in terms of strain, stress and deflection. Besides, investigate the effects of different aggregate gradation and sub-grade material qualities. It was found that in the elastic domain, considering linearity of the material and stress dependency can significantly affect the critical responses of the pavement layers.

Key Words: *ABAQUS software, Aggregate gradation, Finite Element Model, Flexible Pavement, Modeling Rutting (permanent deformation) and Sub-grade material.*

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ACRONYMS

AASHTO;	American Association of State Highway and Transportation Officials
AC;	Asphalt Concrete
ASTM;	American Society for Testing and Material
CAA;	Course Aggregate Angularity
CBR;	California Bearing Ratio
Eng.;	Engineer
ERA;	Ethiopian Roads Authority
FE;	Finite Element
FEM;	Finite Element Method
HMA;	Hot Mix Asphalt
L;	Length
LL;	Liquid Limit
MA;	Mastic Asphalt
MDD;	Maximum Dry Density
Mr;	Resilient Modulus
Nr;	Number of load
ONRS;	Oromia National Regional State
OMC;	Optimum Moisture Content
PD;	Permanent Deformation
P	Pressure
Pa;	Pascal
PI;	Plastic Index
PL;	Plastic Limit
SMA;	Mastic Asphalt Specimen
VMA;	Voids in Mineral Aggregate

CHAPTER ONE

INTRODUCTION

1.1. Back Ground of the study

Infrastructure facilities are delivered for economic growth of countries' progress. Road transport is the dominant mode of transport in developing countries like Ethiopia, carrying over 90 percent of the passenger and freight transport. It provides the only access to rural communities where over 85 percent of the population lives. Roads create a crucial contribution to economic development and growth. Inadequate road transport infrastructure and lack of mobility pose important constraints to development in developing countries.

Pavement is a durable surface material laid down on ground surface intended to sustain vehicular traffic loading. Permanent deformation (i.e., rutting) of asphalt pavements is one of major types of distress modes experienced in the service life of pavements. Aggregates are one of the key building materials used in the construction industry and the largest portion of an asphalt pavement. Therefore, aggregate characteristics impressively affect the performance of asphalt pavements. Gradation is one of the important characteristics of aggregates affecting permanent deformation of hot mix asphalt.

Permanent deformation (rutting) is observed on the major trunk roads in Ethiopia. Rutting or permanent deformation (PD) is one of the most critical distresses occurring in hot-mix asphalt (HMA) pavements. Despite all of the recent efforts aimed at producing new test methods and better road materials, HMA rutting is still prevalent, particularly in hot regions and/or on highways with heavy truck-traffic loading [1].

Rutting, which appears as longitudinal depressions in the wheel paths of asphalt concrete pavements, has historically been used as a primary criterion for structural performance in many pavement design methods and represents a serious safety issue for road users. The accurate prediction of rutting development is an essential element for the efficient management of pavement systems [2].

A typical asphalt pavement consists of layers of asphalt concrete, and layers of granular base and/or sub-base resting on a prepared subgrade soil. The asphalt concrete layers are the major contributors to the structural capacity of the pavement. Although the condition of the granular layers and subgrade may have a significant impact on the structural condition of the pavement and contribute to pavement permanent deformation (rutting), a number of research studies have indicated that pavement rutting occurs mainly in the asphalt layers [3].

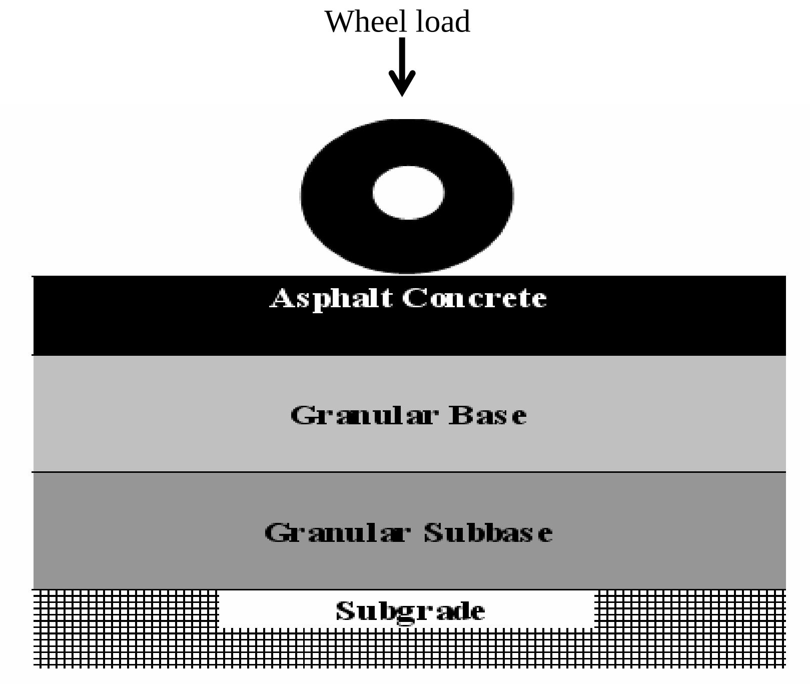


Figure 1.1 Typical asphalt pavement structure sources

The finite element method can be successfully used in the analysis of reinforced pavements to investigate the influence of interface proprieties between HMA layers and the gird [4].

Choosing a suitable constitutive equation to model creep behavior of asphalt mixtures and calibration its parameters using results of dynamic creep and resilient modulus tests, Finite Element Method (FEM) can be used to simulate rutting process of pavement structure under external load repetition and determine each layer contribution to rut depth [5].

Properly specified pavement deterioration models are an important input for the efficient management of pavements, the allocation of cost responsibilities to various vehicle classes for their use of the highway system, and the design of pavement structures [6].

1.2. Statement of the Problem

Permanent deformation (rutting) is which display on pavement surface and most common pavement distresses. Rutting repair can be very expensive and disruptive to traffic operations. In recent years, many of the major trunk roads of Ethiopia have also experienced an increased in the severity and extent of permanent deformation (rutting) over significantly visible stretches. Permanent deformation in paved roads can be attributed to various factors such as the pavement structure, quality of individual constituent pavement materials, magnitude and regime of loading, environmental factors, such as moisture temperature, and others. Asphalt concrete mixes evaluation for their tendency to rutting has been an important research field for many years. The prediction of the amount and growth of permanent deformation or rutting in flexible pavements for pavement design is an important aspect. Aggregate presents major portion of asphalt concrete and sub-grade layer is the one that carry others pavement layers. In this research effect of aggregate gradation and sub-grade quality on resistance to rutting of asphalt mixtures is found out. The finite element method (FEM) has been used in recent years for asphalt materials and pavement performance analysis. Hence, in this study Finite Element Method (FEM) is used to predict rutting depth of flexible pavement considering effects of aggregate gradation and different sub-grade material qualities.

1.3. Research Question

The study will give answer for the following questions: -

1. Does aggregate gradation have effects on permanent deformation (Rutting) formation on HMA and relationship with its severity?
2. Does 3D FE modelling is effective in prediction of rutting performed in flexible pavement?
3. Does a structural response of flexible pavement vary with various quality of sub-grade and different aggregate size?

1.4. Objective of the study

1.4.1. General Objective

General objective of this thesis is; - Investigating a modelling tool for rutting prediction of Flexible pavement considering effects of aggregate gradation and quality of sub-grade material

1.4.2. Specific objectives

The specific objectives of this study are;

- To determine effects of aggregate gradation on rutting development of HMA and its relationship with severity of permanent deformation (rutting).
- To determine effectiveness of using 3D FE modelling in prediction of rutting performed in flexible pavement.
- To determine the structural response of flexible pavement having different quality of sub-grade and different aggregate size due to traffic loads using the 3D FE model.

1.5. Significance of the study

This research attempts to contribute on investigating a model tool for rutting prediction of Flexible pavement. This is expected to be achieved through Finite Element Model (FEM) considering effects of aggregate gradation and quality of sub-grade material and rutting expressed in terms of rut depth.

This research attempts to contribute;

- The proper understanding of factors of aggregate gradation and sub-grade material on rutting performance.
- Motivate those who are interested to conduct further research on pavement structure by finite element program.
- Countermeasure for pertinent severely and early-rutted trunk road segment in Ethiopia.
- Effectiveness of using 3D FE model in flexible pavement design.

1.6. Scope and limitation of the study

The research focuses on investigating a model tool for rutting prediction of flexible pavement considering effects aggregate gradation and quality of sub-grade material. In this study, factors of aggregate gradation and quality of sub-grade are studied. For this purpose, a pertinent severely and early-rutted trunk road segment, Didessa River-I to Bedelle road, is selected for the case study.

This study is supported by series of laboratory experiments (Aggregate gradation test & CBR test for sub-grade soil to be used in FEM) and different types of literatures reviewed. However, the findings of the research are limited to representative sample soil and sample aggregate along the road section from different location is collected in this study. The relevant laboratories that are conducted are aggregate gradation test and CBR test.

The test results are used in prediction of rutting of flexible pavement using finite Element (FE) program, by ABAQUS software considering effect of different aggregate size and specified sub-grade.

CHAPTER TWO

RELATED LITERATURE REVIEW

2.1. Rutting Definition

Permanent deformation in asphalt layers which manifestation on pavement surface is named rutting which represents one of the most significant distress of asphalt pavements [7]. Rutting is one of the primary distresses in hot-mix asphalt (HMA) pavements. In a well-designed HMA mixture, aggregate should be well-proportioned to develop a stable skeleton and provide enough resistance against shearing load. An optimized gradation usually ensures enough contacts between coarse and fine aggregates. In addition, the shapes and surface textures of aggregate (both coarse and fine) intimately influence the shear resistance of aggregate structure. HMA mixtures containing angular and rough aggregates have been believed to be more rut resistant [8-11].

Rutting is a main distress encountered in asphalt pavements, especially when the temperature is high. Rutting is caused by the accumulation of permanent deformation in all pavement layers under the action of repeated traffic loading. Among the contributions of rut depth by the various pavement layers, the cumulative permanent deformation in the surface course of asphalt pavement is known to be responsible for a major portion of the final rut depth measured on the pavement surface. So, rutting occurs only on flexible pavements, as indicated by the permanent deformation or rut depth along the wheel paths [12].

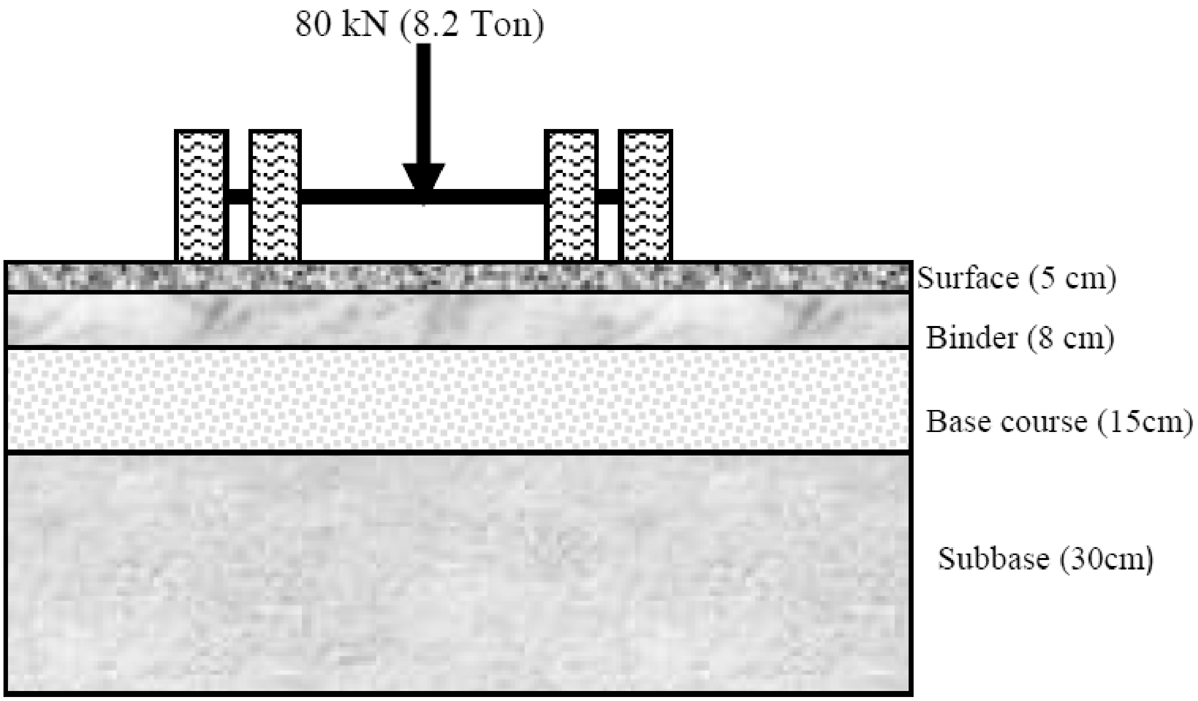


Figure2.1. Pavement design due to rutting criterion source

Ruts are depressions which occur in the pavement’s wheel path as a result of traffic loads. The most common recent cause of rutting is associated with the HMA layer, especially on routes with heavy loads and high tire pressures; much of this rutting is attributed to improper mix design. Some of the most common mistakes when designing heavy duty HMA mixtures are, selection of an asphalt content that is too high, use of excessive filler material (minus 200 material); and use of too many rounded particles in both coarse and fine aggregates in the HMA, the single largest contributor to rutting in HMA is excessive asphalt content. Rutting resulting from accumulation of permanent deformation in the asphalt layer is now considered to be the principal component of flexible pavement rutting. Permanent deformation in asphalt layers is caused by an asphalt mixture that is too low in shear strength to resist the repeated heavy loads to which it is subjected. Asphalt pavement rutting from weak asphalt mixtures is a high temperature phenomenon, it most often occurs during the summer when high pavement temperatures are evident. Mixture factors that causing rutting including: (1) aggregate gradation, (2) aggregate absorption, (3) aggregate affinity for asphalt, (4) aggregate size, (5) coarse aggregate shape, (6) coarse aggregate texture, (7) fine aggregate shape (angularity), (8) mineral filler properties, (9) asphalt content, (10) performance grading, (11) plastic fines in the fine aggregate, (12) low air voids and (13) performance graded asphalts [12,13].

It has been reported that rutting increases with an increase in temperature even under well controlled loading conditions and asphalt mixtures built up more resistance to flow during the process of deforming under repetitive loading [14].

Based on these gradations, it is found that by reducing the air voids percentage and voids in mineral aggregate up to the certain amount, resilient modulus of the mixture will be increased and therefore deformation and non-recoverable strain will reduce. Gradation bands placed in the upper limit of asphalt mixture design gradation chart show the best performance against rutting while lower bands have the highest amount of permanent deformation [15].

Rutting mainly occurred at MA layer, but very small deformation was observed at SMA-13 layer. Rutting resistance of MA layer should be an important consideration in terms of the pavement structure design [16].

The mixture with fine gradation band has the highest stability and the course one has the lowest. Also asphalt mixture with fine gradation band has the highest flow parameter and also the course one has the minimum of flow parameter in three gradation bands. Furthermore, the mixture with coarse gradation band has the lowest special gravity but it has the highest amount of air voids and VMA. The middle gradation mixture has the lowest air voids percentage and VMA but it has the highest special gravity [17].

2.2. Mechanism of Rutting

Rutting is one of the most serious distresses in asphalt pavements affecting the pavement performance and service life. Therefore, the accurate simulation of rutting in asphalt pavements is essential for improving their performance and management. The main mechanism of rutting is the accumulation of permanent deformation that increases progressively with increasing number of loading cycles [18]. The finite element model developed for rutting analysis in flexible pavement give a good indication to find the distribution of stress in the pavement layers. The fine finite element mesh used in this study gives the values of stresses and strains in each point with higher accuracy. The stress has larger values near the applied load where larger deformations occur [12].

2.3. Causes of Rutting

Rutting in paved roads can be attributed to various factors such as the pavement structure, quality of individual constituent pavement materials, magnitude and regime of loading, environmental factors, such as moisture temperature, and others. Despite the fact that HMA mix design has evolved from the conventional empirical mix design approaches (Marshall and Hveem), to the state-of-the-art and more advanced Super pave procedures, due to the lack of technological advancement, the customary Marshall mix design and testing method, bearing the effects of its empiricism, is what is currently being utilized to design ' better' performing HMA mixtures [7].

2.4. Material & mixture properties of Flexible Pavement which resist rutting

Material properties play a vital role to determine the structural and functional performance of pavement layers during its service life. Pavement deformation or rutting is one of the key distresses that affect the pavement performance. The strength parameters of subgrade and granular layer are correlated with the permanent deformation’s characteristics [19].

Rutting resistance of asphalt paving mixes is affected by the mix gradation and type of aggregate. Coarser gradation (3A) had the highest resistance to rutting for all types of aggregate, while open graded mixes (2C) had the lowest resistance. Dolomite had the highest resistance for all types of gradations. Marshall Flow had the highest linear correlation with rutting, with coefficient of determination (R2) of 0.74 [20].

2.4.1. Aggregates

Aggregate is the major component in HMA and the quality and physical properties of this material has a large influence on mix performance. The qualities required of aggregates are described in terms of shape, hardness, durability, cleanliness, bitumen affinity and porosity.

In addition to these properties, the micro texture of the aggregate particles will also strongly influence the performance of a compacted HMA layer. Smooth-surfaced river gravel, even partly crushed, may not generate as much internal friction as a totally crushed aggregate from particles having a course micro texture.

The aggregate should have the following characteristics;

- Be angular and not excessively flaky, to provide good mechanical interlock;
- Be clean and free of clay and organic material;
- Be strong enough to resist crushing during mixing and laying as well as in service;
- Be resistant to abrasion and polishing when exposed to traffic;
- Be non-absorptive - highly absorptive aggregates are wasteful of bitumen and also give rise to problems in mix design; and
- Have good affinity with bitumen - hydrophilic aggregates may be acceptable only where protection from water can be guaranteed or a suitable adhesion agent is used. (ERA manual 2013)

2.4.1. Aggregate Gradation

Aggregate is the major structural framework of asphalt mixture to absorb and control different stresses on the pavement [21]. Gradation is feasibly the most important property of an aggregate. It affects almost all the important properties of HMA, including stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance, and resistance to moisture damage. Therefore, gradation is a primary consideration in asphalt mix design, and the specifications used by most agencies limit the gradations that can be used in HMA [22].

The effects of gradation on permanent deformation accumulation were more noticeable at the higher shear stress ratio values. This was seen for materials M2 to M4, where the differences in accumulated permanent strains between samples tested at the source and engineered gradations were the highest for the SSR of 0.75 and the lowest for the SSR of 0.25 [23].

2.4.1.1. Fine aggregate

The effects of varying grain size distribution on shear strength of aggregate materials were primarily dominated by the number of fines passing No. 200 sieve. Material M2 with higher fines content, especially with plastic fines (i.e. PI = 6), was significantly weaker than the same material with lower fines content [24].

2.4.1.2. Coarse aggregate

The coarse aggregates used for making HMA should be produced by crushing sound, unweather rock or natural gravel. Gravel should be crushed to produce at least two fractured faces on each particle (ERA manual 2013). The aggregate interlock and internal friction is responsible for the HMA pavement performance. Coarse aggregate angularity had an effect on the rutting performance of mixtures, where the rutting performance was generally improved with increase in coarse aggregate angularity. Moreover, increase in coarse aggregate angularity also increased the in-place VMA of HMA mixtures [25].

Coarse aggregate angularity (CAA) has an important effect on the rutting characteristics of HMA. More angular coarse aggregates can increase the stone-on-stone interlocking and consequently reduce the rut-susceptibility of mixtures [26].

2.4.2 Sub-grade

The strength of the road subgrade for flexible pavements is commonly assessed in terms of the California Bearing Ratio (CBR) and this is dependent on the *type of soil*, its *density*, and its *moisture content*. Direct assessment of the likely strength or CBR of the subgrade soil under the completed road pavement is often difficult to make. Its value, however, can be inferred from an estimate of the density and equilibrium (or ultimate) moisture content of the subgrade together with knowledge of the relationship between strength, density and moisture content for the soil in question. This relationship must be determined in the laboratory. The density of the subgrade soil can be controlled within limits by compaction at suitable moisture content at the time of construction. The eventual moisture content of the subgrade soil is governed by the local climate, the depth of the water table below the road surface, and the provisions that are made for both internal and external drainage [27].

Roadbed Soil Resilient Modulus (MR)

A material's resilient modulus is actually an estimate of its modulus of elasticity (E). While the modulus of elasticity is stress divided by strain for a slowly applied load, resilient modulus is stress divided by strain for rapidly applied loads – like those experienced by pavements [28]. The Resilient Modulus (MR) is a measurement of the stiffness of the roadbed soil (AASHTO, 1993).

It is recognized that many agencies do not have equipment for performing the resilient modulus test. Therefore, suitable factors are reported which can be used to estimate MR from standard CBR, R-value, and soil index test results or values. A widely used empirical relationship developed by Heukelom and Klomp (1962) and used in the 1993 AASHTO Guide is equation [29].

$M_g(psi) = 1500 * CBR$ ……………………………………. Equation 2.4.2

The resilient modulus of the hot mix asphalt is the most common method of measuring stiffness modulus. The test procedures for conducting this test are described in ASTM D4123 [30]. In which MR is the resilient modulus in psi. The coefficient, 1500, could vary from 750 to 3000, with a factor of 2. Available data indicate that Eq. 1 provides better results at values of CBR less than about 20.

2.5. Modeling

2.5.1. General

Modelling is used in pavement engineering to evaluate the behavior of a layered structure in response to a given traffic load. The modelling approach in essence is to simplify a complex matter in order to arrive at a possible solution. The same approach is used in flexible pavement engineering. Simplification can apply to the layer geometry, load or material characteristics. The goal of modelling is to provide a close simulation of the actual problem. This can be achieved by improving the simplification of previous models. This section reviews previous scientific attempts to model layered flexible pavement structures [31]. During the past year's Finite element modeling of flexible pavement has been used by many researchers to simulate pavement responses and investigate materials' behavior to different forms of traffic loading.

The finite element method is used for prediction of rutting of flexible pavement by taking in to account effects of aggregate gradation and sub-grade material qualities. Experimental tests are needed to provide input data to the model and for the purpose of verification of simulation results. When the model has been validated it can be used for parametric studies to investigate the influence of various parameters. Based on the nature of the finite element analysis, suitable pavement dimension going to be analyzed; thickness and boundary conditions for the model to be analyzed will be designed or determined. Therefore, to optimize computation times and provide results comparable to the experimental data, the number of trials, gradation of aggregate and sub-grade material quality and suitable dimensions will be determined.

Experimental tests are needed to provide input data to the model and for the purpose of verification of simulation results. When the model has been validated it can be used for parametric studies to investigate the influence of various parameters.

Predication model in pavement performance is the process that used to estimate the parameter values which related to pavement structure, environmental condition and traffic loading. Many local models are developed for predicting permanent deformation [32].

2.5.2. Rutting Prediction of Flexible Pavement

Rutting is simulated as a vertical displacement in the model analysis. The displacement is considered as a response of applying traffic repeated loads. FEA has been proven suitable for application to complex pavement problems. Although using three-dimensional (3D) finite element models can solve all problems that can be solved with two-dimensional (2D) models, it is very expensive to use 3D models in terms of data preparation and computational time [33]. The pavement structure has large longitudinal dimension, which makes it suitable for using 2D plane strain models when studying transverse profiles [34]. Hua compared the FEA results of pavement rutting using a plane strain model versus a 3D model (Hua J. Finite element modeling and analysis of accelerated pavement testing devices and rutting phenomenon.).

The mechanical (analytical) design methodology is based on predictions of pavement performance. There are many components and subsystems involved in making these predictions: inputs such as traffic loading, environmental conditions and material properties; the pavement response model; and the distress prediction model. Each of these components has an inherent inaccuracy or uncertainty. In general, the level of inaccuracy or uncertainty in the material inputs and, especially, the distress prediction model will be far greater than that of the pavement response calculations. Within this context, for example, the additional modest differences between 2D vs. 3D pavement response calculation may be insignificant in practical terms [35].

2.5.2.1. Local Rutting Models

Predication model in pavement performance is the process that used to estimate the parameter values which related to pavement structure, environmental condition and traffic loading. Many local models are developed for predicting permanent deformation [36]. predict the following model Eq. 1:

$\varepsilon_{vp} = 4.7195\times10^{-9}\times\sigma^{0.868}\times t^{0.658}\times T^{1.974}\times \log \varepsilon_{p(N)} = \log \varepsilon_{vp} + S\log(N)$ -------(2.5.2a)

Where:

ε_{vp} = Visco-plastic strain

σ = Level of applied stress
t = Time of loading and
T = Degree of temperature

The classical rutting analysis is focused on protecting the sub-grade, leaving the issue of sufficient rut resistance of asphalt layers to mix designers. The conventional procedures of pavement analysis are based on limiting the vertical stress or strain at the top of the subgrade to control rutting of the entire pavement structure and the tensile stress or strain at the bottom of the lowest hot-mix asphalt layer to control fatigue cracking [37]. A typical rutting prediction model used in pavement design is given in [38].

$$N_r = 1.077 * 10^{18} (10^{-6}/\mathcal{E}_v)^{4.4843} \quad \text{--------------------------}(2.5.2b)$$

Where:

N_r = Load applications

$\mathcal{E}_v$ = vertical compressive strain at the top of subgrade

The output from the pavement response model used in the MEPDG are the stresses, strains and displacement within the pavement layers. Compressive vertical stress/strains within the hot-mix asphalt layer are used for rutting prediction in HMA layers. Rutting is calculated from the following formula [38].

$RD = \sum_{i=1}^{n} \mathcal{E}ph$

Where:

RD = Pavement permanent deformation (rut depth)

Ɛv = total plastic strain in n layers

h = thickness of n layer

2.6. ABAQUS software

ABAQUS is a set of powerful engineering simulation programs, can solve problems ranging from relatively simple linear analyses to the most challenging nonlinear simulations based on the finite element method. It contains an extensive library of elements that can model virtually any geometry.

The commercial finite element software ABAQUS will be used to build rutting prediction model by taking in to account effects of aggregate gradation and sub-grade material qualities to evaluate the changes in pavement response properties. This program has been widely used in other research to model hot mix asphalt pavements systems because this type of model can include consideration of the behavior of viscoelastic materials under repeated loadings.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1. Study area

The study area for this research is located in Buno Bedele zone ONRS Oromia National Regional State which covers a distance of 62km from Didesa River Bridge-I to Bedelle Town. The study area mainly focused specially on investigating rutting model considering effect of aggregate gradation and quality of sub-grade.

