ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

ADDIS ABABA INSTITUTE OF TECHNOLOGY

School of Civil and Environmental Engineering

Cement Concrete as an Alternative Pavement Material Over Asphalt Concrete in Arterial Roads of Ethiopia; Life Cycle Cost Comparison and Economic Analysis

By

Gebeyaw Assefa

A Thesis Submitted to the School of Graduate Studies in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering (Construction Technology and Management)

Advisor

Prof. Abebe Dinku (Dr.-Ing.)

September 2015

Addis Ababa, Ethiopia

ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

ADDIS ABABA INSTITUTE OF TECHNOLOGY

School of Civil and Environmental Engineering

Cement Concrete as an Alternative Pavement Material Over Asphalt Concrete in Arterial Roads of Ethiopia; Life Cycle Cost Comparison and Economic Analysis

By

Gebeyaw Assefa

B.Sc. in Civil Engineering

Addis Ababa University, 2003

A Thesis Submitted to the School of Graduate Studies in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering (Construction Technology and Management)

Approved by Board of Examiners:

Prof. Abebe Dinku (Dr.-Ing.) Advisor	Abebe Dinku Signature	24/12/15 Date
Eng. Yibeltal Zewedu External Examiner	Signature	12/12/15 Date
Dr. Ephraim Senbeta Internal Examiner	Ephraim Senbeta Signature	23/12/2015 Date
Dr. Esayas G/Youhanes Chairman	Esayas Signature	Dec-24-2015 Date

Director of Postgraduate Program
Addis Ababa University
Addis Ababa Institute of Technology

DECLARATION

I, the undersigned, declare that this thesis is my original work performed under the supervision of my research advisor Prof. Abebe Dinku (Dr.-Ing.) and has not been presented as a thesis for a degree in any other university. All sources of materials used for this thesis have also been duly acknowledged.

Name Gebeyaw Assefa

Signature

Place Addis Ababa Institute of Technology,
Addis Ababa University,
Addis Ababa

Date: September 2015

ACKNOWLEDGEMENTS

I owe a debt of special gratitude to my advisor, Prof. Abebe Dinku (Dr. - Ing.), for his valuable advice, suggestions, timely comments and guidance throughout the work of this thesis.

I would like to extend my heart felt appreciation to Ethiopian Roads Authority (ERA) for financing of this M.Sc. program.

I want to express my sincere gratitude to the following persons who helped me while I was collecting data for my research: W/ro Hiwot Mossisa – G/ Manager of toll roads (formerly, Director, Central Region Directorate, ERA); Eng. Temesgen Abebe - Ass. Director Construction, MIDROC Construction Ethiopia Plc.; Eng. Afework Amare - G/Manager, Towers Consult and Eng. Robel Mergia - Highway Engineer, Towers Consult.

I would also like to use this opportunity to convey my gratitude to the academic staff of the School of Civil and Environmental Engineering, Addis Ababa Institute of Technology, Addis Ababa University. Without their support and encouragement I couldn't have this opportunity to complete my study. I also gratefully acknowledge the contributions of my friends and all those individuals who had contributed in one way or the other in the realization of this research.

Special thanks are due to my mother W/ro. Ayalnesh Kebede, my spouse W/ro. Adelahu Kebede, my children Brook Gebeyaw and Binyam Gebeyaw and other members of my family for their love, unconditional support and encouragement.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AA	Addis Ababa
AACRA	Addis Ababa City Roads Authority
AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ACBFS	Air Cooled Blast Furnace Slag
ACP	Asphaltic Concrete Pavement
ACPA	American Concrete Pavement Association
ACR	Alkali Carbonate Reaction
ASR	Alkali Silica Reaction
APA	Asphalt Pavement Alliance
BCA	Benefit Cost Analysis
BRB	Bituminous Road Base
CBR	California Bearing Ratio
CCP	Cement Concrete Pavement
CM	Cementitious material
CRCP	Continuously Reinforced Concrete Pavement
DOT	Department of Transportation
EF	Equivalent Factor
EIRR	Economic Internal Rate of Return
EPA	Environmental Protection Agency
ERA	Ethiopian Roads Authority
ESA	Equivalent standard axles
ETB	Ethiopian Birr
EUAC	Equivalent Uniform Annual Cost
FHWA	Federal Highway administration
GB	Granular Base
GDP	Gross Domestic Product
GGBFS	Ground Granulated Blast Furnace Slag
GHGs	Green House Gasses
GTP	Growth and Transformation Plan
HMA	Hot Mixed Asphalt
IRI	International Roughness Index
HDM-4	Highway Development Model – 4
IMF	International Monitory Fund
JRCP	Jointed Reinforced Concrete Pavement
JUCP	Jointed Unreinforced Concrete Pavement
KN	Kilo Newton
Kwh	Kilo Watt Hour

LCCA	Life Cycle Cost Analysis
LTPP	Long term Pavement Performance
MC	Medium Curing
MEPDG	Mechanistic Empirical Design Guide
MoFED	Ministry of Finance and Economic Development
NPV	Net Present Value
NRC	National Research Council of Canada
OPC	Ordinary Portland Cement
PBPPE	Prefabricated Building Parts Production Enterprise
PCA	Portland Cement Association
PW	Present Worth
RCC	Roller Compacted Concrete
RC	Rapid Curing
RSDP IV	Road Sector Development Program Phase IV
SB	Sub-Base
SCMs	Supplementary Cementitious Materials
TCP	Thin Concrete Pavement
URRAP	Universal Rural Road Access Program
US	United States
VOC	Vehicle Operating Cost

ABSTRACT

Cement concrete pavement usually has design life span of 25 to 40 years whereas flexible pavement can have design life span of 15 to 20 years. Hence it becomes necessary to determine which pavement is more economical for entire life. The cost of initial construction of pavements depends upon availability and cost of construction resources like: the cost of aggregates; cost of binders, equipment renting charges and cost of labor. The cost of maintenance of roads depends upon a number of factors among them being the volume and intensity of traffic, cost of materials, labor and machinery, type of terrain, type of wearing surface, the minimum level of serviceability which is acceptable for that category of road, climatic conditions etc. All types of asphalt binding materials used in our country are imported with hard currency and its cost is becoming increasingly high. On the other hand cement materials have been produced and have high potential of production in Ethiopia and its cost becomes reduced.

In this study life cycle cost comparison and economic analysis carried out between cement concrete pavements and bituminous pavements in five selected trunk/arterial roads of Ethiopian Federal Roads. Traffic analysis, equivalent pavement design for Asphalt Concrete and Cement Concrete Pavements, cost break down analysis for initial cost comparison, life cycle maintenance costs, user costs and different economic and environmental considerations were performed for carrying out economic evaluation of pavements. Present Worth economic evaluation method was used for the evaluation of life cycle costs of pavements. From the evaluation of the study both initial and maintenance costs of Cement Concrete Pavement are found more economical than Asphalt Concrete pavements.

Keywords*: Asphalt pavement, Cement concrete pavement, cost comparison between rigid pavement and flexible pavement, Flexible pavement, life cycle cost of pavements, Rigid pavement.*

1. INTRODUCTION

1.1 Background of the Study

In the context of Ethiopia's geography, pattern of settlement and economic activity, transport plays a vital role in facilitating economic development as 95% of the movement of people, and goods is still carried out by road transport. In particular, it is road transport that provides the means for the movement of peoples and agricultural products from rural areas to urban areas and movement of industrial goods, modern agricultural inputs and peoples from urban areas to rural areas. Road transport also provides a means for the utilization of land and natural resources, improved agricultural production and marketing, access to social services, and opportunities for sustainable growth [1].

According to Ethiopian Roads Authority 16 year's Road Sector Development Program (RSDP) report of October 2013 as presented in the Table 1.1 below, the total road network of the country is 85,966 km. Of this, 11,301 km are paved roads surfaced with asphalt concrete or bituminous surface treatment. Gravel roads comprise around 14,445 km of the network, with a further 32,582 km of regional, unpaved rural roads and 27,628 km of gravel Woreda (URRAP) roads. The road network of Ethiopia has seen expanded by an average of 7.9% between 1997 and 2013.

Table 1-1 Growth of the Classified Road Network and Change in Road Density (1997 – 2013) [1]

Year	Road network in km					Growth Rate (%)	Road Density (km/1000 population)	Road density (km/1000 Sq. km)
	Asphalt	Gravel	Rural (Unpaved)	URRAP (Unpaved)	Total			
1997	3,708	12,162	10,680		26,550		0.46	24.14
1998	3,760	12,240	11,737		27,737	4.5	0.46	25.22
1999	3,812	12,250	12,600		28,662	3.3	0.47	26.06
2000	3,824	12,250	15,480		31,554	10.1	0.50	28.69
2001	3,924	12,467	16,480		32,871	4.2	0.50	29.88
2002	4,053	12,564	16,680		33,297	1.3	0.49	30.27
2003	4,362	12,340	17,154		33,856	1.7	0.49	30.78
2004	4,635	13,905	17,956		36,496	7.8	0.51	33.18

2005	4,972	13,640	18,406		37,018	1.4	0.51	33.60
2006	5,002	14,311	20,164		39,477	6.6	0.53	35.89
2007	5,452	14,628	22,349		42,429	7.5	0.55	38.60
2008	6,066	14,363	23,930		44,359	4.5	0.56	40.30
2009	6,938	14,234	25,640		46,812	5.5	0.57	42.60
2010	7,476	14,373	26,944		48,793	4.2	0.58	44.39
2011	8,295	14,136	30,712	854	53,997	10.70	0.66	49.09
2012	9,875	14675	31550	6983	63083	16.80	0.75	57.30
2013	11301	14455	32582	27628	85966	36.3	1.0	78.20

1.1.1 Distribution of the Road Network

The average road density in Ethiopia is 78.2 km per 1000 square kilometers. This is far lower than the average road density of 260 km per 1000 square kilometer for Middle income countries [1].

A fair distribution of road network amongst the regions is attributable both to construction of new rural roads by the regions from their own resources and also the Federal Governments' adoption of an equitable regional development policy in the construction of missing links and other roads. Federal Government allocates resources for construction of links and other important roads in each region in proportion to both the regional area and population size [1].

Approximately 46 percent of the land area in Ethiopia lies more than 5 km from all-weather roads. More than 30.84 million people in the rural areas of Ethiopia live further than 2 km away from the nearest all weather road. On average, households are often more than 6.4 kilometers away from a dry-weather road and the average rural access index of the country is reached around 43% currently [1].

