UNIVERSITY OF NAIROBI

FACULTY OF ENGINEERING

DEPARTMENT OF CIVIL & CONSTRUCTION ENGINEERING

Investigation of the Performance of Pavement founded on Reinforced Earth Sections along Outer Ring Road, Nairobi

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F56/76654/2014

A thesis submitted in partial fulfilment of the requirements for the award of the Degree of Master of Science in Civil Engineering (Transportation Engineering) of the University of Nairobi

AUGUST 2023

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ACKNOWLEDGMENT

Special thanks to Prof. S.K. Mwea and Dr. S.N. Osano for their commitment and guidance in every stage of this thesis. I express sincere gratitude to my employer, Kenya Urban Roads Authority (KURA), Material Testing and Research Division (MTRD) and TIMCON Associates for the immense support during the data collection. Special appreciation to my husband, my family, my colleagues and friends for the moral support throughout this journey.

May God bless you all!

ABSTRACT

Urbanization in Nairobi city has resulted to increase in traffic demand exerting more pressure on the existing transport infrastructure. Outer ring road which is a critical artery within the city was improved to dual carriageway to meet the surge in traffic demand. Despite the use on reinforced earth embankments, there has been observed pavement surface distresses and increased traffic volume. This raised concerns of the performance of pavement founded on reinforced earth embankments of the road in meeting the transport demands of the rapidly growing city. The primary objective of this study was to investigate the performance of pavement founded on reinforced earth sections along Outer ring road. The specific objectives were to; evaluate the impact of the existing traffic loading on the pavement, establish the structural adequacy of the pavement and evaluate the functional performance of the pavement founded on the reinforced earth sections of Outer ring road. Quantitative and qualitative methods of data collection and analysis were adopted for this study. Pavement deflection measurements were taken using Falling Weight Deflectometer (FWD), roughness and rut depth measurements using Hawkeye 2000 Pavement Surface Profiler and through visual condition survey. Classified traffic counts and axle load survey were undertaken to determine the existing traffic. It was established that pavement on reinforced earth sections exhibited lower performance compared to pavement on other sections of the road. While reinforced earth embankments are designed to provide a robust foundation to the pavement, this study concludes that they must be meticulously designed and constructed taking into consideration the local dynamics to ensure longevity and performance of the pavement. It is recommended that future similar projects incorporate detailed long term traffic projection and consideration of performance of the indigenous construction materials and methodologies. In addition, regular monitoring, evaluation and maintenance practice of road infrastructure should be established to promptly arrest any potential pavement distresses before they deteriorate into major pavement failures and increased safety hazards to the public.

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ABBREVIATIONS

AASHO	American Association of State Highways Official
AASHTO	American Association of State Highways & Transportation Officials
AC	Asphalt Concrete
ARRB	Australian Road Research Board
ASTM	American Society for Testing and Materials
ATC	Automatic Traffic Counter
Avg	Average
CBR	California Bearing Ratio
CSA	Cumulative Standard Axles
CESA	Cumulative Equivalent Standard Axle
EF	Equivalent Factor
ESA	Equivalent Standard Axles
DESA	Daily Equivalent Standard Axles
FHA	Federal Highway Administration
GCS	Graded Crushed Stone
GDP	Gross Domestic Product
GSU	General Service Unit
HGV	Heavy Goods Vehicle
Kgs	Kilograms
Km	kilometre
kN	Kilo Newton
KPa	kilopascal
KRB	Kenya Roads Board
KURA	Kenya Urban Roads Authority
LGV	Light Goods Vehicle
LHS	Left Hand Side
m	Metre
MDD	Maximum Dry Density
MGV	Medium Goods Vehicle

mm	Millimetres
Min.	Minimum
MTRD	Materials Testing and Research Department
No.	Number
PMS	Pavement Management System
PCI	Pavement Condition Index
PSI	Present Serviceability Index
PSR	Present Serviceability Rating
RDM	Road Design Manual
RE	reinforced earth
RHS	Right Hand Side
Std	Standard
UCS	Unconfined Compressive Strength
VEF	Vehicle Equivalent Factor
v/h/l	vehicles/hour/lane
yr	Year

CHAPTER ONE

1. INTRODUCTION

1.1. Background of the Study

Efficient transport infrastructure is essential towards national development by providing access which directly boosts productivity and competiveness of the economy. Nairobi, the capital city of Kenya has continuously experienced rapid population and economic growth hence requiring improvement, rehabilitation or construction of new roads for meet the transportation infrastructure demands. Amidst this backdrop, Outer ring road which traverse a densely populated area in Nairobi forms a critical artery within Nairobi road network. Therefore to accommodate the increasing traffic demands within Nairobi city, Outer ring road was improved to dual carriageway with interchanges at the major intersections. Road infrastructure projects are capital intensive calling for deliberate efforts to make the most optimal national investment decisions. Therefore, to cater for the anticipated traffic load and maintain road durability, Reinforced Earth (RE) embankments were provided for the road.

The need for cost reduction, limited space, unlimited height of structure and lack of firm foundations, has made RE technology increasingly become popular especially where high embankments are unavoidable in urban areas. The RE structures are more stable consequently offering a strong foundation for the pavements constructed on them. However, the effectiveness of the RE structures to improve performance of pavement for outer ring road need to be investigated. The Kenya Road Design Manual (RDM), Part III for materials and pavement design only provides a guide on the factors that will affect the design and cost of embankments. The manual is silent on the use of RE embankments despite the many benefits. Consequently, Kenya relies on design manuals and construction guidelines of reinforced earth (RE) from other countries such as China, Japan, United Kingdom, American states among others which may not be suitable for the existing local conditions. This implies that variabilities in the local natural construction materials, traffic patterns and climatic conditions could result to unanticipated poor performance of the pavements found on reinforced embankments of Outer ring road.

Despite there been several studies evaluating the performance of pavements, there is lack of research specifically focussing on performance of pavement constructed on RE embankments to the conditions of Outer ring road in Nairobi, Kenya. In addition, there has been no baseline data for monitoring and evaluating the performance of pavements found on RE structures on Outer ring road despite the technology gaining popularity on major urban roads. This study aimed to fill this knowledge gap.

This study has provided vital information to road management agency on the maintenance interventions and provided an objective basis for allocation of maintenance resources .The findings have also provided useful baseline data for monitoring and evaluating the performance of pavement on Outer ring road. In addition, the findings will also provide useful insights into potential design and construction improvement for future similar projects. Further, by understanding how pavements founded on RE embankments perform under the local conditions in Nairobi, it ensures that Outer ring road continues to effectively and efficiently serve its role in Nairobi's transportation network. The pressure on transport infrastructure continues to increase as Nairobi grows especially due to the increased urbanisation. Therefore, this study based on Outer ring road is aimed to add knowledge to engineers and policymakers particularly in providing durable transport infrastructure that are optimised to the unique conditions in Nairobi.

1.2. Problem Statement

Most roads in urban areas in Kenya exhibit signs of distress a short period after commissioning raising questions on the performance of the road pavements within the country. Noticeable distresses on the pavement include but not limited to are unevenness, rutting, potholes and cracking which not only disrupt smooth traffic flow but also potential safety hazards. There has been significant increase in traffic on major urban roads in Kenya leading to unexpected increase in traffic loading on the pavements despite traffic projections during the design phase which has resulted to premature pavement failures.

If these issues are not promptly addressed, the deteriorating condition evidenced by the distresses on the pavement surface may increase the safety concerns and economic loss of the road by increasing the risk of incidences. Increased traffic volume on the road may lead to increase in traffic loading which might undermine the pavement structural capacity. Such phenomenon are catastrophic to the economy in cases where road failure result to frequent road repairs hampering movement of goods and people leading to economic losses.

It was anticipated that the reinforced embankments on Outer ring road will enhance pavement durability, however, the observable pavement distresses on some sections of the road suggested a possible divergence between the expected and actual performance of pavement founded on RE embankments. Investigating these discrepancies was essential for road maintenance, safety and good economy of the nation. In addition, the findings have provided insightful information in improving the design and construction of RE embankments in Nairobi. The research, in addition aimed to provide empirical data on the current state of the road and recommendations based on the findings.

The findings of this study bridged the gap between theory and real world outcomes hence contributing to the broader knowledge on sustainable transport infrastructure in a rapidly developing cities like Nairobi.

1.3. Research Questions

i. Is the current traffic loading on the Outer ring road pavement similar to the projected design traffic?
ii. What is the condition of the pavement surface founded on reinforced earth sections of Outer Ring road?
iii. What is the current structural capacity of the pavement founded on reinforced earth sections of Outer Ring road project?

1.4. Objective of the Study

The overall objective of this study was to investigate the performance of pavement founded on reinforced earth sections of Outer Ring Road in Nairobi, Kenya as a case. To respond to the research questions, the specific objectives of the study were:

i. To evaluate the impact of the current traffic loading on the performance of pavement founded on reinforced earth sections of Outer ring road by undertaking classified traffic counts and axle load survey for seven days to determine the current traffic loading and then compare with the projected traffic loading during design of the project.

ii. To establish the structural adequacy of the pavement found on reinforced earth sections of Outer Ring road using a non-destructive testing method to quantify the pavement structural bearing capacity.
iii. To evaluate the functional performance adequacy of the pavement founded on reinforced earth sections of Outer Ring road by undertaking visual condition survey, roughness, rut depth measurements and consequently determine the Pavement Condition Index (PCI).

Relevant permits were acquired from Kenya Urban Roads Authority (KURA) and Nairobi regional traffic police commander to facilitate data collection on Outer ring road.

1.5. Scope and limitation of the study

1.5.1. Scope of the study

The study was on Outer Ring road (UCA3) in Nairobi County, the location map is attached in Appendix A. The reinforced earth sections are approaches to Mathari River, Kangundo flyover and intersection at Eastern bypass sections. To establish the structural capacity and the surface condition of the pavement the following activities were undertaken; pavement deflection measurement using Falling Weight Deflectometer, visual condition survey, roughness surveys using profilometre, rut depth measurements , traffic studies and desktop study of outer ring road design report.

1.5.2. Limitation of the study

The study was not able to capture long-term effects or seasonal variations in pavement performance within the set research timeframe. The results from Outer ring road might not be applicable to other roads due to variations in quality of construction, materials used, underlying geology on the road corridor and the local climatic conditions.

The automatic traffic counters and the Falling weight Deflectometer equipment may have their own accuracy limitations that were difficult to capture during the study. In addition, the traffic counters might have not captured all the vehicles or misclassified some vehicles on the road. This might have affected the accuracy of the traffic data collected.

This study did not explore on the performance of reinforced earth structures that have a direct influence on the performance of the overlying pavement but only focused on the performance of the pavement founded on the reinforced earth structures. External factors such as drainage issues, nearby construction activities or utility works can influence the performance of the pavement and not directly related to the reinforced earth.

1.6. Justification of the Study

The study has established the surface condition and the structural capacity of the pavement built on reinforced earth sections of Outer ring road. This adds knowledge to the road designers, contractors and road agencies on the expected behaviour of pavements on reinforced earth that will enhance their designs and make improvements on the conventional practices during construction.

The study has developed baseline data to research organizations, scholars and road agencies who will want to carry out further research on pavement performance on reinforced earth in Kenya or other similar countries. The study will also facilitate individual researchers to identify gaps in the current research and carry out research in the identified areas.

The findings on the functional and structural performance of pavement found on RE sections of Outer ring road are immensely useful to the road agencies while formulating polices, manuals and guidelines on the design, construction and maintenance of pavements founded on reinforced earth. The findings have also provided critical information necessary to improve on the current practices of design and construction of reinforced earth structures in the country. It is worth noting that this study was ripe in a time Kenya is in the process of revising road design manuals.

The Materials Testing and Research Division of the Ministry of Transport, Infrastructure, Housing and Urban Development is a direct beneficially of the pavement performance baseline data collected should they undertake the subsequent monitoring to establish the behaviour of pavements on reinforced earth.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. General

This chapter provides the theoretical framework, empirical literature review and the conceptual framework under which this research was undertaken. The selection of the reviewed literature was based on previous publications, searching of relevant books and articles from the internet, library and from experienced road engineers in Kenya.

2.2. Theoretical Framework

2.2.1. Pavement Performance

A properly designed and well-built road pavement has to satisfy the minimum performance criteria and adequate to carry over a specified period of time the designed traffic volume within the prevailing environmental conditions (Goswami, 2022). It has a good skid resistance with a comfortable and safe ride, withstand the expected design traffic without undue distress, and all the layers should be resilient to stresses and strains due to loading. In addition, it should withstand the prevailing environmental factors and the foundation should provide adequate load spreading capacity to have a stable platform for construction vehicles. In a related literature, Ibraheem and Faiq (2018) concur with the minimum performance criteria and in addition states that a good pavement requires minimum maintenance in its design life.

Road pavements are usually subjected to heavy loadings and severe environmental conditions over time that manifests various distresses and undermines the pavement performance as noted by Ibrahim (2012), Khattak & Peddapati (2013) and poor performance is often characterised by the formation of distress parameters on the pavement. The three primary causes that lead to the occurrence of distresses in pavement as stated by Al-Zwainy et al. (2020) are traffic loading, environmental damage, and inadequate construction methods, design or materials.

The deterioration rate depend on factors such as the volume and type of traffic, construction materials, the methodologies employed, the adopted maintenance strategy, rate of loading and environmental conditions (Al-Zwainy et al., 2020; Gupta et al., 2012). Therefore, pavement performance can also be assessed based on individual pavement distresses (for instance cracking, rutting and deflection), pavement serviceability index derived from the condition of the pavement as evaluated by the users and the structural condition. Anish and Sitesh (2018) concluded that failure in pavements is a phenomenon that has a definite mechanical cause, possibly due to traffic and adds that when a pavement is incapable of performing the task that it was designed for, it has failed. In addition, distresses can also be caused by deficiencies during construction, lack of maintenance and climatic factors.

2.2.2. Pavement Behaviour and Deterioration

Pavements in seldom fail suddenly but deteriorates with the passage of time (Elena & Costel, 2010). Instead, flexible pavements usually begin to deteriorate after entering service and gradually get worse with time until an undesirable or failure condition is reached. Failure condition is characterised by undesirable levels of rutting, unevenness, cracking, pot holes among other distress parameters.

The deterioration of structural capacity of flexible pavement is classified into the following phases as suggested by Al-Zwainy et al. (2020) and O'Flaherty (2002) which concurs pavement deterioration curve shown in Figure 2-1.

i. The stabilizing phase; this is where a new or a strengthened pavement is variable but gradually gaining stability. The phase ends at point A.
ii. A stability phase; in this phase the pavement strength tends to remain steady or gradually change (positively or negatively) and the rate of deterioration can be determined with allowable level of accuracy. This phase begins at point A. The pavement may exhibit minor distress that may call for routine maintenance.
iii. Investigatory phase; it is difficult to predict the structural behaviour of the pavement at this phase. The structural capacity may be steady or deteriorate rapidly or gradually. This phase begins at point B shown in the curve. It is at this phase where monitoring is essential to curtail any distress since the pavement rate of deterioration begins to increase rapidly. At this point the structural adequacy of the pavement is relatively constant from the original capacity and any intervention actions significantly improves the strength and the condition of the pavement.

iv. A failure phase is the final phase whereby the pavement deterioration can only be intervened by reconstruction. The phase sets in at point C of the curve. This phase can be very short or quite long and the pavement can live for several years before major intervention is required.

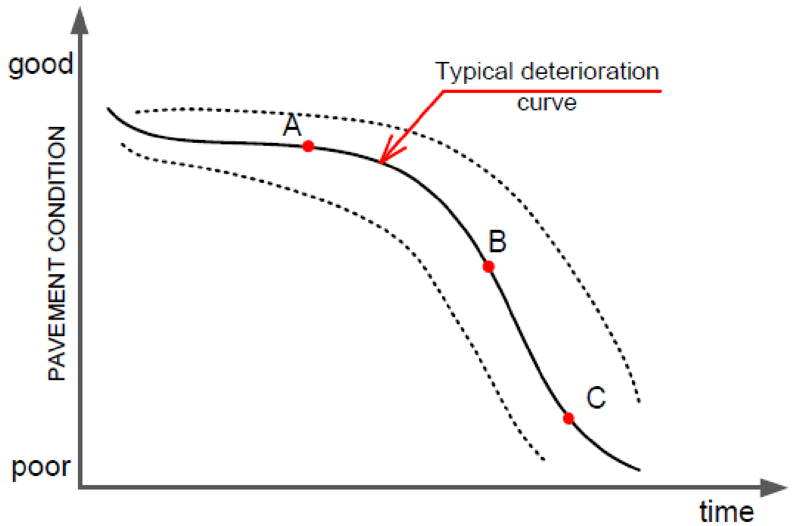


Figure 2-1: Pavement Deterioration Curve
Source: O'Flaherty (2002)

The dotted line indicates effect of maintenance on a pavement condition. A pavement without prompt maintenance intervention deteriorates faster following the lower dotted line while on the other hand, prompt and appropriate maintenance interventions extends a pavement life which is represented by the upper dotted line.

Ministry of Roads and Public Works (1988) describes the above phases as consolidation phase, elastic phase, plastic phase and failure phase respectively. The phases are described based on the deflection on the pavement which is considered to have a direct effect on the structural performance in flexible pavements.

Rapid deterioration of pavements usually occurs due to the following reasons; rapid increase of heavy vehicles or wheel loads, poor drainage system or poorly maintained drainage system and in hot climates especially in uphill sections carrying low speed heavy vehicles wheel load caused by bitumen viscoelastic properties. Al-Zwainy et al. (2020) classifies pavement deterioration modes into cracking, joint seal damage, disintegration , distortion and loss of skid resistance.