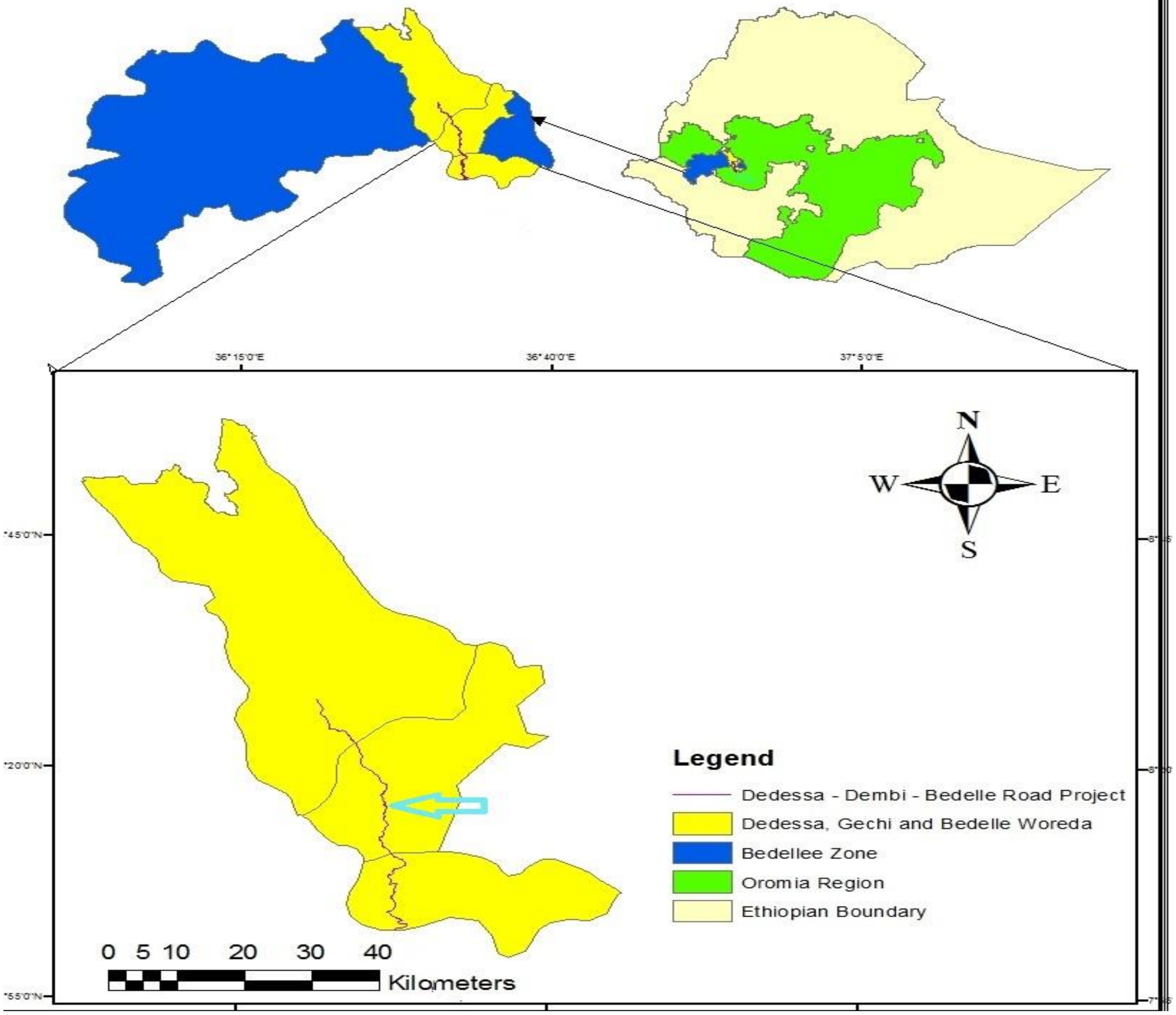


Figure 3.1: Study area

3.2. Methodology

The study methodology of this research consists of the following main tasks

- Performed Experimental work
    - Degree of Compaction and Voids Analysis of Core Samples
    - Extraction of Asphalt and Aggregates and Binder Content Determination
    - Aggregate Gradation
    - Standard Proctor Test
    - California Bearing Ratio
    - Atterberg Limits
- Finite element modeling for Rutting Prediction of the flexible pavement under repeated load.
- To compare rutting depth under load repetition with different aggregate gradation and different subgrade material quality.

3.3. Study design

So as to accomplish the objectives the investigation is done by utilizing different computer skills and attend great theoretical background and analysis done by different researchers related to rutting prediction of Flexible Pavement using effects of aggregate gradation and sub grade material qualities.

The stages involved in the study include: -

- Design of research objective and question
- Taking sample from site
- preparation of sample for laboratory tests
- Review As-built design of flexible pavement to determine pavement structure thickness
- Finite element analysis of the of the pavement layer.

The finite element method is a very powerful for analyzing the pavement layers and their contribution in formation permanent deformation (Rutting) of Hot Mix Asphalt. ABAQUS is employed to simulate the response of pavement layer.

3.4. Research procedure

The first steps of this research are problem definition followed by design of research objective and question then sample collection was performed. For the case of this study the sample collected are aggregates of different size of wearing and base course and sub grade materials.

Following to the above step laboratory tests were performed. The laboratory is the primary input for my study. The test begins with the evaluation of aggregate size and properties of sub-grade materials. Then test results were converted and compiled to possible input values for FEM; with determined different aggregate size and sub-grade material quality, the pavement thickness reviewed from As-built drawing and reports. Next to this modeling with different aggregate size and different sub-grade quality were analyzed.

Finally, discussion, recommendation and conclusion of the research was performed.

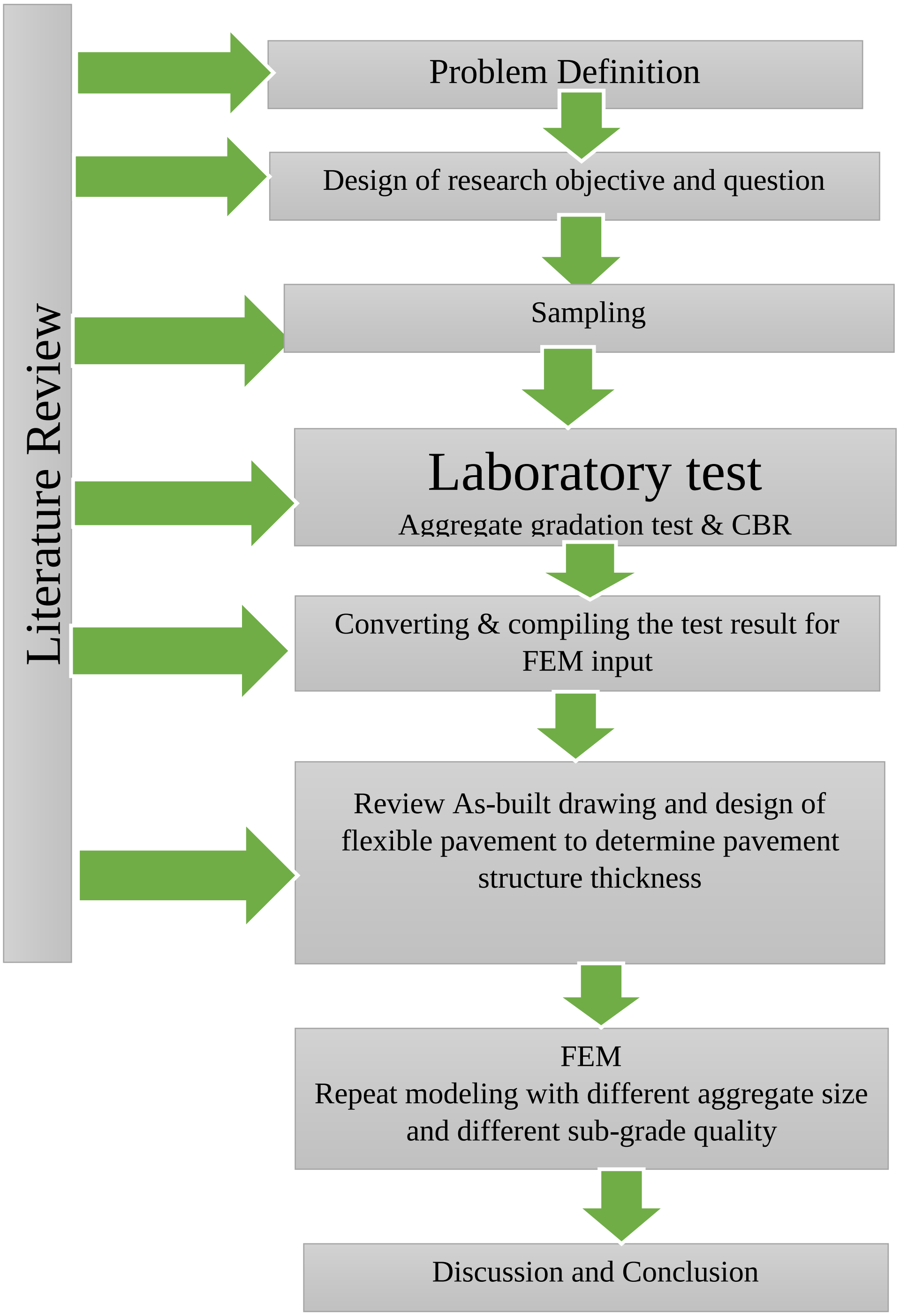


Figure 3.4: Research design flow

3.5. Populations

The total number of populations that considered in my studies area includes; The permanent deformation or rutting formed on Dedessa River Bridge–I – Dembi – Bedelle Road Project, aggregate gradation and sub-grade materials quality.

3.6. Sample size and sampling technique

3.6.1. Sampling technique

The sampling technique used for this research was a purposive sampling which is non-probability method. The sampling technique is projected based on the laboratory test performed on the asphalt aggregate and sub grade soils/materials to investigate material property of flexible pavement. Moreover, the finite element model for rutting prediction of flexible pavement layers after determines material properties of the pavement layers.

3.6.2. Sample size

For this study, pavement layers such as wearing coarse, base course and sub grade soils was taken from deformed road section of Didessa River-I to Bedelle. From those based performance of pavement, the sample were taken from road section which have permanent deformation (rutting); this were determined by observing visually the road segment. The samples were taken by cutting with asphalt concrete cutter and for excavation shovel was used. The samples for CBR were taken at a depth of below 1.5 m to remove organic material.

3.7. Rut Depth Measurement

The rut depth measurement was accomplished using a straight edge and wedge. The rut depth measurements were made on a number of locations, in which the source of rutting was considered. For each location, rut depth measurements were conducted on three spots of 1m interval, along the rut line, and the average value was taken. The details of the rut depth measurements and related site conditions are included in table below.

Table3.7. On site Rut depth measurement

Sample Location ID	Station	Measured average rut depth(mm)	Horizontal Alignment (radius)	Vertical Alignment (grade)
1	1+500	33.4	RHS Curve, R=200m	5%
2	2+700	47.5	On tangent	6%
3	3+000	17.5	On tangent	6%
4	4+700	52.6	On tangent	7%

Figure3.7. Photo rut depth measurement

3.8. Laboratory Tests

This study is supported by the following laboratory experiments of all existing pavement layers for the successful accomplishment of the research.
Such as;

- Degree of Compaction and Voids Analysis of Core Samples
- Extraction of Asphalt and Aggregates and Binder Content Determination
- Aggregate Gradation
- Standard Proctor Test
- California Bearing Ratio
- Atterberg Limits

3.8.1. Sample Collection

Following Condition Survey of the Road segments and gathering information, Four (4) pavement layers were taken from different Five (5) locations of Dedessa River Bridge-I – Dembi – Bedelle Road Project. From those two, which have high rut depth, were selected by observations and by rut depth measurement, because of time constrain and the intension of the study is to predict rutting model by considering aggregate gradation and sub grade material quality. Those are found at station 2+700 and 4+700 from Dedessa River Bridge –I. While sampling first Asphalt Concrete is sawed by Asphalt Cutter and excavation was made manually using the shovel and Pick axe.

Figure3.8.1. Photo of the two selected Sample

3.8.2. Sample preparation

3.8.2.1. Extraction of Asphalt and Aggregates and Binder Content Determination

These methods cover the quantitative determination of bitumen in hot-mixed paving mixtures and pavement sample. The quantitative extraction of bitumen from as outlined in AASHTO designation T 164-97 was adopted, with the exception of the use of benzene instead of the specified extracting reagents such as Trichloro ethylene and Methylene chloride. The procedure has been applied on two out of the three core samples the same samples which have been used to determine in-place Marshall Stability and flow tests. The samples were first broken-up with their weights initially recorded. The bowl containing the test portion and solvent was then placed in the centrifuge extractor, with dry filter ring fit around the edge of the bowl. The centrifuge was set to revolve, and sufficient extractant (benzene), of measured volume, was added. The procedure was repeated until pure benzene begins to drain. All of the aggregate in the centrifuge bowl was then carefully transferred in to a tared metal pan, and oven dried to a temperature of around 110°C. To determine the filler content, the benzene-bitumen-filler mix was stirred thoroughly, and 100ml of sample was taken. The 100ml sample was then heated in a cylinder flame. Upon heating, first the benzene evaporates, and then the asphalt burns and adheres to the sides of the container, leaving the mineral filler concentrated around the middle of the container.

The asphalt was then carefully cleaned from the container until the 'ash-like' mineral filler remains. The weight of filler obtained from the 100ml of the benzene-bitumen-filler was then extrapolated to obtain the total weight of mineral filler in the entire benzene-bitumen-filler mix. This mineral filler weight along with the additional miner filler content from the filter paper (obtained by oven-drying and weighing), was used to determine the total weight of mineral filler in the total mix. The total mass of the extracted aggregates was determined by adding the total weight of fillers to the mass of oven-dried aggregate after extraction. The mass of bitumen will finally be determined from the difference between the mass of the sample before extraction and the mass of total aggregates, and the corresponding bitumen content will be expressed as the mass of bitumen to the total mass of sample.

Figure3.8.2.1 Photo of Bitumen Extraction

3.8.2.2. Determination of Degree of Compaction and Voids Analysis of Core Samples

This method covers determination of the percent air voids in compacted dense and open bituminous paving mixtures. as outlined in AASHTO designation T 269-94 for dense bituminous paving mixtures, determine the bulk specific gravity of the compacted mixture either by AASHTO designation T 166 or T 275. Determine the theoretical maximum specific gravity in accordance with T209 on a comparable bituminous mixture to avoid the influence of different gradation, asphalt content.

3.8.2.3. Aggregate Gradation

The gradation of aggregate is normally expressed as total percent passing various sieve sizes. It affects the HMA performance in many respects including stiffness, durability, stability, permeability, workability, resistance to rutting and fatigue cracking, frictional resistance. Therefore, gradation is a critical consideration in asphalt mix design. Aggregate gradations are described as dense (well graded), open (uniformly-graded), and gap-graded, as shown in Equation 3.1 proposed one of the best-known gradations for maximum density [39].

The particle size distribution of the extracted aggregates was determined on the basis of the 0.45 Power Gradation Chart. The 0.45 Power Gradation Chart was plotted with sieve sizes raised to 0.45 power on the X-axis, and percent material passing on the Y-axis. The gradations were then evaluated in comparison with the Maximum Density Curve, for the respective nominal maximum aggregate sizes, which was obtained using the following formula: -

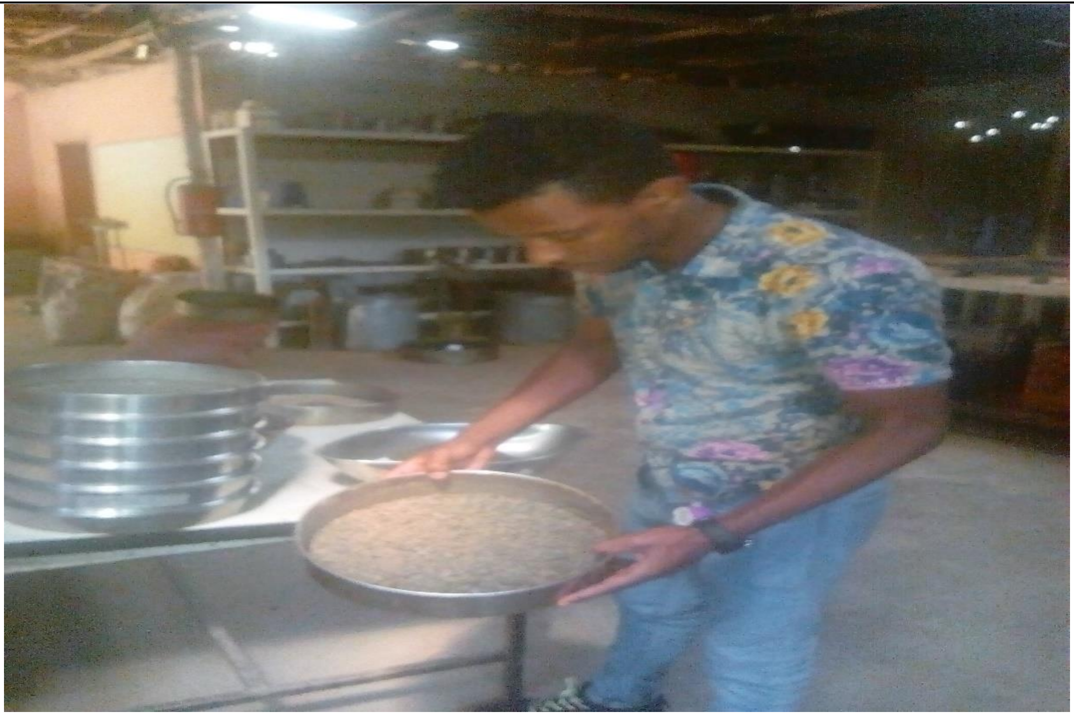
$$P = 100 * (\frac{d}{D})^n \quad \text{------------------------------------} 3.1$$

Where:

P = % finer than the sieve

d = aggregate size being considered

D = maximum aggregate size to be used



Figuure3.8.2.3. Photo of test while aggregate gradation analysis

3.8.2.4. Standard Proctor Test

These methods of test are intended for determining the relation between the moisture content and density of soil compacted in a mold of given size with a 2.5 kg rammer dropped from a height of 305mm (AASHTO 99 – 95). This laboratory test was conducted to determine optimum water content at maximum dry density of soil. Compaction is when mechanical loads applied to soil result in expulsion of air, increase in bulk density and resistance to penetration. The laboratory standard proctor test was performed as per AASHTO T 99-95. The test was performed on disturbed samples of soil passing sieve sizes 4.75mm or 19mm mixed with water to form samples at various moisture contents ranging from the dry state to wet state. These samples were compacted in three layers at 25 blows per layer in accordance with the specified nominal compaction energy of standard proctor test. Dry density was determined based on the moisture content.

Fig.3.8.2.4. Photos Compaction test and procedures

3.8.2.5. California Bearing Ratio

This method is to determine the relationship between force and penetration. The CBR is expressed by force exerted by the plunger and the depth of its penetration into the specimen; it is aimed at determining the relationship between force and penetration. A three-point CBR test at 10, 30 and 65 blows were conducted according to AASHTO T193 and the CBR values at 95% MDD was determined. The CBR test indirectly measures the shearing resistance of a soil under controlled moisture and density conditions. The CBR is obtained as the ratio of load required to affect a certain depth of penetration of a standard penetration piston into a compacted specimen of the soil at some water content and density to the standard load required to obtain the same depth of penetration on a standard sample of crushed stone. The equation to be computing the CBR value is as follows.

$$\mathrm{CBR}(\%) = \frac{\text{Applied Load on samPle}}{\text{Standard Load on the crushed stone}} \mathrm{X}100 \ldots\ldots\ldots\ldots\ldots\ldots 3.2$$

Figure3.8.2.5. Photo of CBR test

3.8.2.6. Atterberg Limits

The test procedure adapted for the determination of Liquid limit, Plastic Limit and plasticity index of soil sample was in accordance with AASHTO T89-94 and T90-94 respectively. A sample weighting about 200 gm was taken from the mixture prepared for liquid limit and plastic limit test for each sample. Soil samples were first air dried and pulverized and then sieved with number 40 sieve. The liquid limit of soil had been determined by using Casagrande apparatus. The plastic limit of soil was determined by using soil passing through a 475 µmm sieve and rolling 3-mm diameter threads of soil until they began to crack.

Figure3.8.2.6. Photo of Atterberg limit test

3.9. Study variables

The study variable both dependent and independent which display the finite Element model for rutting prediction of Flexible Pavement of constructed and maintained road section. The independent variable which is more related to specific objectives and the dependent variable more related to general objectives.

3.9.1. Independent variable

- Extraction of Asphalt, Aggregates and Binder Content Determination
- Aggregate Gradation
- Atterberg Limits
- Standard Proctor Test
- California Bearing Ratio

3.9.1. Dependent variable

- Finite Element model for rutting prediction of Flexible Pavement

3.10. Data process and analysis by laboratory & ABAQUS software

Rutting prediction of flexible pavement is modeled considering effects of aggregate gradation and sub-grade quality using nonlinear FEM software. Rutting predictions are modeled with different size of aggregate gradation, good sub-grade and weak sub-grade this will be taken from laboratory test result. The modeling is done with appropriate inputs for material properties by selecting appropriate inputs from ABAQUS 6.14 library. This model is subjected to traffic load. Sensitivity analysis are done by applying traffic load as a parameter and the resulted combinations response is taken and permanent deformation is done to relate this input parameters to determine the effects of aggregate gradation and sub-grade material quality on rutting prediction.

3.11. Finite element Modelling

FEM is a new engineering method based on computer technology to solve complicated problems in engineering. Mathematically, it is a numerical approach to finding estimated solutions to a set of differential equations with defined boundary values. FEM employs variation calculus procedures to minimize a defined error function. In this approach, a medium of physical problem is discretized to a smaller domain (called an element) and the partial differential equation (such as an equilibrium equation) is solved in each of these elements. The connectivity of the elements should satisfy certain conditions (usually continuity) and the solution should be compatible with defined loading and boundary conditions. Having solved the problem in the element, a general solution for the whole domain may be predicted [40]. The finite element method is one of the most powerful techniques used to simulate the behavior response for different pavement engineering problem. In this study the following modeling was considered: -

- The first FE model created was to study the existing flexible pavement which found in Buno Bedelle Zone.

- The 2nd different models were developed to study the effects of different aggregate gradations and subgrade material quality on rutting performance and on its severity.
- Determination of rutting depth from vertical displacement

All these models were developed using the commercial software ABAQUS

3.11.1 Materials Properties

The material in this model was assumed to be homogenous isotropic linear elastic materials because of nonlinear behavior requires a lot of input parameters and computational time. Therefore, natural subgrade materials were modeled in terms of the elastic modulus and Poisson’s ratios.

Resilient Modulus

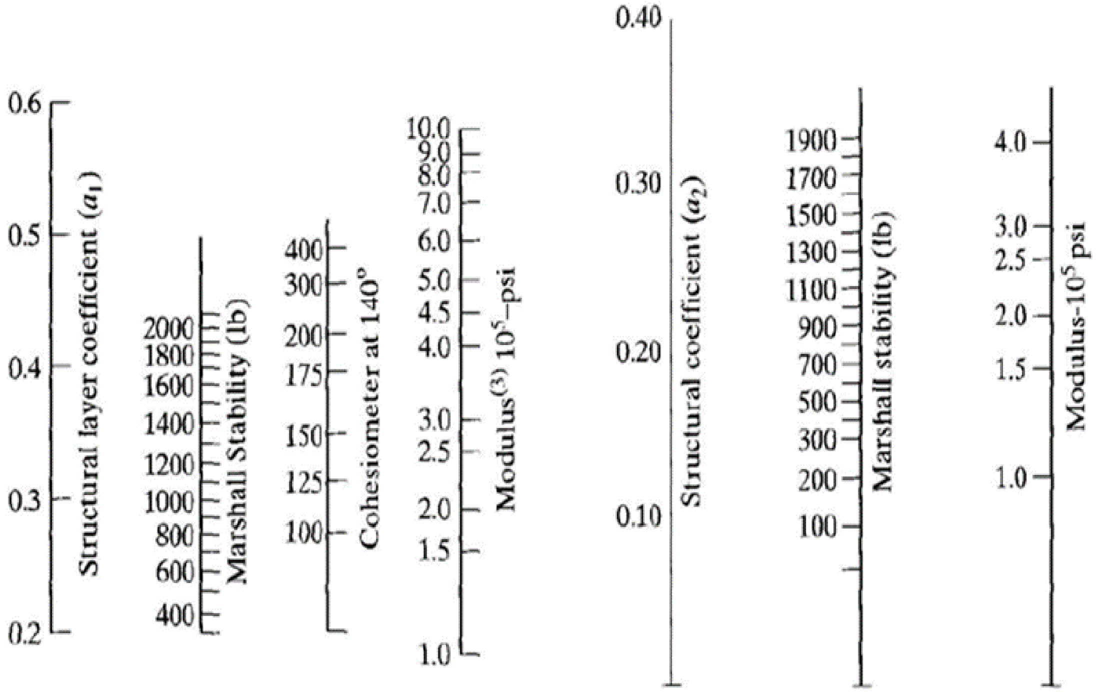
The resilient modulus is the elastic modulus to be used with the elastic theory. It is well known that most paving materials are not elastic, but experience some permanent de - formation after each load application. However, if the load is small compared to the strength of the material and is repeated for a large number of times, the deformation under each load repetition is nearly completely recoverable (and proportional to the load) and can be considered elastic.

Models used for determining the "Mr. Resilient Modulus " value can be classified into two main categories;

- ✓ The model which is not the stress dependent characteristics of materials, generated from some empirical correlations based on the California Bearing Ratio (CBR) test or stabile meter test (R).
- ✓ Models developed from the repeated load triaxial test results, describing the stress-dependent non-linear behavior of the materials.

It is recognized that many agencies do not have equipment for performing the resilient modulus test. Therefore, suitable factors are reported which can be used to estimate MR from standard CBR, R-value, and soil index test results or values. A widely used empirical relationship developed by Heukelom and Klomp (1962) and used in the 1993 AASHTO Guide is equation [41].

$M_g(psi) = 1500 * CBR$ …………………. Equation 3.12.1 For **CBR** is less than 20% [41]



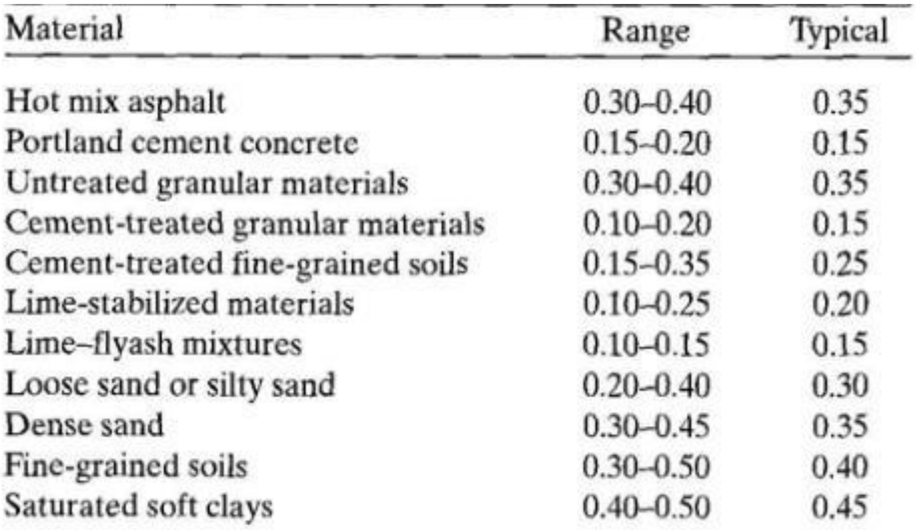
(a) Surface Course (b) Base Course

Figure 3.11.1Correlation charts for estimating resilient modulus of HMA (1 lb = 4.45 N, 1 psi = 6 .9 kPa) [42].

Poisson's ratio

By measuring the axial and lateral strains during a resilient modulus test, the Poison ratio can be determined. Because Poisson ratio has a relatively small effect on pavement responses, but due to lack of resilient modulus test it is customary to assume a reasonable value for use in design, rather than to determine it from actual tests. For Poisson's ratio the common practice is to use typical value based on the type of material.

Table 3.11.1Poisson ratio for different material after [42].



Material	Range	Typical
Hot mix asphalt	0.30–0.40	0.35
Portland cement concrete	0.15–0.20	0.15
Untreated granular materials	0.30–0.40	0.35
Cement-treated granular materials	0.10–0.20	0.15
Cement-treated fine-grained soils	0.15–0.35	0.25
Lime-stabilized materials	0.10–0.25	0.20
Lime–flyash mixtures	0.10–0.15	0.15
Loose sand or silty sand	0.20–0.40	0.30
Dense sand	0.30–0.45	0.35
Fine-grained soils	0.30–0.50	0.40
Saturated soft clays	0.40–0.50	0.45

3.11.2. Loading and Boundary Conditions

A standard axle ranges from 80 to 90KN. Traffic data are key inputs for the analysis and design of pavement structures. AASHTO (1993) design guides design guides usually were used for the analysis or design of the traffic quantify in terms of Equivalent Single Axle Loads (ESAL). The total estimation or projected magnitude of the various traffic loadings are converted to the total number of passes of the equivalent standard axle loading, usually the Equivalent 80-kN (18-kip) Single Axle Load (ESAL). The total number of ESAL is used as the traffic loading input for analysis and design of the pavement structure. In this study, a load of one set of dual tires of 40KN is considered. It is assumed that this load is transferred to the pavement surface through a contact pressure of a single tire.

The load was assumed to be transferred to the pavement over a rectangular contact area having a length of (0.8712L) and width of (0.6L). These dimensions were derived by assuming that the rectangular area is an equivalent of two semicircles of 0.6L diameter at the end and a central rectangle [43]. The contact area shape and derivations are shown in Figure.3.12.2A and B. Contact pressure was assumed to be equal to the tire pressure which is typically taken as 80 psi. Static analysis was adopted for this model. The boundary condition used in this 3D model were the conventional ones which are basically rollers along the sides of the model where no horizontal movement is allowed and fixed at the bottom of the subgrade layer where no deflection existed beyond a specific depth [44]. The loading configuration allow developing a symmetric FE model edge of the mesh in order to represent the middle of pavement of others opposite side of vertical edge is also fixed in horizontal direction over the whole pavement section while the bottom of the FE mesh is fixed on both horizontal and vertical direction.