1.1.2 Quality of the Road network

According to ERA's 16 years performance report the condition of the road network, as indicated in Table 1.3, has shown improvement particularly since 1997 [1]. However, improving the overall condition of the road network remains a challenge. In 2013, the proportion of road network in good condition was 70% with a further 30% in fair to poor condition. With 34% of the road network is URRAP based and new for the report period and that need frequent maintenance in the year to come there remains a substantial maintenance challenge. As per ERA Design manual 2013 paved road condition classification criteria are elaborated in Table 1.2.

Table 1-2 Paved Road Condition Criteria Based on International Roughness Index (IRI) Values

Condition	Very Good	Good	Fair	Poor	Very Poor
IRI values (m/km)	Lower than 4	4 to 7	7 to 10	10 to 13	Larger than 13

Source: ERA Design Manual 2013

Table 1-3 Change in Selected Indicators

Indicator	1997(RSDP Start)	2013 (Third year RSDP IV)
Proportion of Asphalt roads in Good Condition	17%	74%
Proportion of Gravel roads in Good Condition	25%	28%
Proportion of Rural roads in Good Condition	21%	54%
Proportion of Woreda roads in Good Condition	-	95%
Proportion of Total Road network in Good Condition	22%	70%
Road Density 1/1000 sq.km	24 km	78.2 km
Road Density 1/1000 population	0.49 km	1 km
Proportion of area more than 5 km from all-weather road	79%	46%
Average distance to all weather road	21 km	6.4 km
Road length (in km) including URRAP Roads	26,550	85,966

Source: ERA, RSDP 16 year’s performance report, Oct. 2013.

1.1.3 Pavement Type Selection

Road infrastructure requires substantial amount of money for construction, improvement and maintenance but the benefits of good roads are not immediately visible to common men and politicians. A systematic approach is required to justify and include the amount needed for its maintenance in road infrastructure planning.

A material/pavement engineer has often to make a choice between various types of pavements. The flexible pavements (Bituminous Pavements) and Rigid Pavements (Cement Concrete) are widely used pavements in worldwide practice. Mostly Bituminous pavement consists of sub-grade, granular sub-base, granular-base and bituminous wearing course. Whereas, cement concrete pavement consists of cement concrete slab resting on sub-base course. In cement concrete pavement joints play a very important role. There are various types of joints namely longitudinal joint, expansion joint, contraction joint and construction joints provided in cement concrete pavement. The joints are filled with joint seals [2].

Michigan Department of Transportation recommended that pavement cost below $1 million do not require life cycle cost comparison. But for pavement costs above $1 million a more scientific and equitable approach is to design the same standards, evaluate the total cost of initial construction, periodic and routine maintenance, cost of operation of vehicles and life of pavements. The cement concrete pavement usually has a life span of 40 to 60 years whereas flexible pavement can have a life span of up to 20 years [3]. Hence it becomes necessary to determine which pavement is more economical for entire life. As the life span of the two pavements is different, it becomes necessary to assume same life of both pavements for comparative study.

The cost of initial construction of pavements depends upon the cost of aggregates; cost of binder, equipment hire charges and cost of labor. The cost of maintenance of roads depends upon a number of factors among them being the volume and intensity of traffic, cost of materials, labor and machinery, type of terrain, type of wearing surface, the minimum level of serviceability which is acceptable for that category of road , climatic conditions etc.[2].

The discussion above indicates that consideration of life cycle cost factors for the selection of most economical pavement is very important.

1.2 Statement of the Problem

The dramatic increase in traffic volume in built-up areas, such as the Capital Area, road corridor to the port Djibouti and other Federal Trunk Roads of Ethiopia results in more and more construction of new roads and modernization of old ones. Therefore, this requires further studies on how road pavement types are selected.

Road Authorities could make more informed and better investment decisions, because pavement type has a significant impact on future cost and service quality. Traffic growth, especially in heavy axle traffic, can cause damage to pavements much quicker than expected, in turn causing more maintenance and thereby increasing agencies' and users' costs.

Pavement type choice is usually based on traffic level, soil conditions, atmospheric factors and costs. In many cases, the initial construction cost is the main consideration; the future maintenance and rehabilitation costs may sometimes be forgotten.

Life Cycle Cost Analysis (LCCA) is a process that compares the long-term economic worth of competing alternatives and the results could be useful as a decision-supporting tool.

According to the American Association of State Highway and Transportation Officials (AASHTO) Guide for the Design of Pavement Structures, life cycle costs "refer to all costs which are involved in the provision of a pavement during its complete life cycle". That means that all pavement options are evaluated by taking into account different agencies' and users' costs. Agencies' costs include initial construction costs as well as future costs of rehabilitation, maintenance and facility operation. User costs are a result of many different issues, for instance increased delay costs, increased vehicle operating costs or charges in accident costs due to future maintenance actions [4].

All types of asphalt binding materials used in our country are imported with hard currency and its cost is becoming increasingly high from time to time. On the other hand cement materials have high potential of production in Ethiopia and it is hoped that the price will decrease. Asphalt pavement requires heavy maintenance activities starting from early stages of its service life, but rigid pavements do have long design life time and not required as such maintenances in its early service life. Hence, this study will try to address the problem and show economic advantages of using locally available resource for sustainable pavement construction.

1.3 Objectives of the Research

1.3.1 General objective

The general objective of the study is to identify the sustainable and economical pavement material in arterial roads of Ethiopia by making life cycle cost comparisons and economic analysis of Cement Concrete with Asphalt Concrete pavement materials in selected representative arterial roads of the country.

1.3.2 Specific objective;

- To identify the initial cost for both concrete and bituminous pavements.
- To identify the required types of life time maintenances for both concrete and bituminous pavements.
- To identify the various costs related to various maintenances involved in concrete and bituminous pavements.
- To carry out economic evaluation of concrete and bituminous pavements on selected segments of roads in Ethiopia for forty years and to determine which pavement type is more economical and sustainable.
- To draw conclusions and forward recommendations based on the findings of the study.

1.4 Scope and Limitations

The primary objectives of road construction project planning are to optimize quality, cost and time. In Ethiopia, this construction industry and its management is at an infant stage, fulfilling these requirements is difficult and challenging. This research work therefore, focuses on one of the basic requirements i.e. cost. Hence, the scope of the study is restricted to the identification of more economical pavement material over life cycle cost comparison and economic analysis using primary and secondary data.

The scope of the study is, therefore, limited to evaluation of two alternative pavement types based on life cycle cost and economic advantages for sustainable road construction projects. Environmental impact and societal benefits from this sustainable road construction projects will not be fully quantifiable in this study. Because of technological differences, calibration problems and data availability limitations in our country, the researcher couldn’t use models like HDM-4 for the evaluation of user costs and environmental impacts.

1.5 Outline of the Research – Thesis Organization

The thesis is organized into five chapters as follows:

Chapter 1−this chapter begins with the discussion on background and general introduction to the research, statement of the problem, objectives, scope, methodology adopted to achieve the objectives of the study and organization of the thesis.

Chapter 2 is literature review from professional journals, research papers, manuals, books, internet searches and informal interview with road design, construction, and contract administration experts. This chapter essentially provides a review of the current state of the art in road construction project pavement type selection trends. Brief definition aspects of different pavement materials, their properties, design criteria, etc. is discussed within this chapter.

Chapter 3 is the research methodology followed in order to achieve the objectives of the study. The results of the data obtained from the desk study on selected road construction projects and literature review is presented and discussed accordingly in Chapter 4.

Finally, in Chapter 5, conclusions and recommendations are forwarded based on the major findings of the study and discussed how the research objectives align with the findings.

1.6 Research Methods Materials and Procedures

The research work is started with problem identification, which is followed by literature review, formal and informal discussion with professionals in the federal road construction sectors.

The research has then proceeded through economic analysis and life cycle cost comparison of Cement Concrete Pavement material against Asphalt Concrete material in trunk type roads of Ethiopia. Literatures include magazines, books, journals, internet etc. In parallel with literature review, an in-depth desk study has been conducted to identify construction costs, maintenance costs, environmental impacts and road user benefits of each pavement material type.

During the desk study, various documents such as design manuals of different countries, technical specifications, feasibility studies reports, Engineering design reports, correspondences, progress reports, completion reports, payment certificates, statements on final account, road asset management documents etc. has been critically evaluated. Whenever there is unclear primary data or ambiguity during the desk study, further explanation or information has been obtained through informal interviews with professionals involving in road construction projects especially pavement or material Engineers, in order to maximize the clarity and to gain adequate understanding of the data for its use in analysis.

The document search was intended to collect pavement design trends, values of initial/construction costs consumed and annual maintenance or rehabilitation costs allocated from some randomly selected upgrading and rehabilitation trunk type road construction projects which are completed/substantially completed.

Then analysis and discussion has been conducted based on the primary & secondary data obtained. Finally, conclusions have been drawn and recommendations forwarded based on the finding of the study and literature reviews. The study has been conducted on projects with high traffic volumes (50 million ESAL to 80 million ESAL) of Trunk type Federal Roads of Ethiopia.

Life Cycle Cost Analysis provides a methodology for computing the cost of a product or service during its lifetime. It is used to compare competing design alternatives over the lives of each alternative, considering all significant costs and benefits, expressed in equivalent monetary units [5]. For infrastructure assets such as roads, a large proportion of the total cost over the lifetime of these assets is incurred after construction, i.e. during their service lives. It is possible to avoid most of the “unknown” costs by introducing long-term costs into the pavement valuation processes instead of comparing only initial material and construction costs [5].

Analysis period of 40 years has been determined based on the recommendation of AASHTO 1993 and in order to utilize the full design life of concrete pavement for proper comparison of the two pavement type alternatives.

1.7 Significance of the Study

In the area of road construction, proper planning of projects is vitally important to highway organizations (authorities) as their construction program outlines how highway funds are to be spent over time and to be sustainable in its serviceability for the comfort of road users, any deviation from the established program often brings a quick response from the public, the press, and politicians. When this occurs, the highway organization loses creditability. On the other hand, if a highway organization can produce realistic program estimates that it is able to attain, then the image of the agency is enhanced.

Therefore, it is the responsibility of the Authorities to make an accurate project planning in the selection of economical pavement materials for the construction of sustainable roads for allocation of justifiable budgets. Thus beneficiaries of this research are;

- The implementing authorities (ERA and AACRA),
- consulting and construction firms plus practicing Engineers,
- Educational institutions, which use the information for academic purposes,
- Investors to focus on manufacturing of ready mix concrete for pavement works,
- Other researchers who will work in relation to pavement LCCA, etc.

2. LITERATURE REVIEW

2.1 Introduction

Transport and mobility are essential for economic and social development. For this reason, developed countries have devoted considerable resources to the development of high-quality transport networks which need to be adequately maintained. Current road construction methods lead to significant maintenance requirements, which can only be met at a very high cost. The continued growth in road traffic and axle loads and the pressure to restrain government spending put growing pressures on road authorities to come up with new solutions. At the same time, the cost to economies due to congestion and disruption during road works on high volume roads has become unacceptably high.