Pavement deterioration is usually a complex blend of effects in the various pavement layers, for instance, deformation on underlying layer will adversely affect the overlying layer leading to cracking or other defects. Ingress of water in the underlying layers is often caused by defects such as cracking in the overlying layers. Pavement deterioration usually results in characteristic defect patterns which can be related to particular causes. The most common defects are; bleeding, corrugations, cracks, deformation, peeling, potholes, ruts, shoving among others. Lack of prompt intervention measures leads to pavement deterioration pattern that follow a classical sequence of degradation (Ministry of Roads and Public Works, 1988). The manual is emphatic that even the slightest defects on the pavement may cause major failures if they are not promptly addressed.

Therefore, it is paramount to monitor the performance of any pavement to determine the rate of deterioration or the extent of distresses, to evaluate the maintenance needs or rehabilitation and to inform the scheduling of maintenance and rehabilitation activities (Ibrahim, 2012). This provides adequate details for developing an effective strategy for maintenance and rehabilitation of a road or road network. Thom (2014) and Huang (2004) in different literatures, concur that pavement designers are expected to be knowledgeable on the various distress types as it helps in identifying the causes of the distress and this leads to improvement of future similar or related designs.

2.2.3. Factors Affecting Pavement Performance

Pavement performance is influenced by the following; subgrade soil, the original strength after construction, quality of construction materials, the amount of traffic loading and repetitions, the condition of the drainage system, prevailing environmental factors, maintenance policies and practices (Goswami, 2022; Al-Zwainy et al., 2020; Gupta, 2014). For pavements on embankments, their performance will largely be dependent on the stability of the embankment. It is worth noting that many researchers have concluded that there exists complex relationship among factors that affect pavement performance which is not well understood and their confounding effects are not well quantified. A change in any one of the factors may considerably affect the relationships uncovered in an investigation (Gupta, 2014; Lu, 2005). The major factors are briefly described below.

2.2.3.1. Traffic

Traffic is the most important factor in pavement design and pavement performance analysis. The key factors include wheel load, contact pressure, axle configuration and load repetitions (Sushmita et al., 2022). The design and construction methodology of pavements is based on the projected traffic loading during a given period of time, which is the desired pavement design life. Traffic on the pavement causes pavement fatigue which causes failure. Pavement fatigue is a progressive damage from many applications of traffic load. To achieve an adequate or a satisfactory structural design of any pavement, one must have an accurate prediction of the anticipated traffic loading. This is achieved by having a knowledge of the expected volume of traffic on the given roadway during the design stage and the existing traffic at the time of commissioning a road.

The performance of a pavement is also dependent on the frequency of the load application (Tom, 2007). Every load application causes some deformation and the resultant deformation is the summation of all individual small deformations. Even though the pavement deformation due to a single axle load can be very small, the cumulative effect of number of load repetition is significant. Hence, current designs are mostly based on total number of standard axle load (usually 80 kN single axle). In understanding the effects of structural factors and traffic loading on flexible pavement performance, Sushmita et al. (2022) concluded that rutting and roughness are significantly influenced by heavy vehicle loads.

2.2.3.2. Pavement Structure and Subgrade Material

Pavement structure is characterised by layer thicknesses, layer type and properties which influence the performance of a given pavement (Gonzalo et al., 2013). The strength and stiffness of the subgrade soil influences the strength of the overlying pavement structure. Pavements are designed to distribute the applied stresses to such an extent that the subgrade soil is not overstressed.

2.2.3.3. Embankment stability

Factors that affect the stability of a road embankment are settlement, slope stability and bearing capacity which in turn contribute to road damage (Rufaizal et al., 2019). The overall embankment stability is critical in road construction and performance. A publication by Washington State Department of Transportation (2021) concurs that to ensure embankment stability, bearing capacity of the fill material, slope stability and settlement should be adequately analysed during the design process. Inadequate provision of these parameters leads to deformation of the embankment structure that results to loss of support of the pavement structure which leads to pavement structural failure (Washington State Department of Transportation, 2021).

2.2.3.4. Environment

A pavement must function satisfactorily or as expected within its environment. Environmental conditions are very dynamic in nature making it quite tasking for a pavement engineer to accurately quantify them (Goswami, 2022). Environmental variations can have a significant impact on pavement materials and the underlying subgrade which in turn can drastically affect pavement performance particularly for flexible pavements. The main climatic aspects that affect pavement performance are; temperature, precipitation, relative humidity, solar radiation and the atmospheric pressure, (Gupta et al., 2012). Temperature and moisture changes affects the strength, durability, load carrying capacity of the pavement and/ or its foundation according to Goswami. In a related literature, (Sushmita et al (2022) concurs that temperature and precipitation have a significant effect on rutting, roughness and alligator cracking of a pavement.

2.2.3.5. External factors

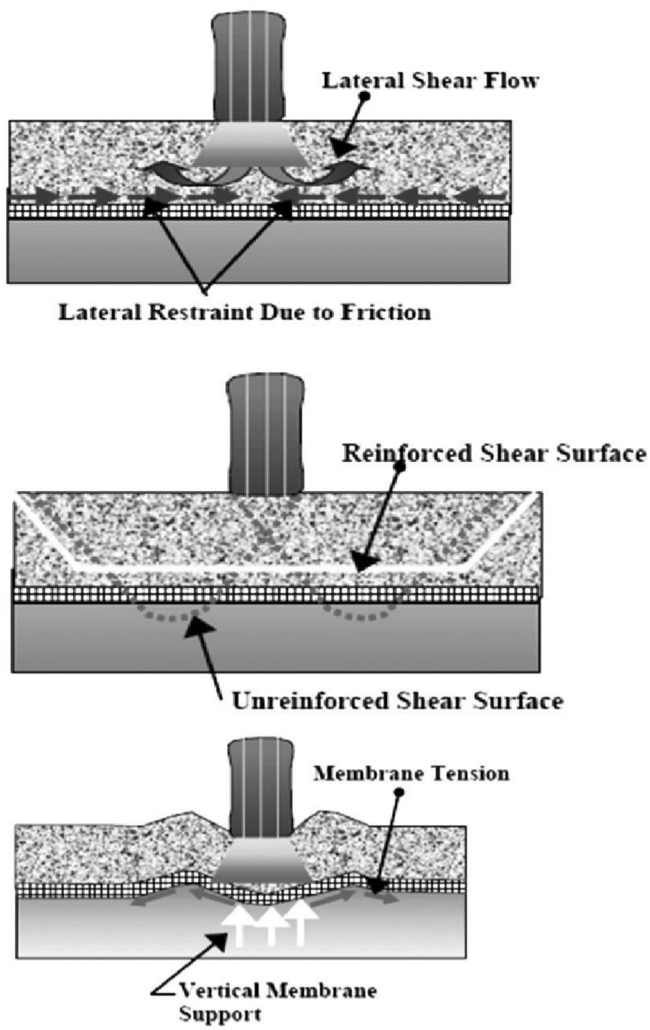
External factors that affect the performance of flexible pavement are construction factors and maintenance practices or policies. Construction factors are influenced by the quality of the construction materials, the construction methodologies employed and the consistency in quality control. Well planned maintenance operations and treatments enhance the performance of a pavement. Therefore, it is recommended to consistently monitor the performance of a given pavement immediately after commissioning to identify any signs of distress and plan for an appropriate intervention rather than waiting for an actual failure to occur.

External factors such as chemicals or pollutants from the external environment have adverse effect on the pavements. Chemicals may corrode or react with some of the materials used during the construction process leading to deterioration of the exposed pavement.

A study on effects of aging on asphalt mixture and pavement performance by Nooralhuda et al. (2020) established that aging of pavement makes the pavement material stiffer, more brittle, and more susceptible to cracking especially due to traffic and thermal loading.

2.2.4. Effect of reinforced earth embankments on pavements

The overall performance of pavement structure depends upon proper construction of the subgrade, embankment and the underlying foundation. The application of vehicular load to a flexible pavement results in dynamic stresses within various pavement components. As vehicular loads are repeatedly applied, permanent strain is induced in all layers of flexible pavements and accumulates as traffic passes increase, which leads to rutting of the pavement surface. The rutting appearing at the surface of flexible pavements can be caused by shear deformation within bituminous mixtures and/or by plastic deformation in the underlying unbound layers such as foundation or embankment (Asphaltic Academy, 2008). **Error! Reference source not found.** illustrates the reinforcement function induced by geosynthetic (Sitharm et al., 2020).



Lateral restraint

Increased bearing capacity

Membrane support

Figure 2-2: Reinforcement mechanisms induced by geosynthetic

Source: Sitharm et al. (2020)

Design and construction of any embankment ensures that the material used is well compacted and capable of supporting the overlying pavement and also withstand the stresses and strains imposed by the wheel loadings without deflection, deformation or undesirable movements.

Various literatures have established that reinforced earth embankments provide a stronger foundation compared to unreinforced embankment for pavement but there is very little investigation on the performance of pavements in urban areas founded on reinforced earth embankments.

2.2.5. Pavement Performance Evaluation

Pavement performance evaluation is essential to establish the pavement characteristics, structural integrity and to determine the maintenance or rehabilitation interventions necessary for a pavement to be serviceable throughout its design life. Pavement performance evaluation principally involves the assessment of the structural and functional adequacy and pavement's ability to withstand the design traffic (Anjaneyulu et al., 2022; Al-Zwainy et al., 2020). Pavement evaluation techniques differ from country to country and between different highway agencies in the same country.

Pavement evaluation involves site assessments and testing carried out to establish the condition of the pavement structure. The structural condition is the pavement capacity to support the existing and future expected traffic loadings whereas the functional condition is the pavement's ability to provide a safe, smooth, and comfortable riding surface for the traveling public. The evaluations may involve either destructive or non-destructive techniques or both. Pavement performance evaluation can be at project level or may be carried out at network level depending on the level of details to be collected and/or the resources available. The evaluation techniques differ between different countries or highway agencies. The different approaches to conducting a pavement evaluation are distinguished by the extent of the assessment, the level of the detail to be collected, the assessment tools used and the resources available.

Field surveys and testing are undertaken during the pavement performance evaluations in order to characterize the condition of an existing pavement structure, both structurally and functionally. The most commonly collected and recorded pavement performance data are described below:

2.2.5.1. Pavement structural adequacy

The main objective of pavement structural adequacy evaluation is to assess the pavement's future behaviour based on the anticipated loading and the prevailing environmental conditions (Anjaneyulu et al., 2022; Al-Zwainy et al., 2020). Complete structural evaluation involves determining the pavement's bearing capacity and analysing the pavement layers and subgrade characteristics through sampling and testing. Al-Zwainy et al. states that structural evaluation should inform if there are deflections and pavement distortions in any of the pavement layers attributable to stresses and strains induced by traffic or other loads. Deflection testing through using non-destruction testing techniques presents a simple and reliable methodology for evaluation the structural capacity. However, destructive testing such as coring and component analysis techniques are employed as well.

2.2.5.2. Pavement functional evaluation

Pavement functional performance evaluates how a given roadway serves the user. Ride quality is the dominant characteristic of functional performance characterized by the surface texture of a road section. Functional evaluation established presence of cracks, unevenness, rutting or any other defects that may affect the serviceability of a pavement (Anjaneyulu et al., 2022; Al-Zwainy et al., 2020). Smooth roads offer more comfort and reduce vehicle operating costs to the user while rough roadways offer increased costs of vehicle operations. However, a very smooth pavement surfaces increases the stopping distances and consequently the probability of accidents.

The roughness of a pavement is defined by its irregularities in the longitudinal profile of its surface that causes discomfort to the users (Chandra & Kumar, 2021). There is less dynamic loading from truck traffic on smooth pavements resulting to less pavement distresses hence lower life cycle cost because of the reduced maintenance needs. For this reason, pavement sections are sometimes rehabilitated to provide a smoother surface that offers more comfort to the road users and not based on the structural inadequacy of the given pavement section. Therefore, monitoring of the pavement roughness is an important criterion during pavement performance monitoring.

2.2.5.3. Pavement surface condition survey

Surface condition survey reveals the extent of defects or distresses on the pavement surface caused by traffic and the prevailing environmental factors. Surface condition ratings give an indication of how well the road is serving the travelling public however not sufficient to judge the structural adequacy of the pavement (Chandra & Kumar, 2021). The damage on the surface is established by visually inspecting the pavement surface. The process involves a distress survey which is performed to determine the type, severity and quantity of surface distress. The common basic methods for quantification of the defects are rutting, cracking and crazing, longitudinal deformation, general determination of surface patching and other defects such as depressions, upheaval and potholes (Adlinge & Gupta, 2013).

Surface condition rating is used in the preliminary evaluation and planning of appropriate maintenance and rehabilitation interventions. Thus, surface condition surveys are vital for evaluating the performance of a pavement.

2.2.6. Pavement performance criteria

Effective Pavement Management Systems (PMS) requires establishment of pavement performance criteria which normally are key performance indices to guide on the desired overall pavement condition. The key performance indices usually scored, are a pavement condition rating to quantify a pavement's overall performance and very useful in managing pavement networks. Pavement Tools Consortium (2012) states that the pavement condition indices are performance criteria used to; trigger treatment, determine the extent and cost of repair, determine a network condition index and allow equal comparison of different pavement. The common performance criteria and based on Present Serviceability Index (PSI), Pavement Condition Index (PCI), pavement damage (consumed life) and friction resistance.

One of the earliest pavement condition indices was the Present Serviceability Rating (PSR) developed at the American Association of State Highways Official (AASHO) Road Test done by having a group of raters to assess the existing condition of the road and consequently record their ratings on a standard form. The PSR is the mean of individual ratings made by the members of a specific panel. Other commonly used pavement condition index methods that are more objective than PSR are the PSI and PCI. Pavement Quality Index (PQI) is increasingly becoming common in the developed countries.

PSI is obtained by correlating various information from raters to various pavement measurements to develop the PSI equations. PSI ranges from 5, for excellent conditions to 0 for poor condition

(Gulfam & Susan, 2015). PCI is a mathematical combination of values obtained from certain physical measurements which is a calculated numerical value from surface distress for a particular pavement section and it indicates the surface condition of the pavement in a range from 0, worst condition possible to 100, best condition possible based on American Society for Testing and Materials (ASTM) D6433-16. It is basically a numerical number criterion that rates the surface condition of the pavement based on the distresses observed on the surface of a pavement (Sherif & Chen, 2019; Anish & Sitesh, 2018). PCI cannot measure structural distresses nor does it provide direct measurement of skid resistance or roughness. It can be used only to determine the improvement of the current pavement design or maintenance and repair needs and their priorities (Anish & Sitesh, 2018). Different countries, municipalities or agencies have adopted different pavement condition index methods.

PQI is a composite of Visual Condition Index (VCI), Riding Comfort Index (RCI), and Structural Adequacy Index (SAI) is used to measure, monitor and predict the condition of pavements (Government of Alberta, 2012).

2.2.7. Pavement performance evaluation in Kenya

Pavement performance evaluation in Kenya is outlined in the rehabilitation and overlay design manual that was published in 1988. The manual recognises that constant evaluation of condition of pavement is required to establish the pattern of deterioration for strategizing and design of the necessary interventions and give guidelines on criteria for maintenance and rehabilitation. The manual has suggested the following criteria for maintenance and rehabilitation of pavements in Kenya (Ministry of Roads and Public Works, 1988).

2.2.7.1. Surface condition survey

Surface condition surveys (SCS) are used to determine the possible causes of surface distress and to establish the need for maintenance operations and surface rehabilitation. The survey involves recording and photographing of pavement defects and evaluation of drainage and shoulder conditions after which the data is entered into a standard form. All defects such as rutting, cracking, potholes, raveling among others are measured, recorded and quantified based on the provided guideline by the ministry.

Conventionally, rut depth is measured using a 3 metre (m) straight edge while cracks by visual inspection and measuring. The country is warming up to modern equipment for identification, measurements and recording of various surface distresses. The classification of rutting and cracking based on the local manual is shown in Table 2-1.

Minor overlay of resurfacing is required when the cracks cover more than 30% of the wheel paths over the length showing distress for trunk road and 50% for other roads while overlay or reconstruction is required when mean rut depth in either when path exceeds 20 millimetres (mm) for trunk roads and 25mm for other roads.

Table 2-1: Classification of rutting and cracking

Transverse deformation under a 3m straight edge		**Degree of Cracking (Visible Cracks)**	
Index	**Deformation or Rut Depth**	**Index**	**Crack Length per Unit Area**
D1	Greater than10 millimeters	C1	Nil
D2	10 to15 millimeters	C2	Less than 1 m/m^2
D3	15 to 20 millimeters	C3	1 to $2m/m^2$
D4	20 to 15 millimeters	C4	2 to $5m/m^2$
D5	Greater than 25 millimeters	C5	Greater than $5m/m^2$

Source: Ministry of Roads and Public Works (1988).

2.2.7.2. Surface roughness criteria

Surface condition survey is supplemented by quantitative techniques such as straight-edge, crack and roughness measurements. The local manual heavily relies on TRRL findings and the following criteria bases on bump integrator readings was suggested: -

i. Resurfacing is undertaken when the surface irregularity exceeds 2800mm/km on trunk roads and 3100mm/km on other roads.
ii. Reconstruction or overlay is required when the surface irregularity exceeds 3400mm/km on trunk roads and 3750mm/km on other roads.

2.2.7.3. Pavement surface condition indices in Kenya

Present serviceability rating is conducted through visual observations by a panel and recording of defects in a standard PSR rating form. The rating of each condition ranges from zero (0) representing very poor condition to five (5) for very good surface condition. The local manual proposes a rating of 2.5 and 2.0 for trunk roads and other roads respectively to be considered as the critical rating that indicates when rehabilitation in necessary. The manual proposed that pavement rehabilitation should be undertaken immediately when the values reach 3.0 for trunk roads and 2.5 for other roads.