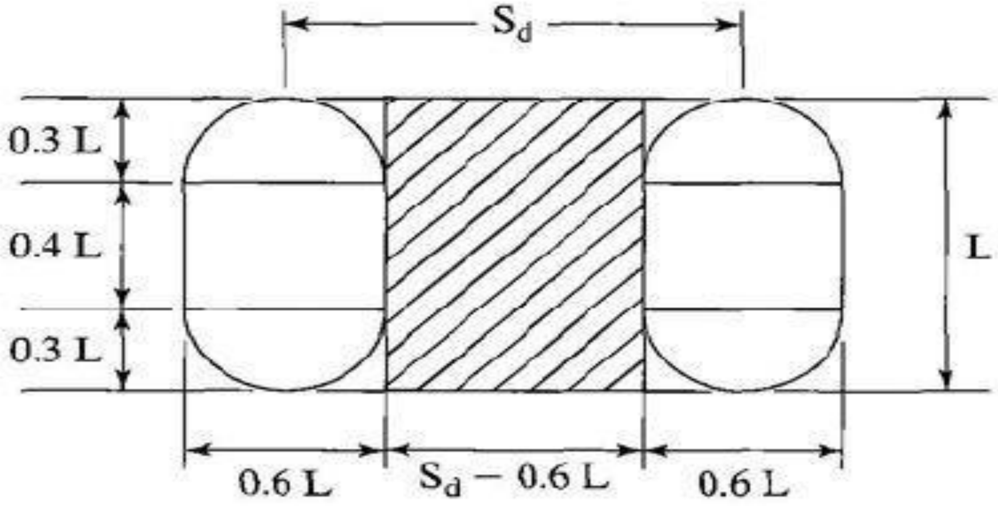
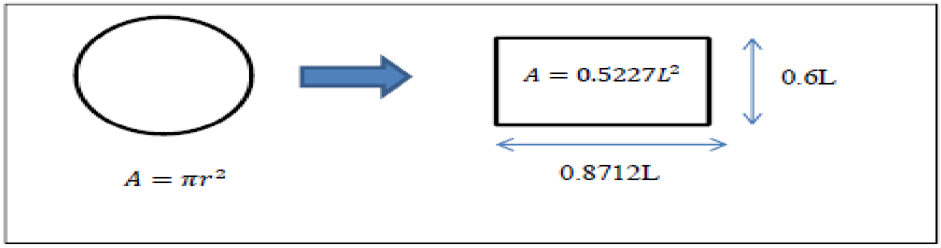


Fig 3.11.2A Contact area of the dual tires on the flexible pavement [42].

The suitable approximation shape of contact area for each tire is composed of a rectangle and two semicircles, having length L and width 0.6L. This shape of two semicircles and rectangle is converted to a single rectangle [42]. having a contact area of $0.5227L^2$ and a width of 0.6L



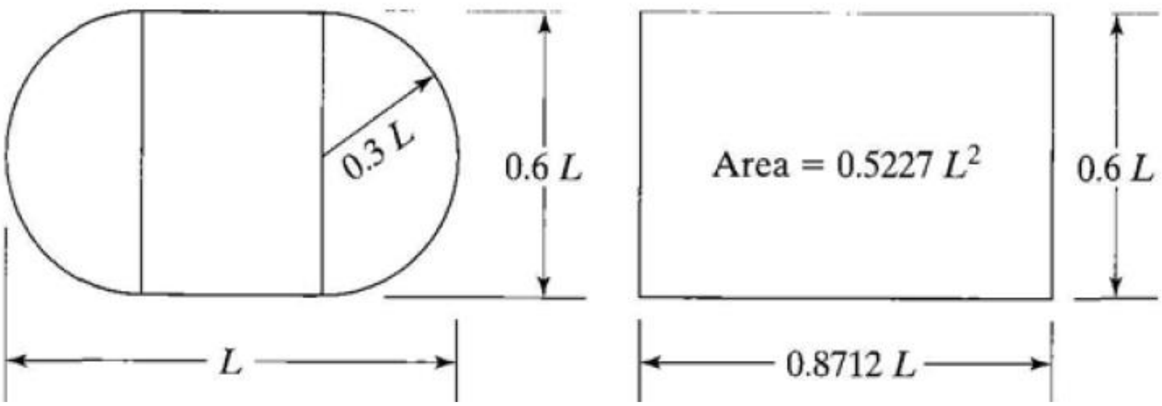


Fig 3.11.2B Dimension of tire contact area between tire and pavement surface & Translation of Contact Area

$Ac = (0.3L)^2 + (0.4L)(0.6L) = 0.5227L^2$

$$L = \sqrt{\frac{Ac}{0.5227}} \text{ ---1}$$

The contact area, Ac is obtained by dividing the Load on each tire-by-tire inflation pressure.

$$L = \frac{P}{Pi} \text{---2}$$

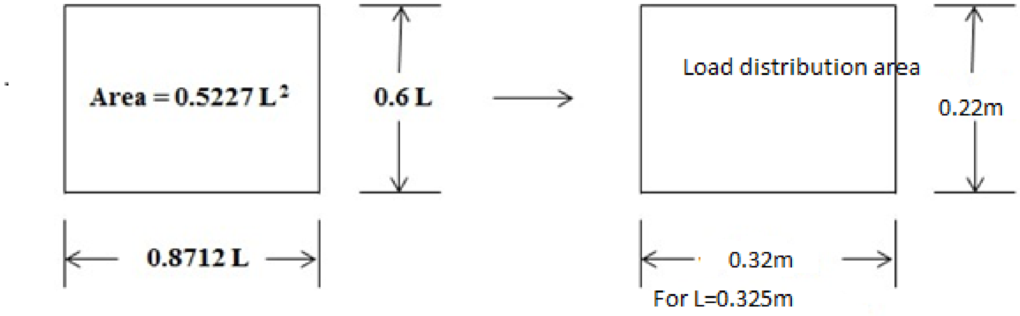


Fig 3.11.2C Equivalent contact area for a dual tire (Huang 1993)

$$\mathrm{P} = \frac{F}{A} = \frac{40}{0.32X0.22} = 568.18Kpa \ = \mathbf{0.56818Mpa}$$

Approximately in this research **0.6Mpa** pressure is used in modelling

Whereas; - P=pressure (kPa)
F=force (KN)
A=Area (m^2)

For finite element analysis, it was concluded that a boundary condition as far as 12 times the loading radius in the horizontal and 18 times the loading radius in depth could provide acceptable results. However, a 50- times R (loading radius) was recommended in order to achieve more accurate results [40]. Good agreement was found between the results of the FE analysis and KENLAYER when the model dimension was 140-times R in the vertical and 20- times R in the horizontal direction [45]. In this study, based on the above concepts the dimensions of the model have been selected as 25 - times R in the horizontal direction and 140 – times R in the vertical direction. Therefore, the model has 3.75 × 3.75 dimension in transversal and longitudinal direction respectively with depth 21m.

The bottom surface of the subgrade is assumed to be fixed, which means that nodes at the bottom of the subgrade cannot move horizontally or vertically. The boundary nodes along the pavement edges are horizontally constrained, but are free to move in the vertical direction. The boundary conditions in this FE models are imposed to the horizontal direction on the opposite side of the symmetric boundary is fixed, whereas the bottom of the slab is fixed in the vertical direction [46].

3.11.3. Model Mesh and Element Type

A series of finite element analyses was performed with decreasing the element size to determine the suitable mesh size. The mesh was a fine mesh around the loading area along the wheel path, and a relatively coarse mesh was used far away from the loading area in vertical and horizontal directions. The used element types in the 20-node quadratic brick with reduced integration was employed for this model since quadratic elements produce more accurate results than linear elements [47].

3.11.4. Geometry of Flexible Pavement Structure

The thickness of each layers is the same From Dedessa River-I throughout Dembi – yembero – Gechi - Bedelle except at some places where there are capping layers where California bearing ratio is less than fifteen (15). The components are surface course, base course, sub base course, and subgrade. (Source: ERA, Jimma Road Network and Safety Management Branch Directorate from Road upgrading documents). The flexible pavement structure contains a finite-element discretization of a four -layer system having a 50 mm-thick AC layer, a 175 mm-thick unbound base layer, a, a 250 mm – thick sub- base layer and a 300mm – thick Subgrade of CBR is less than Seven (7) Percent [48]. Appendix A

3.12. Data collection procedure

The primary data of this research (aggregate gradation and CBR of existing road) are collected through experiments, whereas the secondary data are collected from the concerned government organization, which is from ERA, Jimma district and through the existing relevant documents or literature tried to review and analyze the issues related to the concerned objectives of the study.

3.13. Ethical consideration

While doing anything concerned my research without any harm and oppressed of men, women, children and other those who help me, rather with great respects. It is also very important to all the community by minimizing potential harms and maximizing their benefits. The planning and conducting of this research proposals must meet the standards of the ethical practice.

3.14. Data quality assurance

The quality of data collection is assured without any uncertainties, because I have tried to follow two ways of data collections from the sources. Thus, primary source of data collection (the first witness of a fact) and secondary source of data collection (record of an event, books or circumstance). Therefore; the assurances of those data are highly recognized and those data are true

CHAPTER FOUR

4. RESULTS AND DISCUSSION

4.1. General

Based on the methodology discussed in Chapter 3, the test result data was used to predict rutting of pavement structure under repeated load. An attempt was made to discuss the 'raw' test results initially and then analyze relationship between rut depth and Sub-grade material quality & gradation of aggregate. Modeling of Flexible pavement is performed using finite element method; a 3-D dimensional finite element model using ABAQUS (ver. 6.14-1) computer programs were developed. The pavement response such as, stress, strain and surface deformation are investigated Considering the Effect of Sub-grade Material Quality and Gradation of Aggregates used in pavement layers.

4.1.1. Material properties and Test Results of Existing Pavement Structures

4.1.1.1 Summary of Test Result

The laboratory test required as an input of the ABAQUS software to model the existing pavement layers were performed as per the methodology discussed in Chapter 3, the sample were taken from Dedessa – dembi – Bedelle Road project.

The tests which were carried out on the sample taken from the site are;

a) Degree of Compaction and Voids Analysis of Core Samples
b) Extraction of Asphalt and Aggregates and Binder Content Determination
c) Particle size distribution
d) Standard Proctor Compaction
e) California Bearing Ratio
f) Atterberg Limits

a) Degree of Compaction and Voids Analysis of Core Samples

As reported in Chapter 3 and discussed under Section 3.9.2.2. degree of compaction and air void is done its detail is attached in appendix B

b) Extraction of Asphalt and Aggregates and Binder Content Determination

It is done as discussed in Chapter 3 Section 3.9.2.1. to determine percent of bitumen and filler and its detail is attached under appendix B. the corrected bitumen content is 5.06%

c) A Particle size distribution

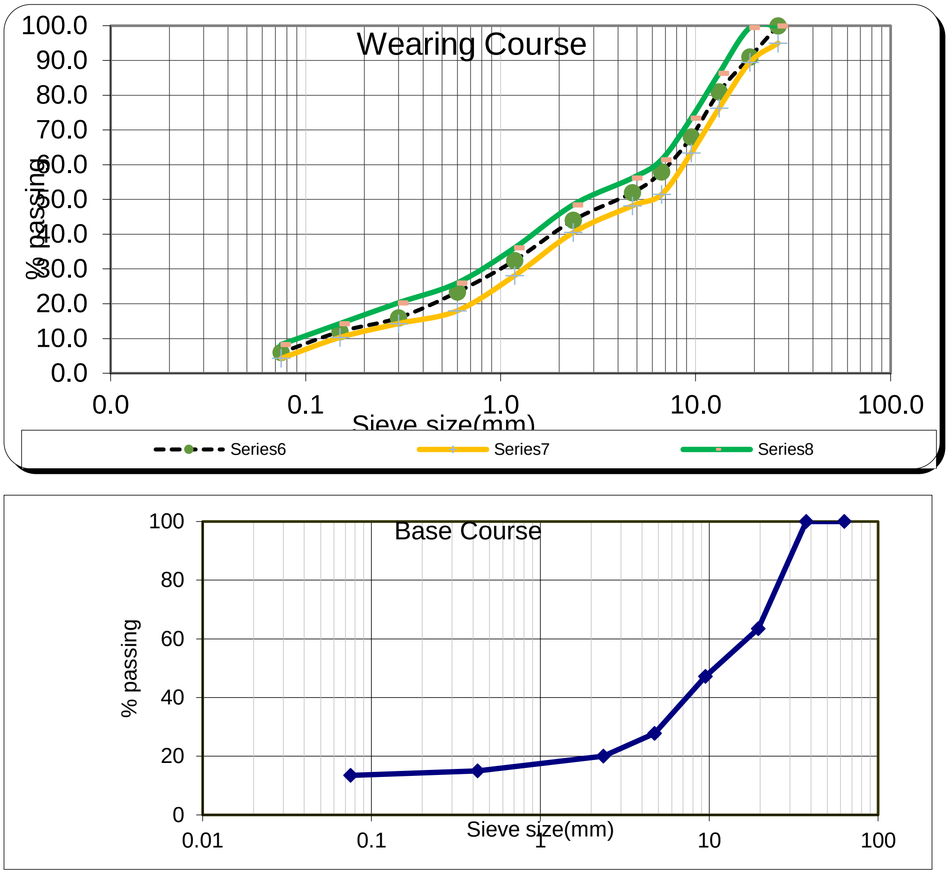


Figure4.1.1.1a Particle size distribution of AC & BC of sample 1

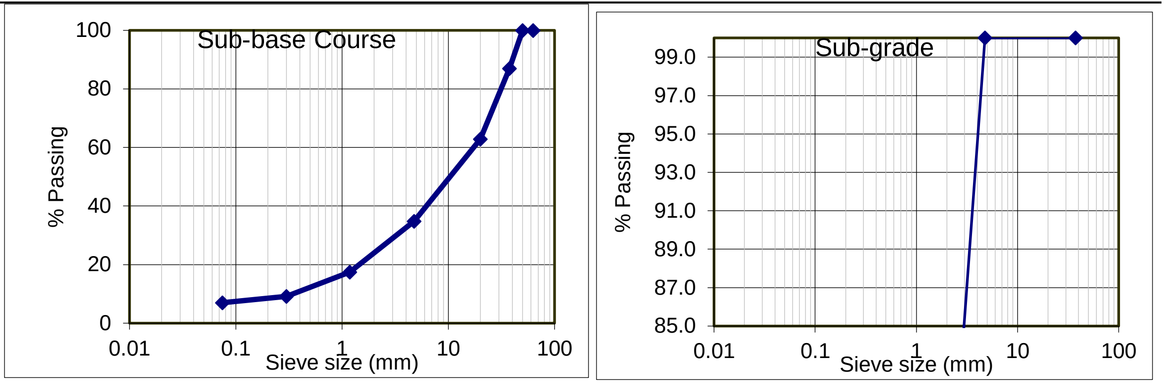


Figure4.1.1.1b Particle size distribution of SB & SG of ample 1

d) Standard Proctor Compaction

The proctor tests were conducted for sample 1 and 2 of base course, sub base and sub grade

Table 4.1.1.1a Summary of proctor test

Sample number	Pavement layers	Maximum Dry density (MDD), KN/m^3	Optimum Moisture Content (OMC), (%)
Sample 1	Base Course	2.070	5.9
	Sub base	2.103	12.4
	Sub grade	1.703	18.8
Sample 2	Base Course	2.070	5.9
	Sub base	2.127	10.6
	Sub grade	1.729	17.8

e) California Bearing Ratio

The California Bearing Ration test was performed to be used in the finite element method in terms of resilient modules of the material. This is done for base course, sub base and sub grade.

Table 4.1.1.1b Summary California Bearing Ratio of Base Course

Calculation of CBR, %						
Number of samples	**Sample 1 @ 2+700**					
	65 Blows		30 Blows		10 Blows	
Penetration	2.5mm	5.08mm	2.5mm	5.08mm	2.5mm	5.08mm
Dial RDG	1059	1800	625	1380	480	1056
Load, (KN)	13.54	23.02	7.99	17.65	6.14	13.51
CBR, %	102	115	60	88	46	67
CBR, %	115		88		67	
Number of samples	**Sample 2 @ 4+700**					
	65 Blows		30 Blows		10 Blows	
Penetration	2.5mm	5.08mm	2.5mm	5.08mm	2.5mm	5.08mm
Dial RDG	1045	1788	610	1360	470	1035
Load, (KN)	13.36555	22.86852	7.8019	17.3944	6.0113	13.23765
CBR, %	100	114	58	86	45	66
CBR, %	114		86		66	

Table 4.1.1.1c Summary California Bearing Ratio of Sub base

Calculation of CBR, %						
Number of samples	**Sample 1 @ 2+700**					
	65 Blows		30 Blows		10 Blows	
Penetration	2.5mm	5.08mm	2.5mm	5.08mm	2.5mm	5.08mm
Dial RDG	460	740	410	701	170	310
Load, (KN)	9.88	15.90	8.81	15.06	3.65	6.66
CBR, %	74	79	66	75	27	33
CBR, %	79		75		33	
Number of samples	**Sample 2 @ 4+700**					
	65 Blows		30 Blows		10 Blows	
Penetration	2.5mm	5.08mm	2.5mm	5.08mm	2.5mm	5.08mm
Dial RDG	490	830	380	595	190	290
Load, (KN)	10.53	17.83	8.16	12.78	4.08	6.23
CBR, %	79	89	61	64	31	31
CBR, %	89		64		31	

Table 4.1.1.1d Summary California Bearing Ratio of Sub grade

Calculation of CBR, %						
Number of samples	**Sample 1 @ 2+700**					
	65 Blows		30 Blows		10 Blows	
Penetration	2.5mm	5.08mm	2.5mm	5.08mm	2.5mm	5.08mm
Dial RDG	55	92	45	74	40	64
Load, (KN)	1.18	1.98	0.97	1.59	0.86	1.37
CBR, %	9	10	7	8	6	7
CBR, %	10		8		7	
Number of samples	**Sample 2 @ 4+700**					
	65 Blows		30 Blows		10 Blows	
Penetration	2.5mm	5.08mm	2.5mm	5.08mm	2.5mm	5.08mm
Dial RDG	99	190	70	130	41	82
Load, (KN)	2.13	4.08	1.50	2.79	0.88	1.76
CBR, %	16	20	11	14	7	9
CBR, %	20		14		9	

f) Atterberg Limits

The result of Atterberg limit test using Casagrande method for all layers

Table 4.1.1.1e Summary of Atterberg limit test results

Sample number	**Pavement layers**	**LL, %**	**PL, %**	**PI, %**
	Sub base	32	27	10
	Sub grade	35	22	14
	Sub base	39	28	11
	Sub grade	34	19	15

4.2. Discussion of Modeling Results

The finite element model developed for rutting analysis in flexible pavement gives a good indication to find the distribution of stress in the pavement layers. Flexible pavement modelling was performed using finite element method; a 3-dimensional finite element model using ABAQUAS (ver.6.14-1) computer program was developed. The fine finite element mesh used in this study gives the values of stresses and strain in each point. The stress has large values near the applied load where larger deformation occurs.

4.2.1. Material Properties and Pavement Geometry

Empirical relationships based on CBR have been historically used for the determination of the resilient modulus of granular soils. One of these relationships is referred to in the AASHTO guide for pavement design [49]. California Bearing Ratio CBR is one of the most widely known parameters for characterizing the bearing capacity of soils and unbound granular materials [50].

Table4.2.1. Material Properties and pavement geometry

Section	Thickness (mm)	E (MPa)	ν	Material Properties
AC	50	2800	0.35	Isotropic and Linear Elastic
Base Course	175	400	0.30	Isotropic and Linear Elastic
Sub-base Course	250	150	0.35	Isotropic and Linear Elastic
Sub-grade or Existing Soil	300	82.80	0.40	Isotropic and Linear Elastic

The material assumed in this model is to be homogenous isotropic linear elastic materials.

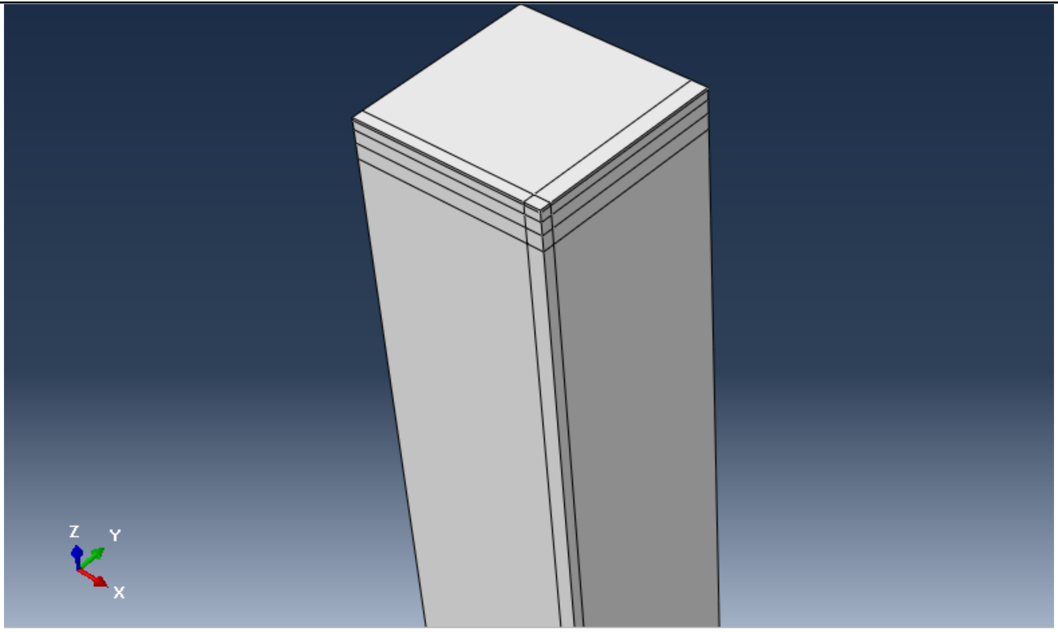


Figure4.2.1. Pavement layers and geometry

4.2.2. Loading and Boundary Condition

The bottom surface of the subgrade is assumed to be fixed, which means that nodes at the bottom of the subgrade cannot move horizontally or vertically. The boundary nodes along the pavement edges are horizontally constrained, but are free to move in the vertical direction [51]. The 3-D finite element model developed using ABAQUS/CAE 6.14-1 has dimensions 3.75m X 3.75m in transversal and longitudinal direction respectively with depth 21m. The side boundary of the model is approximately 25 times the tire radius in order to minimize edge effects. The subgrade layer, which implicitly is assumed to be 140 times the radius.

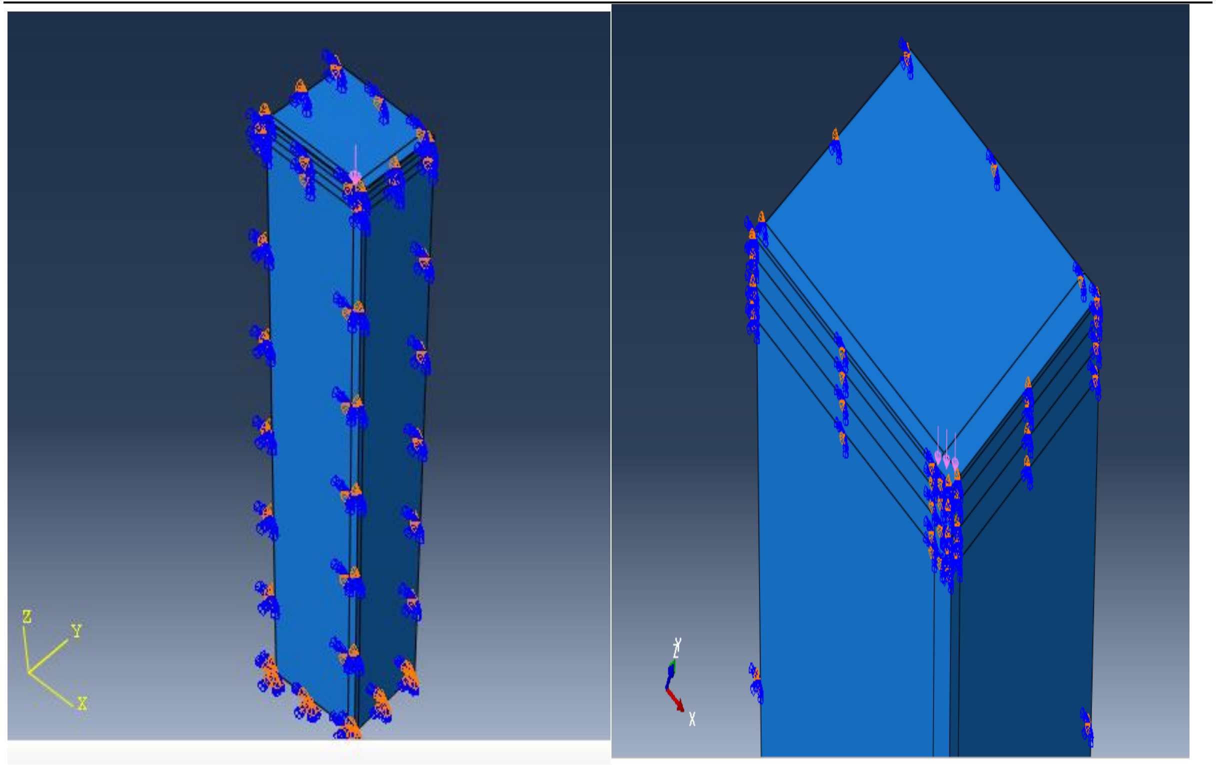


Figure4.2.2. Boundary condition and loading of 3D-FE model for prediction of Rutting or permanent deformation of flexible pavement

4.2.3. Model Mesh and Element Type

A series of finite element analyses was performed with decreasing the element size to determine the suitable mesh size. The mesh was a fine mesh around the loading area along the wheel path, and a relatively coarse mesh was used far away from the loading area in vertical and horizontal directions [52].

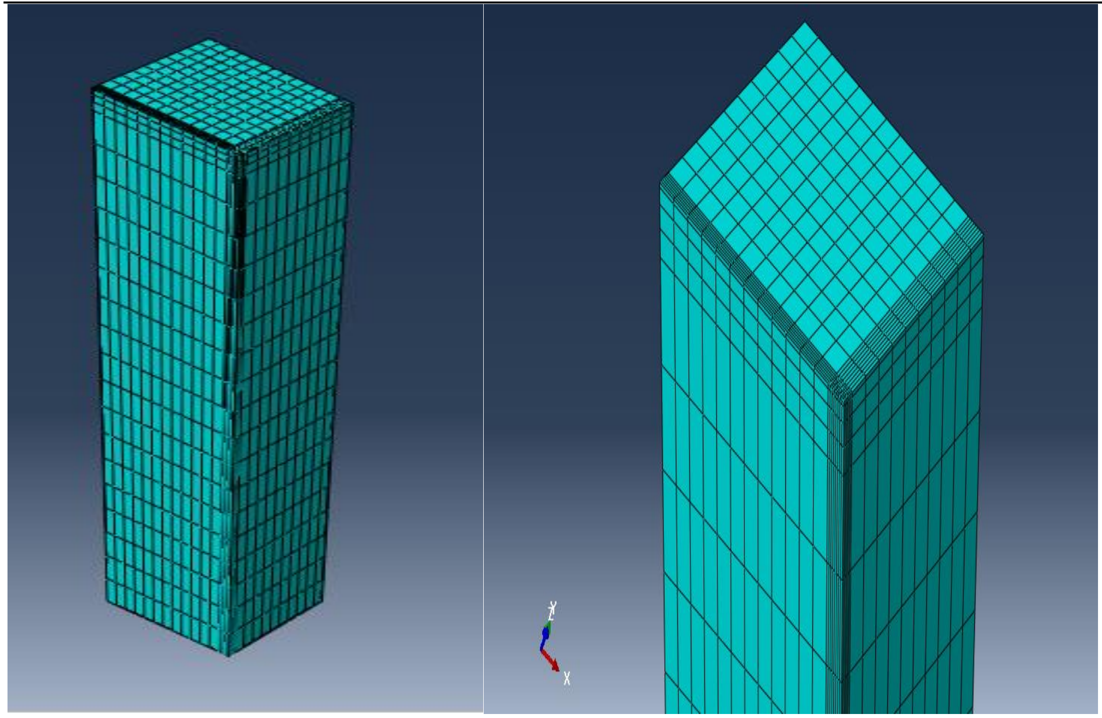


Figure4.2.3. 3D-Finite Element Model meshing for prediction of Rutting or permanent deformation of flexible pavement

4.2.4. Model Analysis

4.2.4.1. Prediction of Permanent Deformation (Rutting) of existing pavement

Rutting is simulated as a vertical displacement in the model analysis. The displacement is considered as a response of applying traffic repeated loads. The 3D finite element model developed for rutting analysis in flexible pavement give a good indication to find the distribution of stress in the pavement layers considering effects of aggregate gradation and quality of sub-grade material. The fine finite element mesh used in this study gives the values of stresses and strains in each point with higher accuracy. The stresses have larger values near the applied load where larger deformations occur.