There are growing pressures for long-life road infrastructures that require minimal maintenance [6]. Pavements are the critical elements of an efficient highway transportation system for moving people and goods. Without well-performing pavements, the transportation infrastructure cannot effectively function, road users suffer (in terms of increased costs, travel time, and unsafe roads) and the overall economy suffers (in terms of higher costs for goods and commodities) [6].

Modern societies cannot function without mobility, and mobility requires well-performing pavements [7]. In recent years, innovation in the road sector has focused on economic and organizational structures, while changes in road paving techniques have been much less dramatic. Rather, they have at best been incremental. Yet, in order to optimize national highway budgets, whole-life costing methods are increasingly used to determine how, where and when to best spend budget funding on road construction and maintenance. Within this framework, the shift to full maintenance contracting has helped reduce costs, and the adoption of long-term contracts has helped establish an environment in which the development of more durable pavement types could be stimulated [6].

Therefore, long-lasting pavements that are safer, smoother, and environmentally sensitive and can be cost-effectively constructed and maintained are an important part to modernize the Ethiopian transportation system. In Ethiopia, billions of ETB are spent every year to construct, maintain, preserve, and rehabilitate the Nation's highway pavement infrastructure.

The accumulated investment in our roadway pavements is above ETB 142 billion for the last 16 years of RSDP [1]. This investment needs to be protected and managed efficiently so that future generations of our citizens can have high standard infrastructure which is to be one of the best highway systems in Africa and to enjoy the benefits of it.

Initial cost of construction, maintenance cost of pavements and road user costs play major role for deciding which pavement will be more economical. There is no intensified life cycle cost comparison research conducted in this regard in Ethiopia, but various studies have been conducted worldwide in different countries in this subject matter through different researchers.

It is becoming increasingly apparent that a host of human activities and development practices are negatively affecting the economic, environmental and social well-being of the planet, putting future generations of human being, as well as other species, at risk. Confronted with this reality, stakeholders in the pavement industry are being challenged to adopt practices that maintain economic vitality while balancing environmental and social needs [8].

At the same time, stakeholders are facing other challenges: pavements are aging and deteriorating; 26% of the paved road system are not in a good condition [1]. Traffic volumes and axle loads continue to increase, putting more demands on the already stressed pavement system in the country. Road way authority budgets continue to fall short of funds needed to substantially improve pavement conditions. The trend and budget allocation attention for pavement condition improvement, comparing with new projects, is very poor in a developing country like Ethiopia.

The people responsible for the management, design, construction, maintenance and rehabilitation of the deteriorating network of pavements are overwhelmed, recognizing that the current approach to solving problems inherent in the countries pavement infrastructure is not sustainable. What is needed is a new approach, the implementation of truly sustainable pavement solutions that result in reduced cost over the life cycle, lessened environmental impact and enhanced societal benefit [8].

2.2 Definition

Concrete is basically a mixture of two components: aggregates and paste. The paste, comprised of Portland cement and water, binds the aggregates (usually sand and gravel or crushed stone) into a rocklike mass as the paste hardens because of the chemical reaction of the cement and water [9].

ERA Pavement Design Manual 2013 required a 28-day characteristic compressive strength of 30, 35 or 40 MPa for pavement construction. However, the 28-day concrete flexural strength is a principal design factor. The suitable value for road pavement construction is typically 3 – 5 MPa [10].

Rigid pavements (also called concrete pavements), as the name implies, are rigid and very strong in compression. The strength of the pavement is contributed mainly by a concrete slab, unlike flexible pavements where successive layers of the pavement contribute cumulatively. The rough surface required for an adequate resistance to skidding in wet conditions can be provided by dragging stiff brooms transversely across the newly-laid concrete or by cutting shallow randomly spaced grooves in the surface of the hardened concrete slab [10].

As the name ‘rigid’ implies, the deflections under a loaded wheel are very small compared with the deflections observed in flexible pavements and the stresses within the underlying sub-base and subgrade are also comparatively small. Rigid pavements therefore deteriorate through quite different mechanisms from those that affect flexible pavements [10].

This constitution implies the following advantages [10]:

- It is feasible to design rigid pavements for longer design lives, up to 60 years.
- Little maintenance is generally required
- Rigid pavement deforms less under traffic as compared to flexible pavements
- A relatively thin pavement slab distributes the load over a wide area due to its high rigidity. Localized low strength sub-grade materials can be overcome due to this wider distribution area.
- Concrete is very resistant to abrasion making the anti-skidding surface texture last longer.

- In the absence of deleterious materials (either in the aggregate or entering the concrete in solution from an external source), unlike with flexible pavements, concrete does not suffer deterioration from weathering. Neither its strength nor its stiffness is materially affected by temperature changes.

The main disadvantages compared to flexible pavements are as follows [10]:

- The initial investment is often more costly.
- If badly designed or not properly constructed, they tend to be more troublesome and reconstruction or repair is more difficult.

Until now, concrete pavements have not been extensively used in most tropical countries and in Ethiopia in particular, mainly due to a lack of tradition and experience in their design and construction. One characteristic of concrete pavements is that either they prove to be extremely durable, lasting for many years with little attention and maintenance, or they give troubles from the start, sometimes because of faults in design, but more often because of mistakes in construction [10].

Asphalt concrete can be described as a combination of bitumen and aggregates which are mixed together, spread and compacted while hot, to form a pavement surface. The strength of asphalt is derived from friction between the aggregate particles, the viscosity of the bitumen under operating conditions and the cohesion within the mass resulting from the bitumen itself and the adhesion between the bitumen and aggregate [11].

In reality asphalt concrete is visco-elastic in nature due to the bitumen in the mixture. However, at the normal operate rates and magnitude of loading and temperature, asphalt may be considered as an elastic isotropic material [12].

Initial cost is generally the major factor in deciding the type of the pavement in design. The Planners often think that flexible pavement is cheaper than rigid pavements. In fact this is not always the case. In the last decade the price of bitumen which is the main ingredient of flexible pavement has increased because of the increase in crude oil prices. However the rigid pavement’s main ingredient cement price is relatively stable [2].

Life Cycle Cost Analysis; means a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, user costs, reconstruction, rehabilitation, restoring and resurfacing costs over the life of the project segment [13].

According to the American Association of State Highway and Transportation Officials (AASHTO) guide for the design of pavement structures, life cycle costs “refer to all costs which are involved in the provision of a pavement during its complete life cycle” [4]. That means that all pavement options are evaluated by taking into account different agencies’ and users’ costs. Agencies’ costs include initial construction costs as well as future costs of rehabilitation, maintenance and facility operation. User costs are a result of many different issues, for instance increased delay costs, increased vehicle operating costs or changes in accident costs due to future maintenance actions.

Life Cycle Cost Analysis provides a methodology for computing the cost of a product or service during its lifetime. It is used to compare competing design alternatives over the lives of each alternative, considering all significant costs and benefits, expressed in equivalent monetary units [5]. For infrastructure assets such as roads, a large proportion of the total cost over the lifetime of these assets is incurred after construction, i.e. during their service lives. It is possible to avoid most of the “unknown” costs by introducing long-term costs into the pavement valuation processes instead of comparing only initial material and construction costs [5].

Pavement type decisions are usually based on traffic level, soil conditions, atmospheric factors and construction costs. Usually, construction cost is the main consideration; the future maintenance and rehabilitation costs may be forgotten [14].

2.3 Experience and Practices of Life Cycle Cost Analysis (LCCA)

2.3.1 Practices from Asphalt Associations

In 2004, the Asphalt Pavement Alliance (APA) released a position paper that concluded that pavement type selection should be a road user-oriented process, not an industry-oriented process.

It states that the system used to select pavement type should be objective, defensible, understandable, and based on historical records, primarily driven by economics and periodically reviewed.

APA supports the use of life-cycle cost analysis in the decision making process and recommends the methodology developed by the Federal Highway Administration (FHWA) in Demonstration Project 115. The Net Present Value (NPV) is used for the purpose of comparing alternatives. Initial costs, maintenance costs, and salvage value are recommended for consideration in the life-cycle cost analysis. APA recommends a 40-year analysis period when comparing asphalt with concrete pavements. APA states that asphalt pavements possess many advantages when compared with concrete pavements including low initial cost, low maintenance costs, flexibility and speed of construction, the ability to handle heavy loads, a long life, and complete recyclability [15].

APA conducted another study in 2005 to determine the average service life of flexible pavements to reach an unacceptable surface condition. Researchers considered six types of distresses in the analysis including fatigue cracking, longitudinal cracking in the wheel path area and longitudinal cracking outside the wheel path area, transverse cracking, rut depth, and smoothness measured by the International Roughness Index (IRI). Data for the analysis were extracted from the Long-Term Pavement Performance (LTPP) database. The median age of the 643 sections considered in the study was 17 years with 109 sections that were older than 20 years. An analysis to determine the probability of failure was performed for each distress type. According to the study, the expected service life to a moderate distress level exceeds 20 years for all distresses [16].

2.3.2 Practices from Concrete Associations

The American Concrete Pavement Association (ACPA) states that concrete pavements are a better choice than asphalt pavements because they have advantages in several areas including safety, durability, smoothness, versatility, and value. On safety, it provides better visibility, reduced wet spray since concrete never ruts, and provides the best traction grip. On durability, concrete hardens over time, and outlasts flexible materials since their average lifespan is 30 years. On smoothness, concrete stays smoother longer, creating safer, comfortable transportation surfaces and saving fuel. On versatility, concrete pavements can be; 1) designed to last from 10 to

50 years, 2) used to rehabilitate old asphalt pavement using white topping, or 3) used to rehabilitate a worn concrete pavement. On value, concrete pavements provide the best long-term value due to their longer life, they are easy to repair, and they can be built and opened to traffic in less than 12 hours [5].

In 2002, ACPA published a guide for comparing alternate pavement designs using LCCA. The guide describes the LCCA process factors that influence the results including agency costs (initial cost, maintenance and rehabilitation costs, and salvage value), user costs (delay of user-costs, roadway deterioration costs, and accident crash cost), discount rate, selection of rehabilitation activities, use of comparable sections, and length of the analysis period. Present worth (PW) and the equivalent uniform annual cost (EUAC) are mentioned as economic indicators used to express LCCA results. APA recommends EUAC because all costs are expressed in terms of an annual cost over the analysis period. The guide also presents a brief summary of life-cycle cost and performance studies conducted with historical data in Michigan, Minnesota, Iowa, Florida, Tennessee, South Dakota, Utah, and Georgia. According to these studies, concrete sections lasted between 1.6 and 2.6 times longer than the asphalt sections and were from 14 percent to 250 percent more effective than the asphalt pavements [17].