For a more objective evaluation, the country has adopted PSI which is a statistical analysis of PSR to quantify a road section’s rideability. The PSI is mainly dependent on the roughness of the pavement surface. Modern cameras inbuilt in special equipment are currently being used in the country and has made the process faster.

2.2.7.4. Pavement structural evaluation

The Kenya road design manual has adopted both destructive and non- destructive techniques to evaluate the structural performance of a pavement. To determine the residual strength of the existing pavement, pavement bearing capacity are determined from deflection measurements are conducted using Benkelman beam deflection, dynaflect or Falling Weight Deflectometer (FWD). The test method covers the determination of pavement surface deflections as a result of the application of an impact and impulse load to the pavement surface. Deflections are used to determine the in-situ material characteristics of the pavement layers which aid in structural evaluation of load carrying capacity and determination of any interventions required.

The other method is analysis of the characteristics of all pavement layers and subgrade through sampling and laboratory tests. The test results for each sampled pavement material layers and the respective layer thickness are analysed to establish the adequacy of the pavement structure.

2.2.8. Pavement Performance Evaluation in Alberta

Alberta is the fourth largest province in Canada. It has one of the strongest economies in the world and has a good transportation system enhanced by good integration of air, water and road networks. Alberta has over 226,000 kilometres of roads with approximately 61,700km roads paved, (Government of Alberta, 2012). The province has a well-developed and maintained PMS implemented by Alberta Transportation and Utilities, (AT&U) agency. The database provides comprehensive information on the pavement network and performance of individual pavement sections especially for major roads.

The most critical data for pavement performance evaluation are, structural strength, roughness, visual distress and rut data. The information mainly provides input for final stage pavement and rehabilitation design, review of the structural and functional performance, operational research, the Pavement Management System and rehabilitation programming, (Alberta Transportation and Utilities, 1997).

Based on the Alberta pavement design manual, the PMS uses Visual Condition Index (VCI), Riding Comfort Index (RCI), Structural Adequacy Index (SAI), and Pavement Quality Index (PQI) to measure, monitor and predict the condition of highway network. The Pavement Quality Index (PQI) is a composite index that incorporates RCI, SAI and VCI into one index $\boldsymbol{PQI = 1.1607 + 0.0596\,(RCI\ x\ VCI) + 0.4264\,(RCI\ x\ log10SAI)}$ (**2-1**).

$$\boldsymbol{PQI = 1.1607 + 0.0596\,(RCI\ x\ VCI) + 0.4264\,(RCI\ x\ log10SAI)} \qquad (2\text{-}1)$$

The four indices are scaled from zero (0) to ten (10) where 0 represents very poor to absolute minimum and 10 very good to near perfect. The index, PQI is for identifying pavement sections that are calling for rehabilitation, for monitoring, forecasting network performance and for budgetary needs. The values for minimum acceptable levels are shown in Table 2-2 below:

Table 2-2: Alberta pavement performance minimum acceptable values

Performance Parameter	Acceptable Level
Pavement Quality Index (PQI)	4.7
Riding Comfort Index, (RCI)	5.5
Structural Adequacy Index, (SAI)	3.0
Visual Condition Index, (VCI)	3.5

Source: Alberta Transportation and Utilities (1997)

2.2.8.1. Pavement surface condition survey

Two procedures adopted by Alberta for pavement condition survey provides the Visual Condition Index (VCI) for the PMS and quantities and severities of rutting, cracking and transverse cracking. The survey is undertaken by visual inspections on the road.

2.2.8.2. Pavement ride quality (roughness)

AT&U collects the Riding Comfort Index (RCI) data by utilizing the James Cox Roadometer. The RCI is an index scaling from zero (0) to ten (10), with ten representing a smooth pavement with an excellent ride. In most cases, the riding quality of new pavements ranges from (eight and half) 8.5 to nine (9), whereas RCI of four (4) is the minimum acceptable for older pavements.

The department has currently adopted the International Roughness Index (IRI) as a measure for roughness.

2.2.8.3. Pavement safety evaluation

The pavement safety evaluation is based on the rutting and skid resistance of the pavement. The rut measurements are carried out for the purposes of pavement evaluation and maintenance activities. The rut data is collected by a modern equipment with ultrasonic sensors and receivers which also collect the roughness data. For PMS purposes the rut depth classification is presented in Table 2-3 below.

Table 2-3: Alberta rut depth scale classification

Rut depth scale	Classification
0 to 3mm	Minimal
4 to 6mm	Minor
7 to 12mm	Moderate
13 to 25mm	Major
Over 25mm	Severe

Source: Alberta Transportation and Utilities (1997)

Several methods are used by agencies to evaluate skid resistance. The measurements are reported as the Skid Number. The Skid Number rating and classification is shown Table 2-4 below.

Table 2-4: Alberta Skid Number scale classification

Skid Number scale	Classification
Equal to or greater than 46	Adequate friction characteristics
45 to 30	Medium friction characteristic
Equal to or lesser than 29	Poor friction characteristic

Source: Alberta Transportation and Utilities (1997)

2.2.8.4. Pavement structural evaluation

The structural evaluation of the existing pavement is based predominantly on pavement deflections measured using FWD since 1992 (Alberta Transportation and Utilities, 1997). The FWDs used in Alberta are equipped with nine deflection sensors. The analysis of the deflection data is based in American Association of State Highways & Transportation Officials (AASHTO) method (American Association of State Highways & Transportation Officials (AASHTO), 1993).

2.2.9. Comparison of Alberta and Kenya Pavement Management System

Kenya is a developing country faced with numerous challenges such as lack of adequate resources for infrastructure development and maintenance while Alberta, a developed province is Canada, has a well-established road infrastructure network with an integrated pavement management system. PMS offers numerous benefits to a national or local government such as optimal use of scarce resources, results to accurate and accessible information of the road transport network and allows for monitoring of pavement performance which is fundamental to data based decision making at all levels of road network management. Table 2-5 below shows the comparison of Alberta and Kenya PMS.

Table 2-5: Comparison Alberta and Kenya Pavement Management Systems

No.	Comparison Criteria	Alberta	Kenya
1	Economic Status	Developed province in Canada	Developing Country
2	Road network	Approx.226 300 km	Approx. 161 451 km (Kenya Roads Board)
3	Paved roads	Approx. 61 700 km	Approx. 14 000 km
4	Pavement Management System (PMS)	Well-developed and maintained PMS	Lacks a harmonized PMS
5	Pavement performance Criteria	Based on Pavement Quality Index (PQI) which is a composite of Visual Condition Index (VCI), Riding Comfort Index (RCI), and Structural Adequacy Index (SAI).	Based on pavement structural evaluation analysis and pavement surface condition surveys to provide PSR and PSI.

No.	Comparison Criteria	Alberta	Kenya
6	Pavement structural evaluation	Predominantly adopted non-destructive technique based on deflection measurements criteria methodology using FWD	Adopted both destructive and non-destructive techniques which uses sampling then laboratory testing of pavement materials and deflection measurement using FWD respectively.
7	Pavement ride quality	Determined by the Riding Comfort Index (RCI) using James Cox Roadometer. Currently has adopting IRI with defined critical values for an acceptable smooth ride.	Based on IRI criteria developed by TRRL with a criterion for resurfacing and reconstruction or overlay based on maximum allowable deflection values.
8	Pavement surface condition survey	Based on visual inspection to provide VCI that is used to evaluate the severities of rutting and cracking	Based on visual inspection and recorded in the standard PSR rating form to evaluate rutting, cracking, potholes and raveling.
9	Pavement Safety Evaluation	Based on rutting and skid resistance	Based on rutting and pavement surface texture

2.3. Empirical literature review

Reinforced earth structures are composite structures made up of reinforcement and compacted backfill leading to attainment of both tensile and compressive strength. Various materials such as metal strips, jute chorus and polymers are used as reinforcements. Geosynthetic materials are more popular because of their availability in various types, sizes and strength making them more versatile in their application. Sitharm et al. (2020) summarized the main geosynthetic functions as; separation, reinforcement, drainage, protection, barrier and erosion control. In a related study, Manohara (2019) and Victor et al. (2001) concluded that considering the challenges of the normal embankments of compacting soft fill materials and need for flexibility in design and ease of construction, the reinforced earth embankments are gaining favour over the other methods particularly in urban areas. The findings of these studies further indicated that reinforced earth has a significant reduction on pavement maintenance costs which definitely offers a viable option especially for roads in urban areas. These studies strongly advocated for use of reinforcements on embankments due to increased embankments' stability, the varied geography and infrastructure differences within the region could lead to subtle variations that were assumed or not addressed. It is normal practice to utilize the locally available materials for fill during the construction of road embankments, therefore, Nairobi being in different geographical region from where the studies were conducted will most probably have varying natural material. The aspect of difference in soft fill material utilized was not explored in the studies which might give varying results on the performance of reinforced earth embankments. In addition, Outer ring road is in Nairobi with distinct challenges tied to urbanization, traffic loads, and climate which might impact pavement performance in ways not seen in other regions.

Sitharm et al. (2020) and Rufaizal et al. (2019) concur in their respective studies that integrating reinforcements into earth embankments significantly boosts their overall strength and stability, leading to enhanced safety margins. By acting as reinforcement agents within the soil, geosynthetics optimize stress distribution and curtail the deformation typically observed in unreinforced soil. As a result, these reinforced embankments present a viable solution for constructing structurally robust pavements in areas characterized by naturally soft or weak soils. Thus, this research offer insights into the longevity and durability of such pavements under typical urban traffic conditions, like those on Outer ring road.

A study on the mechanism of road embankment fortified with geotextile established that the lateral displacement of embankment decreased and the stability of embankment was enhanced (Liu et al., 2008). The researcher concluded that road embankments on soft soil foundation can effectively be reinforced with geotextiles. While the study provides valuable insights, it lacks consideration of varying environmental conditions and different traffic conditions of the specific road. Nairobi has different climatic conditions and traffic loadings that could influence the performance of pavement found on reinforced earth differently.

2.4. Conceptual Framework

This conceptual framework demonstrated the relationship of independent, dependent and intervening variables for this study. The independent variables were; traffic loading, pavement structure, embankment stability and environmental factors whereas the dependent variables were the pavement performance indicators which were the structural capacity and the functional adequacy of the pavement. The intervening variables were the quality of the construction materials and the pavement maintenance practices or policies. The conceptual framework is illustrated in Figure 2.3.

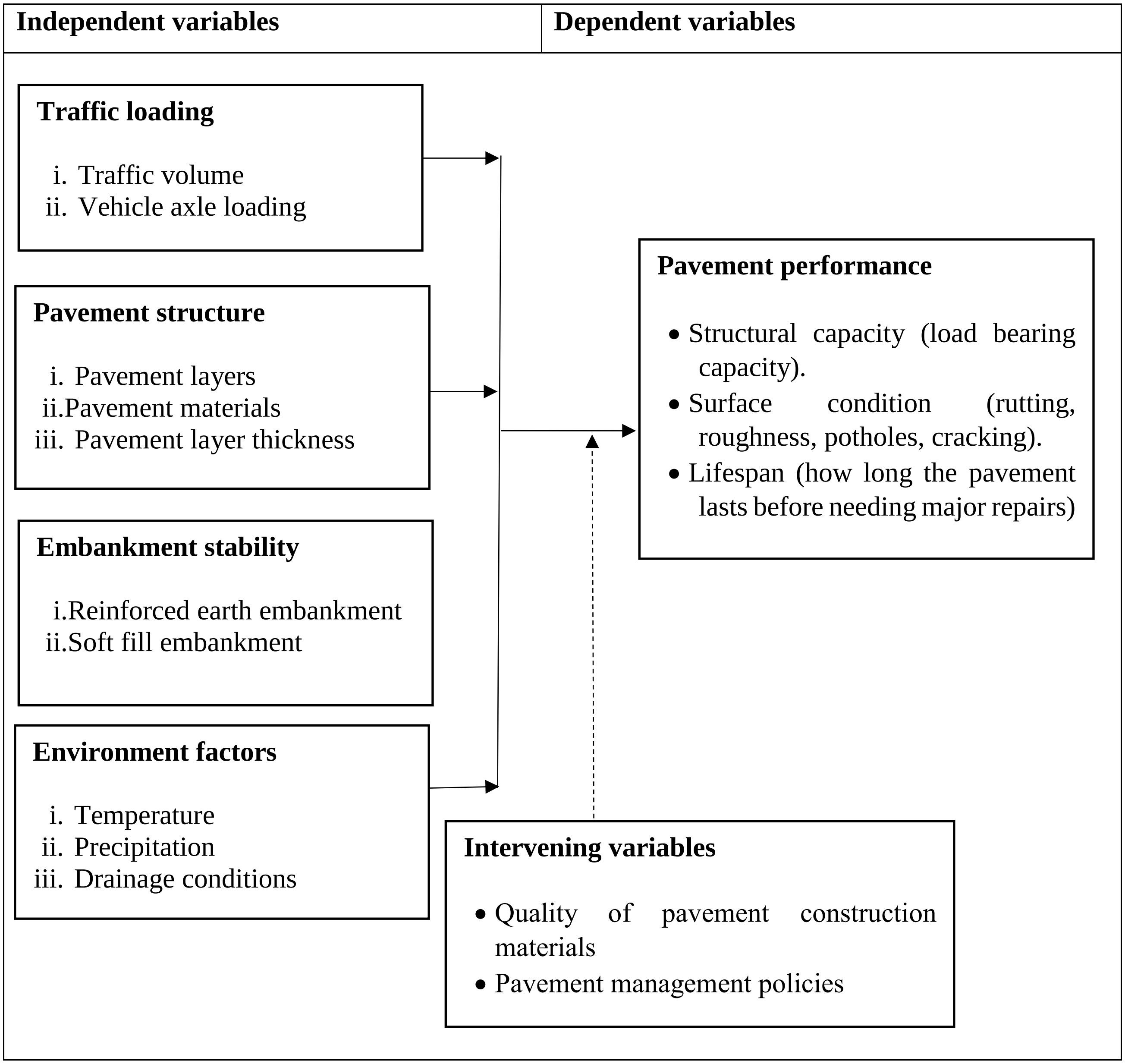


Figure 2-3: The conceptual framework

2.5. Literature Review Summary and Literature Gap

2.5.1. Literature review summary

Numerous studies such as those undertaken by Goswami (2022); Ibraheem & Faiq (2018); Khattak & Peddapati (2013); Ibrahim (2012) and Anish & Sitesh (2018) have underscored pavement structural capacity and functional adequacy as the key pavement performance indicators. The major factors influencing the performance of pavements are traffic loading, pavement structure and subgrade, stability of the underlying embankment and environmental factors (Goswami, 2022; Al-Zwainy et al., 2020; Gupta, 2014; Sushmita et al., 2022; Gonzalo et al., 2013; Rufaizal et al., 2019; and Gupta et al., 2012). Further, studies by Goswami, Al-Zwainy et al., and Gupta have highlighted the quality of construction materials and prevailing maintenance policies and practices to significantly affect pavement performance. The synthesis of scholarly works provides a thorough insight into the various components influencing pavement performance. Numerous scholars highlight that the interrelationships among factors impacting pavement performance remain intricate and their intertwined effects yet to be precisely quantified (Gupta, 2014; Lu, 2005). Notably, alterations to any singular factor can significantly modify the observed relationships in a given study.

The deterioration of structural capacity of flexible pavement is classified into sequential phases in the following consecutive order; stabilizing phase, stability phase, investigatory phase and failure phase as delineated by Al-Zwainy et al. (2020) and O'Flaherty (2002).

Reinforced earth embankments have over the years gained traction in road construction across the world. Studies such as those by Manohara (2019), Victor et al. (2001) and Sitharm et al. (2020) have highlighted the increased stability and strength of embankments resulting to enhanced structural capacity and reduced surface distresses on the pavements. Geosynthetics as elucidated by Sitharm et al., Liu et al. (2008) and Rufaizal et al. (2019) are reinforcing agents within the soil (soft fill) that offer lateral restraint, increased bearing capacity and membrane support by optimizing stress distribution and reducing typical deformations seen in unreinforced soils.

The researchers concur that earth reinforcement increases the stability of embankments hence overall improved performance of the road pavement. The performance of a pavement is greatly influenced by the strength and stability of a road embankment among other factors. Based on the reviewed literature, notwithstanding the benefits of reinforced embankments which provide a stronger and stable foundation for pavements, there exists a gap to establish the performance of pavements founded on reinforced earth embankments. Therefore, this research has investigated the performance of the pavement founded on reinforced earth sections on Outer ring road project and provides baseline data for the pavement performance monitoring which will be useful in formulation of design manuals and/ or construction guidelines of reinforced earth embankments in Kenya and related environs.

Different countries employ different techniques for data collection, analysis and performance criteria. A comparison of Alberta and Kenya pavement performance evaluation has established that Kenya lacks harmonized pavement management system. Kenya and Alberta have adopted almost similar pavement performance criteria only that Alberta have advanced data collection and analysis techniques and a more quantitative performance criteria. The comprehensive PMS has made Alberta have a very reliable pavement performance and condition monitoring system which is vital to management of road assets unlike in Kenya that lacks a national PMS but evaluations are made in silos by the different agencies and sometimes departments.

2.5.2. Literature Gap

The reviewed literature on use of reinforced earth for road embankments majorly focusses on the impacts of reinforcements on embankments without evaluation of the performance of pavement founded on such reinforced earth embankments.

While the studies offer foundational appreciation, the specificities of their application in unique urban settings like Nairobi have been sparingly explored. The distinct traffic loads, climatic conditions, and local material characteristics in Nairobi present potential variables that could impact pavement performance, especially when juxtaposed with global or broader regional findings.