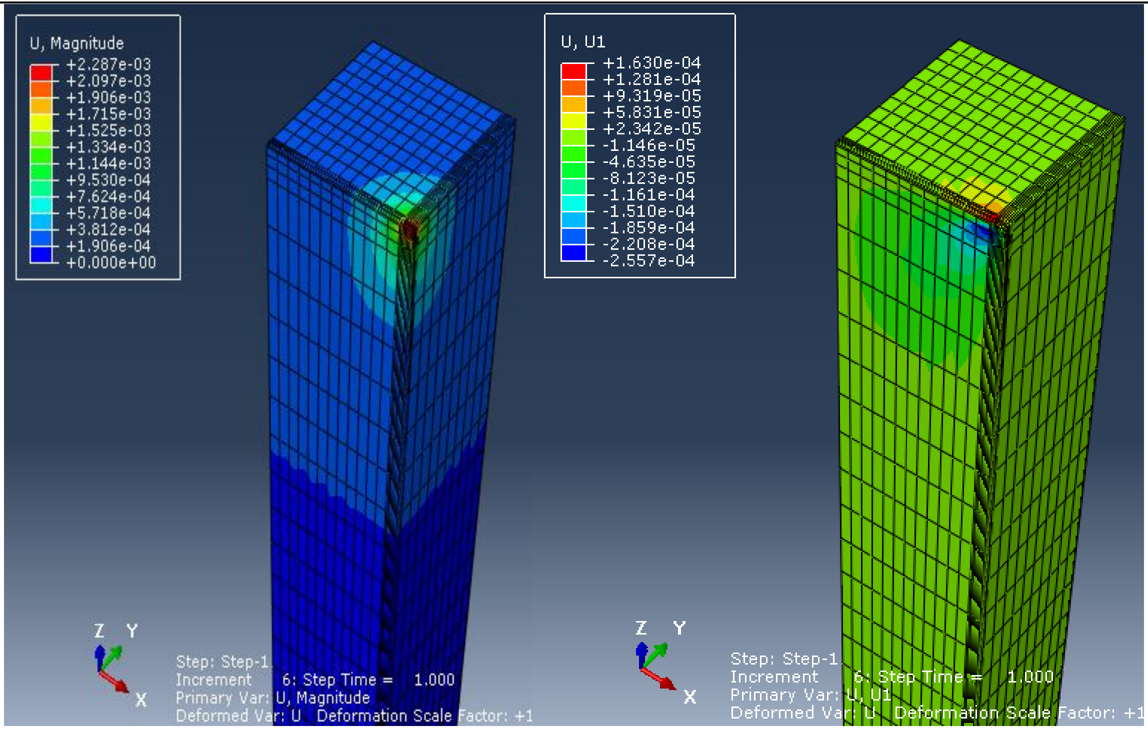


Figure4.2.4.1. Permanent deformation of existing pavement

The result from predictive surface rut depth with a number of wheel load is compared with the actual rut depth measurement on the site.

Table4.2.4.1. Comparison between predictive surface rut depths with the actual rut depth measurement.

Sample Location ID	Station	Measured average rut depth(mm)	Predictive surface rut depth (mm)	Comparison (Difference in %)
1	1+500	33.4	34.567	3.49 increment
2	2+700	47.5	43.375	8.68 decrement
3	3+000	17.5	16.308	6.81 decrement
4	4+700	52.6	53.258	1.25 increment

As shown in Table 4.2.4.1. and Figure 4.2.4.1 the finite element model developed for rutting analysis of existing flexible pavement give a good indication to find the distribution of stress in the pavement layers.

Sensitivity Analysis

After the rutting analysis and validation of the model, a sensitivity analysis was performed to investigate the effects of different aggregate gradation and sub-grade material quality on permanent deformation (rutting) and their relation with severity of permanent deformation.

4.2.4.2. Effects of different Aggregate Gradation on Rutting Development and its relationship with Severity of permanent deformation (Rutting)

As described in the methodology section, effects of aggregate gradation on the rutting performance and on its severity, has been evaluated on the basis of the depth of rut predicted from the model by considering different aggregate gradation in terms resilient modulus. The rut depth is predicted with three different value of resilient modulus of base courses-based marshal stability of base course as shown on Figure 3.12.1 of Chapter 3 Correlation charts for estimating resilient modulus of HMA.

As shown in Table 4.2.4.2 and Figure 4.2.4.2A, the rut depth increases as aggregate gradation decrease from well graded to poor graded and also show that severity of permanent deformation is increase as the aggregate gradation changed to poor graded from well graded. From Table 4.2.4.2 the vertical strain changed 4.78% as aggregate gradation changed from well graded to medium graded and 2.9% aggregate gradation changed from medium graded to poor graded. This designates that rut depth increases with decreasing the aggregate density and consequently the severity of permanent deformation (rutting) decreases within increasing quality and gradation or density of aggregates.

Table4.2.4.2. Effects of different Aggregate Gradation on Rutting Development and its relationship with Severity of permanent deformation (Rutting)

ABAQUS Linear Elastic Analysis			
Pavement Response	Three-dimensional model (25R X 140R)		
	well Graded base course	medium Graded base course	poor Graded base course
Vertical Strain Ɛc (10-6) at the top of subgrade	-0.0008994	-0.0009424	-0.0009704
No. of Load Repetitions to Failure Nr	61066.747	49528.189	43434.246
Rut depth (mm)	18.887	19.7904	20.3784

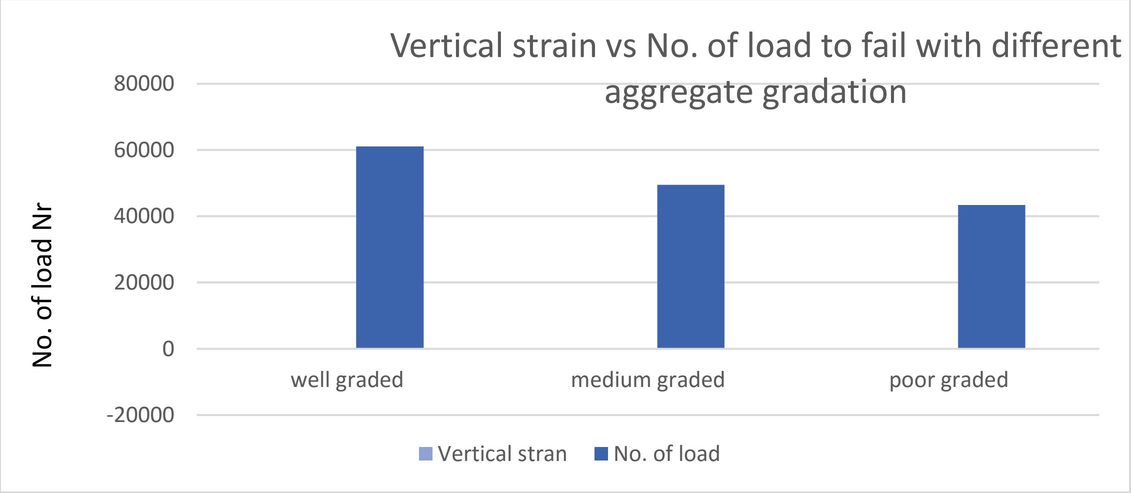


Figure4.2.4.2A. Vertical strain vs Number of loads with different aggregate gradation

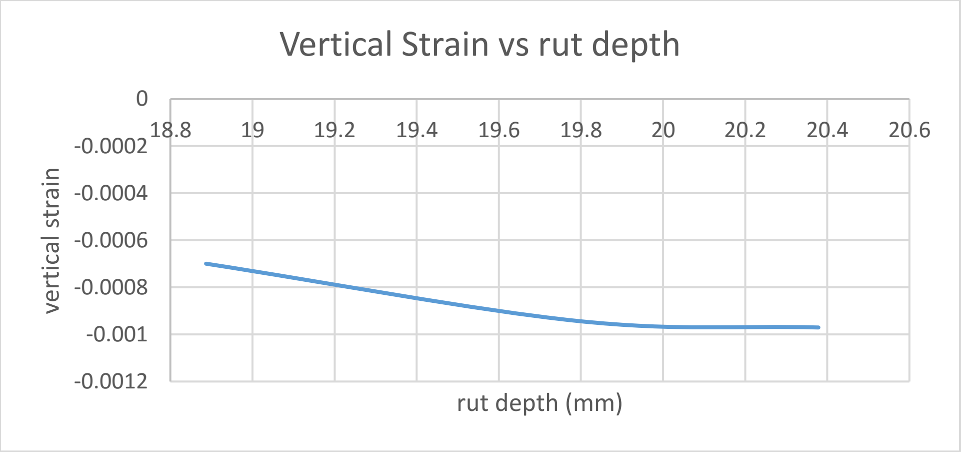


Figure4.2.4.2B. Vertical strain vs rut depth with different aggregate gradation

As shown in Figure 4.2.4.2A and Table 4.2.4.2 the number load to fail is 61067 for well graded aggregate, 49529 for medium graded and 43435 for poor graded. This shows that the load resistance increases with aggregate gradation approach to well graded or as density increase. From Figure 4.2.4.2B rut depth is 20.3784mm at vertical strain is -0.0009704µmm and 18.887mm at vertical strain is -0.0008994µmm this shows that rut depth increases as vertical strain approach to zero and vertical strain increase with density or as aggregate gradation decreases.

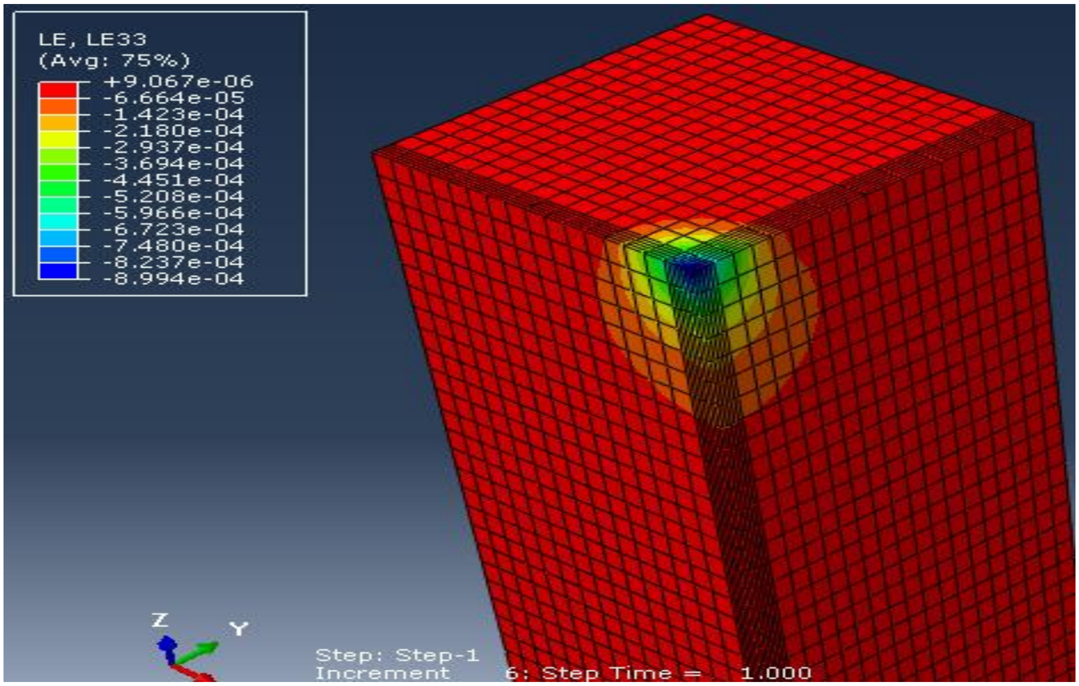


Figure 4.2.4.2C. Vertical Strain at the top of subgrade

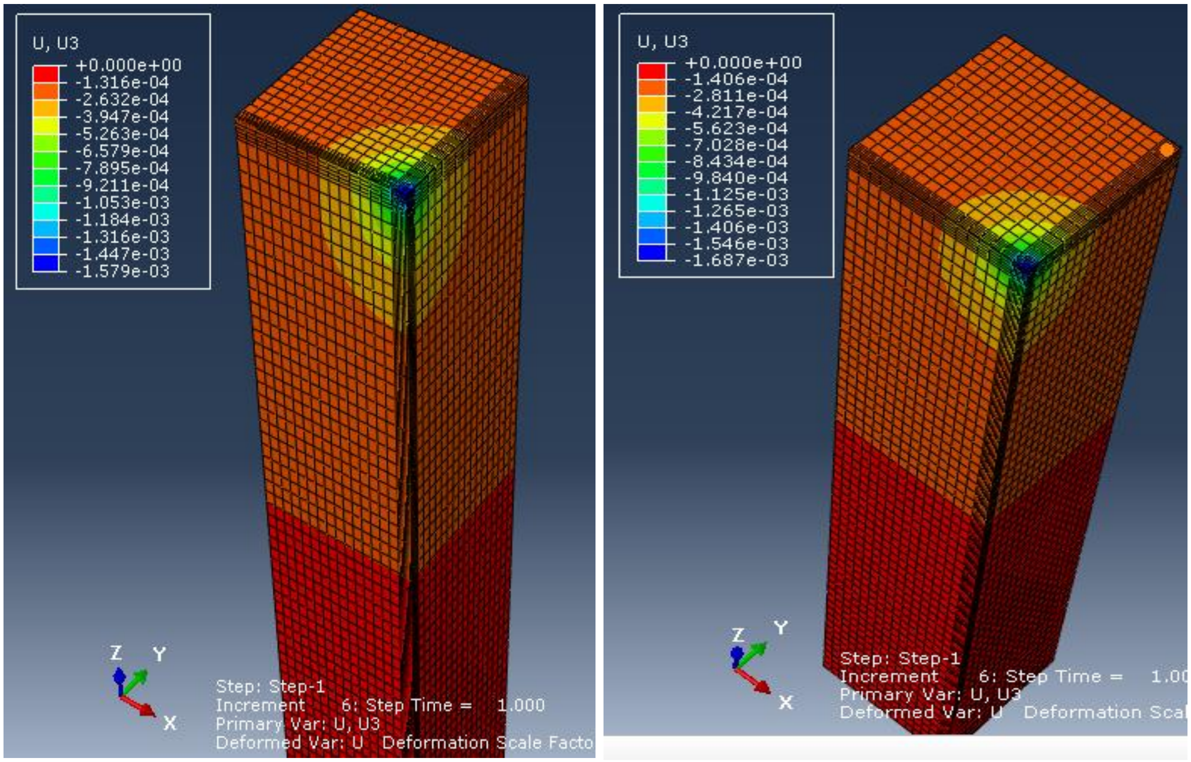


Figure4.2.4.2D. Effects of aggregate gradation on permanent deformation

4.2.4.3. Effects of quality of sub-grade on permanent deformation (Rutting)

The California Bearing Ratio CBR is one of the most widely known parameters for characterizing the bearing capacity of soils and unbound granular materials [49]. Empirical relationships based on CBR have been historically used for the determination of the resilient modulus of granular soils. One of these relationships is referred to in the AASHTO guide for pavement design [48]. Subgrade quality is evaluated in terms of CBR to analyze the impact of this parameter on the rut depth.

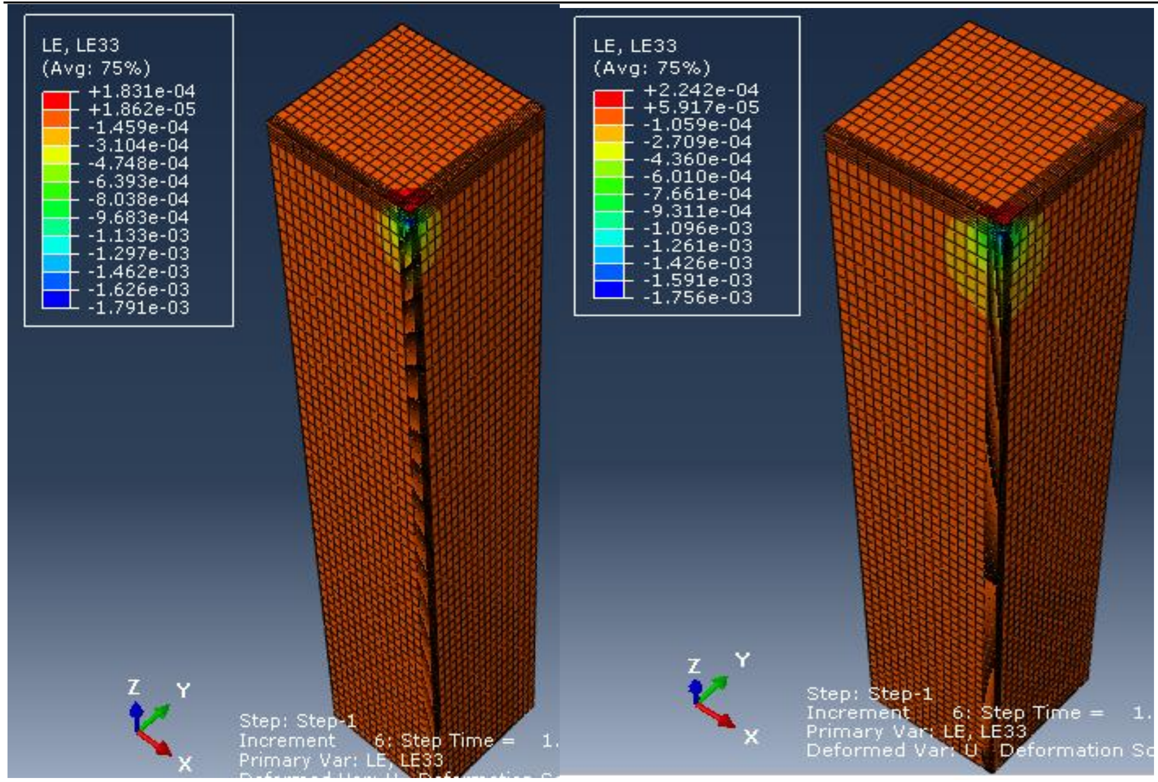


Figure4.2.4.3A. Vertical strain with different subgrade quality in terms of CBR

Table4.2.4.3. Effects of quality of sub-grade on permanent deformation (Rutting)

It. No.	CBR of sub-grade	Rut depth (mm)
1	7	43.375
2	8	37.365
3	9	34.567
4	10	31.005
5	11	16.308

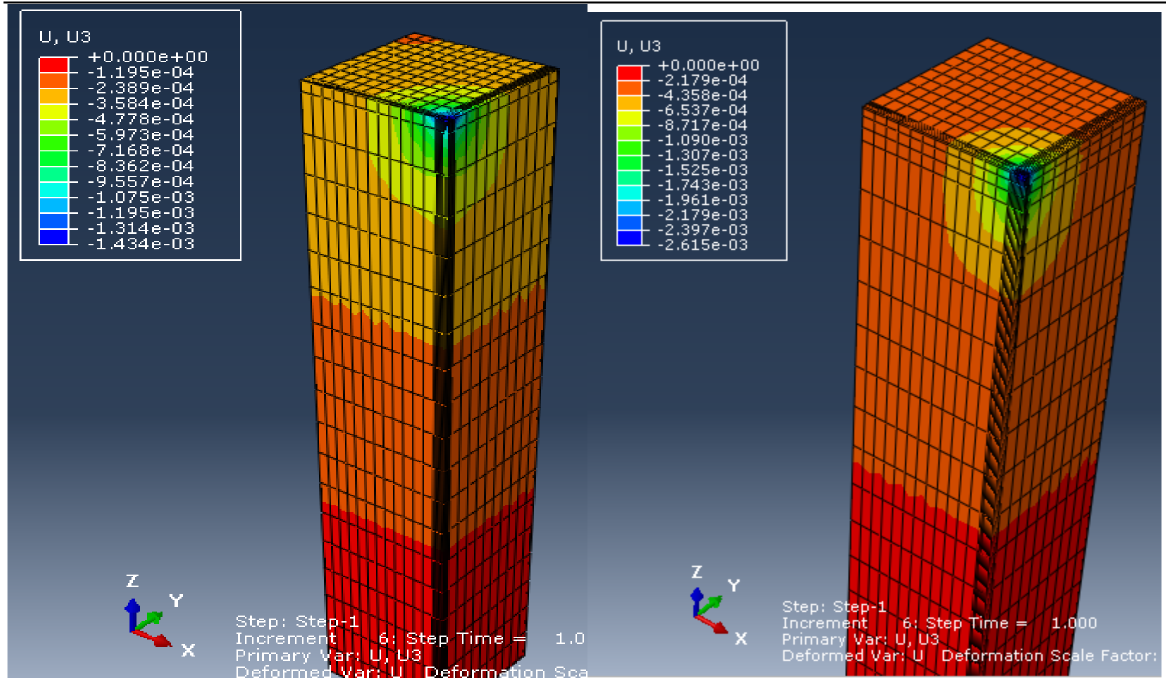


Figure4.2.4.3B. vertical deformation with different subgrade quality in terms of CBR

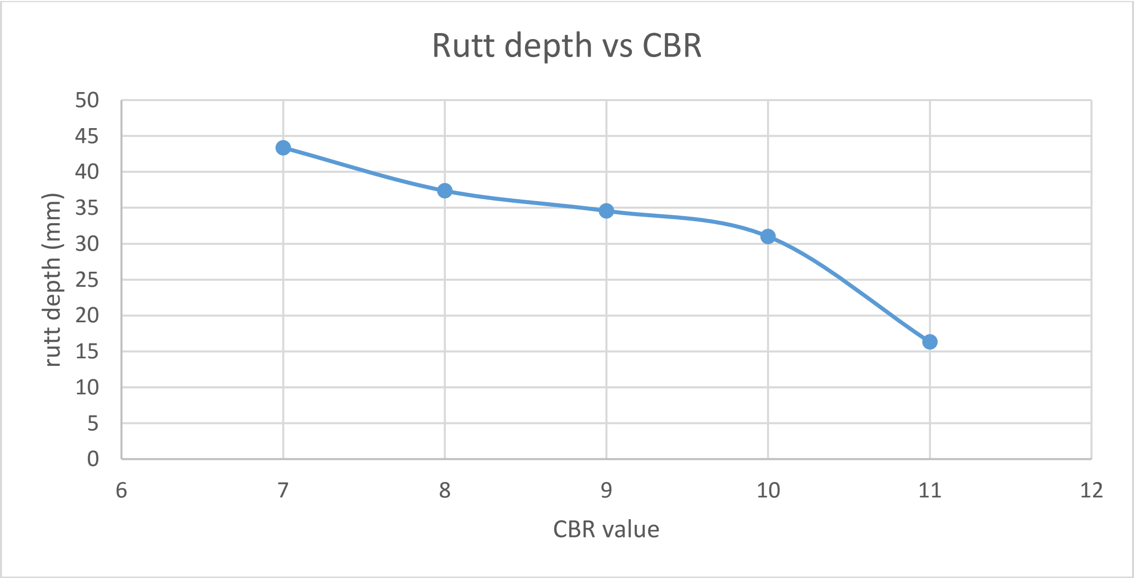


Figure4.2.4.3C. rut depth vs different subgrade quality in terms of CBR

From Figure 4.2.4.3A the vertical strain decreases by 1.99% as CBR value decrease from 11% to 7% and vertical strain decreases by 0.5% as CBR value decrease from 11% to 10% this shows vertical strain increase as quality of subgrade material decreases.

As shown in Figure 4.2.4.3C as value of CBR approaches to zero the predicted rut depths moves from 15mm to 45mm. this implies that rut depth or severity of permanent deformation increase with decrease in subgrade material quality or bearing capacity of subgrade

4.2.4.4. Predicting Structural Response of Flexible Pavement with Different aggregate gradation and Sub-grade quality

The displacements as a result of the effect of the loading cycles at the point beneath the center of the wheel load are illustrated as shown in Figure 4.2.4.4E. Particles of the pavement materials are moved as a response of applying repeated wheel loads. A part of these displacements is recovered at the end of the load pulse, according to the resilient properties. The other parts continue. The permanent response is related to the plastic strains and represents the field rutting.

As shown in figures 4.2.4.4A-E pavement responses that plays the great role in flexible pavement design are vertical strain at the top of sub-grade, surface deflection, Tensile Strain below AC layer, Vertical Stress above Subgrade and Tensile Stress below of AC layer.

As shown in Table 4.2.4.4 and appendix the value of vertical strain, surface deformation and vertical stress are -0.001306µmm, 0.002207mm and -0.09401µmm respectively with poor aggregate gradation and CBR value of 7%. and vertical strain, surface deformation and vertical stress are -0.0008994µmm, 0.001579mm and -0.1031µmm respectively with well graded aggregate and CBR value of 11%. Accordingly, number of loads is increase from 11466 to 61067 times. This implies that number load to fail is increase as quality of subgrade and aggregate density is decreases. Correspondingly, as vertical strain and vertical stress increase as quality of subgrade and aggregate density decreases.

Table4.2.4.4. Predicting Structural Response of Flexible Pavement with Different aggregate gradation and Sub-grade quality.