2.3.3 Experience from the U.S. Department of Transportation, Federal Highway Administration

In 1998, the Federal Highway Administration (FHWA) published an Interim Technical Bulletin with recommended procedures for conducting life-cycle cost analysis (LCCA) of pavements.

The bulletin discusses how to address alternative pavement design strategies, length of performance periods and activity timing, agency costs (initial cost, maintenance and rehabilitation cost, residual value), and user costs (delay costs, vehicle operating, and crash cost) in LCCA. The Net Present Value is proposed as the economic indicator for comparing alternatives. The FHWA encourages risk analysis. A sensitivity analysis is recommended as a minimum to study the impact of the individual outputs on LCCA results. The discount rate is one of the major factors considered in the sensitivity analysis. The use of simulation techniques incorporated into LCCA, such as Monte Carlo, is recommended to account for the variability of the input values and their influence in the results of the analysis [18].

In 2002, the office of Asset Management at the FHWA published a Life-Cycle Cost Analysis Primer. The primer was intended to provide background information to evaluate infrastructure investment alternatives. The LCCA approach considers total user and agency costs when comparing alternatives. The application of Benefit Cost Analysis (BCA) to account for benefits in the comparison of alternatives is discussed in the primer. If expected benefits provided by the alternatives under comparison are different, then BCA is considered more appropriate than LCCA. A description of the LCCA process steps is included with a discussion on how to establish design alternatives, determine activity timing, estimate costs (agency and user), compute life-cycle costs, and analyze the results. The use of the equivalent uniform annual cost or the present value is recommended as economic indicators to compare alternatives [19].

2.3.4 Experiences from California Department of Transportation

The California Department of Transportation published a Life-Cycle Cost Analysis (LCCA) Procedures Manual in November 2007. Caltrans plans to use this manual on pavement projects to evaluate alternative pavement designs for new and existing roads. The LCCA procedures recommended in the technical Bulletin published by the FHWA in 1998 are followed in the manual. LCCA begins with the selection of alternative pavement designs to accomplish the same performance objectives. When comparing a flexible and a rigid pavement alternate, the same design life should be used. However, Caltrans recommends the comparison of pavement alternates with different design lives for the same type of pavement. The intention is to determine during the project initiation document phase which alternate pavement design life is the most cost effective. Pavement design alternatives for a 10-year, 20-year, and 40-year pavement design life are compared using a discount rate of 4 percent [20].

2.4 Types of Rigid Pavements

According to the American Concrete Pavement Association [20], concrete pavement can be classified into three types: jointed unreinforced concrete pavement (JUCP), jointed reinforced concrete pavement (JRCP), and continuously reinforced concrete pavement (CRCP). This classification was done based on the joint spacing and use of reinforcement [10].

2.4.1 Jointed Unreinforced Concrete Pavement

In Jointed Unreinforced Concrete Pavements (JUCP), the pavement consists in an unreinforced concrete slab cast in place continuously and divided into bays of predetermined dimensions by the construction of joints. The bays dimensions are made sufficiently short (usually 15 times the slab thickness) so as to ensure that they do not crack. The bays are linked together by tie bars, the main function of which is to prevent horizontal movement (i.e. the opening of warping joints) and thus ensure load transfer through aggregate interlock [10].

2.4.2 Jointed Reinforced Concrete Pavement

In Jointed Reinforced Concrete Pavements (JRCP) the pavement consists generally in a cast in place concrete slab divided in reinforced concrete bays separated by joints at every 25 m. The reinforcement is made to prevent developing cracks from opening. This allows designing much larger bays than with JUCP. The bays are linked together by tie bars to prevent horizontal movement and thus ensure load transfer through aggregate interlock. The longitudinal reinforcement is the main reinforcement. A transverse reinforcement though not absolutely necessary in most cases is usually added to facilitate the placing of longitudinal bars [10].

Jointed reinforced concrete pavement, or JRCP, is distinguished from JUCP by longer slabs and light reinforcement in the slabs. The slab steel content is typically in the range of 0.10–0.25 percent of the cross-sectional area, in the longitudinal direction, with less steel in the transverse direction. This light reinforcement is often termed temperature steel [21].

2.4.3 Continuously Reinforced Concrete Pavement

Continuously reinforced concrete pavement, or CRCP, is characterized by heavy steel reinforcement and an absence of joints. Much more steel is used for CRCP than for JRCP, typically on the order of 0.4–0.8 percent by volume in the longitudinal direction. Steel in the transverse direction is provided in a lower percentage as temperature steel [21].

Continuously Reinforced Concrete Pavement (CRCP) is made of a cast in place reinforced concrete slab without joint. The expansion and contraction movements are prevented by a high level of sub-base restraint. The frequent transverse cracks are held tightly closed by a large amount of continuous high tensile steel longitudinal reinforcement [10].

Basically, the use of the different types of rigid pavement is as follows [10]:

- JUCP is suitable for all levels of traffic, whenever the risk of sub-grade movement is low.
- JRCP is suitable for all levels of traffic and is used when the risk of settlements of the sub-grade cannot be neglected.
- CRCP shall basically be considered only for rather high design traffic (>30 million ESAL). They can also be included for less heavily trafficked schemes where the advantage of lower maintenance throughout the design life may be worthwhile. They are particularly suitable where settlement of the sub-soil is expected.

2.5 Materials for Rigid Pavement

Careful selection of concrete materials and careful mixture design and proportioning, combined with good design and construction practices, is a key contributor to success [21].

2.5.1 Cementitious Materials

Portland cements are hydraulic cements composed primarily of hydraulic calcium silicates. Hydraulic cements set and harden by reacting chemically with water. During this reaction, called hydration, cement combines with water to form a stone like mass, called paste. When the paste (cement and water) is added to aggregates (sand and gravel, crushed stone, or other granular material) it acts as an adhesive and binds the aggregates together to form concrete, the world's most versatile and most widely used construction material.

Hydration begins as soon as cement comes in contact with water. Each cement particle forms a fibrous growth on its surface that gradually spreads until it links up with the growth from other cement particles or adheres to adjacent substances. These fibrous build up results in progressive stiffening, hardening and strength development. The stiffening of concrete can be recognized by a loss of workability that usually occurs within three hours of mixing, but is dependent upon the composition and fineness of the cement, any admixtures used, mixture proportions, and temperature conditions. Subsequently, the concrete sets and becomes hard [9].

2.5.1.1 Portland Cement

Different types of Portland cement are manufactured to meet various normal physical and chemical requirements for specific purposes. Portland cements are manufactured to meet the specifications of ASTM C 150, AASHTO M 85, or ASTM C 1157. ASTM C 150, Standard Specification for Portland cement, provides for eight types of Portland cement using Roman numeral designations as follows:

Type I Normal

Type IA Normal, air-entraining

Type II Moderate sulfate resistance

Type IIA Moderate sulfate resistance, air-entraining

Type III High early strength

Type IIIA High early strength, air-entraining

Type IV Low heat of hydration

Type V High sulfate resistance

AASHTO M 85, Specification for Portland Cement, also uses type designations I through V for Portland cement. The requirements of M 85 are almost identical to ASTM C 150. AASHTO specifications are used by some state departments of transportation in lieu of ASTM standards. ASTM C 1157, Performance Specification for Hydraulic Cements, provides for six types of Portland cement as discussed under “Hydraulic Cements” below. A detailed review of ASTM C 150 and AASHTO M 85cements follows.

Type I Portland cement is general-purpose cement suitable for all uses where the special properties of other types are not required [21]. Its uses in concrete include pavements, floors, reinforced concrete buildings, bridges, tanks, reservoirs, pipe, masonry units, and precast concrete products.

Type II Portland cement is used where precaution against moderate sulfate attack is important [21]. It is used in normal structures or elements exposed to soil or ground waters where sulfate concentrations are higher than normal but not unusually severe. Type II cement has moderate sulfate resistant properties because it contains no more than 8% tricalcium-aluminate (C_3A). Sulfates in moist soil or water may enter the concrete and react with the hydrated C_3A, resulting in expansion, scaling, and cracking of concrete. Some sulfate compounds, such as magnesium sulfate, directly attack calcium silicate-hydrate. Use of Type II cement in concrete must be accompanied by the use of a low water to cementitious materials ratio and low permeability to control sulfate attack [9].

Type III Portland cement provides strength at an early period, usually a week or less. It is chemically and physically similar to Type I cement, except that its particles have been ground finer. It is used when forms need to be removed as soon as possible or when the structure must be put into service quickly. In cold weather its use permits a reduction in the length of the curing period [9].

Type IV Portland cement is used where the rate and amount of heat generated from hydration must be minimized. It develops strength at a slower rate than other cement types. Type IV cement is intended for use in massive concrete structures, such as large gravity dams, where the temperature rise resulting from heat generated during hardening must be minimized. Type IV cement is rarely available [9].

Type V Portland cement is used in concrete exposed to severe sulfate action; principally where soils or ground waters have high sulfate content. It gains strength more slowly than Type I cement. Sulfate concentrations requiring the use of Type V cement. The high sulfate resistance of Type V cement is attributed to low tricalcium-aluminate content, not more than 5% [9].

2.5.1.2 Supplementary Cementitious Materials

Supplementary cementitious materials, or mineral admixtures, include fly ash, slag, and silica fume, as well as other materials. Fly ash and slag are commonly used in pavements [21].

Blended cements are produced by intimately and uniformly inter-grinding or blending ordinary Portland cement (OPC) with one or more supplementary cementitious materials (SCMs). Most SCMs, such as ground granulated blast-furnace slag (GGBFS) or fly ash (FA), are industrial by-products. These materials are generally not used as cements by themselves, but when blended with OPC, they make a significant cementing contribution to the properties of hardened concrete through hydraulic or pozzolanic activity [9].

Typically, these materials retard early strength gain of concrete, but improve the ultimate strength and durability. Overall heat of hydration and the rate of heat buildup are both reduced. Workability is improved, and the concrete surface is often easier to finish [21]. SCMs are increasingly used in concrete because of following benefits [22]:

- Reduction of economic and environmental concerns by utilizing industrial wastes, reducing carbon dioxide emissions, and lowering energy requirements for OPC clinker production; and
- Improvements in concrete properties, such as workability, impermeability, ultimate strength, and durability, including enhanced resistance to alkali-silica reactions, corrosion of steel, salt scaling, delayed ettringite formation, and sulfate attack [22].