Several studies have strongly recommended the use of reinforcements on embankments due to their enhanced stability. However, differences in geography and infrastructure could introduce variations that might have been overlooked or unaddressed in the previous studies. It is common practice to use locally sourced materials for fill during road embankment construction, Nairobi's distinct geographical location might have natural materials differing from those in the regions studied. The studies did not delve into the potential variations in soft fill materials, which could influence the performance of reinforced earth embankments.

There is conspicuous lack of detailed research focusing on the specific performance metrics on pavements founded on reinforced earth embankments in Nairobi and Kenya at large. Factors such as load-bearing capacity, deformation characteristics, and fatigue resistance in the specific setting of Outer ring road are not adequately covered in current studies. Despite the in depth understanding of the benefits accrued on pavements constructed in reinforced earth embankments, there is pressing need for studies specifically tailored to the distinct socio-economic and environmental context of Outer ring Road, Nairobi.

CHAPTER THREE

3. METHODOLOGY

3.1. Introduction

This chapter provides a description of the study area. Secondly, it outlines the data, materials, data collection methods for each objective of the study and data analysis techniques to derive the results required for the specific objective. The validity, reliability and accuracy of this research was duly considered throughout the study.

3.2. Description of the study area

Outer ring road presented a perfect case for study. It was recently commissioned and employed reinforced earth embankments at the interchanges. Outer ring road (UCA3-Nairobi) is on the eastern edge of Nairobi County, Kenya. It is an important road connecting Thika Superhighway Road, A2S-Right hand side and Mombasa Road, A8-R2 trunk roads. The road starts at the junction of General Service Unit (GSU) along Thika Superhighway, (Km 0+000) and ends at the intersection of Eastern Bypass and Airport South road, (Km 10+400). The total length of the road is approximately 13 Km (inclusive of interchanges) and comprised of two single lane carriageway prior to the upgrade. Based on the traffic data analysis of the project road in 2012, the road carried about 1040 vehicles/hour/lane (v/h/l) which was 30% more than the design capacity for a standard lane design capacity of 800v/h/l (Kenya Urban Roads Authority [KURA], 2012).

The reinforced earth embankments were provided at the approaches of the following grade separated intersections; Mathari River underpass, Kangundo flyover and Pipeline flyover. The reinforced earth sections along Outer ring road are shown in Appendix A. Figure 3-1 is a photograph of the built-up reinforced earth section at Mathari River.

Figure 3-1: Mathari river reinforced earth section, 2021

3.3. Materials, Methods and Data analysis

The data, materials required for data collection, the methodology of data collection and analysis of data for each specific objective are described below.

3.3.1. Evaluation of the impact of the current traffic loading on the pavement

To achieve this objective, primary data was collected through traffic surveys and secondary data was obtained by a detailed analysis of the design reports for Outer ring road project. The data collected during classified traffic counts were; date and day of traffic count, vehicle type, direction of traffic flow and volume of each vehicle type. The axle load survey involved recording vehicle origin and destination, axle weights, wheel configuration and cargo or service description.

The classified traffic counts were conducted to determine the traffic on the road in terms of volumes and traffic composition while axle load survey was conducted to determine Vehicle Equivalence Factor (VEF) for derivation of axle loading. In addition, the traffic loading forms a crucial input parameter in the back analysis of deflection data for the structural evaluation of the pavement.

3.3.1.1. Materials

The following materials were used for classified traffic count; traffic volume counters (MetroCount@5600, an Automatic Traffic Counter (ATC)), traffic data collection sheets and a laptop. A portable axle load survey equipment, standard sheets used for axle load data recording, a laptop and a torch (flashlight) were used for axle load survey. The traffic data collection sheet in Appendix C while the standard sheet used for axle load data recording is attached in Appendix D.

Outer ring road design reports and as-built drawings were used to provide the design traffic and the specific traffic data collection stations during the design of the road.

3.3.1.2. Data Collection methodology

Traffic volume counts and axle load survey were done in accordance to the recommendations of Kenya road design manual Part III (Ministry of Transport and Communication, 1987) and specific methodology provided by Overseas Road Note 40 (Transport Research Laboratories [TRL], 2004).

i. Classified Traffic counts

The selected traffic count stations were at the following sections; between Thika road and Juja road, between Kangundo road and Jogoo road and between Jogoo road and Airport North road. The location map for the traffic count stations is in Appendix B.

Classified traffic counts was conducted over a cumulative period of seven days for twenty-four hours, from 23rd to 29th July, 2021 using MetroCount@5600 ATC. Each ATC was connected with a pair of pneumatic tubes laid across the pavement of each side of the carriageway as illustrated in the layout in Figure 3-2. The tubes were carefully fixed to manufacturer’s specifications.

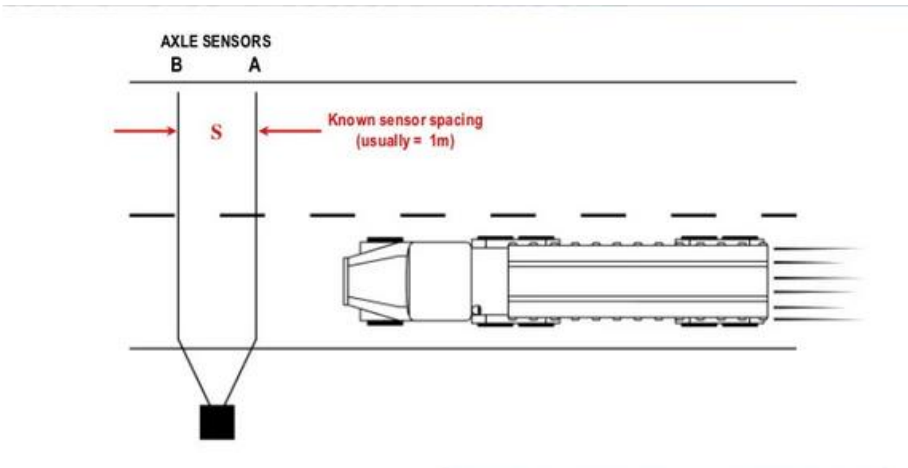


Figure 3-2: General layout of pneumatic rubber tubes on the pavement

The vehicle category of the ATC was axle-based classification scheme implemented by the Federal Highway Administration which is different from the Kenya classification system (Ministry of Roads and Public Works, 1979). Table 3-1 and Source: *Federal Highway Administration (n.d)*

Table 3-2 shows the Federal Highway Administration and Kenya classification system respectively. Type of vehicles based on Federal Highway Administration (FHA) classification system.

Table 3-1: Type of vehicles based on FHA classification system

Class	Description	Number of axles
F1	Motorcycles	1 axle
F2	Passenger car or light pick up	2 axles
F3	Heavy pickup	2 axles
F4	Bus	2 axles
F5	2 axles truck	2 axles
F6	3 axles truck	3 axles
F7	4 axles truck	4 axles
F8	Single truck trailers	3 or 4 axles
F9	Single truck trailers	5 or 6 axles
F10	Single truck trailers	6 axles
F11	Multi trailer truck	4 or 5 axles

F12	Multi trailer truck	6 axles

Source: Federal Highway Administration (n.d)

Table 3-2: Type of vehicles based on Kenya Road Design Manual, Part 1, 1979

Vehicle Type	Description
Pedal cycles	Basically, a bicycle
Motor cycles, scooters	Two-wheeled motor vehicle
Passenger cars	Passenger vehicles with less than nine seats
Light goods vehicles	Land rovers, minibuses and goods vehicles of less than 1500 kg unladen weight with payload capacities of less than 760 kg
Buses	All passenger vehicles larger than mini buses
Medium good vehicles	Maximum gross vehicle weight 8500 kg
Heavy goods vehicles	Gross vehicle weight exceeding 8500 kg

Source: Ministry of Transport and Communication (1987)

The data retrieved from the ATC was reorganized to match the Kenya vehicle classification system. Some categories of the Federal Highway Administration were combined under the same class in the Kenya vehicle classification. The adopted vehicle classification system based on the matched classification scheme is presented in Table 3-3.

Table 3-3: Adopted vehicle classification system

Kenya vehicle Classification System	Combined F Vehicle classification system categories	Description
Motor cycles, scooters	F1	Motor cycles and scooters
Passenger cars	F2	Passenger vehicles with less than nine seats
Light goods vehicles	F3	Land rovers, minibuses and goods vehicles of less than 1500 kg unladen weight with payload capacities of less than 760 kg
Buses	F4+F5	All passenger vehicles larger than mini buses (Buses)
Medium good vehicles	F6	Maximum gross vehicle weight 8500 kg

Heavy goods vehicles	F7+F8+F9+F10+ F11+F12	Gross vehicle weight exceeding 8500 kg

The traffic data was recorded in the traffic data collection sheet.

ii. Axle load survey

The axle load survey was undertaken at a section approximately 320m from Kangundo roundabout towards Jogoo road intersection which presented an adequate space and safe location for axle load survey exercise. A portable axle load survey equipment was used for the survey. The survey was undertaken for 7 days from 23rd August to 29th August 2021 for 12 hours. The survey was taken for the two directions during the exercise as illustrated in Table 3-4.

Table 3-4: Axle load survey days and duration

S/No.	Dates	Days	From	To	Duration (Hrs.)
1	29/08/2021	Sunday	Eastern Bypass side	Thika road side	12
2	28/08/2021	Saturday	Eastern Bypass side	Thika road side	12
3	27/08/2021	Friday	Eastern Bypass side	Thika road side	12
4	26/08/2021	Thursday	Thika road side	Eastern Bypass side	12
5	25/08/2021	Wednesday	Thika road side	Eastern Bypass side	12
6	24/08/2021	Tuesday	Eastern Bypass side	Thika road side	12
7	23/08/2021	Monday	Eastern Bypass side	Thika road side	12

A photograph taken during axle load survey is in Figure 3-3.

Figure 3-3: Axle load survey

3.3.1.3. Data analysis

The Average Daily Traffic (ADT) was established by getting the average traffic for the seven days. A seasonal factor of 1.2 was adopted to convert ADT to Annual Average Daily Traffic (AADT) based on the recent traffic analysis undertaken for roads with almost similar characteristics to Outer ring road (KURA, 2022).

The main objective of carrying out an axle load survey was to determine the VEF for each type of vehicle. The Equivalence Factor (EF) of an axle is its pavement damaging effect in relation to a standard axle where a unit of standard axle load is considered equivalent to 8200 Kilograms (Kgs). The vehicle axle load was converted into standard axles using Liddle's equation presented in Equation $\mathbf{EF} = (\frac{\mathbf{AL}}{\mathbf{8200}})^{\mathbf{4.5}}$

(**3-1**) (TRL, 2004; Ministry of Roads and Public Works, 1979).

$$\mathbf{EF} = (\frac{\mathbf{AL}}{\mathbf{8200}})^{\mathbf{4.5}} \quad (3\text{-}1)$$

Where: EF is the Equivalent factor
AL is the Axle load weight in Kgs.

The VEF for each vehicle weighed during the survey was calculated by summing up the VEF for all axles. The Daily Equivalence Standard Axles (DESA) was calculated by summing up the product of vehicle EF and the average daily traffic (ADT) for the heavily loaded direction shown in Equation DESA = ∑ (EF * ADT) .

DESA = ∑ (EF * ADT) (3-2)

The Cumulative Standard Axle (CSA) was then computed using Equation$\mathbf{T} = [\mathbf{365t}(\mathbf{1} + \boldsymbol{i})^{\boldsymbol{n}} - \mathbf{1}] / \mathbf{I}$ below:

$$\mathbf{T} = [\mathbf{365t}(\mathbf{1} + \boldsymbol{i})^{\boldsymbol{n}} - \mathbf{1}] / \mathbf{I} \quad (3\text{-}3)$$

Where:

T

The

Table

Year	Projected
2018	6.3
2019	5.0
2020	4.0
2021	5.0
2022	5.9
Average	5.24

Source:

3.3.2. Establishment of the pavement structural adequacy

Pavement

3.3.2.1. Materials

Falling

3.3.2.2. Data collection methodology

Deflection

Figure

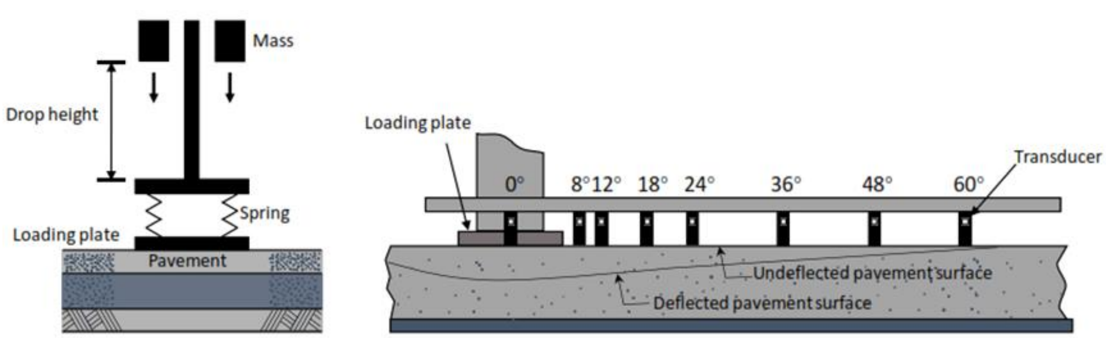


Figure
The

The target load during testing was 50 kN, which result to standard pressure of 707 KPa as per the manufacturer's specifications. In the field, attempts are made at testing at this pressure as much as possible. Due to gradient and nature of road surface, the resultant pressure is in most cases slightly lower or above this pressure. To standardize, the FWD deflection data were normalized to a standard pressure of 707 KPa using $\mathbf{dn} = \{\mathbf{d_i} \times \mathbf{L_t}\}/\{\mathbf{L_i}\}$

(**3-4**.

$$\mathbf{d_n} = \{\mathbf{d_i} \times \mathbf{L_t}\}/\{\mathbf{L_i}\} \tag{3-4}$$

Where:

d_i is the deflection reading for the sensor located *i* mm from the centre.

nd_i is the normalized deflection reading for the sensor located i mm from the centre.

L_i is the load level applied during the test

L_t is the target load level of 566KPa based on the standard axle of 8-tonne

A summary of the FWD test procedure is attached in Appendix D based on Overseas Road Note 18 (TRL, 1999).

3.3.2.3. Data analysis

The deflection data was analyzed using RoSy Design Software. The following design parameters in Table 3-6 were considered during data input for RoSy Design analysis;

Table 3-6: Pavement analysis Parameters

Pavement analysis parameter	Value
Existing road lane width	3.5m
Pavement design temperature	25^0C
Fatigue laws	As presented in RDM Part III
Pavement analysis period	10 years, 15 years and 20 years
DESA	Established from the traffic survey

The pavement analysis criteria was carried out following conditions in Kenya Road Design manual part III and V and therefore compared to elastic moduli in section 8.2.2 and 8.2.3 of RDM Part III for Material and Pavement Design for New Roads as indicated in Table 3-7.

Table 3-7: Pavement analysis criteria

Pavement material	**Moduli (MPa)**
Asphalt Concrete (0/19)	4000 MPa
Dense Bitumen Macadam (0/37.5)	5000 MPa
Cement Improved Graded crushed stone (2%) where Unconfined Compressive Strength (UCS) is 1800kN/m^2	2700 MPa
Cement Stabilised Gravel (4%)	4000 MPa
Improved subgrade (required for cement stabilised gravel subbase)	1000 MPa

Source: Ministry of Transport and Communication (1987)

Back calculation was conducted using Rosy design software to establish pavement and subgrade layers moduli and thereby the condition of pavement and the subgrade. The software complies with ASTM D5858 – 96 (2015) and it simulates the performance of the pavement based on the design parameters especially design traffic loading and pavement layers moduli from back calculation to determine pavement residual structural life and critical layers. In the analysis, the bituminous layers of surfacing and base were combined and analysed as one layer to provide room for the crack relief layer since the software analyses a maximum of four layers. Additionally, the pavement was checked for residual life and hence strength, critical layer and overlay requirements for each section.

3.3.3. Evaluation of the pavement functional performance adequacy

To achieve this objective of the study, the primary data collected was; surface distresses (cracking, potholes, reveling, rutting, bleeding),drainage condition (signs of water ponding, drainage flow, camber and cross slope condition), pavement surface roughness and rut depth. The secondary data was the specific sections for the reinforced earth embankments.

3.3.3.1. Materials

Surface condition survey (SCS) was conducted using the Hawkeye 2000 Pavement Surface Profiler (PSP) which is an automatic equipment that can perform roughness and rutting measurements using the Laser Profiler Beam (LPB) and pavement surface distress logging using Pavement Logging Video Cameras (PLVC). It is basically a video and a camera mounted on a vehicle to record and photograph pavement defects and the general condition of the road. Figure 3-5 shows surface condition survey equipment mounted on a vehicle.

Figure 3-5: surface condition survey using Hawkeye 2000

The profiler was used for undertaking the visual condition survey, roughness and rut depth measurements. Outer ring road design reports and as-built drawings provided the constructed road pavement structure and the specific sections for the reinforced earth embankments.