ABAQUS Linear Elastic Analysis							
Three-dimensional model (25R X 140R)							
Pavement Response	Aggregate Gradation and Sub-grade material quality						
	Unit	Poor Graded base course crushed Aggregate		medium Graded base course crushed Aggregate		well Graded base course crushed Aggregate	
		With 7% CBR	With 11% CBR	With 7% CBR	With 11% CBR	With 7% CBR	With 11% CBR
Vertical Strain at the top of Sub grade Subgrade	μmm	-0.001306	-0.0009704	-0.001266	-0.001196	-0.001206	-0.0008994
Surface Deflection	mm	0.002207	0.001766	0.002121	0.001687	0.002005	0.001579
Tensile Strain below AC layer	μmm	-0.0002827	-0.0001777	0.0002766	-0.0002451	-0.0002773	-0.000241
Vertical Stress at the top of Subgrade	Mpa	-0.09401	-0.1112	-0.09106	-0.1079	-0.08676	-0.1031
Tensile Stress below of AC layer	Mpa	-1.581	-1.432	-1.571	-1.415	-1.603	-1.441
Number of load (Nr)		1465.466	3434.246	13181.7	2154.79	16388.15	61066.75

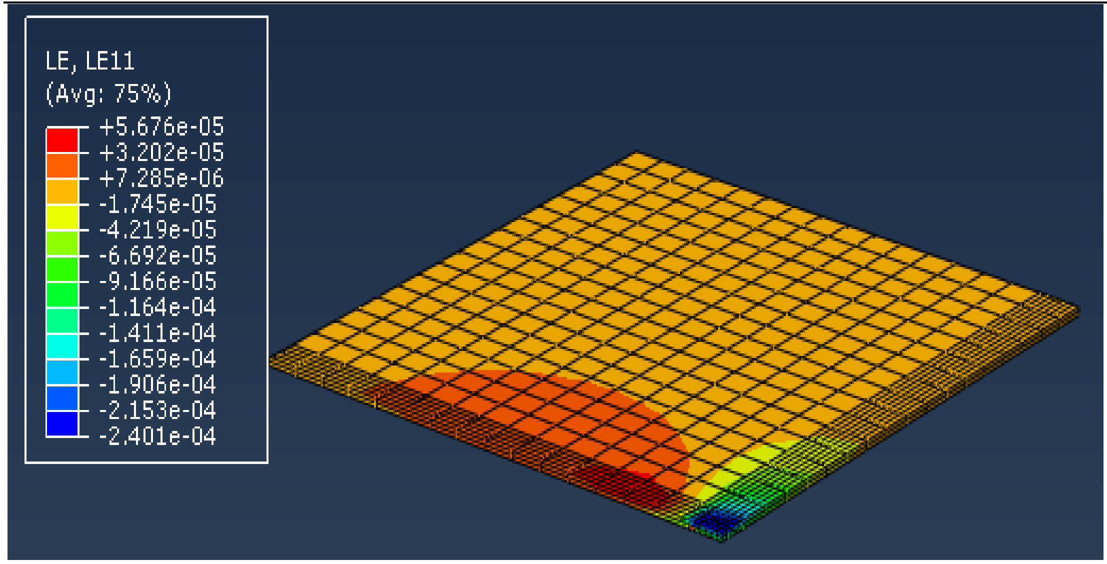


Figure4.2.4.4A. Horizontal Tensile strain below AC with well graded aggregate and 7% CBR value

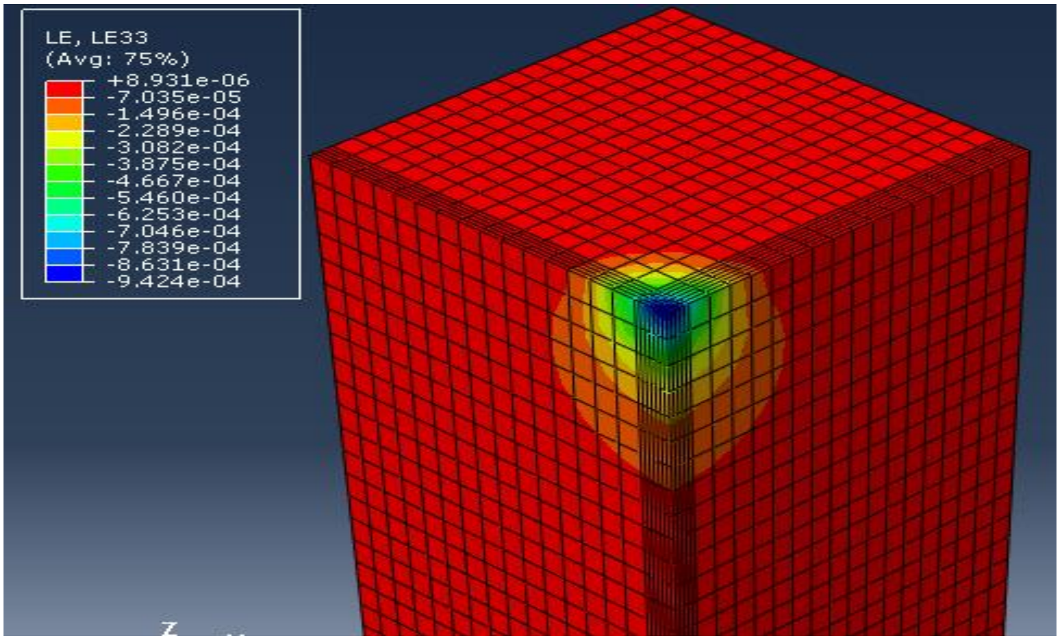


Figure4.2.4.4B. Vertical Strain above Sub-grade

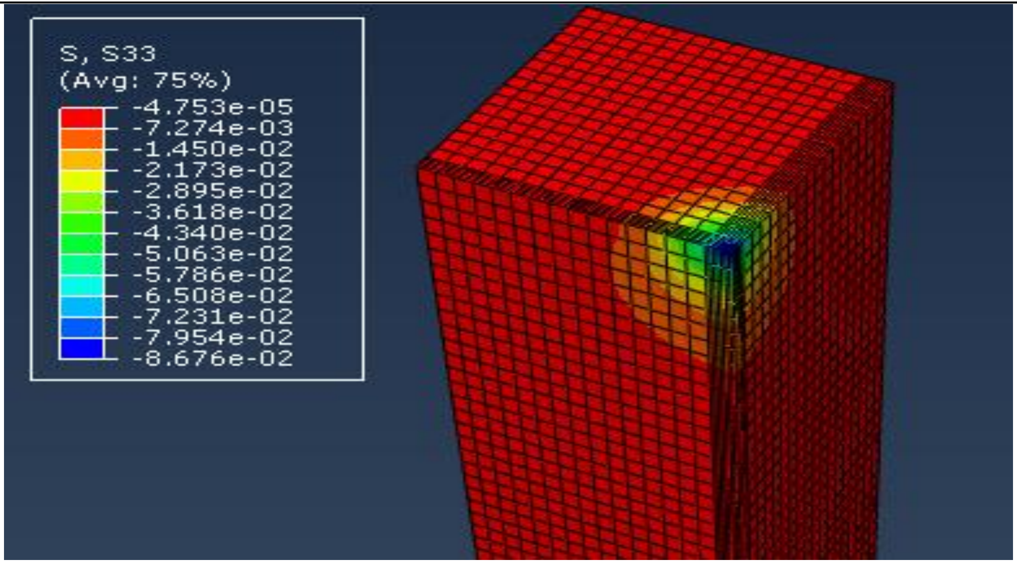


Figure4.2.4.4C. Vertical Stress above sub-grade with well graded and 7% CBR value

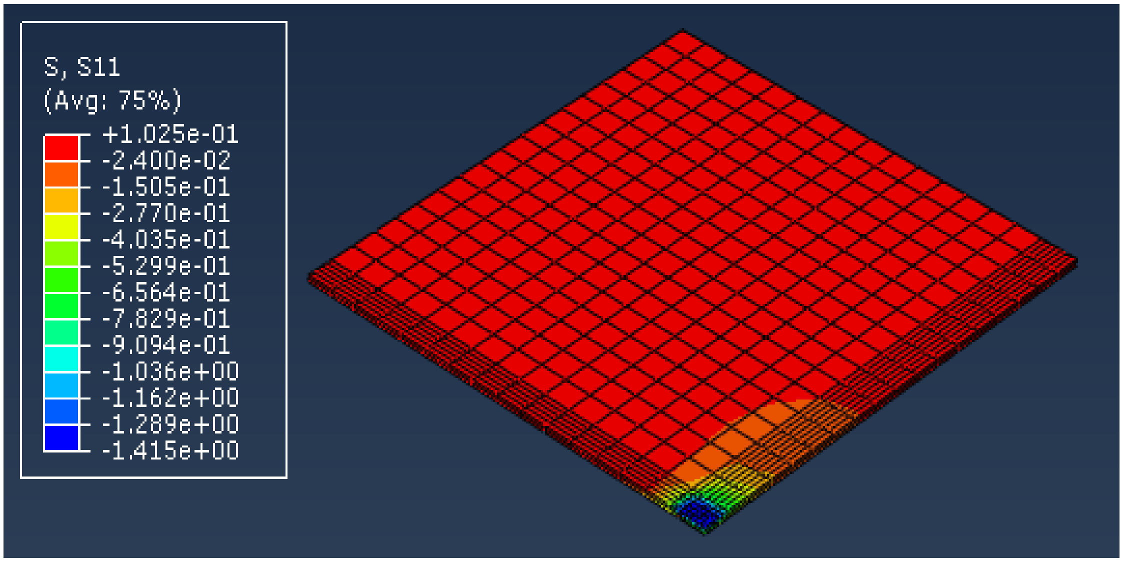


Figure4.2.4.4D. tensile stress below AC with medium graded aggregate gradation and 11% CBR value

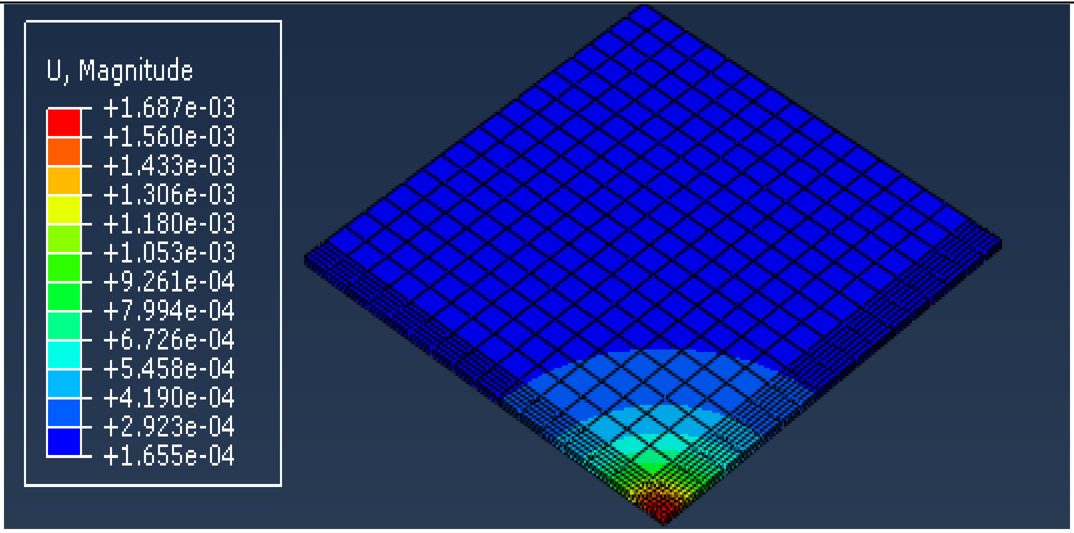


Figure 4.2.4.4E. Surface Deformation with medium graded aggregate gradation and 11% CBR value

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1. CONCLUSION

Conclusions of this study, end to end with recommendation for the future development of research along the same lines are presented under this chapter. Initially, the full thesis is briefly reviewed and then discussion is made of the objectives achieved by the research and their contribution to knowledge and practical works.

Based on the result of this thesis, the following major conclusion are derived.

- FEM analysis shows that rutting severity and extents increases as aggregate gradation changed to poor graded from well graded. vertical strain decreases by 4.78% as aggregate gradation changed to medium graded from well graded. Besides, decreases by 2.9% as aggregate gradation changed from medium graded to poor graded. This designates that rut depth increases as aggregate density decreases.
- This thesis presented the static loading response of flexible pavement layers in terms of strain, stress and deflection. Besides, investigate the effects of different aggregate gradation and sub-grade material qualities. It was found that in the elastic domain, considering linearity of the material and stress dependency can significantly affect the critical responses of the pavement layers.
- It was found that the predictive rut depth is 20.3784mm at vertical strain is -0.0009704µmm and 18.887mm at vertical strain is -0.0008994µmm this indicates that rut depth increases as vertical stain approach to zero or increase. Additionally, vertical strain increases with decrease in aggregate gradation approaches to poor graded from well graded.
- Vertical strain decreases by 1.99% as CBR value decrease from 11% to 7% and decreases by 0.5% as CBR value decrease from 11% to 10% this show that vertical strain increases as quality of subgrade material quality decreases. Correspondingly, the predicted rut depth decreases with increase bearing capacity of sub grade material.

5.2. RECOMMENDATION

Base on the results of this research, the following recommendations can be made to facilitate future studies.

- In this research the sensitivity analysis was done considering the aggregate gradation and sub grade material quality in terms of CBR. But, for the future rutting prediction by considering the combination of temperature, aggregate gradation from the different source and sub grade material quality will be good sensitivity analysis.
- In this dissertation, rectangular contact area is used with application of static cyclic vertical pressure; single tire load was used from ERA standard. This is the commonly used methods of simulation. For the future rutting prediction considering circular loading contact area will be advantageous.
- Based on this study (rutting prediction of existing pavement which is Dedessa – Dembi – Bedelle road project is practiced in permanent deformation at some stretchs and based on the condition survey made while under taking this study; this road project have different pavement failure addition to the permanent deformation, some them are; big pothole, side drainage score and closed up at some stretch, fatigue crack, areal crack, longitudinal crack and slide are happen on this road segment. While reviewing the construction history of this road project and its maintenance history it serves for more than Ten (10) years without any maintenance. At this time, the Road Project is under critical condition, to overcome these problems and restore it to its original condition it is recommended that heavy maintenance is preferable.

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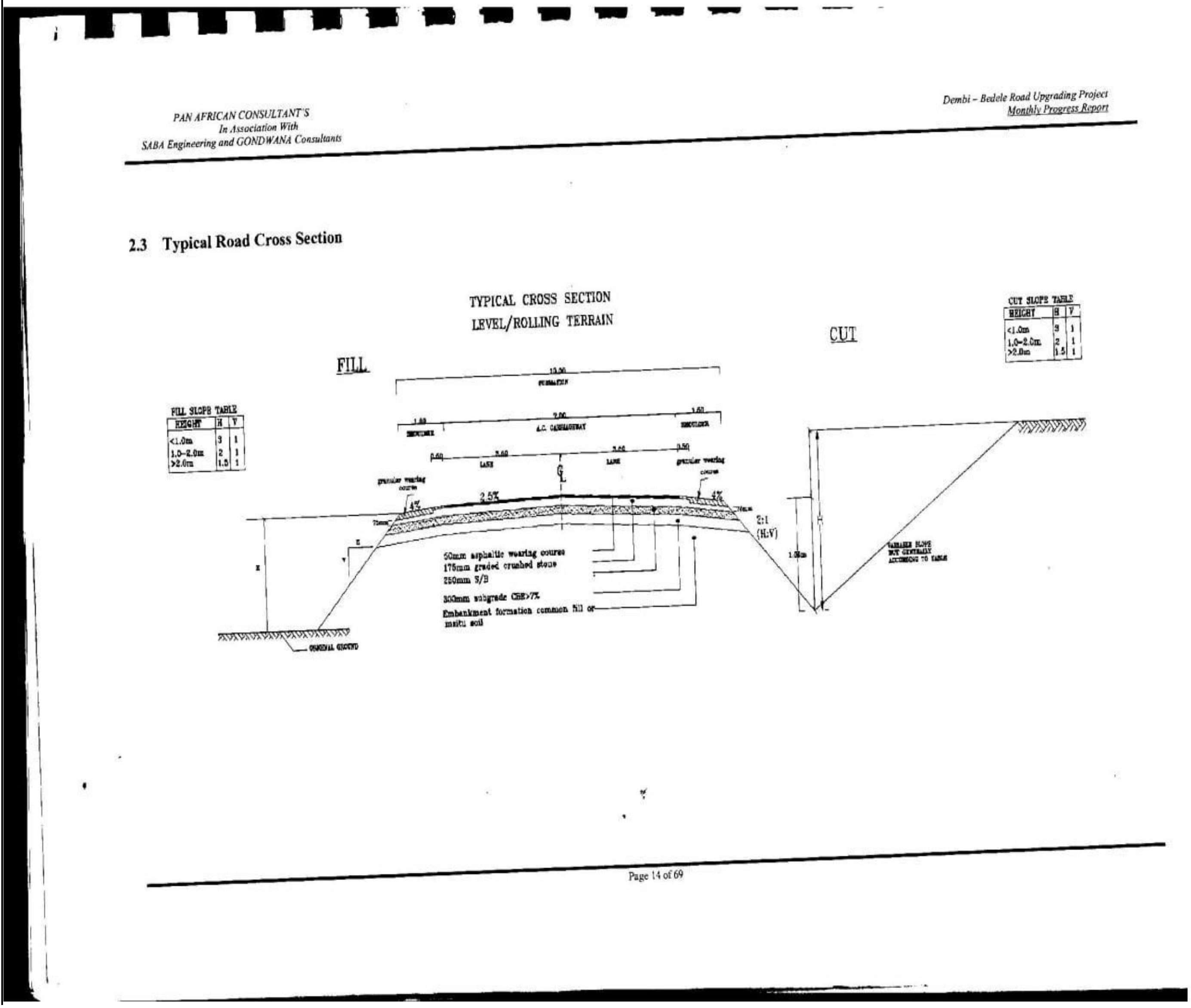
Appendix A: Typical section of the Road Project [48]



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2.3 Typical Road Cross Section

TYPICAL CROSS SECTION
LEVEL/ROLLING TERRAIN

FILL SLOPE TABLE

HEIGHT	H	V
<1.0m	3	1
1.0–2.0m	2	1
>2.0m	1.5	1

CUT SLOPE TABLE

HEIGHT	H	V
<1.0m	3	1
1.0–2.0m	2	1
>2.0m	1.5	1

50mm asphaltic wearing course
175mm graded crushed stone
250mm S/B
300mm subgrade CBR>7%
Embankment formation common fill or insitu soil

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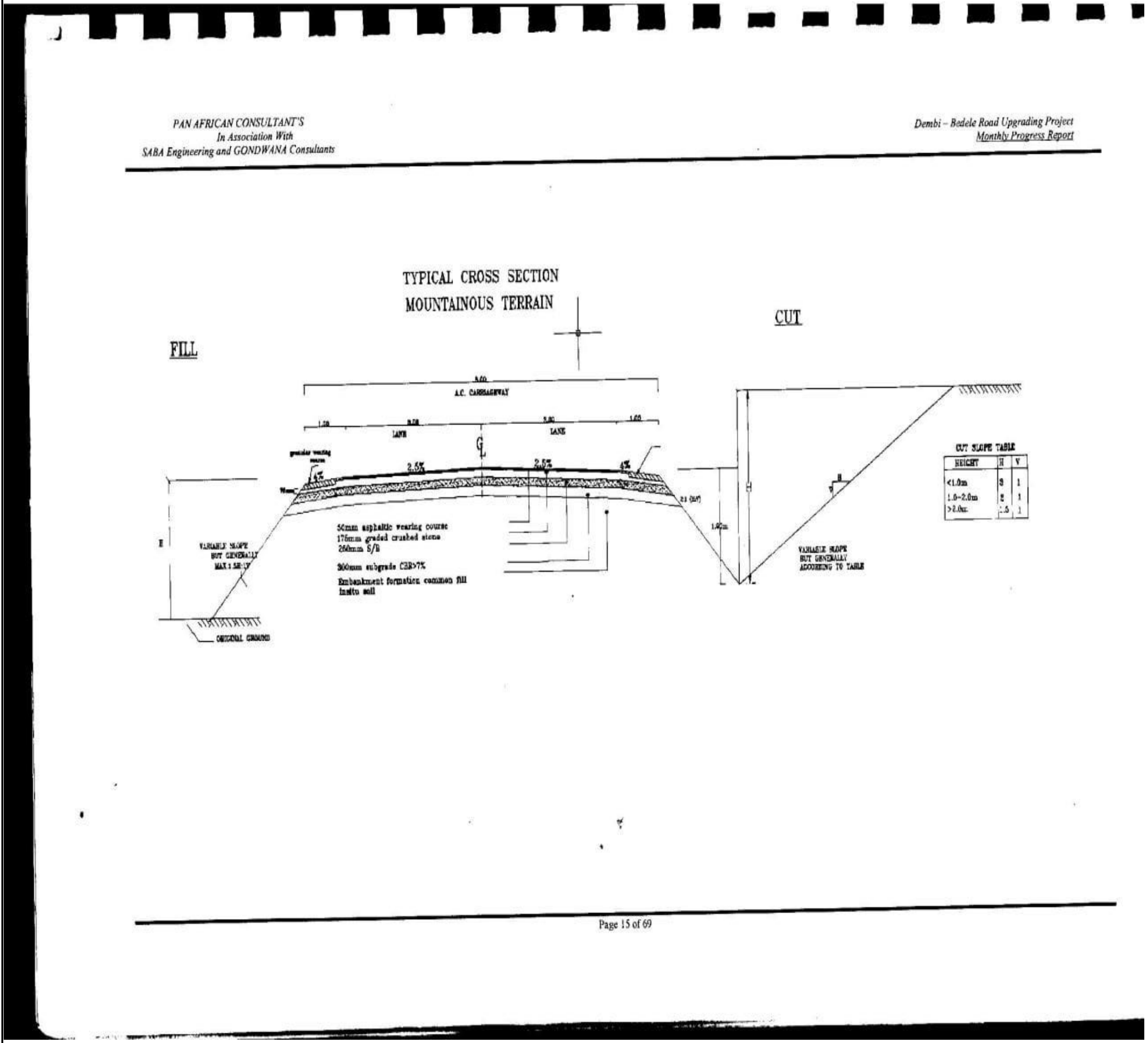

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TYPICAL CROSS SECTION
MOUNTAINOUS TERRAIN

50mm asphaltic wearing course
175mm graded crushed stone
250mm S/B

300mm subgrade CBR>7%

Embankment formation common fill
insitu soil

CUT SLOPE TABLE

HEIGHT	H	V
<1.0m	3	1
1.0–2.0m	2	1
>2.0m	1.5	1

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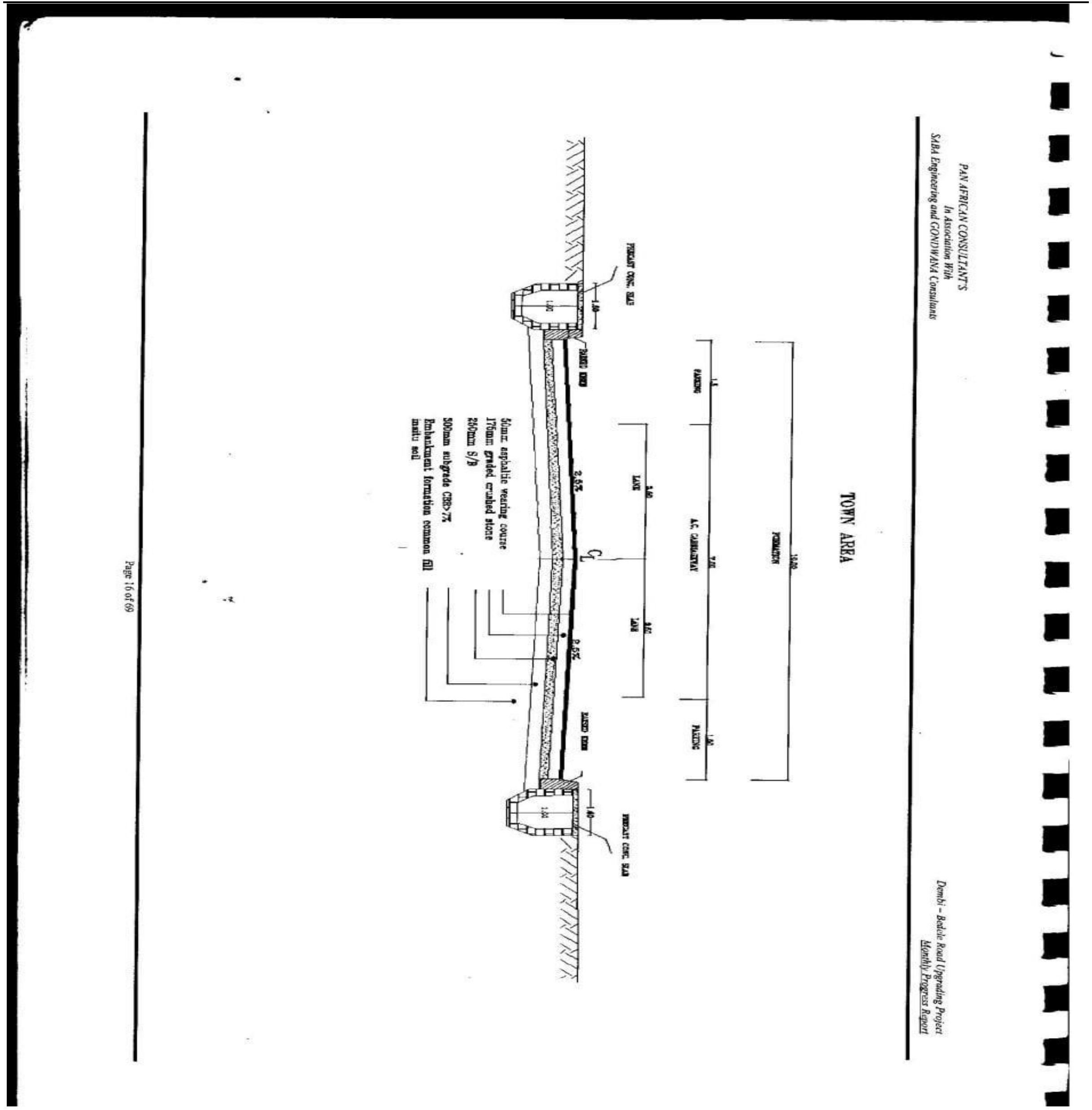

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TOWN AREA

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Appendix B: Details of the Laboratory Test Results

Appendix B: Details of the Laboratory Test Results

B1. Degree of compaction and void analysis of core sample

Material Type: Asphalt Layer

Source: Dedessa - Dembi - Bedelle Road Project

Station: 2+700 & 4+700

DEGREE OF COMPACTION AND VOIDS ANALYSIS OF CORE SAMPLES

Sample No.	Chainage	Paving Lane	Offset, m	Thickness, mm	Weight in, gm			Volume, cc	Density, gm/cc	Average lab. Density	Average G_{mm}	% Air Voids	Theoretical Density	Degree of Compaction
					Air	Water	SSD							
1	2+700	LHS	3.40	47	803.8	492.2	804.2	312.0	2.576	2.541	2.654	2.9	97.1	101
2	4+700	LHS	1.70	59	1011.7	611.9	1013.0	401.1	2.522	2.541	2.654	5.0	95.0	99
				53					2.549			3.9	96.1	100

B2. Average extraction of asphalt, aggregate and binder content determination of Sample 1 & 2

Mass of Sample (g) A	**1169.05**
Mass of Aggregate (g) (after extraction) B	**1106.4**
Mass of Filler + Filter (g) C	**18.6**
Mass of Filter (g) D	**17.8**
Mass of Filler rtd. by Filter (g) E=C-D	**0.8**
Mass of Total Aggregate (g) F=B+E	**1107.2**
Mass of Dust in the extract, gm (G)	**2.65**
Mass of Total Aggregate+ Filler H=B+E+G	**1109.9**
Mass of Bitumen (g) I = A-F	**61.85**
Uncorrected Bitumen Content (%) J=I/A*100	**5.29**
Correction Factor for Mineral Matter (g) K=G/A*100	**0.23**
Corrected Bitumen Content (%) L=J-K	**5.06**

B3. A particle size distribution

Wearing layer

Mass of Total Aggregate			
Before wash, F	**1109.9**	After Wash	**1107.2**

AASHTO Sieve Size mm	Mass Retained (g)	% Retained	% Passing	Spec.Limit Job Mix Formula		Median
26.5	0.0	0.0	100.0	95.0	100.0	97.5
19.0	99.9	9.0	91.0	89.5	99.5	94.5
13.20	111.5	10.0	81.0	76.3	86.3	81.3
9.50	144.3	13.0	68.0	63.4	73.4	68.4
6.70	111.1	10.0	58.0	51.5	61.5	56.5
4.75	66.6	6.0	52.0	48.2	56.2	52.2
2.36	87.7	7.9	44.1	40.5	48.5	44.5
1.18	128.7	11.6	32.5	28.1	36.1	32.1
0.600	101.0	9.1	23.4	18.0	26.0	22.0
0.300	82.1	7.4	16.0	14.3	20.3	17.3
0.150	44.4	4.0	12.0	10.3	14.3	12.3
0.075	66.6	6.0	6.0	4.3	8.3	6.3
Passing 0.075	66.3	6.0	0.0			
Sum	1109.9	100.0				

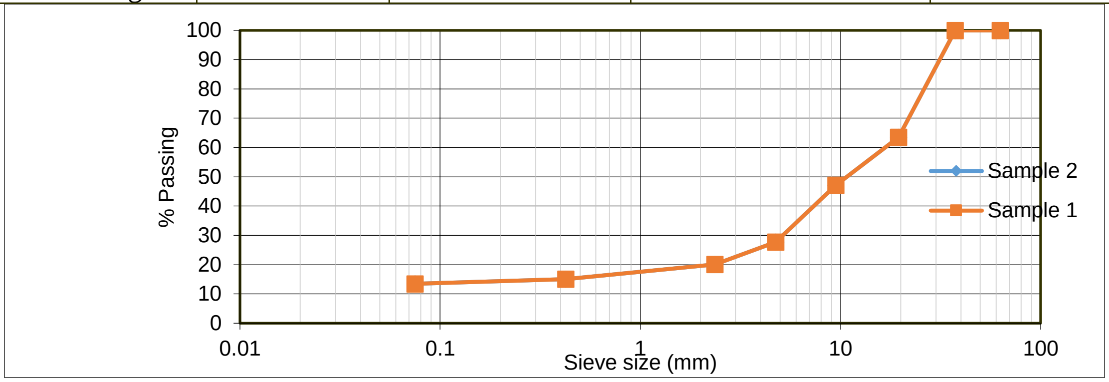
Base course

Sample 1

sieve size, mm.	weight retained (Partial)	% retained	% passing	Limit
63	0	0	100	100
37.5	0.0	0.0	100.0	80 -100
19.5	2726.5	36.5	63.5	60 - 80
9.5	1217.4	16.3	47.2	40 - 60
4.75	1447.5	19.4	27.8	25 - 40
2.36	574.9	7.7	20.1	15 -30
0.425	377.2	5.1	15.0	7 - 19
0.075	114.7	1.5	13.5	5 - 12
Pan	13.0	0.2		
Dry weight before washing	7463.2	100.0		