In Iowa of U.S. most blended cements used for pavement concrete contain 20% to 35% GGBFS. In addition, 15% Class C fly ash is often employed together with the blended cements to improve concrete workability and further reduce cost. The cementitious material (CM) containing fly ash, slag, and OPC were defined as ternary cement. If a CM consisted of only fly ash and OPC, it was defined as binary cement [22].

As discussed above, most SCMs are byproducts from other industries that beneficially react with Portland cement to enhance the performance of concrete. The effective use of SCMs reduces not only the amount of Portland cement required but also the need to dispose of what otherwise would be industrial waste [22].

The two most commonly used SCMs in paving concrete are fly ash and slag cement. Fly ash is a byproduct of burning pulverized coal for the generation of electrical power. The rock embedded in the coal melts in the furnace and is carried up the stack in the flue gases. As it rapidly cools, small glassy spheres are formed that are collected before the flue gases are emitted to the air. Because of the small size, glassy form, and chemical composition of the ash, it dissolves and reacts with the cement paste to contribute to the performance of the mixture. About 63 million tons of fly ash were produced in the United States in 2009, of which about 12 million tons were used either to make cement or in concrete [23].

Fly ash is currently specified in AASHTO M 295/ASTM C 618 in two classes based on the chemical composition. The differences are generally influenced by the source of the coal. In general, Class C fly ash is higher in lime content (CaO) and tends to be more reactive at early ages than Class F. The higher CaO content is beneficial for early strength gain but can have negative effects on alkali-silica reactivity and sulfate resistance. It should be noted that the specification for fly ash is broad and that two ashes from different sources, albeit of the same class, are likely to perform very differently; therefore, performance testing should be conducted to determine if the chosen fly ash is behaving as desired [21]. Dosage of fly ash is typically between 15 and 40 percent by mass of cement. The amount of fly ash that can be used is often limited by concerns of delayed setting times and lower early strength gain. In some cases, there may be a potential for undesirable incompatibilities and a perceived increase in the risk of salt scaling [21]. Judicious increases in dosage can be accommodated with attention to detail in mix proportioning and construction workmanship. Some factories use coal in our country, but byproduct collection and testing for fly ash is not yet practiced.

Slag cement, formerly known as ground granulated blast furnace slag (GGBFS), is the material left after extraction of iron from iron ore. When quenched from the molten state and ground to the fineness of cement, it is an extremely effective SCM. Slag cement is specified by ASTM C 989, and about 3 million tons are used in concrete in the United States every year [24]. It is generally used in pavements in dosages up to 50 percent but is limited by concerns of early strength gain, especially when placed during cooler ambient temperatures, and scaling resistance. As with fly ash, usage tends to be regional because of limitations on the cost effectiveness of transporting it long distances [24]. But slag cement is not available in Ethiopia currently to consider for our cost comparison.

2.5.1.3 Emerging Cementitious Systems

Work is ongoing in many institutions looking at non-Portland cement based binders [25]. Investigations include the use of geopolymers [26] and alkali-activated fly ash products as well as materials fabricated using waste materials. These are reported to carry significantly lower carbon and energy burdens than Portland cement while providing equivalent or superior performance. Some new cement types even claim to consume CO_2 in manufacture [27]. Many systems have been patented, but they are generally difficult to produce and work with. There are also safety-risks associated with some systems that require the use of a highly alkaline activating solution. Some systems may also require more processing, resulting in increased energy consumption. Significant barriers to the use of these materials are as follow [25]:

- Portland cement is inexpensive and robust
- Practitioners are often resistant to change.

Future work on cementitious materials will likely include finding alternative sources of raw materials that will not involve the decomposition of carbonate but rather use calcium-rich industrial byproducts, or possibly shifting away from the use of calcium-based cements entirely and perhaps using magnesium-silicate raw materials [25].

Titanium dioxide (TiO_2) has been known for decades to have the ability to keep surfaces clean. Cement containing this compound is now available, although it is more expensive than normal Portland cement. Titanium dioxide photo-catalyic cements reportedly can break down almost any organic compound it touches when exposed to sunlight in the presence of water vapor and also can break down the harmful compounds of nitrogen oxides (NO_x). These systems have been used in Europe, and trial sections are being installed in the United States [8].

2.5.2 Aggregates

Aggregates are granular materials, usually natural rock (crushed rock or natural gravels) and sands. Aggregates generally occupy 70 to 80 percent of the volume of concrete and therefore can be expected to have an important influence on its properties. Aggregate is not simply inert filler in concrete, and its properties deserve careful consideration [21].

2.5.2.1 Gradation

Aggregates are often classified by particle size, being normally defined as “coarse” and “fine” split at the No. 4 (4.75 mm) nominal sieve opening. This split is used to reduce the risk of segregation of the material in stockpiles. Ideally the aggregates in a concrete mixture should be composed of optimized, well graded particle sizes representing the range of sieve sizes [21]. This does not mean that good concrete cannot be made with less than ideal aggregate gradations, but the probability of success is increased with improved aggregate systems.

If necessary, multiple aggregate stockpiles representing different sized materials should be blended to create the desired aggregate grading. This, and the use of as large a nominal maximum aggregate size as practical for a given situation, will allow the reduction of the amount of cementitious materials required in a mixture, thus reducing costs and environmental impact [9].

2.5.2.2 Types of Aggregate

I. Natural

Natural aggregates, often referred to as pit-run gravels, are extracted from river beds or pits with minimum crushing or processing. They tend to be of a mixed geological composition because they have been transported some distance by natural forces. Energy and CO_2 burdens associated with obtaining and processing these materials are minimal because of the limited amount of processing required. In some cases washing is required to remove clayey dust, with the attendant use of water which will have to be treated [8].

Sources of high-quality natural aggregates are being depleted, leading to the need to consider whether the current specification requirements (AASHTO M 6 and M 80/ASTM C 33) are overly restrictive or to find methods to beneficiate unacceptable materials. Natural aggregate particles tend to be rounded and smooth from tumbling in rivers or glaciers, producing good workability of the mixture but potentially reducing flexural strength [8].

II. Crushed

In locations where suitable natural aggregates are not readily available, aggregate can be mined from bedrock then crushed and sieved to suitable sizes. Generally the dust in these aggregates is not clayey, and therefore higher quantities of material passing the No. 200 sieve can be accommodated. Additional energy consumption and emissions are associated with mining and crushing activities to obtain these materials. The selection of crushing equipment can influence the shape of the aggregate particles, and care should be taken to avoid systems that produce narrow, flaky, or elongated particles, as these will negatively impact workability and have a tendency to fracture during processing [8].

The workability of mixtures made with crushed materials is generally lower than in mixtures with rounded aggregates, meaning that additional paste may be required to achieve workability. On the other hand, flexural strengths are normally higher [8].

III. Recycled and Industrial Byproduct Materials

There is increased interest in recycling concrete and other construction waste for use as aggregates in paving concrete and supporting layers. This is beneficial because it reduces the demand for virgin aggregates and also reduces the need to place the waste materials into landfills. In pavements, the most common application for recycled materials is in the sub-base or base layers. This can be achieved in-situ using mobile crushing equipment, significantly reducing transportation costs and environmental impact [8]. If recycled materials are used in concrete, the mixes have to be proportioned and tested in the lab to ensure that setting times and strengths are satisfactory. Recycled concrete containing alkali-reactive aggregates or aggregates prone to D-cracking may not be advisable for use in paving concrete unless mitigated [28].

The most common industrial byproduct material used as aggregate is air-cooled blast furnace slag (ACBFS) which is produced from the iron blast furnace. This material has been used in supporting layers and as aggregate in paving concrete. Work currently being conducted for the Federal Highway Administration (FHWA) suggests that if ACBFS is used in paving concrete, special design and construction considerations must be followed to ensure acceptable performance [28].

2.5.3 Water

The traditional rule of thumb is that potable water is good for making concrete. It does not, however, follow that non-potable water cannot be used, although there are limits on dissolved solids and organic material. Sea water should be avoided for any concrete containing reinforcement [21].

Almost, any natural water that is drinkable and has no pronounced taste or odor can be used as mixing water for making concrete. However, some waters that are not fit for drinking may be suitable for use in concrete [9].

The amount of mix water in paving concrete is primarily governed by the w/cm ratio and paste requirement of the aggregate system and the type and dosage of the chemical admixtures in use. The presence of SCMs will normally reduce the amount of water needed for a given cementitious content. Therefore, choosing a good aggregate system, reducing the cementitious content (within limits), and using water-reducing admixtures will all help to reduce the amount of water required to achieve a given workability. There is normally more water in a typical paving mixture than is required to hydrate all the cement. Typically added water accounts for about 6 percent of the mass of a mixture [8].

The quality of the mix water is normally not much of a concern. Water that is potable is considered acceptable for use in concrete. Water contaminated by organics and sugars will tend to delay setting and may reduce early strengths. Grey water or water that has been recycled at a batch plant may accumulate dissolved solids, sulfates, and chlorides that may affect mixture performance and durability. Therefore, wash water used to clean tracks and equipment, as well as water recycled from returned trucks, should be processed to remove solids and organics before it is released to the environment or before it is re-used in a batch plant. ASTM C 1602 provides some limitations on the quality of mix water, particularly recycled water and wash water [8].

Two other significant uses of water at a construction site are for achieving the appropriate moisture content to facilitate compaction of soil and unbound granular materials and for dust control. The amounts of water used should be balanced between the needs to achieve engineering requirements and to minimize waste [8].

2.5.4 Admixtures

Chemical admixtures are a common constituent in modern paving concrete, being added to modify one or more of the fresh or hardened properties of the concrete. Chemical admixtures are typically used in pavement mixtures to entrain air, increase workability, and/or control time of setting. Admixtures are used in small dosages and usually comprise less than 0.2 percent by volume of concrete [21].

Common chemical admixtures are specified using AASHTO M 154/ASTM C 260 and AASHTO M 194/ ASTM C 494. The basic ingredients used in water reducing and retarding admixtures are sugars and lingosulfonates obtained from corn or wood. The most common accelerating admixture is calcium chloride, although non-chloride based accelerators are also available. The primary materials used in modern high-range water-reducing admixtures are poly-carboxylate ethers and polyvinyl copolymers synthesized from oil-based materials. Water-reducing admixtures are primarily used to reduce the amount of water required in a mixture to achieve a given workability. For a mixture with a fixed w/cm ratio, water reducers can be used to reduce the amount of cement material required, leading to significant savings in cost and environmental impact. They also permit use of lower w/cm ratios in mixtures, leading to improved durability and longevity [9].

Air-entraining admixtures are used to develop a system of small air bubbles to increase the resistance of critically saturated concrete to deicer salt scaling and cyclic freezing and thawing, increasing longevity of the pavement. As previously mentioned, lithium-based admixtures can be used to mitigate alkali-silica reaction [8].