3.3.3.2. Data collection methodology

i. Visual condition survey

The Hawkeye 2000 Pavement Surface Profiler (PSP) has four pavement and asset logging video cameras. Collection of the road surface condition and distress data was done using pavement and centre cameras and complemented with windscreen survey. The video imaging captures high resolution digital images of the pavement to enable accurate inventory recording, condition and measurement of such features as; cracking, delamination, pot holing and general pavement condition. Identification, measurement of intensity and determination of severity of surface distress was done in accordance with Kenya roads manual for pavement rehabilitation and overlay design and ASTM D6433-07 (standard practice for determination of roads and parking lots pavement condition through visual surveys using the PCI method of quantifying pavement condition. The observations made during the detailed surface condition survey through the profiler and windscreen survey were captured and recorded. The measurements were made at 100m intervals for the outer and inner lane of right and left hand sides of the main carriageway.

ii. Roughness measurement

Roughness data was collected using the Hawkeye 2000 based on the standard practice for determination of IRI to quantify roughness of pavements prescribed in AASHTO (1993) and standard test method for measuring the longitudinal profile of traveled surfaces with an accelerometer established inertial reference on a profile measuring vehicle prescribed in ASTM E950 – 98. The measurements were made at 100m intervals for the outer and inner lane of right and left hand sides of the main carriageway. The distribution of the IRI were reported per lane with mean, minimum, maximum, standard deviation and characteristic IRI.

iii. Rut Depth Measurement

A rut is a surface depression in the wheel paths. Rutting stems from a permanent deformation in any of the pavement layers or subgrades, usually caused by consolidated or lateral movement of the materials due to traffic load.

Rut depth test was conducted with the Pavement Surface Profiler (PSP) in compliance with ASTM E1703 / E1703M – 10 (2015) (standard test method procedure for the measurement of the depth of the rut at a chosen location in a pavement surface using a straightedge and a gauge). The measurements were made at 100m intervals for the outer and inner lane of right and left hand sides of the main carriageway.

3.3.3.3. Data analysis

i. Visual condition survey

The observations made during the detailed surface condition survey through the Hawkeye 2000 Pavement Surface Profiler and windscreen survey were captured and recorded. Visual inspection and analysis of the captured images was undertaken to establish any pavement surface distress and condition of the road drains.

ii. Roughness measurement

The roughness data was processed using Hawkeye 2000 processing software with IRI expressed in metres per kilometre (m/Km). Distribution of IRI was reported per lane with mean, minimum, maximum, standard deviation and characteristic IRI. The Australian Road Research Board (ARRB) Group rating scale presented in Table 3-8 was used to rate the roughness data and measured average IRI for each delineated homogenous section.

Table 3-8: Australian Road Research Board (ARRB) Group IRI rating scale

IRI Range scale	Rating Colour	Pavement Condition
Below 2		Excellent
2.0 to 4.0		Good
4.0 to 6.0		Fair
6.0 to 10.0		Poor
Above 10.0		Very Poor

Source: ARRB (n.d)

iii. Rut Depth Measurement

The rut depth scale based on ASTM D6433-99 presented in Table 3-9 was used to rate the depth of the rutting on the road surface based.

Table 3-9: Rut depth scale

Range	Rutting condition
0 to 6 mm	No rutting
6 to 13 mm	Low severity
13 to 25 mm	Medium severity
Above 25 mm.	High severity

Source: AASHTO (1993)

iv. Pavement Condition Index (PCI)

PCI was calculated as numerical value that is used to rate the condition of a given road surface. It is determined based on the type and level of distresses observed on a given road surface. The PCI is a function of the IRI and is calculated as shown in PCI =10^ (2-0.436*Log (IRI))

(**3-5**) based on ASTM D6433.

PCI =10^ (2-0.436*Log (IRI)) (3-5)

Where:

PCI is Pavement Condition Index

IRI is International Roughness Index

The PCI values ranges from 0 (Failed) to 100 (Good) based on the ASTM D6433-15 rating scale as presented in Table 3-10 below.

Table 3-10: Pavement Condition Index (PCI) and Rating Scale

PCI Range scale	Rating Colour	Pavement Condition
85-100		Good
70-85		Satisfactory
55-70		Fair
40-55		Poor
25-40		Very Poor
10-25		Serious
0-10		Failed

Source: AASHTO (1993)

CHAPTER FOUR

4. RESULTS, ANALYSIS AND DISCUSSION

The primary and secondary data collected were analysed and discussed in response to the objectives of this study.

4.1. Evaluation of the impact of the current traffic loading on the pavement

4.1.1. Design Traffic

The traffic volumes in AADT based on traffic surveys carried out during the design year, in 2012 by KURA (2012) is tabulated in Table 4-1. Directional AADT volumes on the stations ranged from a minimum of 7,385 on the section from Juja Road to Mumias Road, to a maximum of 10,380 on the section from Jogoo Road to Airport North road.

Table 4-1: Traffic volumes in AADT in the design year, 2012

Direction & Section	**Cars, pick-up,4WD**	**Tourist van, matatu, Minibus<30pass**	**Bus, L.G.V> 30pass**	**All trucks (M.G.V , H.G.V)**	**TOTAL**
Jogoo-Airport north	6,121	2,657	1,177	425	**10,380**
Airport north- Jogoo Rd	5,723	2,477	1,393	413	**10,006**
Jogoo-Kangundo Rd	5,422	2,044	1,132	958	**9,557**
Kangundo Rd- Jogoo Rd	4,807	1,803	689	810	**8,109**
Juja Rd-Mumias south	4,770	1,533	193	889	**7,385**
Mumias South - Juja Rd	4,834	1,546	242	930	**7,551**

Source: KURA (2012)

The projected average daily number of standard axles for one year after opening the project, that is year 2018 and the cumulative number of standard axles after twenty years, which was year 2037 is presented in

Table 4-2. The VEF adopted during the road design was 0.25 for buses and 1.54 for medium and heavy goods vehicles. The adopted growth rates during the project design were 2.6%, 3.5% and 4.4% for low, medium and high growth rate respectively (KURA, 2012).

Table 4-2: Outer ring road project pavement design traffic

Road Section	Average Daily No. of Standard (Std) Axles 1 year (yr) after opening (February 2018)			20 yr Cum No. of Std AXLES (x10^6) January 2037		
	Growth rate			Growth rate		
	Low (2.6%)	Medium (3.5%)	High (4.4%)	Low (2.6%)	Medium (3.5%)	High (4.4%)
Airport north- Jogoo Rd	1301	1313	1324	9.83	10.84	11.97
Traffic Class				**T3**	**T2**	**T2**
Jogoo Rd -Kangundo Rd	2347	2367	2387	17.72	19.54	21.58
Traffic Class				**T2**	**T2**	**T2**
Mumias South - Juja Rd	2001	2018	2035	15.11	16.66	18.40
Traffic Class				**T2**	**T2**	**T2**

Source: KURA (2012)

Pavement traffic class T2 was adopted for the design of Outer ring road pavement structure.

4.1.2. Classified traffic counts

The Average Daily Traffic (ADT) was established by getting the average traffic for the seven days. The summary of analysed traffic volume data in ADT is tabulated in Table 4-3.

Table 4-3: Traffic volume in ADT (2021) for outer ring road

	VEHICLE TYPE					
STATIONS	**Cars**	**LGV**	**BUSES**	**MGV**	**HGV**	**TOTAL**
Baba Dogo - Station 1						
Baba Dogo – Juja road	33252	894	3512	1160	2452	41270
Baba Dogo - Thika road	20582	567	2042	751	1278	25219
Total ADT	53834	1461	5554	1910	3730	66489
Mutindwa - Station 2						
Mutindwa to Donholm	27550	572	2780	1106	1367	33375
Mutindwa to Thika road	16386	319	2048	715	844	20313
Total ADT	43936	891	4829	1822	2211	53688
Pipeline - Station 3						
Pipeline to Airport North road	18845	663	1838	971	1333	23650
Pipeline to Jogoo road	17428	487	2428	838	1127	22308

STATIONS	VEHICLE TYPE					
	Cars	**LGV**	**BUSES**	**MGV**	**HGV**	**TOTAL**
Total ADT	36273	1149	4266	1809	2460	45958

The traffic volume in ADT is displayed in Figure 4-1.

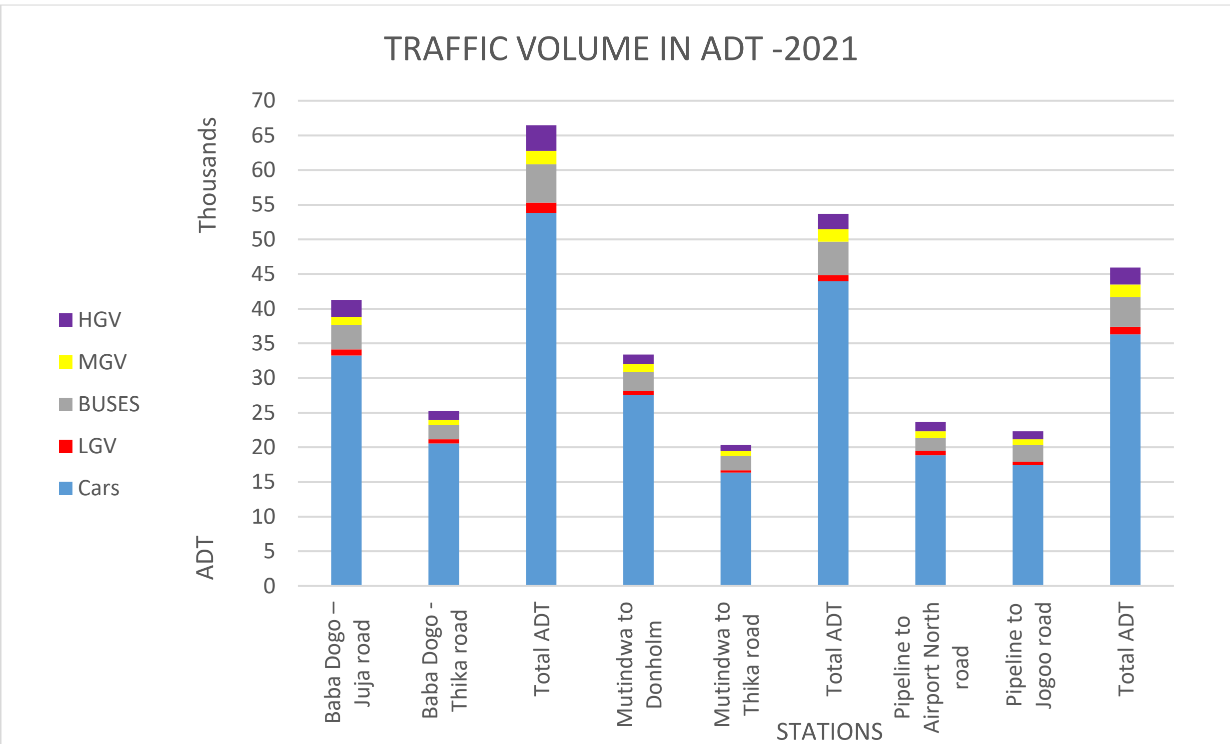


Figure 4-1: Traffic volume in ADT - 2021

Baba Dogo station recorded the highest ADT for each direction and for the two directions combined while Pipeline station recorded the lowest. It was established that the traffic volume towards Airport North road (Eastern bypass) direction was higher that traffic towards Thika road side for all stations. Cars recorded the highest volume in all stations followed by buses and least was Light Goods Vehicles (LGV). Of importance to note is that Heavy Goods Vehicles (HGV) have a significant contribution to the commercial vehicles which consequently have more impact on traffic loading on the pavement.

4.1.3. Axle load survey

The calculated average VEF for each vehicle class based on the axle load survey data is summarized in Table 4-4.

Table 4-4: Average VEF

Vehicle Type	Average VEF
Bus	0.48
Medium Goods Vehicles (MGV)	1.15
Heavy Goods Vehicles (HGV)	4.19

4.1.3.1. Daily Equivalence Standard Axles (DESA)

The Daily Equivalence Standard Axles (DESA) was calculated by summing up the product of VEF and ADT for the heavily loaded direction. In this regard, the Left Hand Side (LHS), Thika Road to Airport North road direction was the heavily loaded direction. The DESA for the various stations are presented in Table 4-5. Baba Dogo station recorded the highest DESA followed by Mutindwa station and the least being Pipeline station as observed in the traffic volume analysis.

Table 4-5: Daily Equivalence Standard Axles

STATIONS	VEHICLE TYPE		
Baba Dogo - Station 1	**BUSES**	**MGV**	**HGV**
Baba Dogo – Juja road	3512	1160	2452
VEF	0.48	1.15	4.19
Daily standard axles, 2021	1686	1329	10273
Daily standard axles -SUM		13288	
Mutindwa - Station 2	**BUSES**	**MGV**	**HGV**
Mutindwa to Donholm	2780	1106	1367
Daily standard axles, 2021	1335	1267	5726
Daily standard axles -SUM		8328	
Pipeline - Station 3	**BUSES**	**MGV**	**HGV**
Pipeline to Airport North road	1838	971	1333
Daily standard axles, 2021	882	1113	5585
Daily standard axles -SUM		7580	

Upgrading of the road resulted to a significant increase of loading on the road confirmed by the growths rates which are higher than the projected rates during the design year. There was a significant increase of axle load on the road in the three stations as illustrated in Table 4-6 and Figure 4-2.

Based on these results, it is evident that high traffic volumes on the road can significantly influence the rate of deterioration and the overall integrity of the pavement. This aligns with findings from the literature, especially as highlighted by Tom (2007) who established a direct relationship between traffic volume, load application frequency, and pavement distresses. While the impact of a single axle load on pavement deformation might be minimal, the cumulative effect from numerous load repetitions can be substantial. Consequently, even though individual small cars might exert limited load on the pavement, a large volume of vehicles with high frequency, such as that observed on Outer ring road, can lead to prominent pavement distresses (Tom, 2007). Hence, urban roads and major arteries like Outer ring road are more susceptible to pavement wear and consequent deterioration due to consistently high traffic volumes encompassing various vehicle types.

Table 4-6: Daily Equivalence Standard Axles growth rate

	DESA		
Station (Directional)	**2012**	**2021**	**Growth rate**
Baba Dogo - Juja Rd	1417	13288	28.2%
Mutindwa to Donholm	1420	8328	21.7%
Jogoo-Airport North Rd	949	7580	26.0%
Average growth rate			25.3 %

During the design year, the maximum adopted growth rate was 4.4% and it was anticipated that in the initial years after opening the road, the traffic growth rate would be at approximately 10% (KURA, 2012). The average growth rate for DESA at the traffic count stations was 25.3% with the highest being recorded at Baba Dogo station and lowest at Mutindwa station at 28.2% and 21.7% respectively. This is a classic case of an exponential growth rate after opening of a new road or upgrading of an existing road. The increase in heavy goods vehicles on the road due to the upgrading of the project road is attributable to reduced travel time and smooth road surface hence reduction in vehicle operating costs and offers more comfortable ride to the drivers.

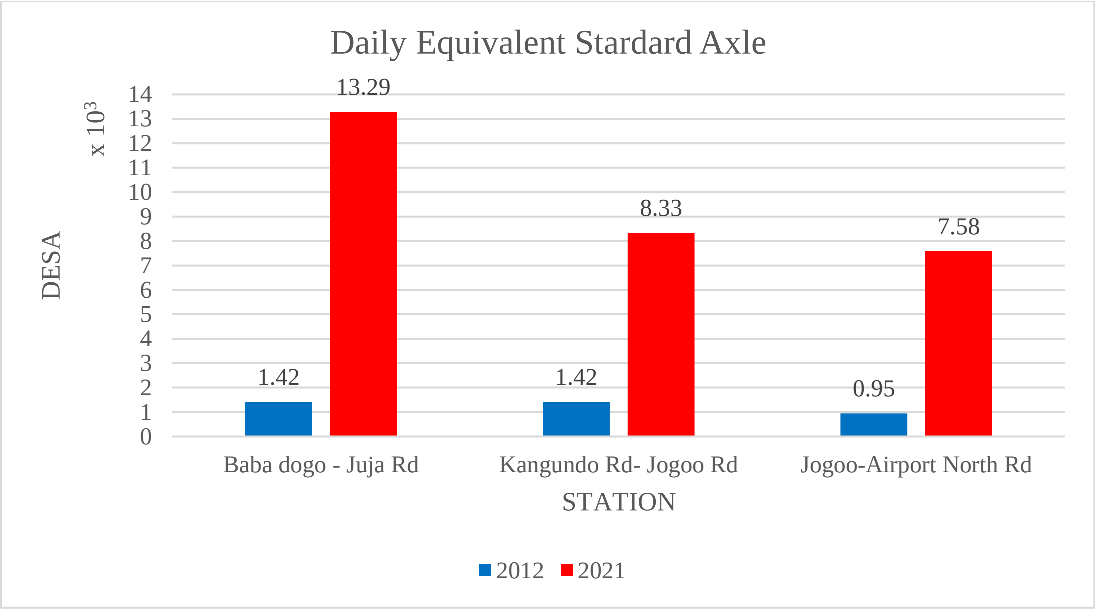


Figure 4-2: Comparison of 2012 and 2021 DESA

Rapid increase in traffic load particularly from heavy vehicles can lead to premature pavement failure, a phenomenon detailed by Al-Zwainy et al. (2020). Having such heavy traffic soon after commissioning of the road can compromise the road pavement structural integrity, leading to distresses like rutting and roughness (Sushmita et al., 2022).

A typical long term growth curve is a combination of exponential growth rate followed by linear growth rate and lastly a declining growth rate. The exponential growth rate is usually 5 years after opening of the road while the linear growth goes to around 10 years and the last 5 years the growth rate declines (Oregon Department of Transportation, 2022). The exhibited average growth rate of 25.3% is 2.5 times higher than the anticipated growth rate of 10%. Whether this kind of exponential growth rate is related to normal increase in traffic volume, increase in vehicle loading or due to increased urbanization it can result to drastic effect on stresses induced on the pavement and consequently undermine the structural integrity of the pavement. Reinforced earth sections are designed to offer a more stable foundation to the pavement found on them, however, if the existing traffic loading on the road exponentially surpass the design traffic, the pavement will not withstand the increased loading and can result to pavement failure. Based on this finding, this study therefore highlights the necessity for proactive traffic engineering measures not only based on the current traffic demands but also on other factors that may lead to exponential increase of traffic of a given road or road network. This will ensure durability of road infrastructure investments and safety of the public.