Sample 2

sieve size, mm.	weight retained (Partial)	% retained	% passing	Limit
63	0	0	100	100
37.5	0.0	0.0	100.0	80 -100
19.5	2726.5	36.5	63.5	60 - 80
9.5	1217.4	16.3	47.2	40 - 60
4.75	1447.5	19.4	27.8	25 - 40
2.36	574.9	7.7	20.1	15 -30
0.425	377.2	5.1	15.0	7 - 19
0.075	114.7	1.5	13.5	5 - 12
Pan	13.0	0.2		
Dry weight before washing	7463.2	100.0		



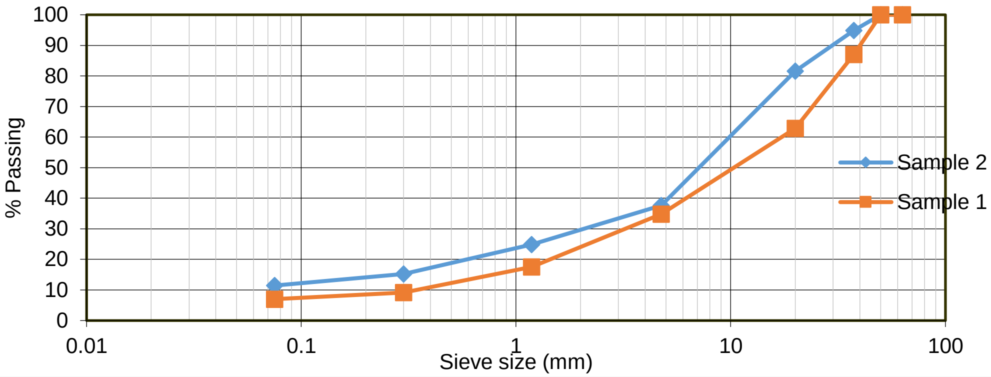
Sub- base

Sample 1

sieve size, mm.	weight retained (Partial)	% retained	% passing
63	0	0	100
50	0.0	0.0	100.0
37.5	1856.1	13.0	87.0
20	3455.3	24.2	62.8
4.75	3997.8	28.0	34.8
1.18	2470.1	17.3	17.5
0.3	1185.1	8.3	9.2
0.075	314.1	2.2	7.0
Pan		0.0	
Dry weight before washing	14278.0	100.0	

Sample 2

sieve size, mm.	weight retained (Partial)	% retained	% passing
63	0	0	100
50	0.0	0.0	100.0
37.5	795.8	5.1	94.9
20	2080.0	13.3	81.6
4.75	6884.0	44.0	37.6
1.18	2005.0	12.8	24.8
0.3	1500.0	9.6	15.3
0.075	596.0	3.8	11.4
Pan		0.0	
Dry weight before washing	15652.0	100.0	



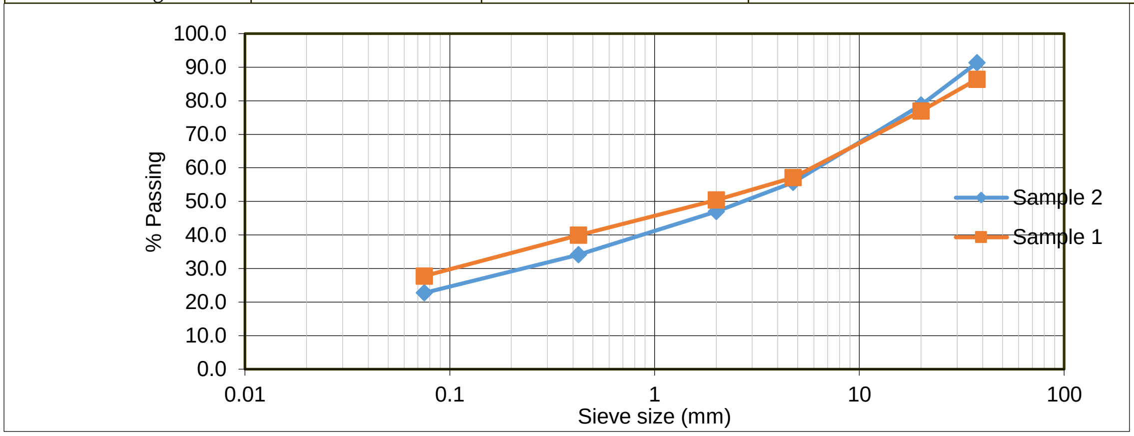
Sub-grade

Sample 1

sieve size, mm.	weight retained (Partial)	% retained	% passing
37.5	862.0	13.6	86.4
20	600.0	9.5	76.9
4.75	1254.0	19.8	57.1
2.00	424.0	6.7	50.4
0.425	664.0	10.5	39.9
0.075	768.0	12.1	27.7
Pan	90.0		
Dry weight before washing	6328.0	100.0	

Sample 2

sieve size, mm.	weight retained (Partial)	% retained	% passing
37.5	643.0	8.7	91.3
20	923.0	12.5	78.8
4.75	1705.0	23.1	55.7
2.00	637.0	8.6	47.0
0.425	953.0	12.9	34.1
0.075	839.0	11.4	22.7
Pan	86.0		
Dry weight before washing	7376.0	100.0	



B4. Standard Procter test

Base course

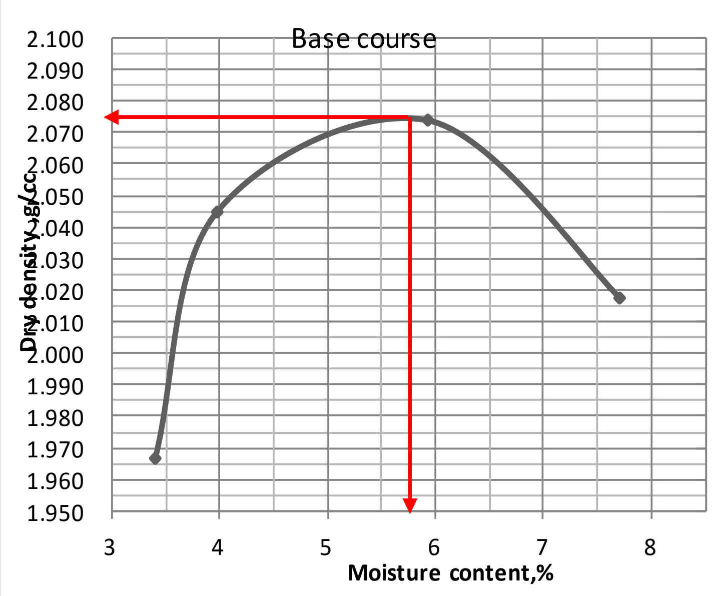
A	Mold	No.	1	2	3	4
B	Wt. of Mold + Wet Soil	grams	10205.0	10400.0	10550.0	10500.0
C	Wt. of Mold	grams	5908.0	5908.0	5908.0	5908.0
D	Wt. Wet Soil	grams	4297.0	4492.0	4642.0	4592.0
E	Volume of Mold	cu.cm.	2123.0	2123.0	2123.0	2123.0
F	Wet Density	gr/cu.cm.	2.024	2.116	2.187	2.163
G	Container	No.	2	5	50	12
H	Wt. Cont + Wet soil	grams	161.5	162.2	162.8	163.1
I	Wt. Cont + Dry soil	grams	157.9	157.9	156.2	154.6
J	Weight of Water	grams	3.6	4.3	6.6	8.5
K	Weight of Container	grams	34.1	34.2	34.8	36.5
L	Weight of Dry Soil	grams	123.8	123.7	121.4	118.1
M	Moisture Content	%	2.9	3.5	5.4	7.2
N	Dry Density	gr/cu.cm.	1.967	2.045	2.074	2.018

Maximum Dry Density (MDD):

MDD = 2.070 gm/cc

Optimum Moisture Content (OMC) :

OMC = 5.9 %



Sub base

Sample 1

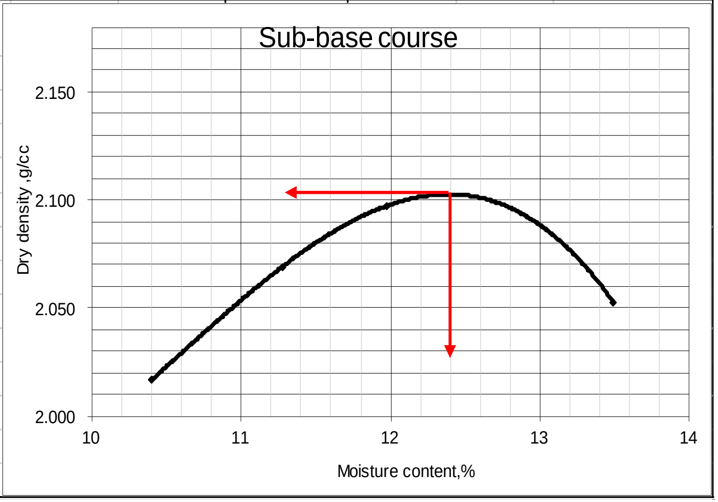
A	Mold	No.	1	2	3	4		
B	Wt. of Mold + Wet Soil	grams	11080.0	11240.0	11338.0	11298.0		
C	Wt. of Mold	grams	6372.0	6372.0	6372.0	6372.0		
D	Wt. Wet Soil	grams	4708.0	4868.0	4966.0	4926.0		
E	Volume of Mold	cu.cm.	2124.0	2124.0	2124.0	2124.0		
F	Wet Density	gr/cu.cm.	2.217	2.292	2.338	2.319		
								N.M.C
G	Container	No.	CV	BG	AF	AH		BJ
H	Wt. Cont + Wet soil	grams	639.7	592.2	502.7	719.0		708.8
I	Wt. Cont + Dry soil	grams	589.0	542.1	458.9	645.3		660.4
J	Weight of Water	grams	50.7	50.1	43.8	73.7		48.4
K	Weight of Container	grams	77.0	77.1	77.3	78.1		78.1
L	Weight of Dry Soil	grams	512.0	465.0	381.6	567.2		582.3
M	Moisture Content	%	9.9	10.8	11.5	13.0		8.3
N	Dry Density	gr/cu.cm.	2.017	2.069	2.097	2.053		

Maximum Dry Density (MDD):

MDD = 2.103 gm/cc

Optimum Moisture Content (OMC) :

OMC = 12.4 %



Sample 2

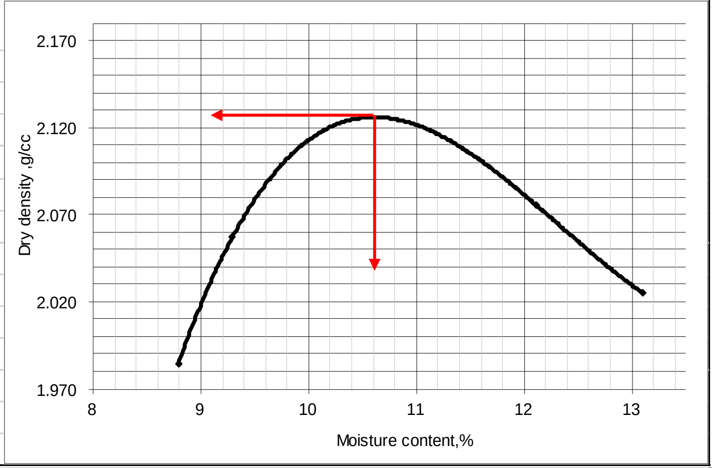
A	Mold	No.	1	2	3	4		
B	Wt. of Mold + Wet Soil	grams	10985.0	11176.0	11342.0	11265.0		
C	Wt. of Mold	grams	6400.0	6400.0	6400.0	6400.0		
D	Wt. Wet Soil	grams	4585.0	4776.0	4942.0	4865.0		
E	Volume of Mold	cu.cm.	2124.0	2124.0	2124.0	2124.0		
F	Wet Density	gr/cu.cm.	2.159	2.249	2.327	2.290		
								N.M.C
G	Container	No.	A-3	P-11	A-4	A-1		A-2
H	Wt. Cont + Wet soil	grams	637.3	668.5	607.8	592.0		691.8
I	Wt. Cont + Dry soil	grams	590.9	616.5	548.4	529.5		663.3
J	Weight of Water	grams	46.4	52.0	59.4	62.5		28.5
K	Weight of Container	grams	63.0	57.0	58.0	52.3		51.7
L	Weight of Dry Soil	grams	527.9	559.5	490.4	477.2		611.6
M	Moisture Content	%	8.8	9.3	12.1	13.1		4.7
N	Dry Density	gr/cu.cm.	1.984	2.057	2.075	2.025		

Maximum Dry Density (MDD):

MDD = 2.127 gm/cc

Optimum Moisture Content (OMC) :

OMC = 10.6 %



Sub-grade

Sample 1

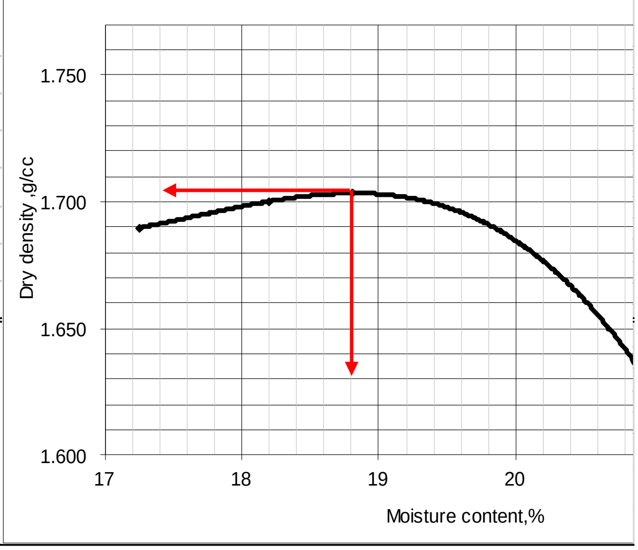
A	Mold	No.	1	2	3	4	
B	Wt. of Mold + Wet Soil	grams	10620.0	10680.0	10710.0	10564.0	
C	Wt. of Mold	grams	6412.0	6412.0	6412.0	6412.0	
D	Wt. Wet Soil	grams	4208.0	4268.0	4298.0	4152.0	
E	Volume of Mold	cu.cm.	2124.0	2124.0	2124.0	2124.0	
F	Wet Density	gr/cu.cm.	1.981	2.009	2.024	1.955	
G	Container	No.	C-B	A-E	A-C	B-J	
H	Wt. Cont + Wet soil	grams	532.4	539.6	587.3	585.1	
I	Wt. Cont + Dry soil	grams	463.9	468.6	505.4	497.1	
J	Weight of Water	grams	68.5	71.0	81.9	88.0	
K	Weight of Container	grams	66.8	78.4	69.8	80.8	
L	Weight of Dry Soil	grams	397.1	390.2	435.6	416.3	
M	Moisture Content	%	17.3	18.2	18.8	21.1	
N	Dry Density	gr/cu.cm.	1.690	1.700	1.703	1.614	

Maximum Dry Density (MDD):

MDD = 1.703 gm/cc

Optimum Moisture Content (OMC) :

OMC = 18.8 %



Sample 2

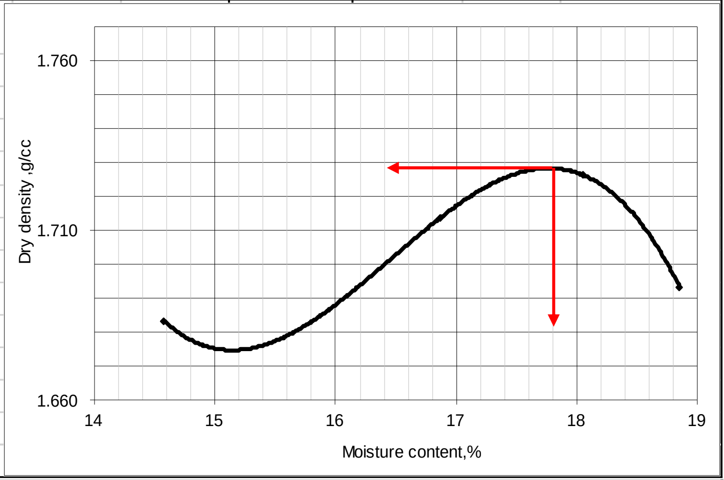
A	Mold	No.	1	2	3	4		
B	Wt. of Mold + Wet Soil	grams	10508.0	10665.0	10740.0	10686.0		
C	Wt. of Mold	grams	6412.0	6412.0	6412.0	6412.0		
D	Wt. Wet Soil	grams	4096.0	4253.0	4328.0	4274.0		
E	Volume of Mold	cu.cm.	2124.0	2124.0	2124.0	2124.0		
F	Wet Density	gr/cu.cm.	1.928	2.002	2.038	2.012		
								N.M.C
G	Container	No.	AJ	N-30	AQ	CM		G-3
H	Wt. Cont + Wet soil	grams	608.7	582.1	567.8	584.6		620.0
I	Wt. Cont + Dry soil	grams	541.0	509.8	492.6	504.3		570.9
J	Weight of Water	grams	67.7	72.3	75.2	80.3		49.1
K	Weight of Container	grams	76.4	81.1	76.0	78.4		79.7
L	Weight of Dry Soil	grams	464.6	428.7	416.6	425.9		491.2
M	Moisture Content	%	14.6	16.9	18.1	18.9		10.0
N	Dry Density	gr/cu.cm.	1.683	1.713	1.726	1.693		

Maximum Dry Density (MDD):

MDD = 1.729 gm/cc

Optimum Moisture Content (OMC) :

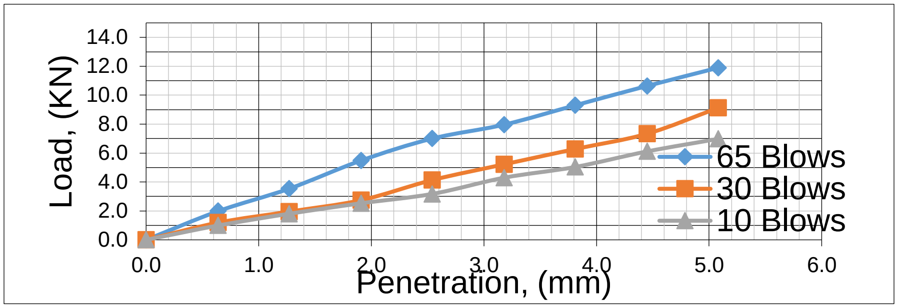
OMC = 17.8 %

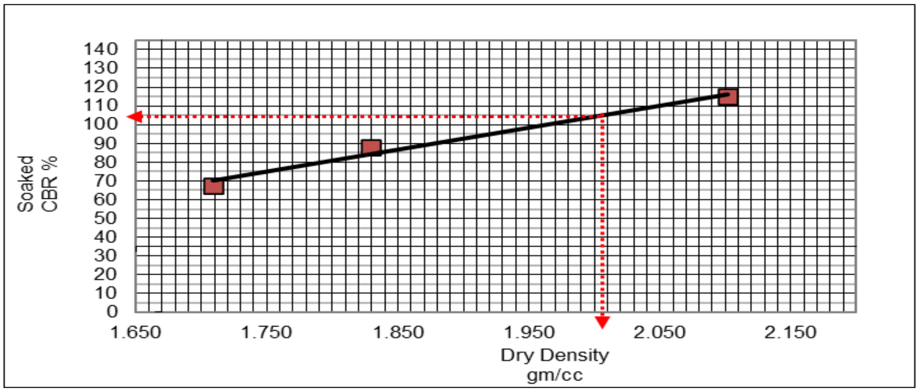


Base Course

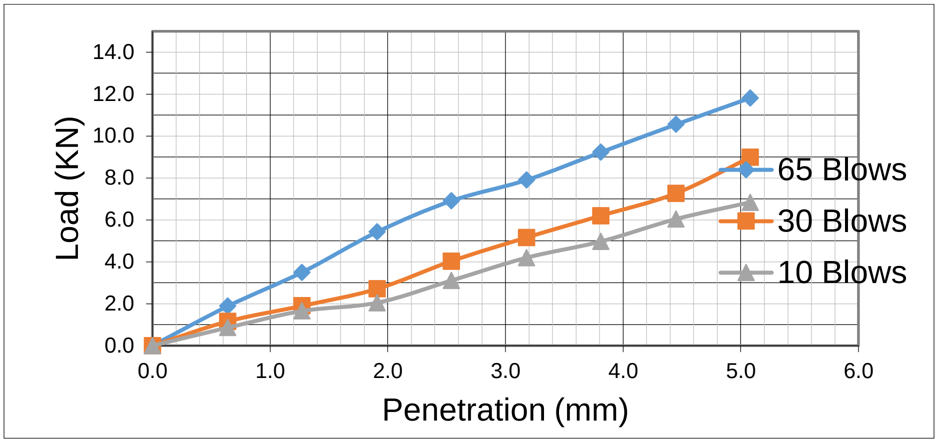
Calculation of CBR, %						
Number of samples	**Sample 1 @ 2+700**					
	65 Blows		30 Blows		10 Blows	
Penetration	2.5mm	5.08mm	2.5mm	5.08mm	2.5mm	5.08mm
Dial RDG	1059	1800	625	1380	480	1056
Load, (KN)	13.54	23.02	7.99	17.65	6.14	13.51
CBR, %	102	115	60	88	46	67
CBR, %	115		88		67	
Number of samples	**Sample 2 @ 4+700**					
	65 Blows		30 Blows		10 Blows	
Penetration	2.5mm	5.08mm	2.5mm	5.08mm	2.5mm	5.08mm
Dial RDG	1045	1788	610	1360	470	1035
Load, (KN)	13.36555	22.86852	7.8019	17.3944	6.0113	13.23765
CBR, %	100	114	58	86	45	66
CBR, %	114		86		66	

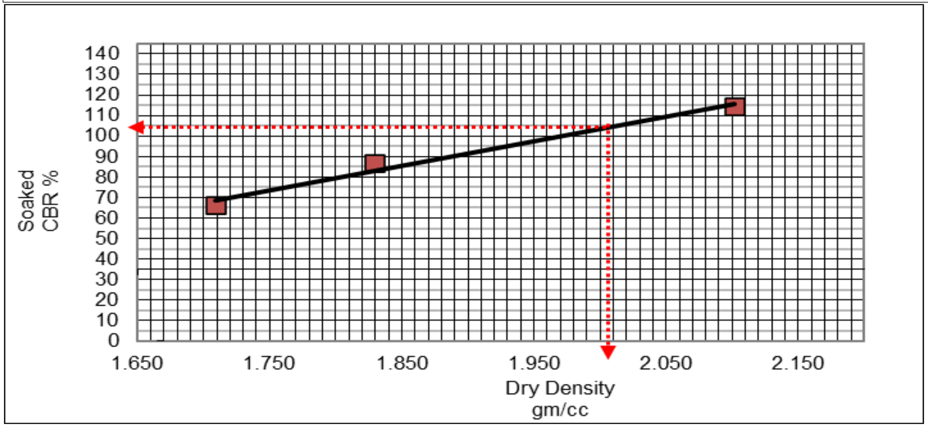
Sample1





Sample 2

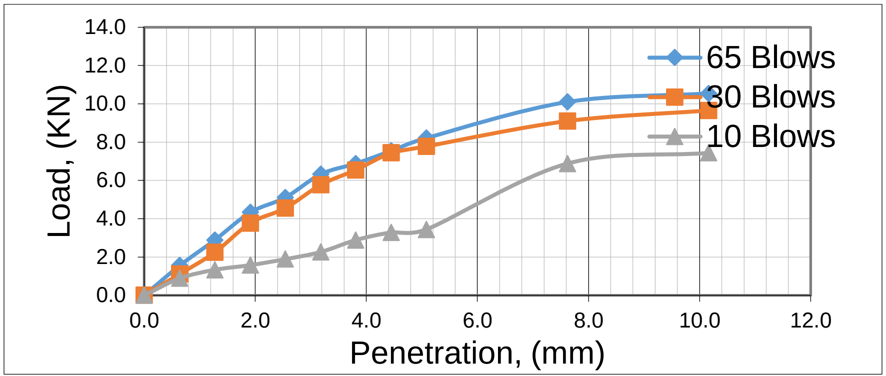


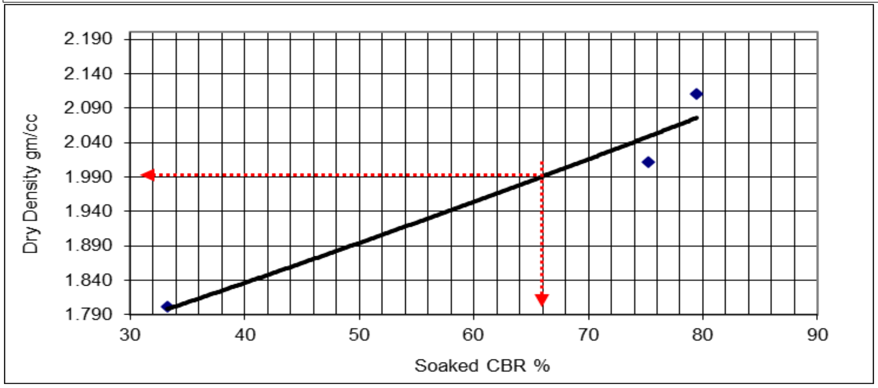


Sub base

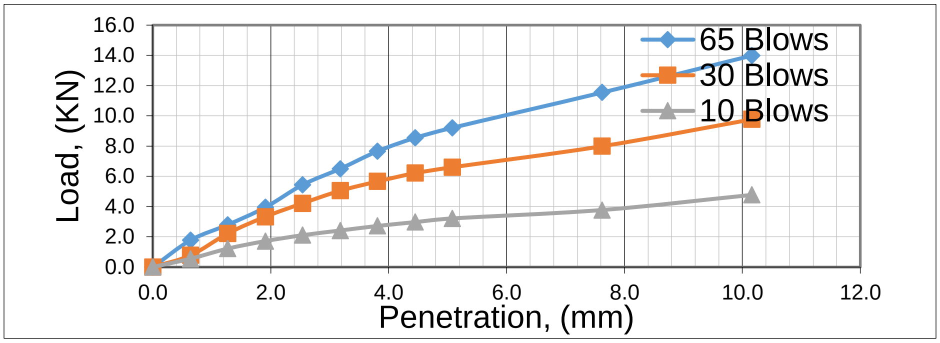
Calculation of CBR, %						
Number of samples	**Sample 1 @ 2+700**					
	65 Blows		30 Blows		10 Blows	
Penetration	2.5mm	5.08mm	2.5mm	5.08mm	2.5mm	5.08mm
Dial RDG	460	740	410	701	170	310
Load, (KN)	9.88	15.90	8.81	15.06	3.65	6.66
CBR, %	74	79	66	75	27	33
CBR, %	79		75		33	
Number of samples	**Sample 2 @ 4+700**					
	65 Blows		30 Blows		10 Blows	
Penetration	2.5mm	5.08mm	2.5mm	5.08mm	2.5mm	5.08mm
Dial RDG	490	830	380	595	190	290
Load, (KN)	10.53	17.83	8.16	12.78	4.08	6.23
CBR, %	79	89	61	64	31	31
CBR, %	89		64		31	