2.5.5 Reinforcement

Reinforcement is used in concrete pavements to improve the ability of concrete to carry tensile stresses and to hold tightly together any random transverse cracks that develop in the slab [8].

Dowel bars (smooth bars), or simply dowels, are placed in concrete across transverse joints to provide vertical support and to transfer loads across joints. Dowel bars are typically used on heavy truck routes. Dowel bars reduce the potential for faulting, pumping, and corner breaks in jointed concrete pavements [8].

Tie-bars (deformed bars), or rebar, are placed across longitudinal joints on centerlines or where slabs meet. Tie-bars prevent faulting and lateral movement of the slabs, assist with load transfer between slabs and are also used to connect curbs and gutters to the pavement [8].

Generally, cracking in jointed concrete pavements is controlled by limiting the spacing between joints. When the concrete slab is reinforced, joint spacing can be increased [8].

2.6 Design of Rigid Pavements

The determination of pavement thickness requirements is a complex engineering problem. Pavements are subject to a wide variety of loading and climatic effects. The design process involves a large number of interacting variables, which are often difficult to quantify [21].

Pavement design is the process of developing the most economical combination of pavement layers with respect to both material type and thickness to suit the soil foundation and the traffic load during the design period. There are different methods for the design of pavement structures. AASHTO design procedure is one of the approved design methods recognized globally [29].

Design input variables included expected traffic and axle loads, different levels of base and subgrade support, concrete strength, design features (such as dowels and tied shoulders), design reliability, climate, drainage, and pavement failure modes.

It is fitting that the design phase is the first to be discussed, as it is only through thoughtful and deliberate design that sustainability can be achieved. Design of concrete pavements has traditionally focused on slab thickness design, although other design details, including joint spacing and load transfer, slab support considerations, drainage, and edge support to name a few, have long been recognized as being of equal or greater importance [30]. These design details are directly considered in the new AASHTO DARWin-ME™ Mechanistic-Empirical Design Guide (MEPDG), which provides a rigorous approach to considering the effect of multiple design variables to assist in optimizing the design for given conditions [31].

The design phase is also where innovative pavement design types, such as two-lift concrete pavement, roller-compacted concrete (RCC), precast concrete and concrete pavers, and thin concrete pavement (TCP) will be considered.

A pavement must be designed and constructed to serve its function to provide a durable all-weather traveled surface for safe and efficient mobility of people and goods with an acceptable level of comfort to the motorists. In meeting these functional requirements, due considerations must be given to the following aspects during the design and construction stages [21]:

- Determination of soil properties, design traffic loadings and environmental parameters
- Selection of materials for various pavement layers
- Structural thickness design of pavement layers
- Drainage design for the pavement system
- Safety and geometric design

The key concern in the structural design of concrete pavement is cracking failure caused by one or more of the following actions: (i) load-induced tension, (ii) Thermally induced tension, and (iii) tension generated by subgrade soil movements or moisture changes. The common design practice for concrete pavement has been to consider load-induced stresses separately from the other forms of stresses when steel reinforcements are used. The thickness of the pavement slab is designed for the design traffic loadings, while the steel reinforcements are designed to resist tensile stresses caused by temperature changes or subgrade soil movements. It is thus common to position the steel reinforcements at mid depth of the pavement slab. In the case of plain concrete pavement where no reinforcements are provided, the total tension due to the various appropriate factors combined must be considered in the pavement slab thickness design [21].

The structural properties of pavement slab and foundation materials are required as input to structural analysis for pavement design to check that the proposed design is adequate and provides sufficient safety margins against possible modes of failure [21].

These designs are established to be structurally equivalent and have the same design life such that a fair comparison may be made. The Maintenance and Rehabilitation plans must be developed by implementing authorities (ERA and AACRA) for both pavement types to ensure that the minimum level of service will be maintained.

Creating equivalent pavement designs has historically been difficult due to differences in the pavement design procedures used for rigid and flexible pavements. However, recent release of the AASHTO pavement design guide, the Mechanistic-Empirical Pavement Design Guide (MEPDG) [32], provides a more robust design procedure that uses substantially more design information and a larger source of data to calibrate the performance predictions than previous editions.

2.6.1 Pavement Layers of Rigid Pavements

Rigid pavements generally consist of a sub-base, and a concrete slab constructed above the sub-grade (capping layer if required) as shown in Fig.2.1. The capping layer consists of selected fill and is provided in cases of CBR of the subgrade is less than 15%. It allows increasing the bearing capacity of the sub-grade and thus enables a lesser pavement thickness to be adopted. The sub-base of a rigid pavement structure is placed between the sub-grade and the concrete slab. In some cases the material can be cement stabilized to increase its quality. If the sub-grade materials quality is acceptable and if the design traffic is low (less than one million equivalent standard axles (ESAs)), a sub-base layer may not be necessary between the prepared sub-grade and the concrete slab. The required thickness of capping layer and sub-base thickness is shown in Table 2.1. The minimum thickness for JUCP and JRCP is 150 mm whereas the minimum thickness of concrete for CRCP is 200 mm [10]. But the require thickness of concrete varies as per the design parameters.

Table 2-1 Thickness of Sub-base and Capping Layers [10]

Subgrade class	CBR range (%)	Sub-base thickness (mm)	Capping layer thickness (mm)
S1	2	200	400
S2	3,4	175	350
S3	5-8	150	250
S4	8-15	150	200
S5	15-30	175	0
S6	>30	0	0

A sub-base layer is required whenever the subgrade material does not comply with the requirement for a sub-base (CBR is less than 30%) but it is usually provided in all cases because the sub-base and capping layers are primarily designed to provide a good working platform for construction activities. This enables construction levels to be more easily achieved within the tolerances required and prevent "pumping" at joints and slab edges [10].

The concrete slab consists of Portland cement concrete, reinforcing steel (When required), load transfer devices and joint sealing materials. Transverse reinforcement is provided to ensure that the longitudinal bars remain in the correct position during the construction of the slab. It also helps to control any longitudinal cracking that may develop [10].

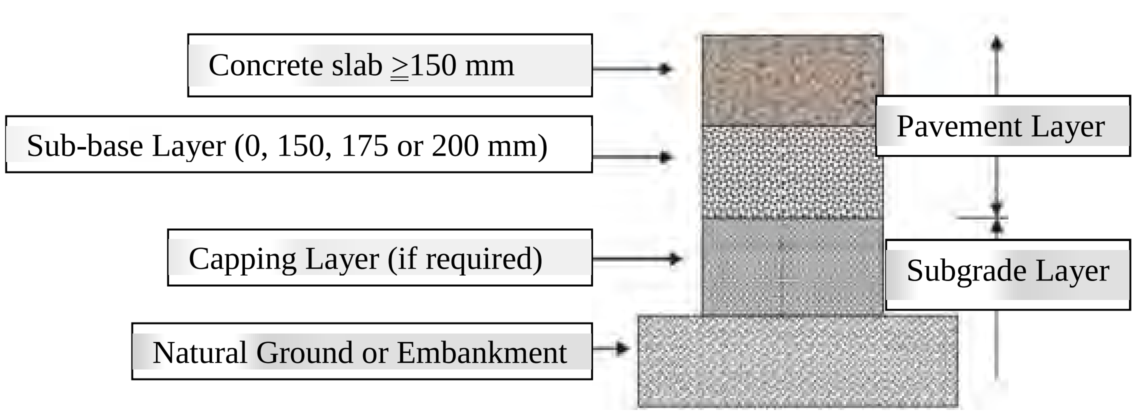

Figure 2-1 Pavement Layers of Rigid Pavements [10].

2.6.2 Design Life

Due to the structural properties of concrete slabs, their durability is very good and they can be designed for periods of up to 60 years. If properly constructed, the pavement will last long with a good level of serviceability and low maintenance requirements [10].

It is common practice to design concrete pavements for 40 years or more. Given that the required slab thickness varies linearly with the logarithm of the cumulated number of ESAs, designing for longer periods generally requires marginal additional slab thickness and reinforcement and proves to be more economical [10].

This possibility to design rigid pavements for more than twice the maximum design life of flexible pavements and the lower associated maintenance costs makes them generally more economical in the long term [10].

2.7 Construction of Rigid Pavements

2.7.1 Proportioning

The aim of mixture proportioning is to find the combinations of available and specified materials that will ensure that a mixture is cost effective and meets all performance requirements. In the case of sustainable design, minimizing the pavement's environmental footprint (e.g., embodied energy and GHG emissions) over the pavement life cycle must be one of the performance requirements [8].

The freedom to vary mixture proportions depends on the specification. There is a movement to write specifications that are less formula based and more focused on the desired performance. This places decision making, and risk, in the hands of the concrete provider and paving contractor, with the attendant economic and environmental impacts. Such a trend will mean that everyone in the process has to be better educated about the broad impacts of their decisions. Ideally a concrete paving mixture will use an optimized combined aggregate gradation that minimizes voids and thus the paste requirement, resulting in minimal cement and water required.

Achieving this should not be at the expense of significantly increased processing or transportation impacts [21].

Aggregates should be resistant to the environment and not prone to D-cracking, Alkali Silica Reaction (ASR), or Alkali Carbonate Reaction (ACR). Cementitious content should be kept as low as possible without compromising mixture performance, both in the fresh and hardened state. The selection of the cementitious system should be to maximize SCM contents while preventing ASR, resisting freezing and thawing distress, and meeting other specified requirements. The quality of the paste, including the w/cm ratio and air void system, should be selected based on the environment to which the mixture will be exposed [21].

2.7.2 Concrete Production

Recommendations regarding materials and proportioning of concrete mixtures from a sustainable perspective are addressed above. Once a mixture has been optimized with regard to sustainability, the concrete production process should be monitored and adjusted as needed to achieve the desired results. Concrete used for pavement is produced at either a central mix plant or a dry batch plant utilizing transit mix trucks. Regardless of the equipment used, it is imperative that the plant produce a concrete mixture that meets or exceeds specification requirements, is uniform within each batch, and is also uniform from batch to batch. Non-uniform concrete leads to non-uniform performance, which in turn results in premature failure with related maintenance and rehabilitation costs [8].

Non-uniformity of the concrete mixture can also lead to wasted materials, because the concrete producer is forced to use more cementitious material to consistently meet specifications. A preferred approach is to implement quality assurance procedures that will improve uniformity and lead to the most efficient use of materials [8].

Most concrete plants utilized for concrete paving projects are equipped with automated batching controls. While this certainly improves productivity, it is no guarantee that quality is improved. Quality assurance procedures aimed at improving the uniformity of the concrete reduces cost through the efficient use of material resources [8].