4.1.3.2. Cumulative Equivalent Standard Axle (CESA) loads

The adopted growth rates during the project design were 2.6%, 3.5% and 4.4% for low, medium and high growth rates respectively. It has been established that the mean growth rate since opening of the road in year 2018 to year 2021 is 25%. To determine the cumulative standard axle loading for the remaining design life years, a conservative growth rate of 5% has been reasonably adopted based on the analysis in Table 3-5. The calculated CESA are shown in Table 4-7 below.

Table 4-7: CESA on Outer ring road project

Target year	**Design CESA -2012**		
	Stations		
	Baba Dogo	**Mutindwa**	**Pipeline**
Base year (2018)	2,035	2,387	1,324
Design year (20 years)	18,400,000	21,580,000	11,970,000
	CESA based on 2021 traffic survey		
Year 2021	13,288	8,328	7,580
	CESA based on 5% Annual Traffic Growth Rate		
Year 10 (2028)	39,488,234	24,749,050	22,525,410
Year 15 (2033)	77,197,072	48,382,873	44,035,793
Year 20 (2038)	125,324,168	78,546,285	71,489,099

The road was opened to traffic in 2018 with a design life of 20 years and design traffic of 18.4 million, 21.58 million and 11.97 million CESA for Thika Road – Kangundo Road, Kangundo Road – Donholm, Donholm – Pipeline sections, respectively (KURA, 2012). Based on the current traffic on the road, it has been established that the projected traffic design at year 20 will be exceed in year 10. Therefore, it is prudent to closely monitor the traffic on the road to accurately determine traffic growth rates over time which may be shaped by micro or macro factors. An effective pavement maintenance strategy hinges on meticulous traffic monitoring which establishes the precise year the expected design traffic will be attained or surpassed. This allows for timely interventions to ensure the road remains functional throughout its intended design life.

4.2. Evaluation of the functional performance adequacy of the pavement

4.2.1. Outer ring road sections

The project road comprised of the following sections, normal construction, bridge deck and reinforced earth embankments (KURA, 2012). A map of Outer ring road project showing the locations of the reinforced earth embankment is presented in Appendix A and the homogenous sections of the Outer ring road project are shown in Table 4-8 below.

Table 4-8: Outer ring road homogeneous sections

Homogenous sections		
From	**To**	**Description of the section**
0+000	0+075	Normal Construction
0+075	0+125	Bridge deck - Thika road overpass
0+125	1+300	Normal Construction
1+300	1+480	RE Embankment
1+490	1+550	Mathari bridge deck
1+550	1+710	RE Embankment
1+710	3+160	Normal Construction
3+160	3+175	Normal Construction (Fill)
3+175	3+210	Bridge deck- Nairobi River
3+210	3+400	Normal Construction (Fill)
3+400	3+660	Normal Construction
3+660	3+950	RE Embankment
3+950	4+864	Bridge deck- Kangundo viaduct
4+864	4+995	RE Embankment
4+995	7+928	Normal Construction
7+928	7+972	Bridge deck – Ngong river
7+972	9+700	Normal Construction
9+700	9+831	RE Embankment
9+831	10+175	Bridge deck –Taj mall
10+175	10+225	RE Embankment l
10+225	End	Normal Construction

Source: KURA (2012)

Based on the design and construction drawings, the reinforced earth sections of the Outer ring road project are shown in Table 4-9.

Table 4-9: Reinforced earth sections of outer ring road

Description	Section from	Section to	Total Length (m)
Mathari River	1+300	1+482	182
	1+550	1+700	150
Kangundo Flyover	3+660	3+908	248
	4+864	4+995	970
Pipeline Flyover	9+750	9+831	81
	10+175	10+225	50

Source: KURA (2012)

The reinforced earth embankments were constructed with 500 mm backfill material compacted layer by layer and composite steel-plastic geobelts of CAT30020B model provided at spacing of 500mm. Non cohesive material meeting the conditions of BS 8006 guidelines was adopted as backfill material. Lateritic gravel (murram) was the backfill material used for the reinforced earth fill construction. The height of the reinforced earth walls varied from four to ten metres (4m to 10m) as established from the construction drawings (KURA, 2012).

4.2.2. Visual condition survey

Visual inspection and analysis of the captured images revealed that there were no significant distresses on the road surface except for few potholes, cracks and raveling at the sections indicated in Table 4-10. The guardrails were generally in good condition except a few short sections that were misaligned due to impacts from vehicles. The drainages were in good condition save for broken drain covers and rampant dumping of garbage on the road side. It was also observed that road markings had faded in most sections of the road.

Table 4-10: Summary of observed surface distresses

Chainage (Km)	Side of the road	Surface Condition distress
5+329	Left Hand Side (LHS)	Rutting
7+177	Right Hand Side (RHS)	Rutting, Upheaving, Ravelling

Figure 4-3 below shows photographs of the pavement locations with observed distresses.

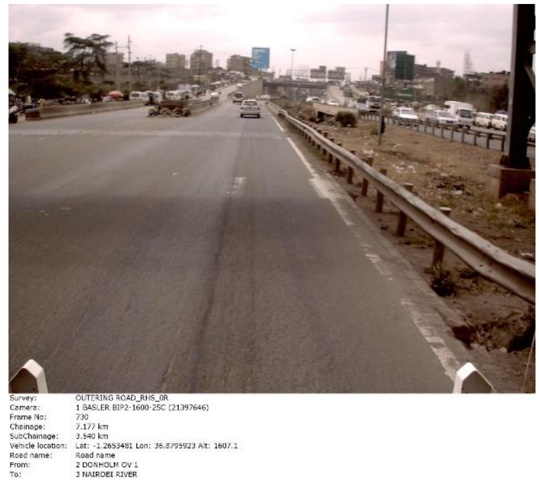


Figure 4-3: Pavement surface condition during the survey

The visual condition survey indicated that the pavement surface condition is good except at Km 5+329 and Km 7+177 that were observed to have mild rutting at LHS and RHS respectively. The distresses could have resulted from poor construction at this specific sections and/ or with combination with high traffic. These distress manifestation may be considered to align with the conclusions drawn by Al-Zwainy et al. (2020) and Anjaneyulu et al. (2022) that surface defects may affect the serviceability of the pavement. Thus, these sections call for immediate maintenance intervention measures and monitoring to prevent further deterioration of the pavement.

4.2.3. Roughness measurements

The summary of the analysis of the roughness measurements data is given in **Table 4-11** and the pavement surface roughness along the entire road on the RHS and LHS is shown in Figure 4-4.

Table 4-11: Summary of analysis of IRI data on Outer ring road

Lane	Min. of IRI Lane, m/Km	Average of IRI Lane, m/Km	Max. of IRI Lane, m/Km	Standard deviation	Characteristic IRI (Ave.+1.3SD)	IRI Rating
LHS-Outer lane	0.83	2.10	4.62	1.015	3.42	Good
LHS-Inner lane	0.85	2.14	5.67	1.075	3.53	Good
RHS-Outer lane	0.97	2.07	5.05	0.968	3.33	Good
RHS-Inner lane	1.02	2.03	4.66	0.842	3.12	Good

Based on the statistical analysis of the IRI data, it is noted that the average IRI for the entire road sections ranged from 2.03 to 2.14 m/Km which is rated as “Good”. This is expected being a relatively new road. It is also observed that the RHS of the road (from Thika road side to Eastern bypass intersection) has higher IRI values than LHS, this is as a result of the heavier traffic on that side on the road.

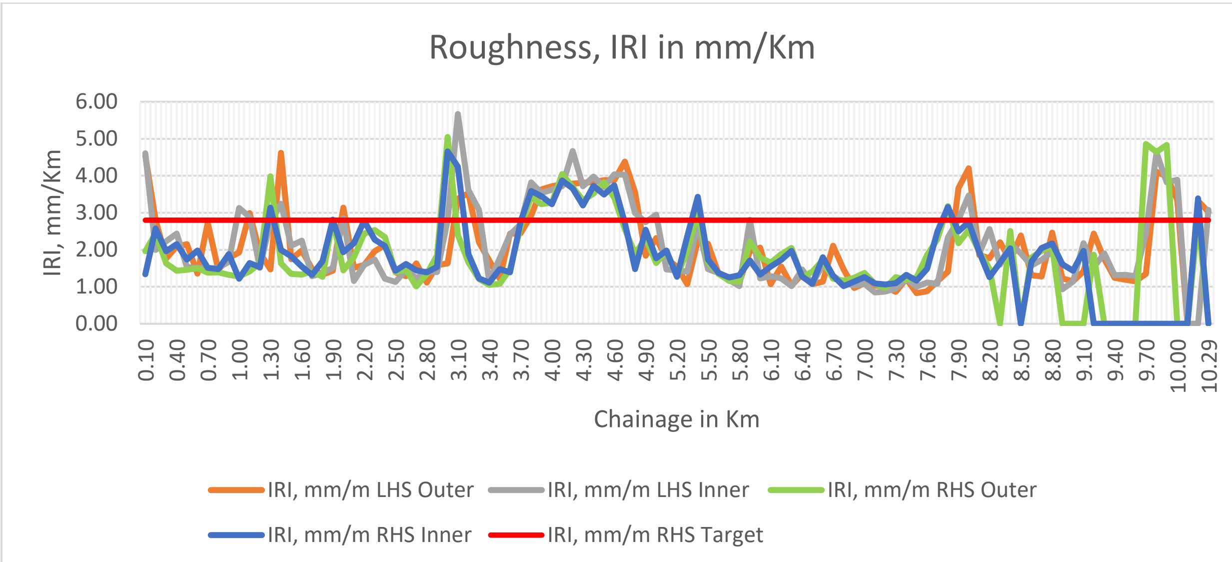


Figure 4-4: Pavement surface Roughness (IRI) along the road

Despite the overall rating of the entire road indicating that the road condition is rated good, specific measurements at the reinforced earth sections showed varying conditions. It was observed that based on the characteristic IRI for the reinforced earth sections, two sections had a rating of "Excellent", while ten sections rated "Good" and "Fair". Roughness is an indicator of pavement surface deformation. The analysis of IRI at the reinforced earth sections is shown in Table 4-12.

Table 4-12: Distribution of IRI at the reinforced earth sections

Lane	Chainage	Min. of IRI Lane, m/Km	Average of IRI Lane, m/Km	Max. of IRI Lane, m/Km	Standard Deviation	Characteristic IRI (Ave.+1.3SD)	IRI Rating
Outer Lane (LHS)	1+300-1+482	1.47	3.06	4.62	2.23	5.94	Fair
	1+550-1+700	1.49	1.74	1.98	0.35	2.19	Good
	3+660-3+908	2.45	3.00	3.63	0.59	3.77	Good
	4+864-4+995	1.84	2.70	3.55	1.21	4.27	Fair
	9+750-9+831	4.11	4.11	4.11	0.00	4.11	Fair
	10+175-10+225	3.03	3.18	3.32	0.21	3.44	Good

Inner Lane(LHS)	1+300-1+482	2.77	3.01	3.24	0.33	3.44	Good
	1+550-1+700	1.29	1.77	2.25	0.68	2.65	Good
	3+660-3+908	2.69	3.35	3.82	0.59	4.12	Fair
	4+864-4+995	2.75	2.87	2.99	0.17	4.63	Fair
	9+750-9+831	4.63	4.63	4.63	0.00	4.63	Fair
	10+175-10+225	0.00	1.54	3.08	2.18	4.37	Fair
Outer Lane(RHS)	1+300-1+482	1.63	2.81	3.99	1.67	4.98	Fair
	1+550-1+700	1.33	1.38	1.42	0.06	1.46	Excellent
	3+660-3+908	2.61	3.09	3.42	0.42	3.64	Good
	4+864-4+995	1.89	2.10	2.31	0.30	2.49	Good
	9+750-9+831	4.64	4.46	4.64	0.00	4.64	Fair
	10+175-10+225	0.00	1.43	2.86	2.02	4.06	Fair
Inner Lane(RHS)	1+300-1+482	2.00	2.57	3.14	0.81	3.62	Good
	1+550-1+700	1.32	1.44	1.55	0.16	1.65	Excellent
	3+660-3+908	2.76	3.27	3.59	0.44	3.84	Good
	4+864-4+995	1.48	2.01	2.54	0.75	2.98	Good
	10+175-10+225	0.00	1.70	3.39	2.40	4.81	Fair

In their evaluation on pavement distresses and their causes Adlinge & Gupta (2013) concluded that pavement deformation is as a result of weakness in any of the pavement layers that has experienced movement after construction. Such deformation may result to cracking and any surface distortions is a traffic hazard. Several studies, including study by Adlinge & Gupta concur that possible causes of pavement deformations are; insufficient compaction or inadequate strength of the subbase layer, insufficient fill compaction, and issues related to slip or ground water. Consequently, it can be deduced that the sections that rated fair and poor were as a result of secondary compaction on the reinforced earth sections on the premise that the entire road was constructed with a similar pavement structure and within the same environmental conditions. Another potential cause could be insufficient compaction during the construction of the road.

The roughness evaluation criteria in Kenya which is based on TRRL recommendations state that IRI above 2.8mm/Km requires resurfacing on trunk roads. Most IRI values at the reinforced earth sections are above the minimum allowable roughness hence requiring resurfacing to restore the surface smoothness.

4.2.4. Rut depth measurements

Rut depth measurements were taken for the entire road length and it was established that all the sections had characteristic rut depth less than 6mm, hence rated as ‘No rutting’. This implies that the entire road is generally in good condition. The summary of the analysis of measured average rut depths based on ASTM D6433-99 rut depth rating scale is presented in Table 4-13.

Table 4-13: Average rut depths for Outer ring road

Lane	Min. Rut, mm	Average Rut, mm	Max. Rut, mm	Standard deviation	Characteristic Rut (Ave.+1.3SD)	Rut Rating
LHS-Outer lane	0.56	2.32	12.93	1.49	4.25	No rutting
LHS-Inner lane	0.724	2.21	8.85	1.27	3.86	No rutting
RHS-Outer lane	0.861	2.25	8.43	1.23	3.85	No rutting
RHS-Inner lane	0.44	1.90	5.58	0.95	3.13	No rutting

The graphical representation of the rut depth measurements for the entire road is shown in Figure 4-5 below.

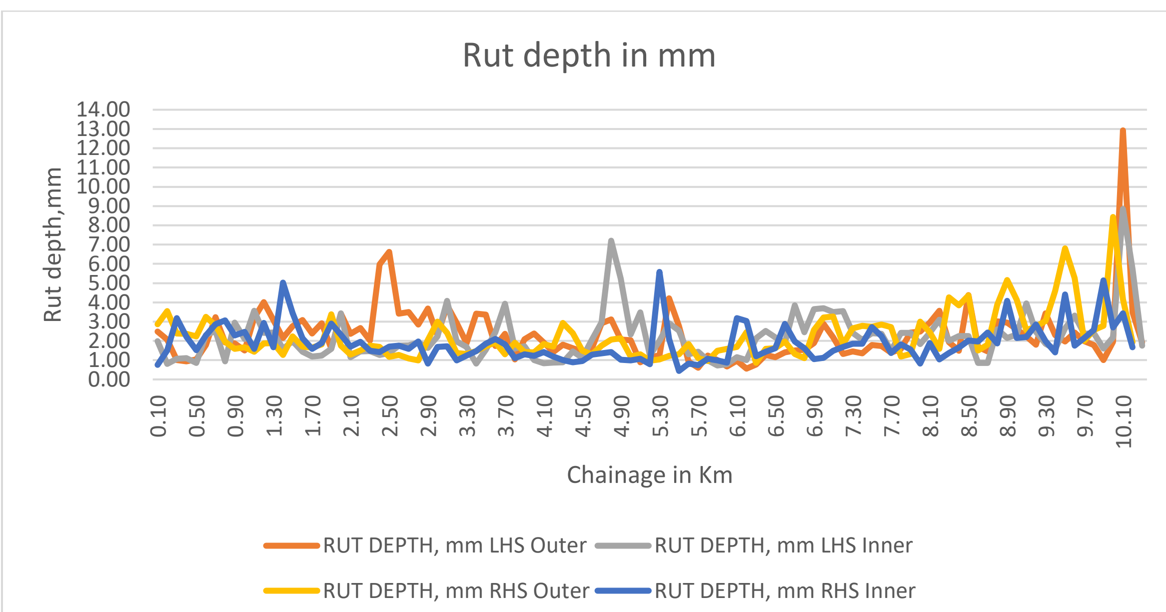


Figure 4-5: Rut depths along Outer ring road

It was observed that the characteristic rut depths on the reinforced earth sections were generally higher than the general lane characteristic rut depth for the entire road. Three sections of the reinforced earth showed low severity while the rest had no rutting. The average rut depths at the reinforced earth sections are presented in Table 4-14.