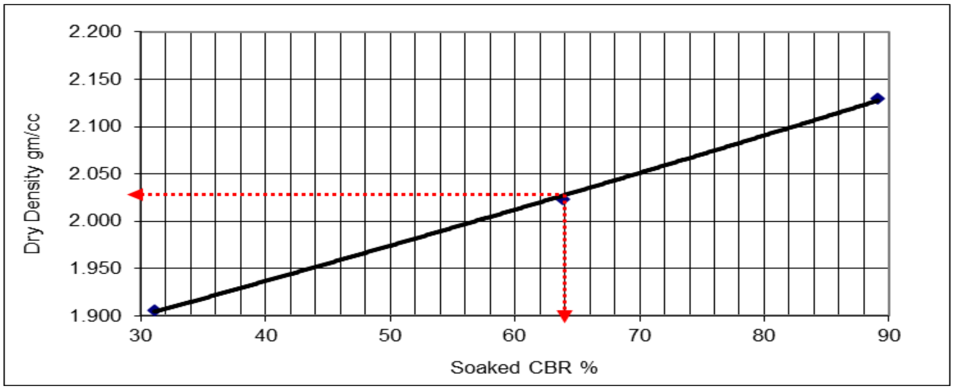
Sample 1





Sample 2

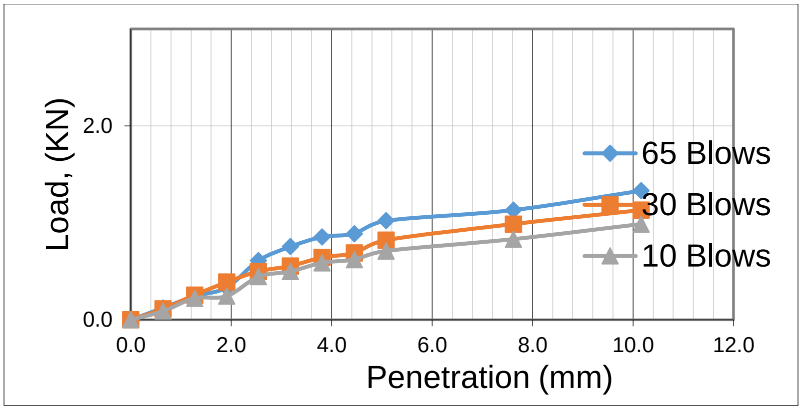


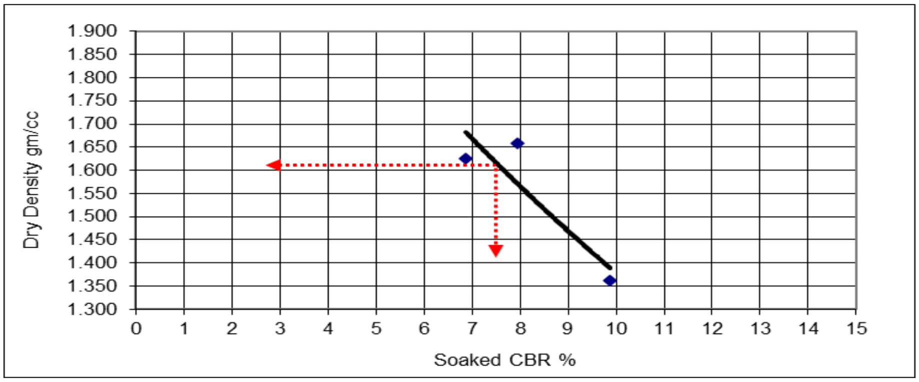


Sub grade

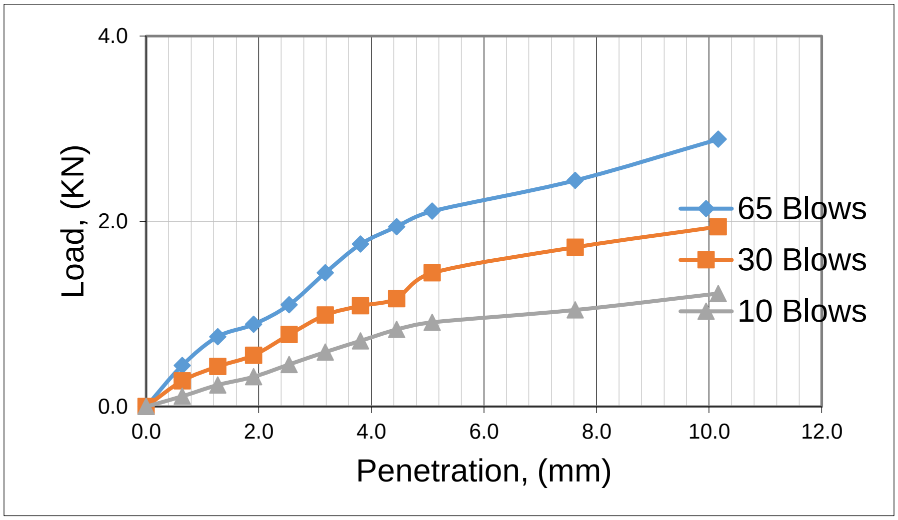
Calculation of CBR, %						
Number of samples	**Sample 1 @ 2+700**					
	65 Blows		30 Blows		10 Blows	
Penetration	2.5mm	5.08mm	2.5mm	5.08mm	2.5mm	5.08mm
Dial RDG	55	92	45	74	40	64
Load, (KN)	1.18	1.98	0.97	1.59	0.86	1.37
CBR, %	9	10	7	8	6	7
CBR, %	10		8		7	
Number of samples	**Sample 2 @ 4+700**					
	65 Blows		30 Blows		10 Blows	
Penetration	2.5mm	5.08mm	2.5mm	5.08mm	2.5mm	5.08mm
Dial RDG	99	190	70	130	41	82
Load, (KN)	2.13	4.08	1.50	2.79	0.88	1.76
CBR, %	16	20	11	14	7	9
CBR, %	20		14		9	

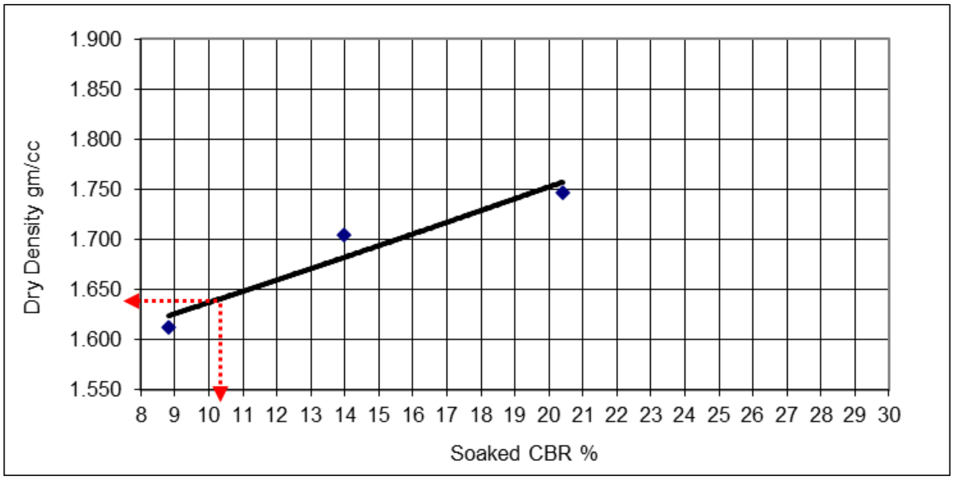
Sample 1





Sample 2





Atterberg Limits

Sample number	**Pavement layers**	**LL, %**	**PL, %**	**PI, %**
	Sub base	32	27	10
	Sub grade	35	22	14
	Sub base	39	28	11
	Sub grade	34	19	15

Appendix C: Results of modelling

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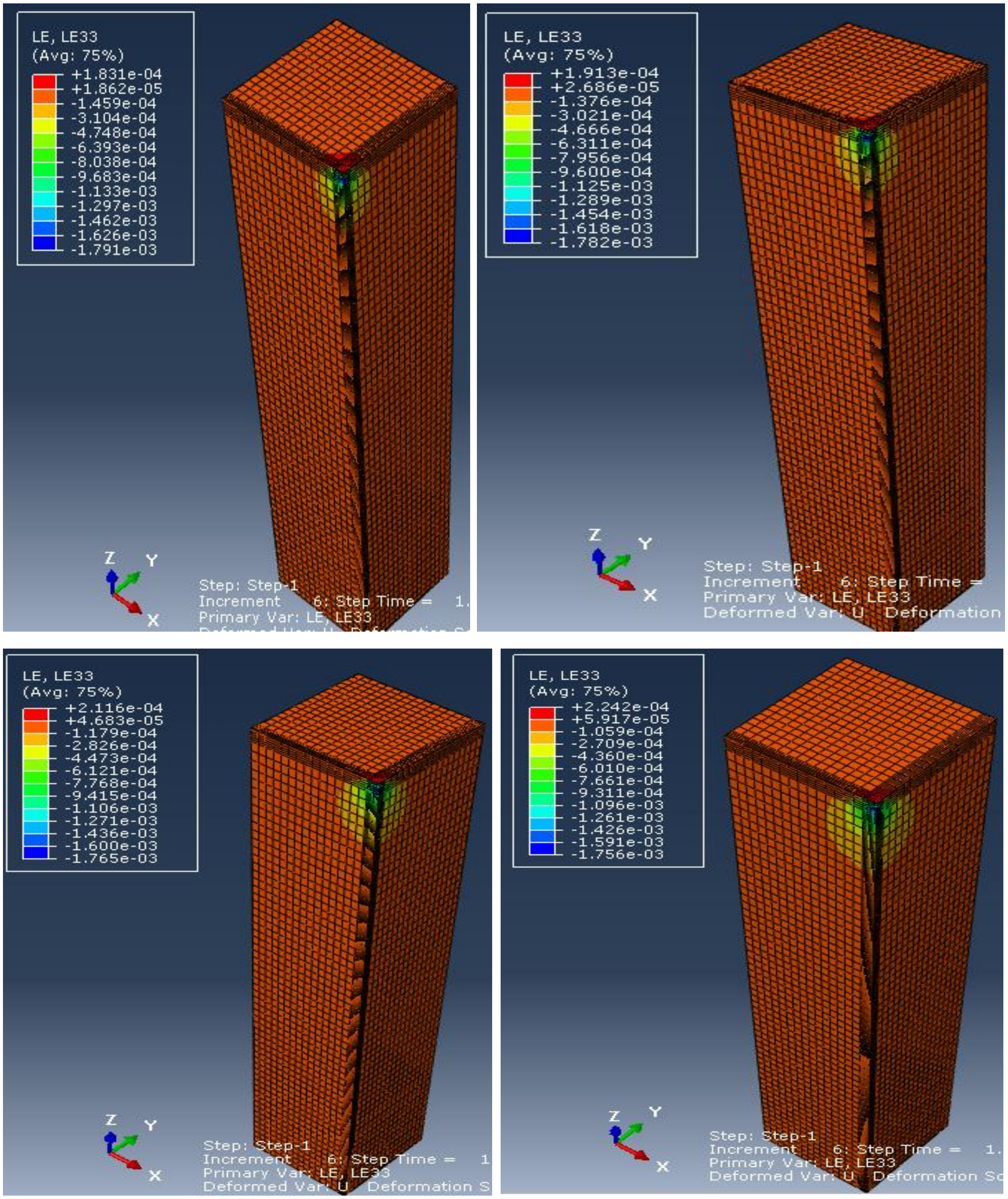
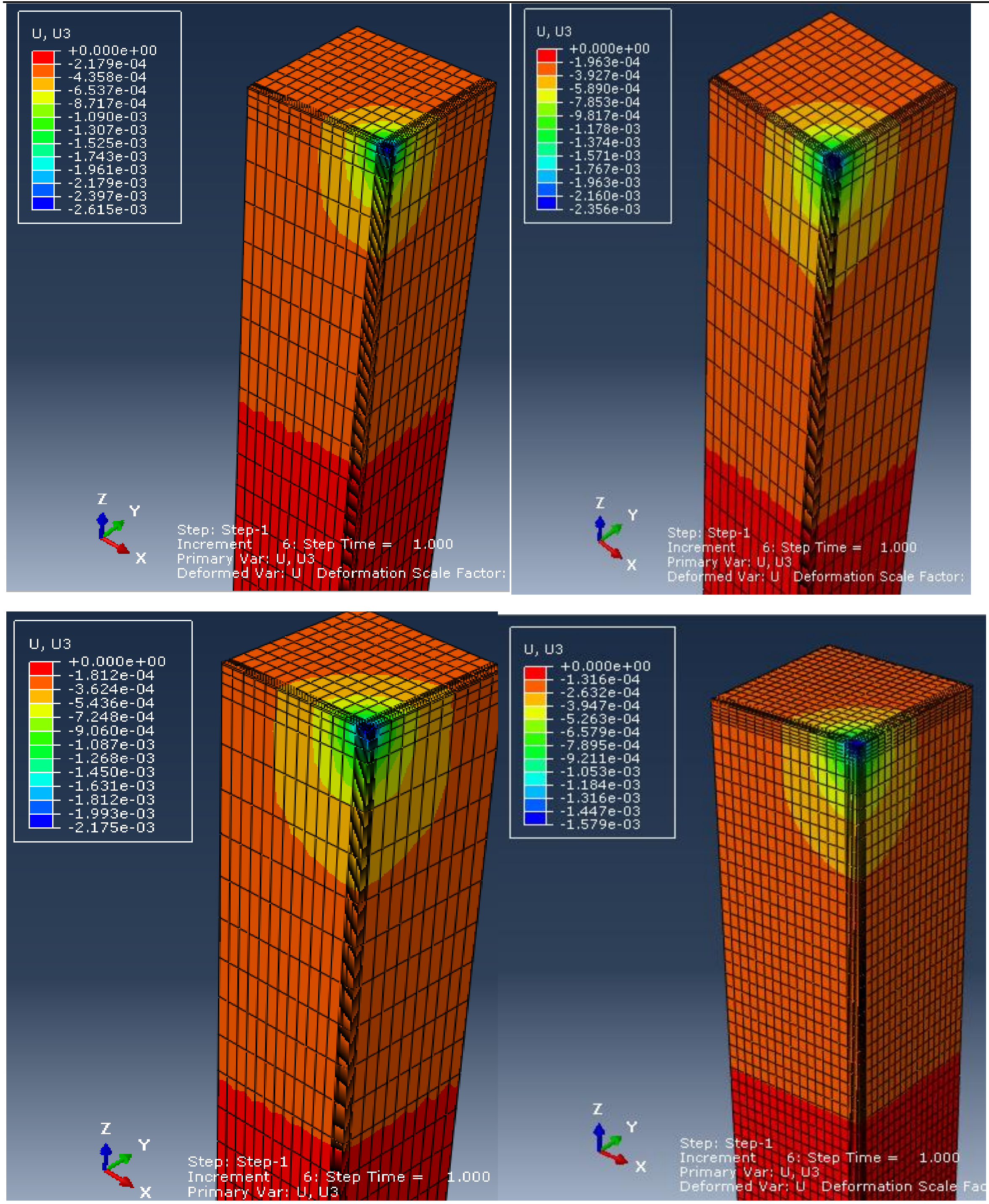
C1. Predicted Permanent Deformation (Rutting) of existing pavement



FigureC1a. Vertical strain with different subgrade quality in terms of CBR



FigureC1b. Vertical deformation with different aggregate gradation & quality of material in terms of CBR value (sampled from Didessa – Dembi – Bedele Road Project)

C2. Effects of different Aggregate Gradation on Rutting Development and its relationship with Severity of permanent deformation (Rutting)

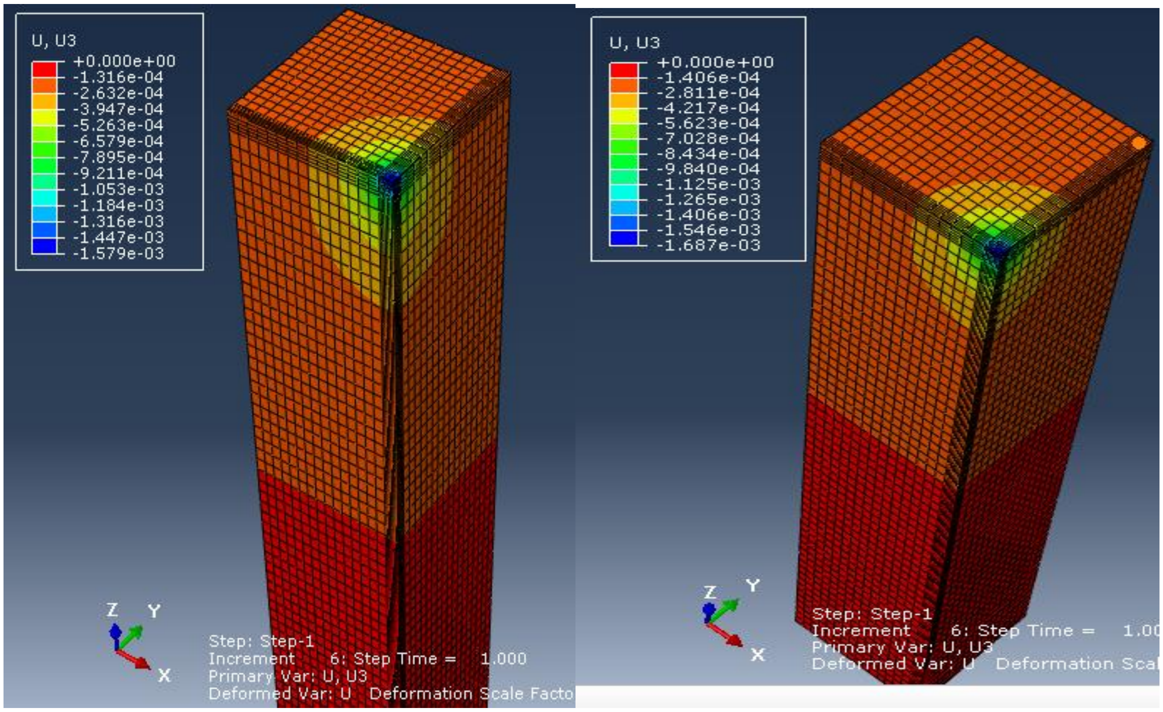
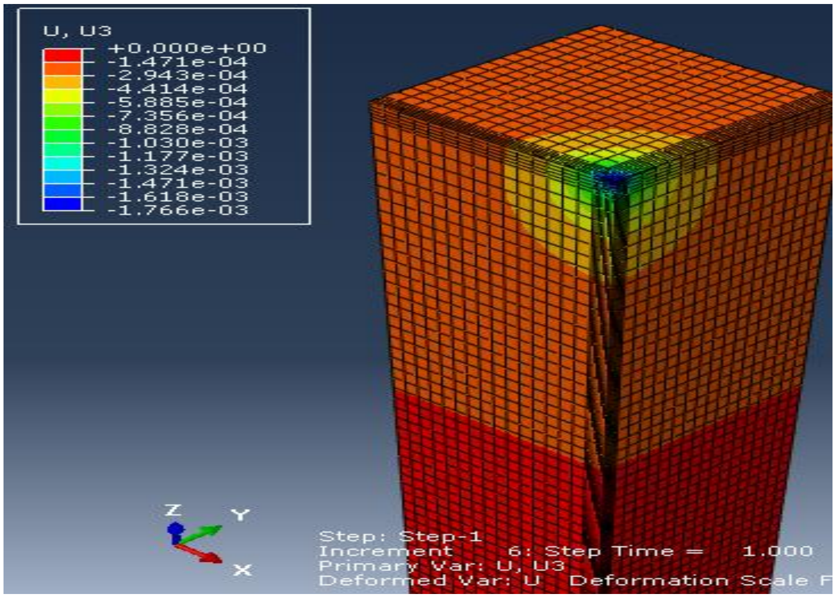


Figure C2a. Vertical Displacement with Well graded and Medium graded Aggregate respectively



FigureC2b. Vertical Displacement with poor graded aggregate

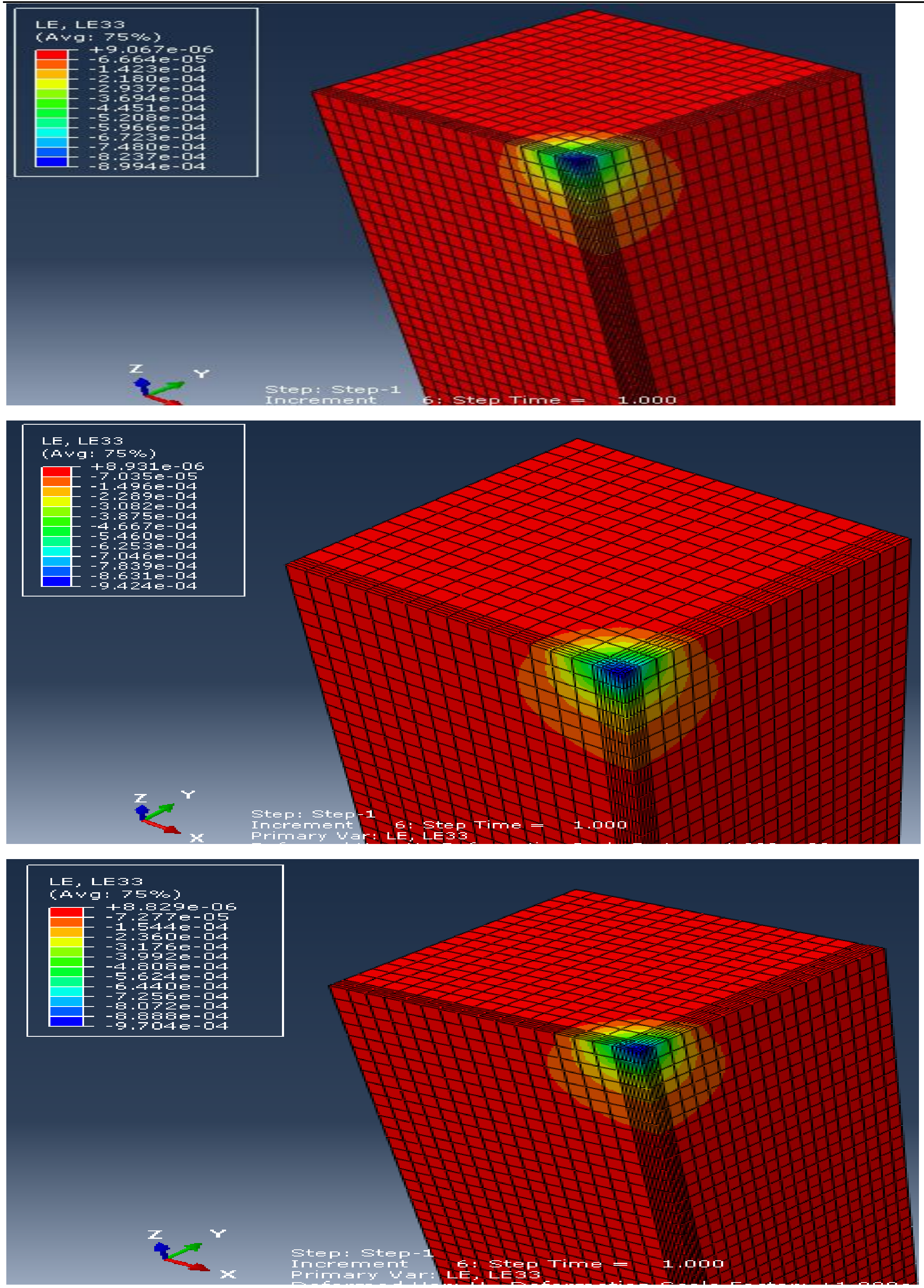


Figure C2c. Vertical Strain at the top of subgrade as aggregate gradations to poor graded decrease from well graded

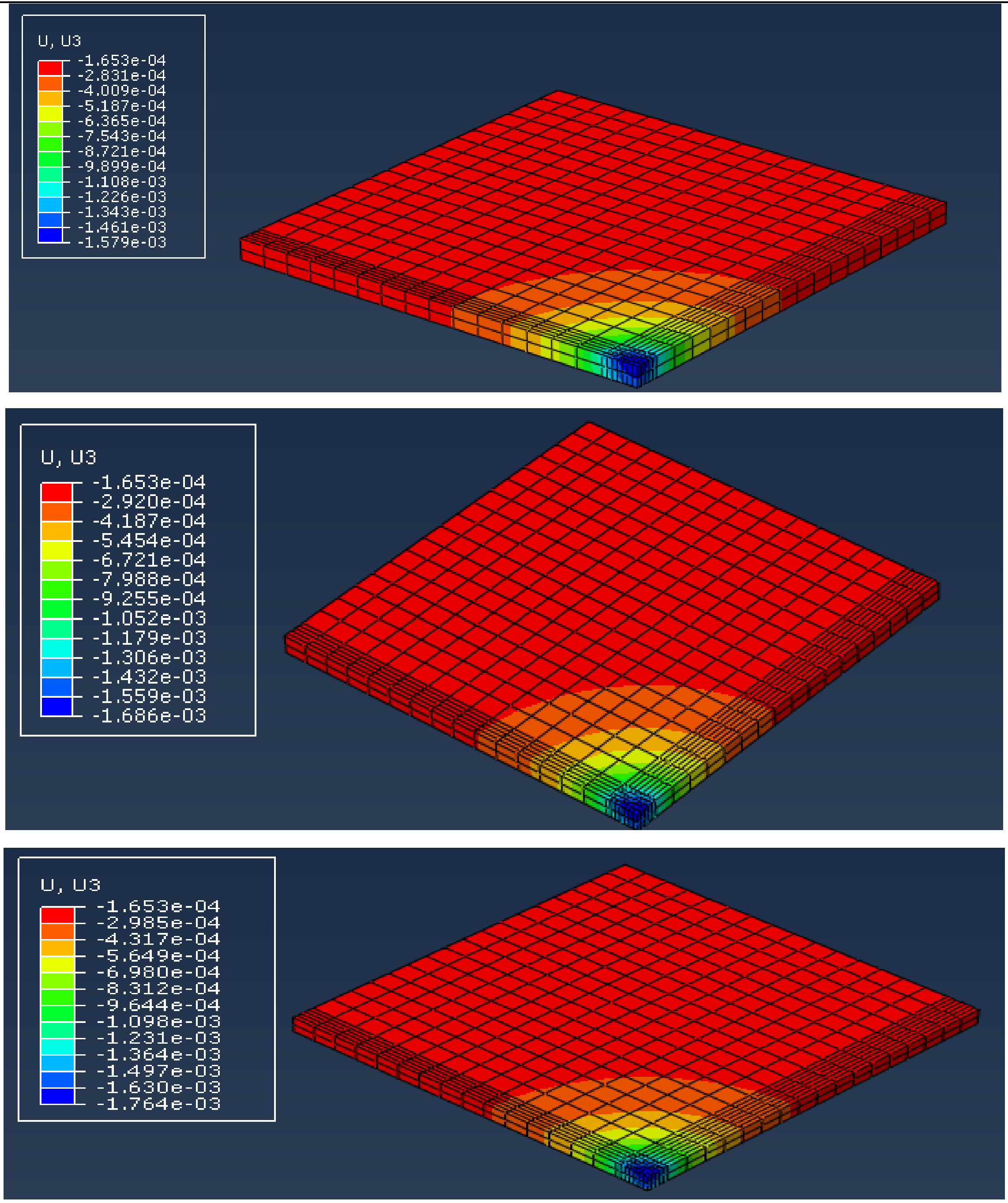
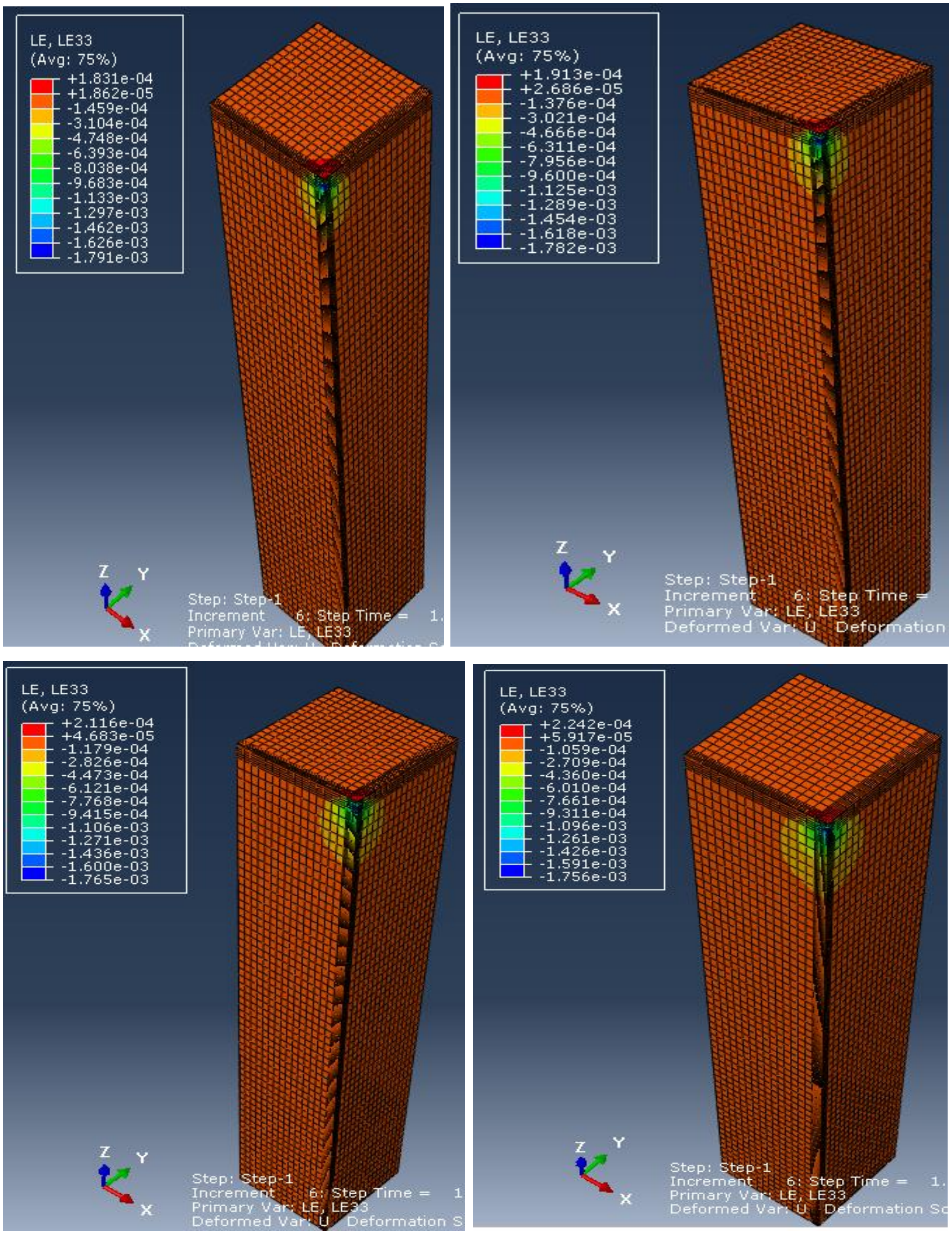
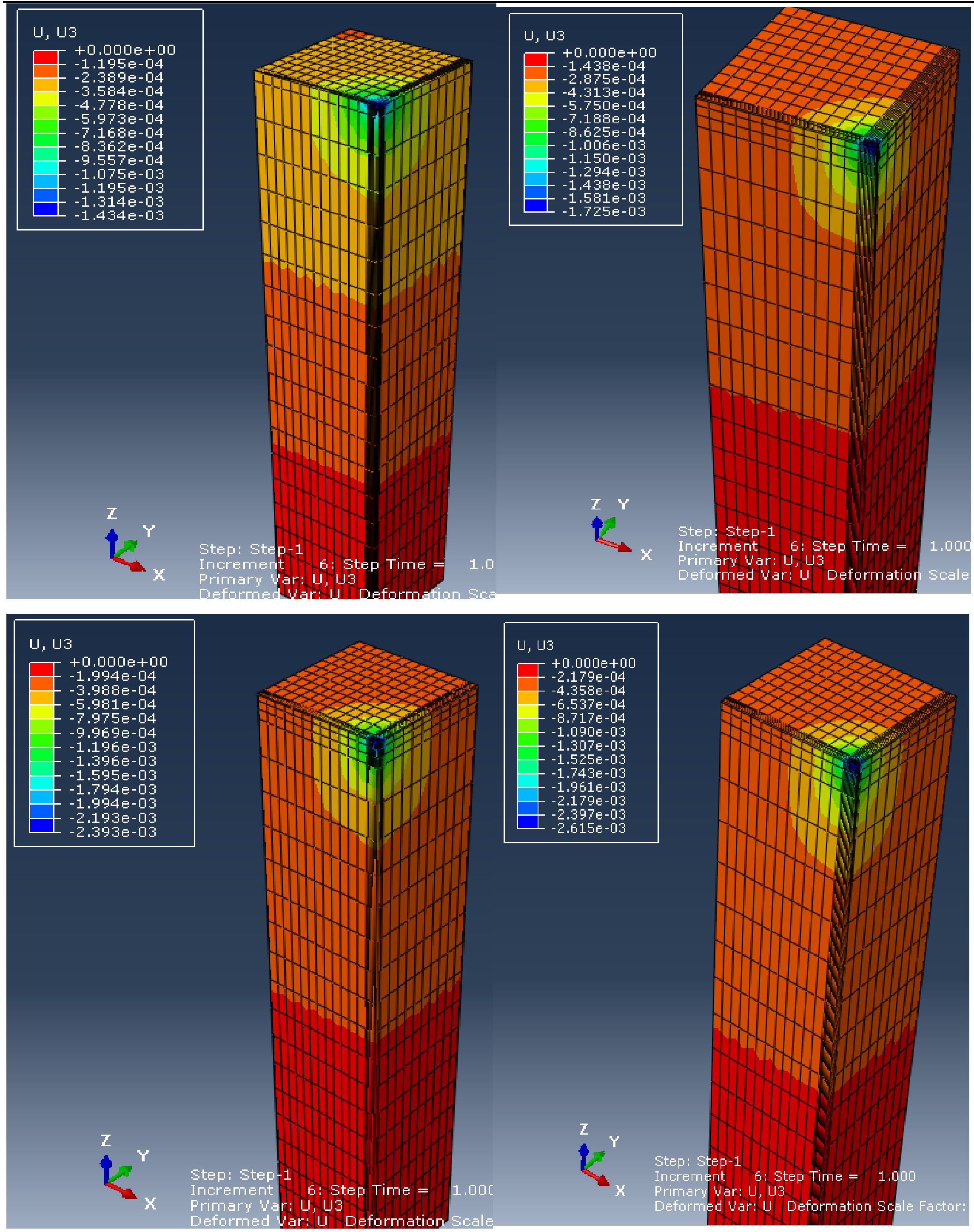