Currently, some private and governmental construction companies in Ethiopia owned concrete batch plants, but all are concentrated in the capital city (Addis Ababa). Hence it is a good start up and experience for the entry of ready mix concrete supply investors.

2.7.3 Transporting Concrete

Various types of hauling equipment are available for transporting concrete for a paving project. These range from transit mix trucks to tractor-trailer rigs. From a sustainability perspective, efficiency should be maximized by matching the type, size, and number of haul units to project constraints (production rate, haul route conditions, maneuverability, etc.) [8].

All equipment should conform to EPA requirements, and the use of alternative fuels should be considered whenever economically feasible to minimize emission of GHGs and particulate through diesel exhaust [8].

2.7.4 Concrete Paving and Finishing

Quality of pavement construction is important. “A well-built but poorly designed pavement is likely to outperform a poorly-built but well-designed pavement [21]. Placing and finishing concrete pavement is a complex process that involves the use of sophisticated equipment in conjunction with the skilled craftsmanship of crew members. By the time the concrete mixture is deposited ahead of the paver, there is nothing that the equipment and crew can do to improve the material properties; these properties are strictly a function of the raw materials, mixture proportions, and mixing process. However, there are many ways that placement and finishing techniques can negatively influence what may be an otherwise acceptable concrete mixture. From a sustainability perspective, it is imperative that the equipment and crew place and finish the concrete pavement in a manner that will maximize the performance capabilities of the concrete mixture [8].

The two main types of concrete paving are slip form paving and fixed form paving. Both have advantages and disadvantages and each is better suited to some projects than to others. On most slip form paving projects, however, small amounts of fixed form paving or “handwork” are still necessary. One important element is avoiding segregation during aggregate and concrete handling and batching operations [21].

For slip-form paving, the pavement is finished behind the paver with a burlap drag and tine texturing. A tube floats, which is a self-propelled machine not attached to the paver, may be used to correct minor variations and seal small imperfections in the finished slab surface. A key consideration for finishing is water management. The concrete should not be finished until the bleed water has disappeared from the surface. Longitudinal or transverse floats may be used. A straight edge may be used to check the pavement for surface imperfections that may be corrected with hand operated floats. Concrete pavement surface textures provide the friction needed for safe roadways. The concrete surface is textured with tinning machines to increase the friction of the surface. The tinning may be longitudinal or transverse, with grooves 3–5 mm deep, 3 mm wide, and 12–20 mm spacing. Tinning provides macro-texture, while micro-texture is achieved with burlap drags [21].

Concrete paving (casting) procedures are similar to any conventional concrete casting procedures in Ethiopia known so far except its precisions on finishing and application of textures.

2.7.5 Curing Concrete

Perhaps one of the most overlooked parts of the concrete paving process, curing has a significant impact on concrete pavement durability and thus on sustainability. Curing must be executed properly to prevent excessive moisture loss and thus to ensure that sufficient water is available in the concrete to completely hydrate the cementitious materials and to prevent shrinkage cracking and excessive warping [8].

Curing is particularly important for pavements because of their high surface to volume ratio. Poor curing can result in significant damage to concrete pavements. Damage occurs due to plastic shrinkage cracking, thermal stress, or drying shrinkage cracking. Poorly cured concrete pavements may also have poor abrasion resistance and may not resist deicing salts and other deterioration mechanisms as well [21].

In general, white pigmented curing compound should be applied before any surface evaporation occurs. All exposed surfaces of the concrete pavement should be completely covered (the pavement surface should be uniformly white). [8]. White pigmented curing compounds were used by the chines contractor for retaining wall concrete curing of Bole International Airport – Meskel Square Road construction project, Addis Ababa.

2.7.6 Sawing and Sealing Joints

A joint is a designed crack. Concrete pavements will crack due to shrinkage and temperature differences. The purpose of joint sawing and sealing is to ensure that cracks form at the proper locations and will be easy to maintain. Generally, transverse joints in JRCP are initiated by sawing through the surface slab to create a plane of weakness.

Joints are often sealed to reduce the amount of water flowing through the pavement and to prevent incompressible material, such as small stones, from becoming trapped in the pavement joint. Incompressible materials can lead to chips or spalls when joints close as temperatures increase. The initial saw cut is made with a thin bladed saw. This is often followed by a widening cut, which is not as deep as the initial cut, to provide a reservoir for sealant material. Special saw blades are available in international markets that make both cuts at the same time [21].

Sawed joints are necessary for non-reinforced pavements to prevent uncontrolled cracking. Practices for sawing and sealing joints vary across the world. The most common options for green sawing concrete pavement are wet sawing with diamond blades (saw cut depth = T/4 or T/3) and early entry sawing using a dry diamond blade (saw cut depth = 25.4 mm to 76.2 mm). Dimension sawing (joint widening) is necessary for certain joint sealants that require a specific joint shape for proper performance. This is most commonly performed by wet sawing with stacked diamond blades that create a joint reservoir from 9.5 mm to 12.52 mm wide and 25.4 mm to 38.10 mm deep [8]. Joints make approximately 5 percent of the cost of new pavement.

Common joint sealant materials used for concrete paving include bituminous (hot poured or cold poured), silicone (tooled or self-leveling), and pre-formed compression seals [8].

2.8 New Developments in Concrete Pavement to Improve Sustainability

2.8.1 Two-Lift Concrete Pavement

Two-lift concrete paving is not new. In fact, the oldest concrete pavements in the United States, constructed by the R.S. Blome Granitoid Co., were placed as two-lifts, wet-on-wet, with the top lift being a different concrete than the bottom lift. Two-lift construction was also used to facilitate the placement of reinforcing mesh in jointed reinforced concrete; the mesh was set upon the surface of the bottom lift and encapsulated by the top lift. Recently, after examining the excellent performance of two-lift concrete pavements in Europe, there has been a resurgence of interest in adopting modern two-lift concrete pavement design in the United States, as shown by recent demonstration projects constructed in Kansas and Missouri [33].

This pavement system typically consist of a thick bottom lift (typically 80 percent or more of the total thickness) and a thin (20 percent or less of the total thickness) top lift that is optimized for carrying traffic [8].

The potential sustainability advantages of two-lift pavement include the following:

I. **Bottom lift –** The concrete mix proportions for the bottom lift can be optimized knowing it will be protected from the elements during construction and will not be subjected directly to traffic. This means that it can use a higher supplementary cementitious material content, higher percentage of recycled aggregate and aggregates with less strict requirements than normal because the bottom lift will not be exposed to traffic. A broader range of locally available aggregates and higher amounts of recycled and industrial byproduct materials can be used, and so reduce the environmental footprint of the concrete [33].

II. **Top lift –** The relatively thin top lift is optimized to carry traffic. It often uses wear-resistant aggregate that may have to be transported longer distances and a higher Portland cement content, but can do so without significantly impacting the environmental footprint of the pavement due to the thinness of the layer. This ensures good long-term durability and a safe riding surface, especially if the thickness of the top lift is designed for multiple diamond grindings over its life [33].

Eleven two-lift projects were constructed from 1970 to 1994 (Florida, Iowa, Kansas, Michigan, and North Dakota), all are still in service. In 2008, the Kansas DOT constructed over five miles of two-lift pavement on I-70 west of Abilene [8].

The versatility inherent in the two-lift design provides the designer with multiple options to cost effectively integrate one or more sustainable attributes into the new pavement, resulting in economic savings while improving environmental and social performance [8]. It is expected that this versatility will result in the widespread adoption of the technology in Ethiopia in the future.

2.8.2 Roller Compacted Concrete Pavement

Roller compacted concrete (RCC) pavements use low slump concrete mixture that is closer in some respects to cement treated aggregate base than a conventional, flowing concrete. The construction process resembles that of hot-mix asphalt pavements. The material is delivered by dump trucks, placed into a paver, and then rolled with steel wheel rollers. The RCC is then cured. The pavement may be allowed to crack naturally, or joints may be cut. Because, RCC shrinks less than conventional concrete, the joints or cracks are further apart than those for JUCP [21].

Traditionally, the construction process has left RCC pavements with rough surfaces which are not suitable for high speed traffic. Unsurfaced RCC pavements have many industrial applications; multimodal freight transfer facilities, automobile plants, and military facilities [21].

RCC is typically placed in layers 125 to 250 mm in thickness using an asphalt-type paving machine. High-density paving equipment is preferred for layers thicker than 150 mm since the need for subsequent compaction by rollers is reduced. Where a design calls for pavement thickness greater than 250 mm, the RCC should be placed in multiple layers [9].

Roller-compacted concrete (RCC) pavement has been used in the construction of various types of civil infrastructure, including dams, other hydraulic structures, cargo handling facilities, and pavements. Although the constituents in RCC are similar to conventional concrete, they differ in proportioning, with RCC typically having less cementitious material and an aggregate gradation similar to that used in Hot-Mix Asphalt (HMA) mixtures. Ultimate load carrying capacity is obtained through a combination of internal, aggregate-to-aggregate friction and the cohesion obtained through hydration of the binder [8].

The final surface is adequate for pavements carrying traffic at low and moderate speeds but often is either diamond ground or overlaid to meet the smoothness demands of high-speed traffic [8].

RCC shares many sustainability attributes with conventional concrete pavements, including low lifecycle economic costs, the ability to incorporate a high amount of recycled and industrial byproduct materials into the mix, and high surface reflectivity [8].

The current practice of RCC in Ethiopia is concentrated on the construction of the two mega hydropower projects of Gilligel Gibe III and Ethiopian Grand Renaissance Dam. So that we can implement the system from the experience at these dams construction projects with some modifications to suite for pavement systems.

I. Advantages of Roller Compacted Concrete Pavement

Some of the specific advantages of RCC include low initial cost and rapid construction compared to both conventionally designed concrete pavements and multi-lift Hot-Mix Asphalt (HMA) pavements of similar structural capacity. In addition, if the lower cementitious content translates into a lower Portland cement content, the carbon footprint is reduced [8]. RCC paving allows for the high-production placement of concrete without the use of large slip form pavers or forms and the consolidation, finishing, and texturing required of conventional Cement Concrete pavement. The amount of labor required is significantly less than conventional Cement Concrete pavement of the same thickness and this usually will result in cost savings. Load transfer across joints may be lower than conventional concrete because dowels are not used [8].

II. Disadvantages of Roller Compacted Concrete Pavement

Considering the rideability or surface smoothness currently attained with RCC, the use of RCC should be limited to areas of low-speed (< 60 km/h) traffic. Areas where fresh longitudinal joints cannot be made require cutting back of the uncompacted edge and removal. These operations can interfere with further construction and hinder curing operations. Areas where aesthetics and ride-ability are important will require that sawed joints are constructed and sealed. The surface texture of an RCC pavement is somewhat coarser than that of a conventional CCP and the surface smoothness is also rougher.