Table 4-14: Average rut depths at the reinforced earth sections

Lane	Chainage	Min. Rut mm	Average Rut, mm	Max. Rut, mm	Standard Deviation	Characteristic Rut (Ave.+1.3SD)	Rut rating
Outer Lane (LHS)	1+300-1+482	2.16	2.62	3.07	0.65	3.46	No rutting
	1+550-1+700	2.39	2.73	3.08	0.49	3.37	No rutting
	3+660-3+908	1.04	1.83	2.37	0.70	2.74	No rutting
	4+864-4+995	2.07	2.59	3.11	0.73	3.55	No rutting
	9+750-9+831	1.78	1.78	1.78	0.00	1.78	No rutting
	10+175-10+225	1.92	2.70	3.47	1.10	4.12	No rutting
Inner Lane(LHS)	1+300-1+482	1.59	2.01	2.44	0.60	2.79	No rutting
	1+550-1+700	1.19	1.31	1.44	0.17	1.54	No rutting
	3+660-3+908	1.60	2.42	3.94	1.32	4.13	No rutting
	4+864-4+995	5.22	6.21	7.20	1.40	8.02	Low severity
	9+750-9+831	2.41	2.41	2.41	0.00	2.41	No rutting
	10+175-10+225	1.76	3.74	5.72	2.80	7.38	Low severity
Outer Lane(RHS)	1+300-1+482	1.27	1.58	1.88	0.43	2.14	No rutting
	1+550-1+700	1.65	1.68	1.71	0.04	1.73	No rutting
	3+660-3+908	1.31	1.54	1.90	0.31	1.95	No rutting
	4+864-4+995	2.06	2.10	2.13	0.05	2.16	No rutting
	9+750-9+831	2.57	2.57	2.57	0.00	2.57	No rutting
	10+175-10+225	0.00	0.97	1.93	1.37	2.74	No rutting
Inner Lane(RHS)	1+300-1+482	1.68	3.35	5.02	2.37	6.42	Low severity
	1+550-1+700	1.58	1.86	2.14	0.39	2.37	No rutting
	3+660-3+908	1.11	1.41	1.83	0.37	1.89	No rutting
	4+864-4+995	1.02	1.22	1.42	0.28	1.58	No rutting
	9+750-9+831	2.57	2.57	2.57	0.00	2.57	No rutting
	10+175-10+225	0.00	0.84	1.67	1.18	2.37	No rutting

The deterioration mechanism of rutting based on the Kenya road design manual is densification which can occur in subgrade and or other pavement layers particularly the subbase and base. The measured pavement rut depths provide a crucial insight into the overall performance and structural integrity of pavement constructed on reinforced embankments of the road in line with Adlinge & Gupta (2013) and Asphaltic Academy (2008) findings that rutting is a key indicator of pavement distress The possible causes of rutting are insufficient stability of base and / or subbase, insufficient base thickness or insufficient subgrade compaction (Adlinge & Gupta, 2013; Ministry of Roads and Public Works, 1988). Therefore, it can be inferred that the cause of rutting observed on the pavement found on the reinforced earth embankments was likely due to insufficient compaction of the backfill material of the embankment.

4.2.5. Pavement Condition Index (PCI)

The calculations and analysis of PCI results established that the average PCI for the lanes are 72 and 73 for the LHS and RHS respectively. The rating is thus "**Satisfactory"** for the two lanes. The calculated PCI for individual lanes for the entire road are presented in Table 4-15.

Table 4-15: Pavement Condition Index for outer ring road

Lane	Average of IRI Lane, m/Km	PCI	PCI Rating
LHS-Outer lane	2.10	72	Satisfactory
LHS-Inner lane	2.14	72	Satisfactory
RHS-Outer lane	2.07	73	Satisfactory
RHS-Inner lane	2.03	73	Satisfactory

This is a general indication that the surface condition of the entire road is satisfactory. However, a single PCI is not itself a measure of absolute pavement performance but it is a representative of the trend of serviceability that gives indication about the performance of the pavement.

The PCI indicated that most reinforced earth sections have lower values compared to the normal road sections. The PCI at the reinforced earth sections ranged from 45 to 92 with the following number of sections rated as "Good", "Satisfactory", "Fair" and "Poor" being three, eight, ten and one respectively. The sections with rut depth rating of low severity recorded pavement condition rating of "Fair" to "Poor". The PCI and the rating for the reinforced earth section are presented in Table 4-16.

Table 4-16: Pavement Condition Index for reinforced earth sections.

Lane	Chainage	Average Rut, mm	Rutting rating	PCI	Pavement Condition rating
Outer Lane (LHS)	1+300-1+482	2.62	No rutting	66	Fair
	1+550-1+700	2.73	No rutting	65	Fair

Lane	Chainage	Average Rut, mm	Rutting rating	PCI	Pavement Condition rating
Inner Lane(LHS)	3+660-3+908	1.83	No rutting	77	Satisfactory
	4+864-4+995	2.59	No rutting	66	Fair
	9+750-9+831	1.78	No rutting	78	Satisfactory
	10+175-10+225	2.7	No rutting	65	Fair
	1+300-1+482	2.01	No rutting	74	Satisfactory
	1+550-1+700	1.31	No rutting	89	Good
	3+660-3+908	2.42	No rutting	68	Fair
	4+864 - 4+995	6.21	Low severity	45	Poor
	9+750-9+831	2.41	No rutting	68	Fair
	10+175-10+225	3.74	Low severity	56	Fair
Outer Lane(RHS)	1+300-1+482	1.58	No rutting	82	Satisfactory
	1+550-1+700	1.68	No rutting	80	Satisfactory
	3+660-3+908	1.54	No rutting	83	Satisfactory
	4+864-4+995	2.1	No rutting	72	Satisfactory
	9+750-9+831	2.57	No rutting	66	Fair
Inner Lane(RHS)	1+300-1+482	3.35	Low severity	59	Fair
	1+550-1+700	1.86	No rutting	76	Satisfactory
	3+660-3+908	1.41	No rutting	86	Good
	4+864 - 4+995	1.22	No rutting	92	Good
	9+750-9+831	2.57	No rutting	66	Fair

The lower PCI values at the reinforced earth sections offers a significant insight into the pavement current state or what to expect in future. Such outcome could result from inadequate compaction of the back fill material of the embankment leading to secondary consolidation of fill layers after opening of the road to traffic. The findings resonate with Anish & Sitesh (2018) who highlighted that reduced PCI values often indicate underlying structural issues and can predict future maintenance challenges. Aligning these results with other studies, particularly with the poor rating at section from Km 4+864 to 4+995 there is an imperative need for prompt interventions. Further Al-Zwainy et al. (2020) emphasized the importance of routine monitoring and proactive maintenance in response to deteriorating PCI values to prolong pavement lifespan and ensure road user safety. This study supports these conclusions and advocates for a strategic approach in managing pavements with diminished PCI values.

4.3. Establishment of the pavement structural adequacy

4.3.1. Typical Pavement Structure

The pavement structure for Outer ring road project was the standard pavement structure type 11 based on Kenya road design manual, Part III suitable for the corresponding design traffic class T2 and design subgrade of strength S4 (KURA, 2012). The designed typical pavement structure for Outer ring road is tabulated in Table 4-17.

Table 4-17: Outer ring road typical pavement structure

Pavement Layer	Convectional pavement sections
Surfacing	50mm thick, 19mm super pave (Asphalt Concrete (AC) type)
Base (Main Carriageway and Service road)	125mm thick, 37.5mm super pave (AC Type) DBM in one layer
Anti-Crack layer	125mm thick 2% cement improved 0/30mm Graded Crushed Stone (GCS) Class A, compacted to 98% Maximum Dry Density (MDD)
Subbase	175mm thick 4% cement improved gravel material of base quality with minimum California Bearing Ratio (CBR) 160% Compacted to 95% MDD
Subgrade	300/350mm improved subgrade material of S4 quality (min. CBR 14%) compacted to 100% MDD in layers of 150mm each.

Source: KURA (2012)

4.3.2. Summary of Design Parameter and Values

Table 4-18 provides a summary of the design parameter and values necessary for calculation of the residual pavement structural capacity as obtained in the design reports of Outer ring road project.

Table 4-18: Summary of design parameters and values for outer ring road project

Parameter	Description	Design Value
Subgrade	Thika road junction to Kangundo Railway Bridge (Native subgrade class – S4)	improved subgrade material of S4 quality
	Railway Bridge to Eastern Bypass (Native subgrade class – S2)	improved subgrade material of S4 quality
Traffic Class	Main carriageway	T2
	Railway Bridge to Eastern Bypass	T2
Design Period	Pavement design	20 years, the opening year set to be January 2017 and the end of

	design horizon to be January 2037.

Source: KURA (2012)

4.3.3. Pavement deflection measurements

The FWD deflection data was normalized to a standard pressure and recorded for all the geophones based on the homogenous sections for the entire road. The analysis of pavement deflections was based on the normalised deflections of the homogenous sections of the road presented in Table 4-19 below.

Table 4-19: Normalised deflections on homogeneous sections

Homogenous Section (approximate chainages)	Geophone offset (mm)								
	0	**200**	**300**	**600**	**900**	**1200**	**1500**	**1800**	**2100**
	Normalised deflections in µm								
Km 0+900 – 1+300	223	201	163	124	90	60	47	33	16
Km 1+300 – 1+480	271	247	203	160	114	76	61	45	26
Km 1+480 – 1+550	274	242	188	139	106	78	68	56	37
Km 1+550 – 1+710	274	248	201	157	111	73	58	42	23
Km 1+710 – 3+175	199	177	144	109	82	56	45	32	15
Km 3+175 – 3+210	150	135	115	86	70	50	42	30	15
Km 3+210 – 3+660	164	146	122	92	73	51	41	29	14
Km 3+660 – 3+950	275	246	199	156	113	77	63	48	28
Km 3+950 – 4+864	175	158	132	101	78	53	42	30	15
Km 4+864 – 4+995	225	203	166	128	95	63	49	34	17
Km 4+995 – 5+367	176	154	123	88	65	45	33	22	8
Km 9+500 – 9+831	159	136	107	75	56	39	30	20	7
Km 9+831 – 10+175	142	120	95	67	50	36	29	20	8
Km 10+175 – 10+225	155	128	93	55	44	34	25	17	6
Km 10+225 – 10+500	241	204	154	108	74	49	36	24	9
Mean	207	183	147	110	81	56	45	32	16

It was observed that the deflections decreased with increasing geophone offsets from the centre as graphically presented in the form of deflection bowls in Figure 4-6 below.

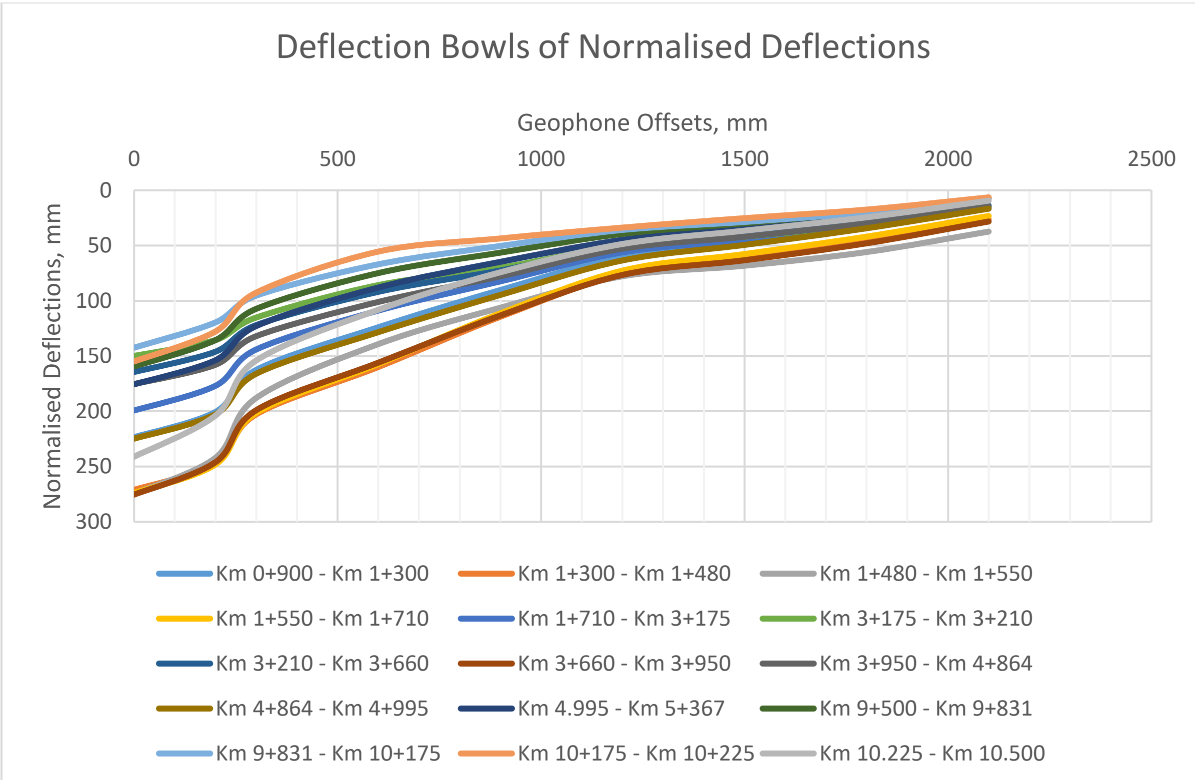


Figure 4-6: Deflection bowls of homogenous sections

Sections Km 3+175 – 3+210 and Km 9+831 – 10+175 recorded least deflections of 150 µm and 142 µm respectively while sections Km 3+660 – 3+950 , 1+480 – 1+550 and 1+550 – 1+710 recorded highest deflections of 275 µm, 275 µm and 274 µm respectively. The normalised deflection data was statistically analysed to provide minimum, mean, maximum, standard deviation and characteristic deflection data of the homogenous sections for the entire road as presented in Table 4-20 below.

Table 4-20: Mean and characteristic deflections on homogenous sections

Homogeneous section	Min. nd1, µm	Mean nd1, µm	Max. nd1, µm	Std. Dev.	Characteristic Deflection D90µm (nd1Mean+1.3SD)
Km 0+900 – 1+300	101	223	326	58	299
Km 1+300 – 1+480	186	271	439	52	338
Km 1+480 – 1+550	246	274	315	36	321
Km 1+550 – 1+710	182	274	363	52	342
Km 1+710 – 3+175	145	199	287	44	257

Homogeneous section	Min. nd1, µm	Mean nd1, µm	Max. nd1, µm	Std. Dev.	Characteristic Deflection D90µm (nd1Mean+1.3SD)
Km 3+175 – 3+210	131	150	159	16	171
Km 3+210 – 3+660	96	164	278	39	215
Km 3+660 – 3+950	153	275	423	75	373
Km 3+950 – 4+864	124	175	236	39	226
Km 4+864 – 4+995	119	225	392	77	325
Km 4+995 – 5+367	119	176	272	43	231
Km 9+500 – 9+831	104	159	235	29	197
Km 9+831 – 10+175	110	142	172	20	168
Km10+175– 10+225	106	155	240	54	225

The sections with highest deflection measurements had the maximum characteristic deflection. It was also observed that pavement on reinforced earth embankment recorded higher deflections that adjacent pavement on normal sections. The mean and characteristic deflections on reinforced earth embankment sections are shown in Table 4-21.

Table 4-21: Mean and characteristic deflections on the reinforced earth sections

Reinforced earth sections	Min. nd1, µm	Mean nd1, µm	Max. nd1, µm	Std. Dev.	Characteristic Deflection D90µm (nd1Mean+1.3SD)
Km 1+300 – 1+480	186	271	439	52	338
Km 1+550 – 1+710	182	274	363	52	342
Km 3+660 – 3+950	153	275	423	75	373
Km 4+864 – 4+995	119	225	392	77	325
Km 10+175 – 10+225	106	155	240	54	225

Pavements constructed on reinforced earth embankments exhibited higher FWD deflections compared to those on normal sections This observation contrasts with the study findings of Sitharm et al. (2020) and Rufaizal et al. (2019) which indicated that reinforcing earth embankments substantially enhances their strength and stability, thereby improving pavement performance. This contrasting data indicates that although reinforced earth sections might enhance structural integrity of overlying pavement as emphasized by Liu et al. (2008), factors such as construction techniques, quality of construction materials or local environmental conditions can introduce variations. This complexity in pavement behavior underscores the significance of comprehending local conditions, material properties and local construction methodologies (Al-Zwainy et al., 2020).

Therefore, the high deflections observed on reinforced earth sections is a clear indication that the adopted design manuals and construction guidelines might not adequately address the unique local conditions in Nairobi. As a result, the anticipated advantages of reinforced earth structures may not be fully realized in Nairobi and Kenya at large.

4.3.4. Back calculation and analysis

The deflection data recorded was used for back calculation and analysis to determine the pavement layer moduli which is a key parameter for the existing pavement structure. The output of back calculation and analysis using Rosy software to determine the Pavement Layers Moduli (PLM) per homogenous sections is summarized in Table 4-22.

Table 4-22: Average pavement layers moduli on homogeneous sections

Homogenous section	Mean Moduli, MPa			
	Surfacing and Base	Crack relief	Subbase	Subgrade
Km 0+900 – 1+300	6065	3200	1457	164
Km 1+300 – 1+480	4900	2063	916	128
Km 1+480 – 1+550	4875	3748	1961	113
Km 1+550 – 1+710	5036	2319	986	127
Km 1+710 – 3+175	6695	3100	1054	187
Km 3+175 – 3+210	7490	3796	888	232
Km 3+210 – 3+660	6999	4576	1458	207
Km 3+660 – 3+950	3795	2116	703	140
Km 3+950 – 4+864	7458	3902	1263	188
Km 4+864 – 4+995	5308	3942	2568	151
Km 4+995 – 5+367	6124	4847	2478	195
Km 9+500 – 9+831	5449	4666	1811	238
Km 9+831 – 10+175	6337	4368	1252	292
Km 10+175 – 10+225	6019	5262	3087	398
Km 10+225 – 10+500	4371	4361	2909	198
Mean	**5795**	**3751**	**1653**	**197**

The elastic moduli of the bituminous layer (surfacing and base) ranged from 3795 to 7490 MPa at sections Km 3+660 – 3+950 and Km 3+175 – 3+210 respectively. The average of the moduli was 5795 MPa which is higher than the expected elastic modulus which leads to a conclusion of a stable surfacing and base layer for the road. The average pavement layer's moduli of the reinforced earth sections was lower than for the entire road but higher than the expected layer moduli (4500MPa). The Pavement Layers Moduli (PLM) for reinforced earth sections is summarized in Table 4-23 below.