Figure C2d. Vertical Displacement as aggregate gradations decrease from well graded to poor graded

C3. Effects of quality of sub-grade on permanent deformation (Rutting)



FigureC3aVertical strain with different subgrade quality in terms of CBR



FigureC3b. Effects of sub-grade material quality

C4. Predicting Structural Response of Flexible Pavement with Different aggregate gradation and Sub-grade quality

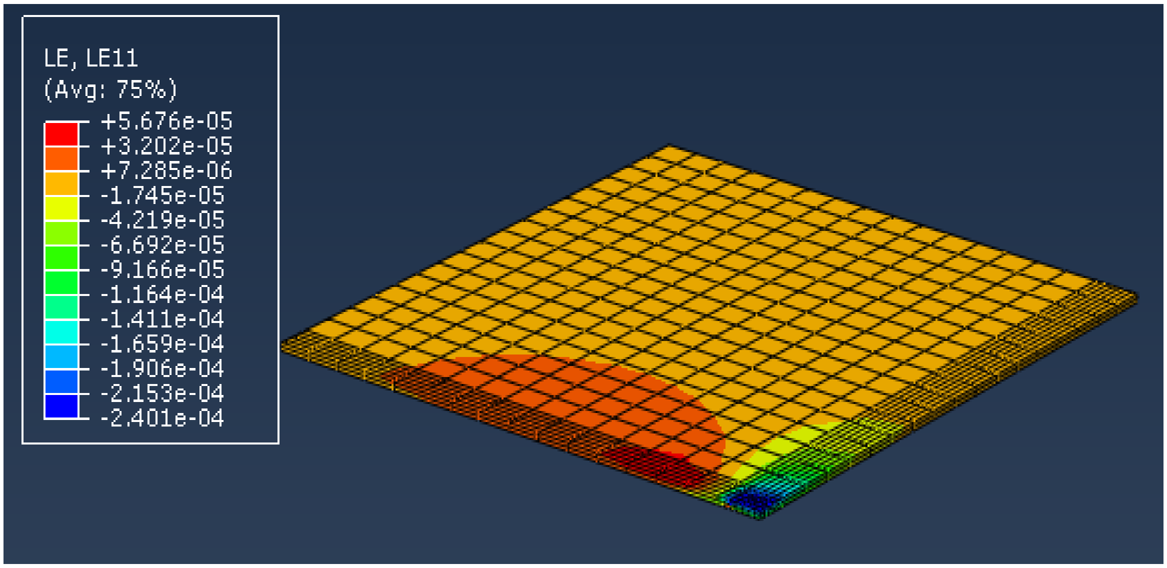


Figure C4a. Horizontal Tensile strain below AC with well graded aggregate and 7% CBR value

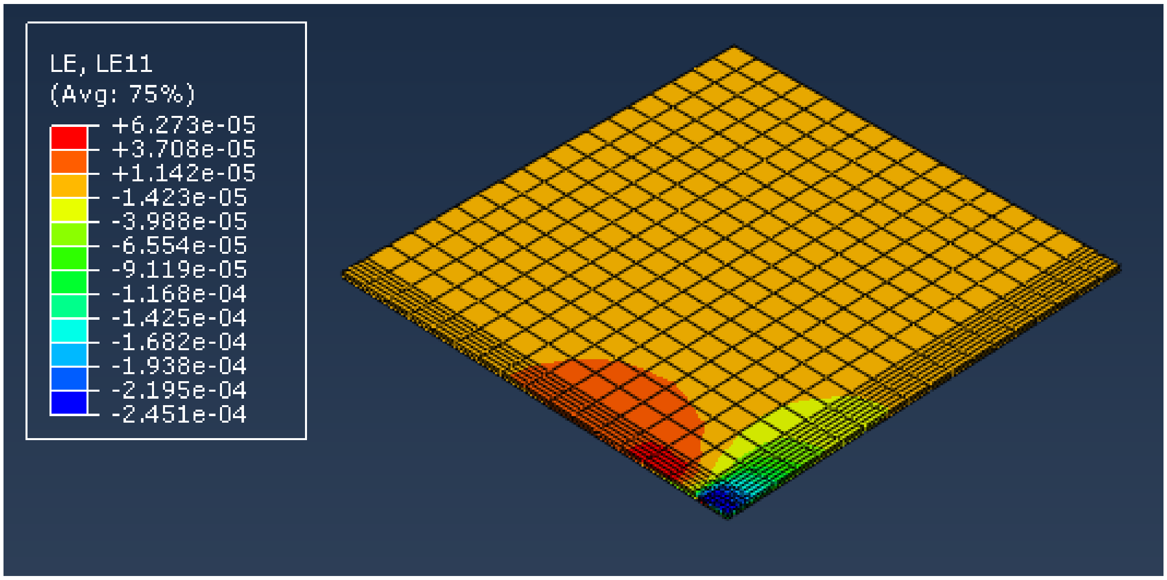


Figure C4b. Horizontal Tensile strain below AC with medium graded aggregate and 11% CBR value

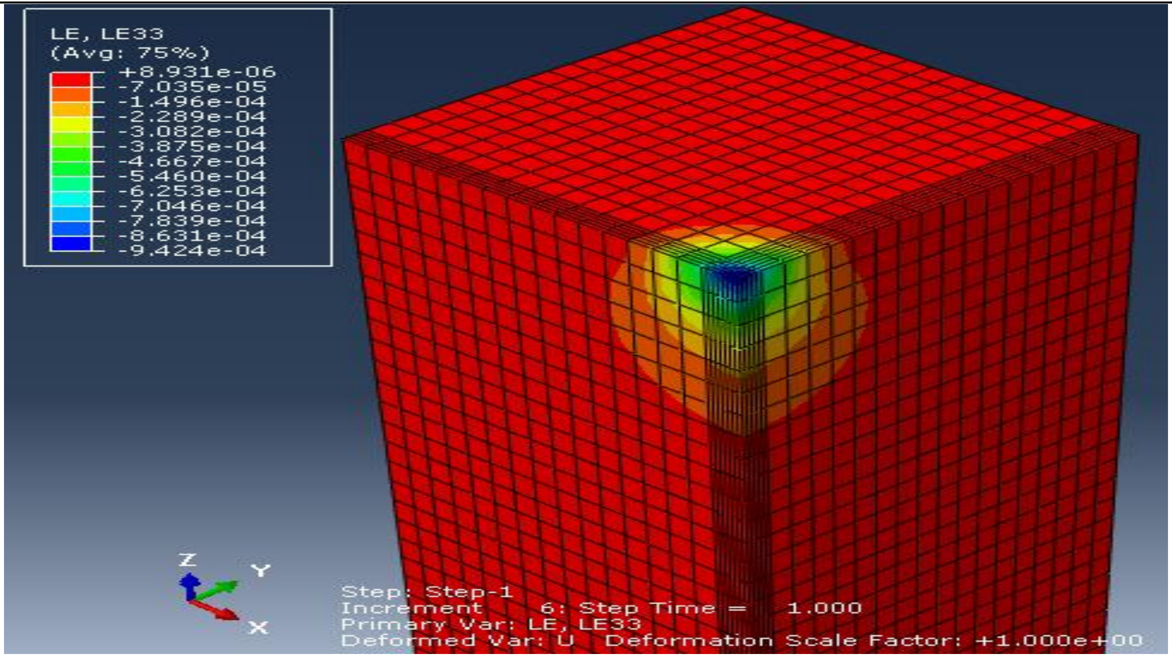


Figure C4c. Vertical Strain at the top of Sub-grade with well graded and 7% CBR value

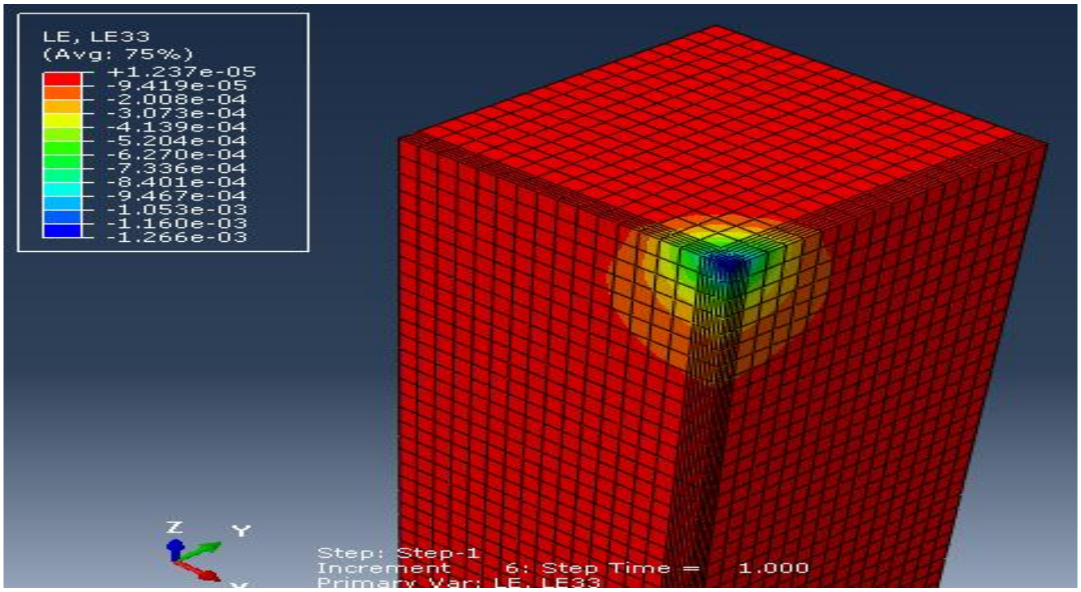


Figure C4d. Vertical Strain at the top of Sub-grade with medium graded and 7% CBR value

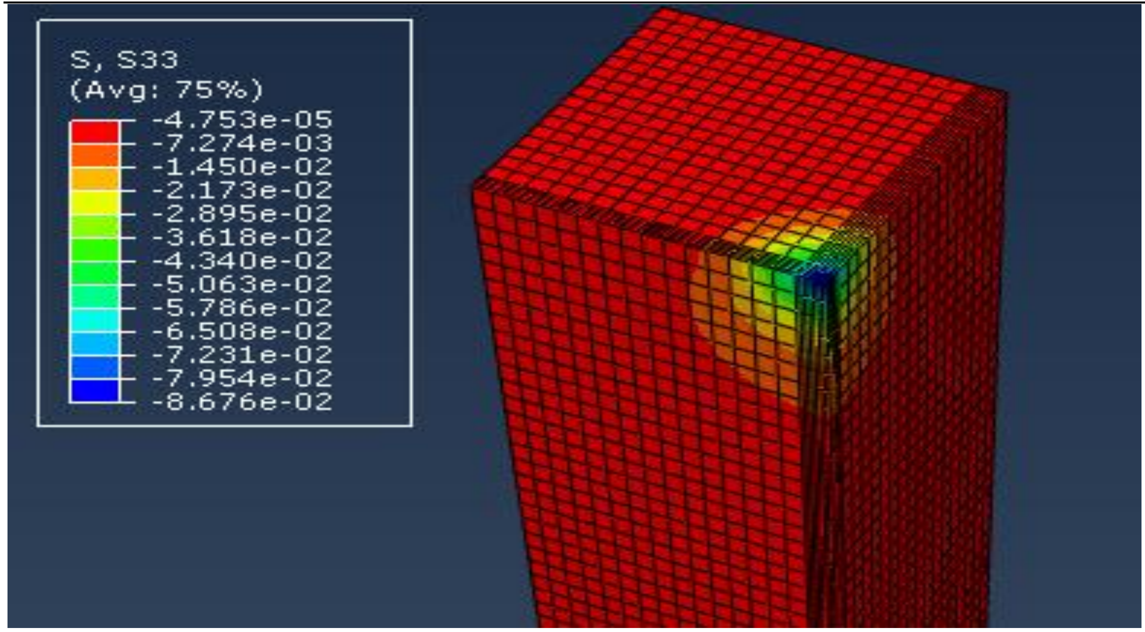


Figure C4e. Vertical Stress above sub-grade with well graded and 7% CBR value

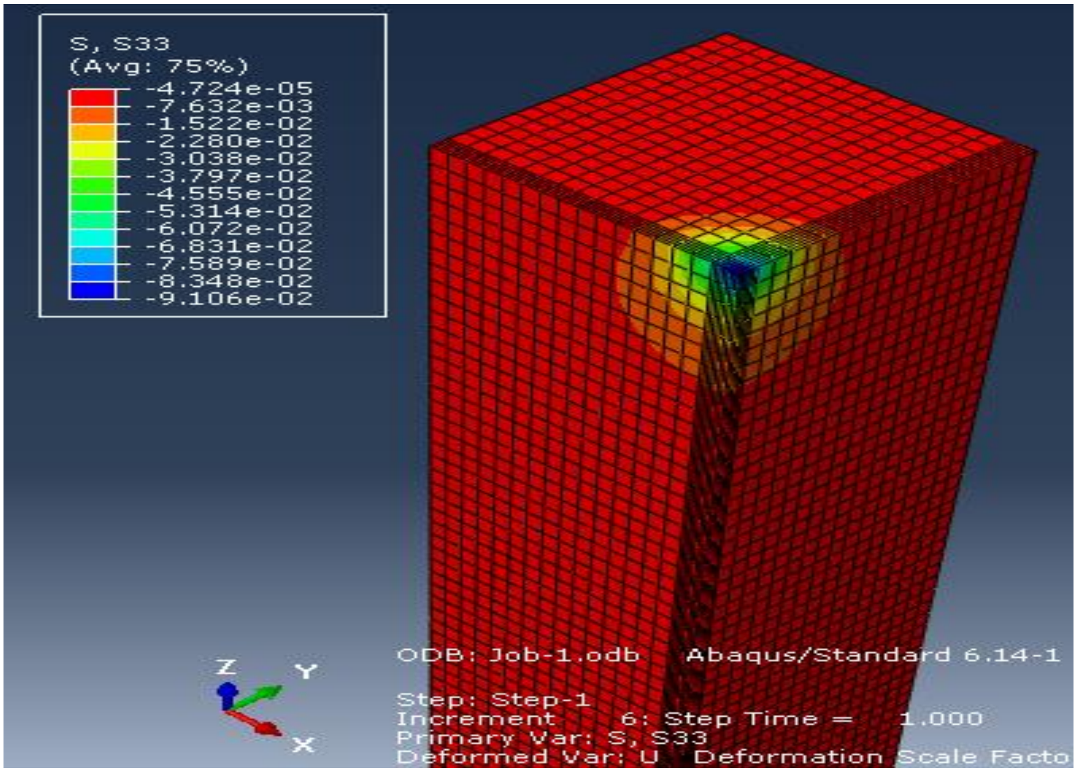


Figure C4f. Vertical Stress above sub-grade with Medium graded and 7% CBR value

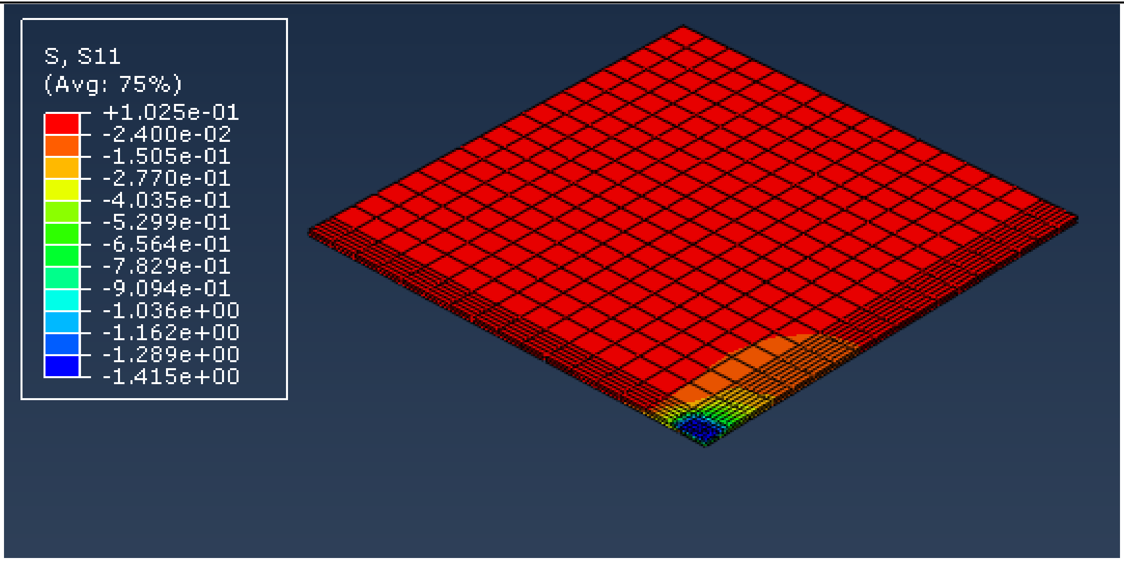


Figure C4g. tensile stress below AC with medium graded aggregate gradation and 11% CBR value

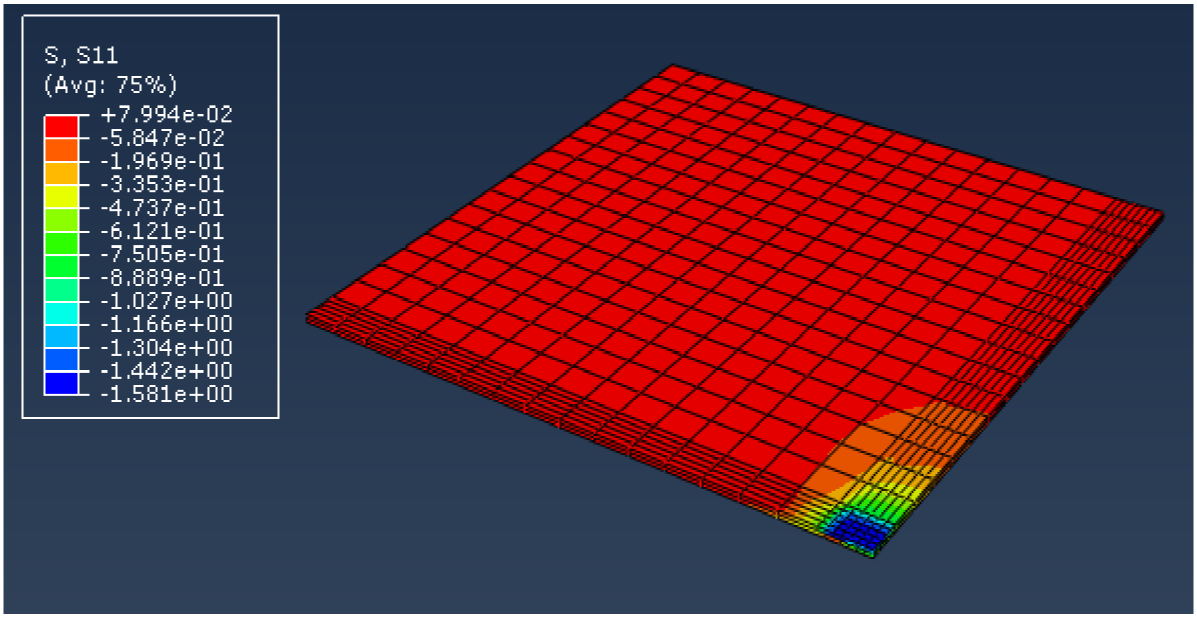


Figure C4h. tensile stress below AC with poor graded aggregate gradation and 7% CBR value

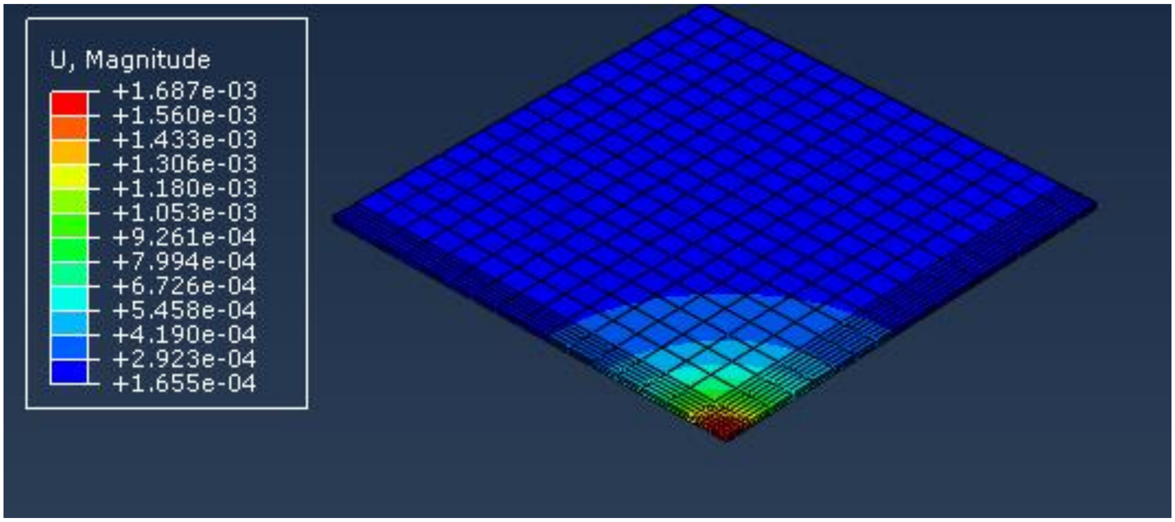


Figure C4i. Surface Deformation with medium graded aggregate gradation and 11% CBR value

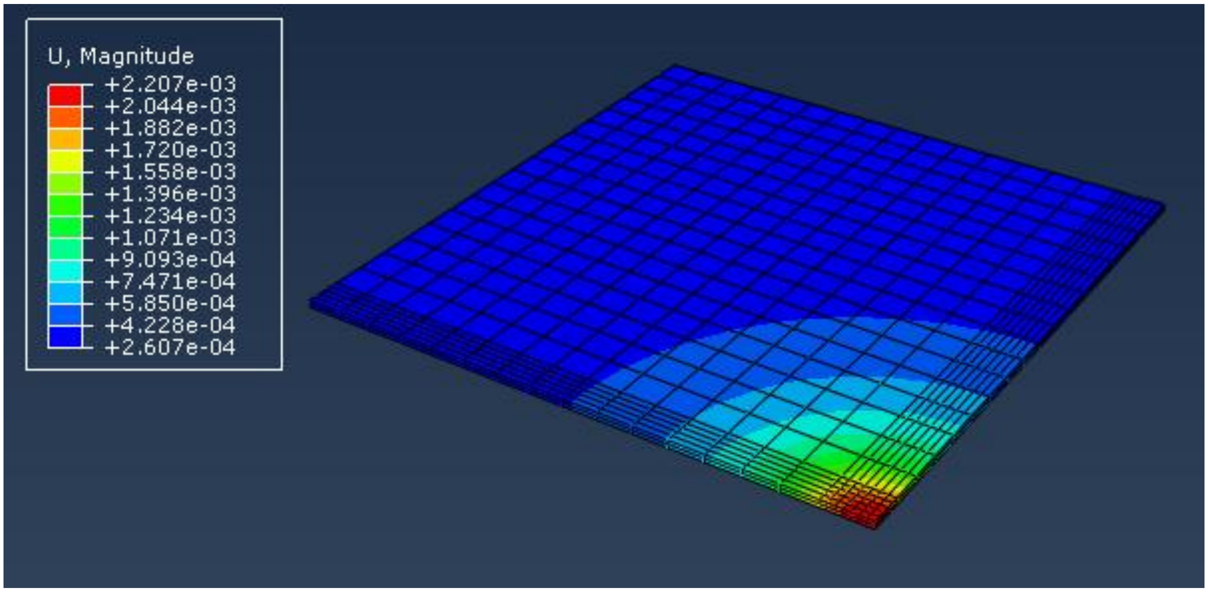


Figure C4j. Surface Deformation with poor graded aggregate gradation and 7% CBR value