Table 4-23: Average pavement layers moduli on reinforced earth sections

Reinforced earth section	Mean Moduli, MPa			
	Surfacing and Base	Crack relief	Subbase	Subgrade
Km 1+300 – 1+480	4900	2063	916	128
Km 1+550 – 1+710	5036	2319	986	127
Km 3+660 – 3+950	3795	2116	703	140
Km 4+864 – 4+995	5308	3942	2568	151
Km 9+500 – 9+831	5449	4666	1811	238
Km 10+175 – 10+225	6019	5262	3087	398
Mean	**5085**	**3395**	**1679**	**197**

However, a comparison of all the sections shows that the pavement layers' moduli of sections Km 3+660 – 3+950 and Km 10+225 – 10+500 is lower than the minimum expected layer moduli, which is an indication of an unstable structure. The lowest mean pavement layer elastic moduli, which was 3795 MPa, was at section Km 3+660 – 3+950 which is on a reinforced earth section.

The GCS layer was provided on the road pavement between the base and the subbase as a crack relief layer. The elastic moduli of the crack relief layer ranged from 3795 to 7490 MPa with an average of 3751 MPa which is higher than the attributable elastic modulus of GCS pavement layer with UCS of 1800kN/m^2. The average moduli for the reinforced earth sections was 3395 MPa which is higher than the attributable elastic moduli of the crack relief layer. A comparison of the exhibited elastic moduli of the crack relief layer showed that the following sections had moduli less than the expected modulus, Km 1+300 – 1+480, Km 1+550 – 1+710 and Km 3+660 – 3+950 having moduli of 2063 MPa, 2319 MPa and 2116 MPa respectively. The three sections are on reinforced earth sections hence presenting an unstable pavement layer which calls for strengthening.

The exhibited elastic moduli of the subbase pavement layer ranged from 703 MPa and 3087 MPa with the entire road having an average of 1653 MPa which is lower than the expected elastic modulus of cement stabilised subbase material. The reinforced earth sections also exhibited average elastic modulus lower than the expected modulus for cement stabilized gravel. Therefore, the subbase layer is unstable and therefore urgent need for strengthening of the pavement.

The elastic moduli of the subgrade layer ranged from 213 MPa to 398 MPa with an average of 197 MPa which is much lower than 1000 MPa, the expected elastic modulus of improved subgrade supporting a cement stabilised subbase layer. Therefore, the provided subgrade on Outer ring road did not meet the support requirement for cement stabilized gravel subbase of at least 1000 MPa in both the reinforced earth sections and the normal construction sections of the road.

In conclusion, the pavement layer moduli are generally lower in reinforced earth sections than on normal construction sections despite various evidences that reinforced earth enhances pavement structural integrity (Liu et al., 2008). There are other factors that may bring diverging outcomes such as construction methods, the quality of construction materials, and unique local environmental factors (Al-Zwainy et al., 2020).

4.3.5. Analysis of overlay requirements

The critical pavement layers based on the analysis is subbase for sections Km 3+175 – 3+210 and Km 9+831 – 10+175 while for all other sections it is the subgrade layer. The exhibited elastic moduli of subbase and subgrade layers do not comply with the provisions of clause 8.3.2 (iv) of RDM Part III. More critically, the subgrade moduli falls way below the expected support strength for the overlaying cement stabilised subbase layer, and hence it is the most critical layer in most of the road sections. The residual life, the overlay requirements and the critical layer based on the analysis using Rosy software for the homogeneous sections are presented in Table 4-24.

Table 4-24: Overlay requirement and residual life on homogeneous sections

Homogenous sections	Critical layer	Residual life in years	Reinforcement, mm. (20 years design period)
Km 0+900 – 1+300	4	17	15
Km 1+300 – 1+480	4	15	25
Km 1+480 – 1+550	4	14	35

Km 1+550 – 1+710	4	14	30
Km 1+710 – 3+175	4	19	5
Km 3+175 – 3+210	3	20	0
Km 3+210 – 3+660	4	19	5
Km 3+660 – 3+950	4	11	50
Km 3+950 – 4+864	4	20	0
Km 4+864 – 4+995	4	17	20
Km 4+995 – 5+367	4	20	5
Km 9+500 – 9+831	4	19	5
Km 9+831 – 10+175	3	20	5
Km 10+175 – 10+225	4	15	45
Km 10+225 – 10+500	4	19	10
Mean	**4**	**17**	**17**

The design period for the project road was 20 years and was commissioned in year 2018. The mean residual life for the entire road is 17 years which is less by the expected residual life by one year, while the mean residual life for the reinforced earth sections is 15 years which is three years less than the expected residual life. This implies that the reinforced earth sections will fail before the other sections of the road. The residual life and overlay requirements for reinforced earth sections are shown in Table 4-25 below.

Table 4-25: Overlay requirement and residual life for reinforced earth sections

Reinforced earth section	**Critical layer**	**Residual Life in years**	**Reinforcement, mm. (20 years design period)**
Km 1+300 – 1+480	4	15	25
Km 1+550 – 1+710	4	14	30
Km 3+660 – 3+950	4	11	50
Km 4+864 – 4+995	4	17	20
Km 9+500 – 9+831	4	19	5
Km 10+175 – 10+225	4	15	45
Mean	**4**	**15**	**29**

Sections Km 3+175 – 3+210 and Km 3+950 – 4+864 did not require any overlay requirements while the overlay requirements for other sections ranged from 5mm to 45mm. The mean overlay requirement for the entire road is 17mm while for the reinforced earth sections is 29 mm. This clearly indicates that the reinforced earth sections are less stable than the normal road sections. In conclusion, the residual life of the pavement founded on reinforced earth embankments is less than for pavement founded on normal sections resulting to larger overlay requirements on the embankments. Km 3+660 – 3+950 and Km 10+175 – 10+225 require overlay of 50mm and 45mm respectively.

It is evident that the reinforced earth sections are less stable compared to the normal road sections. The residual life of pavements constructed on reinforced earth embankments is shorter than that of pavements on normal sections, leading to increased overlay requirements on the embankments. This phenomenon suggests potential pavement failures at those particular sections, and possibly, the wider spectrum of reinforced earth sections. As a result, it is crucial to holistically assess and monitor the road pavement performance with appropriate maintenance interventions to arrest any defects soonest possible (Al-Zwainy et al., 2020; O'Flaherty, 2002).

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATIONS

This chapter present conclusions made from the study findings and the recommendations based on the study objectives.

5.1. Conclusions

Based on the study objectives, the following conclusions were made:

i. The exponential increase in traffic loading especially in urban setting like Nairobi, exerts significant stresses on Outer ring road pavement. Notwithstanding that reinforced earth embankments are robust and designed for durability, they are not insusceptible to failure due to increased traffic loading. The increased traffic on Outer ring road could accelerate the pavement deterioration with exacerbated surface distresses that could potentially undermine the pavement and the pavement's foundation structural capacity over time. Whereas reinforced while reinforced earth sections offer a stable foundation, the unprecedented rise in traffic loading observed on Outer ring road calls for close monitoring of the traffic. This should be in tandem with prompt interventions to enhance the structural capacity of the pavement to withstand the increased stresses.

ii. The entire pavement of Outer ring road was found to have a satisfactory functional performance based on mean PCI ratings. However, pavement on the reinforced earth sections of the road showed varying levels of functional performance based on PCI ratings. Areas of concern were identified in this study regarding the sections with fair and poor rating despite the notion than pavement on reinforced earth are expected to exhibit higher functional performance. Reduced PCI values often indicate underlying structural issues and can predict future maintenance challenges. Therefore it can be deduced that the observed lower performance is an indication that there might be potential gaps or oversights in the reinforced earth design, quality of construction materials, the construction methodologies or influence from the unique climatic conditions. Thus, in response to the varying levels of functional performance, routine monitoring and proactive maintenance to prolong pavement lifespan and ensure road user safety is important.

iii. Pavement on reinforced earth sections of Outer ring road exhibited reduced structural capacity evidenced by lower pavement layers moduli and shorter residual lifespan compared to pavement on normal sections of the road. These findings diverge from various study findings as concluded by Liu et al. (2008) that reinforced earth enhances the overlying pavement structural capacity. This suggests that while reinforced sections enhance capacity, outcomes can differ based on design on the reinforced earth embankment, construction methodologies, quality of the construction materials and unique local environmental conditions.

5.2. Recommendations

5.2.1. Study recommendations

The following are the recommendations based on this study;

i. Regular pavement performance monitoring and evaluation of Outer ring road particularly on reinforced earth embankments so that distresses can be identifies early enough for prompt maintenance interventions to prevent major pavement damages and warrant pavement longevity.

ii. In view of the exponential increase of traffic after commissioning of the road, it is imperative to undertake traffic monitoring and evaluation. This can trigger adoption of traffic management strategies to mitigate the adverse effects of increased traffic loading or appropriate intervention measures to increase the pavement structural capacity.

iii. A comprehensive study on the impact of variability of quality of materials used in construction of reinforced earth such as type of reinforcement and soft fill material can provide valuable insights into whether material choices contribute to performance variations.

iv. There is a necessity to develop local design manuals and construction guidelines for reinforced earth structures in Kenya for the realization of the benefits of reinforced earth structures. This will result to customization of design parameters to the local conditions, indigenous materials and specific construction methodologies.

5.2.2. Areas of further research

The following areas are recommend for further research;

i. A detailed study into the type or quality of soft fill material used for reinforced earth embankments. An in depth understanding on performance based on variability of soft fill material can assist in design of reinforced earth to enhance durability and suitability for the local environment.
ii. Based on the exponential increase in traffic on Outer ring road, a comprehensive study on long term traffic growth projection rates and their implications on the pavement performance especially on opening or improving a road in an urban set up. This will significantly lead to more accurate traffic growth projections during design on urban pavements leading to more future proof transport infrastructure.
iii. Whereas this study considered the effects of traffic on the performance of pavements founded on reinforced earth section of Outer ring road, a focussed study on how climatic variations may impact the performance of such pavements.
iv. The reinforcements used to reinforce outer ring road embankments were composite steel-plastic geobelts of CAT30020B model provided at spacing of 500mm, a research to evaluate other type of reinforcements or reinforcement techniques for road constructed in a similar environment as Outer ring road would greatly improve on design on reinforced earth structures or give alternative type of reinforcements with better or equal performance.
v. A comparative study with similar road in other cities in and out of Africa will provide valuable insights and best practices and promote continuous improvements in road constructions.

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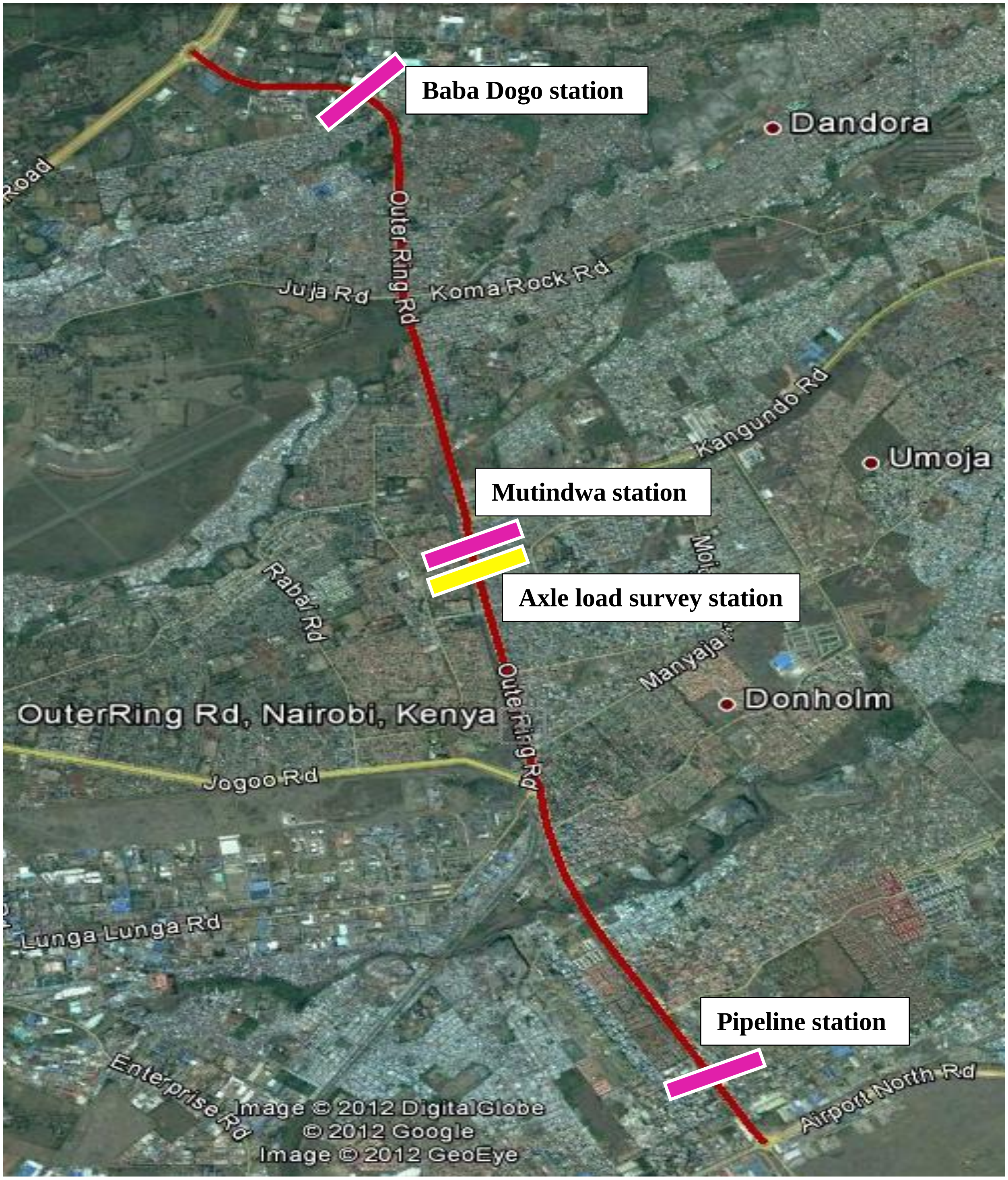
APPENDICES

Appendix A: Project road location map and RE sections.

Appendix B: Traffic count and axle load survey stations



Appendix C: Traffic survey data sheet

TRAFFIC SURVEY DATA SHEET							
KENYA URBAN ROADS AUTHORITY *Efficient and safe urban roads* Barabara Plaza, Mazao Road - Off South Airport Road, JKIA Tel: 254-020-8013844 / 254-717-100233 Email: info@kura.go.ke Web: www.kura.go.ke P.O. Box 41727-00100, GPO, NAIROBI							
PROJECT TITLE : OUTER RING ROAD						**Year: 2021**	
LOCATION:	**STATION**			**FLOW DIRECTION:** ←			
WEEK DURATION :	**From:**				**To:**		
DATE/ DAY	CARS	LGV	BUSES	MGV	HGV	M. CYCLE	**TOTAL**
	Time From:			**Time To:**			
Week sub-total							
ADT - 24 Hr. Count Traffic							

CARS- (Passenger vehicles with less than nine seats)

LIGHT GOODS VEHICLES- (Land rovers, mini buses and goods vehicles of less than 1500 kg unladen weight with pay load capacities of less than 760 Kg.)

BUSES (All passenger vehicles greater than mini buses)

MEDIUM GOODS VEHICLES (Maximum gross vehicle weight 8500 Kg)

HEAVY GOODS VEHICLES (Gross vehicle weight greater than 8500Kg)

Appendix C: Axle load data sheet

MINISTRY OF TRANSPORT, INFRASTRUCTURE HOUSING, URBAN DEVELOPMENT AND PUBLIC WORKS

MATERIALS TESTING AND RESEARCH DEPARTMENT

AXLE LOAD SURVEY DATA

ROAD:														
AXLE LOAD SURVEY STATION:														
DIRECTION FROM:									DIRECTION TO:					
DAY:									DATE :				E = EMPTY	
				AXLE WEIGHT in Kg										
NO.	HR	TYPE	REG. NO.	1st	2nd	3rd	4th	5th	6th	E.F	ORIGIN	DESTINATION	TYPE OF GOODS/ SERVICE	AXLE CONFIGURATION

Appendix D: Falling Weight Deflectometer test procedure

Calibration

I. The deflection sensors and the load cell to be calibrated. The consistency check and the relative consistency check to be carried out as per the manufacturer's specifications.

II. The road sections selected should be representative of the pavement structures that are generally being tested, be in good condition, be lightly trafficked and be efficiently drained such that any seasonal variation in deflection is minimized.

If the sections have significant layers of bituminous material then the temperature of surfacing should be recorded during the tests.

Test procedure

III. A safe working environment should be maintained at all times. Many organizations will have on-site safety procedures which should be followed.

IV. Typically tests should be carried out at intervals of 20-100 metres in the verge side wheel path in each direction. Additional tests should be undertaken on any areas showing a typical surface distress.

V. On flexible pavements the load level should be set at a nominal load of 50kN +/- 10%. The load should be applied through a 300 mm diameter plate and the load pulse rise time should lie between 5 and 15 milliseconds.

VI. The deflection should be measured by at least five and preferably seven deflection sensors having a resolution of one micron.

Temperature measurements

VII. When the road has an asphalt surfacing the deflection may change as the temperature of the surfacing changes. It is therefore necessary to measure the temperature of the surfacing during testing. The temperature of the pavement can be measured using either a short-bulb mercury thermometer or a digital thermometer.