2.8.3 Precast Concrete Pavement Systems

Precast concrete pavement systems have a long history, but with recent innovations they will continue to grow in popularity. Precast concrete pavement systems typically consist of individual panels that are one to two lanes in width and 3 to 4.5 m in length, depending on the system. The pavement panels are produced in a precast plant, where the material is proportioned, molded, consolidated, and cured under controlled conditions, then shipped to the site where they are assembled on grade [8].

Potential advantages of precast concrete panels include higher quality concrete, better curing, less risk of weather disruption, and reduced delay before opening to traffic [34]. Important issues include leveling the panels to avoid bumps at panel edges, and load transfer between precast panels or between precast panels and existing pavement.

Precast panels are generally reinforced with mild steel, primarily to prevent damage during transportation and handling [21].

Fabrication under controlled conditions eliminates a major construction variable, unfavorable ambient weather condition, which can play havoc on conventionally cast-in-place concrete pavements, and it also reduces material and construction variability [8].

Further, precast concrete pavement systems allow the cost-effective implementation of certain sustainability features, including enhanced aesthetics, specialty surface textures, high surface reflectivity, and photo catalytic materials. Many of these features are made possible because the pavement wearing surface can be cast against a mold in two or more lifts if desired, giving a degree of control that is not possible with cast-in-place pavements. Casting the surface against a mold also results in a denser surface, as the lighter concrete mixture constituents (air and water) rise towards what will be the underside of the pavement and the dense cement and aggregate settle to form a dense molded surface [8].

Prefabricated Building Parts Production Enterprise (PBPPE), located in Kality Sub-City could handle the fabrication of precast concrete pavements for some section of roads in and around Addis. Currently, PBPPE is not working at its full capacity due to unknown reasons.

The advantages of using two or more lifts and casting the pavement surface against a mold can be capitalized on in precast pavement systems, optimizing the surface for the given application. For a pavement carrying high-speed traffic, the surface can be designed to be exceptionally quiet while providing good frictional features to enhance safety. For slower speed pavements designed for the urban environment, the surface can be designed to be aesthetically pleasing, cool, photo-catalytic, and drainable and even to provide a “traffic calming” effect by inducing nuisance vibration in vehicles operating too quickly. Further, precast pavement systems for the urban environment can be designed to “snap in and snap out,” meaning that the precast panel over a needed utility repair is simply detached and removed, the repair to the utility completed, and the panel reattached. This eliminates waste, accelerates the repair process, and maintains the integrity of the pavement system. It is easy to envision the ability to design a major urban project, such as an intersection replacement, using a precast pavement system in which all the design, fabrication, and staging are done ahead of time and the work is completed over a few evenings or a weekend [8].

2.8.4 Interlocking Concrete Pavers

Similar to precast concrete pavement systems, interlocking concrete pavers are also produced in a plant, where the material is proportioned, molded and cured under controlled conditions, then shipped to the site where they are assembled on grade. Again, fabrication under controlled conditions eliminates a major construction, unfavorable ambient weather conditions, which can play mess on conventionally cast-in-place concrete pavements and it also reduces material and construction variability [8].

Interlocking Concrete Pavers are the original pavement surfacing material, with the use of stone pavers dating back to antiquity. Modern interlocking concrete pavers have evolved to be extremely versatile and durable and are used in projects as varied as low-volume parking areas to the most heavily loaded cargo handling facilities. Interlocking concrete pavers do not only possess the necessary structural capacity and long-term durability for the application but also are aesthetically pleasing. Permeable interlocking concrete paver blocks make an aesthetically pleasing, well-drained pavement for low-volume streets and parking lots [8].

The practice, in Ethiopia, for interlocking concrete pavers are limited to pedestrian walk ways of large cities; whereas coble stone pavers are widely used throughout the country.

2.8.5 Thin Concrete Pavement Design

Most of the pavement technologies discussed so far have been around for decades and are experiencing something like a revival due to their implications for sustainability.

Thin concrete pavement (TCP) design, however, is truly new and has yet to gain widespread acceptance in North America. TCP design originates in Chile and is still under evaluation there as well as in a number of other countries [35].

In North America, considerable work has been conducted at the University of Illinois with very promising results [36].

The basic concept is simple. Stresses are generated in concrete slabs through a combination of traffic and environmental loads. The larger the concrete slab, the more truck axles it will carry at one time and the higher the stress incurred due to temperature and moisture gradients. Over the time, the repeated stresses generated by the combination of traffic and environmental loading will result in fatigue cracking of the slab. By reducing slab size to a square with the dimensions of one-half a lane (1.8 m by 1.8 m), the stresses generated are significantly reduced to the point that slab thickness can be reduced by almost half. The reduction in slab thickness will be accompanied by higher deflections; thus the need for good base support that resists pumping and erosion is emphasized [8, 36].

The promise of TCP design is that the reduction in slab thickness will substantially reduce the economic and environmental costs of concrete pavements. Slab thickness of as little as 10 to 15cm may be all that is required to carry moderate to heavy traffic volumes, and early results indicate that there is no need for embedded steel load transfer devices [8].

2.8.6 Pervious Concrete

The entire concrete pavement types discussed above provides impervious cover. Except for small amounts of infiltration through joints and cracks, precipitation runs off of the pavement surface and must be handled by a separate drainage system. However, in many regions developers are limited in the amount of impervious cover allowed on a site. This has led to increasing interest in pervious or porous pavements; pavements that allow rapid water flow into and through the pavement structure. Because pervious concrete has a much lower flexural strength than conventional concrete, it has been most widely used for parking lots and light-traffic streets and roads. For these applications, a pavement thickness of 150 mm has generally been found to be adequate. In the future, however, the use of pervious concrete pavement will probably be expanded to heavier traffic [21]. But it cannot be reasonable pavement alternative for our case as we are concerned with arterial roads carrying high cumulative axle loads.

Pervious concrete is manufactured in place with a substantial void content between 15 percent and 25 percent created by the use of little or no sand .With its high void content, pervious concrete allows rain water to drain through it at a rate of about 3 to 8 gallons of water per minute per square foot of surface. This allows rainwater to seep into the ground versus running off, thereby recharging groundwater instead of rapidly moving from the pavement surface to nearby bodies of water. Thus, previous concrete can be used in urban areas to eliminate the need for other storm water management devices such as retention ponds and swales (44).

2.9 Sustainability of Rigid Pavement

The concepts of “sustainability” and “sustainable development” are receiving much attention as the causes of global warming and climate change are debated. In the context of human activity, sustainability has been described as activity or development “that meets the needs of the present without compromising the ability of future generations to meet their own needs” [37].

In 2005, the U.S. Environmental Protection Agency started the Green Highways Initiative as an instrument for coordinating transportation and environmentalism. According to this initiative, “green highways” are those that are environmentally responsible and sustainable in all aspects, including design, construction, and maintenance [38].

Based on the focus of the initiative beyond longevity, other features of concrete pavement further enhance its sustainability [8] as quoted below:

- Properly constructed and textured concrete pavements have reduced pavement deflection, which results in reduced vehicle fuel consumption.
- The construction of concrete pavements consumes less fuel (particularly diesel) during materials production, transportation, and placement than the construction of asphalt pavements.
- Concrete pavement mixtures incorporate industrial by products (i.e., fly ash and slag cement), which lowers the disposal needs, reduces the demand on virgin materials, and conserves natural resources.
- Concrete pavement itself is renewable and 100% recyclable.
- Concrete pavement requires less sub-base and no base-course aggregate materials for structural support than asphalt pavements.
- Concrete pavements’ lighter color and increased reflectivity improve nighttime visibility, reduce the amount of power needed to illuminate roads at night, and help mitigate urban heat island and smog generation.
- Concrete pavements exhibit a lower energy footprint associated with their production, delivery, and maintenance than asphalt pavements do over a predetermined time period.
- Concrete pavements designed with pervious concrete shoulders minimize surface-water discharge and help replenish groundwater aquifers.
- Optimized concrete pavement surface textures produce quieter pavements over longer periods of time, reducing noise pollution.

The overall positive effects of reducing energy use and minimizing the environmental footprint of development through efficient and sustainable use of concrete dramatically outweigh the impact of the cement manufacturing process [39]. Put another way, concrete is one of the world's most CO_2-efficient and sustainable building materials [40].

2.9.1 Performance of Concrete Road

Concrete pavement engineering is the selection of design, materials, and construction practices to ensure satisfactory performance over the projected life of the pavement. Pavement users are sensitive to the functional performance of pavements, smoothness and skid resistance, rather than structural performance [21].

The longevity of concrete pavements is well documented. Numerous concrete highways in North America have lasted 50 years or more, supporting traffic volumes much greater than originally anticipated. Such long-lasting concrete pavements are not confined to one region of North America, nor to a specific type of environment or climate [40].

Concrete highways have excellent track record as a cost-effective investment. Rigid CCP outperforms flexible asphalt pavement with economic and safety benefits and has less impact on the environment. Nearly 30 percent of U.S. interstate highways are built with concrete [41].

In Ethiopia, however, the government typically award highway pavement construction contracts based only upon Asphalt pavements options. Because, AC options are perceived to be less expensive than cement concrete pavements. But planners, in the developed world, are now beginning to recognize that tenders for road infrastructure projects should include a life cycle cost analysis (LCCA) component, based on the estimated costs of a project over its entire service life. When this concept is applied to maintenance, rehabilitation, reconstruction and salvage value of pavements, life cycle costs are evaluated, as well as initial costs, revealing the full expense of materials over the life of a highway, concrete performs better on all counts.

Interstate 10 in the San Bernardino Valley in California was originally constructed in 1946 as part of Route 66. Portions of the concrete highway are still carrying traffic today at an impressive volume of more than 200,000 vehicles per day. After being renewed three times by surface grinding during its more than 60-year life, this highway is a true testament to concrete pavement's sustainability [42].

Such long-lived concrete pavements have demonstrated economic advantages in terms of life-cycle costs. In addition, they contribute directly to the system's sustainability in several important ways.

A long-lasting concrete pavement does not require rehabilitation or reconstruction as often, and therefore consumes less raw materials in the long run. This longevity impacts our environment in other ways as well. Energy savings are realized, since rehabilitation and reconstruction efforts consume energy [40].

2.9.2 Technical and Economic Benefits

There are many different technical and economic reasons to choose rigid (concrete) pavement over flexible asphalt. The following are some of the reasons:

2.9.2.1 Concrete Pavement Lasts Longer

Concrete pavement lasts longer and requires less maintenance over its lifetime than asphalt. Its rigid nature provides a stable surface that will not rut, washboard or heave, and also minimizes the potential for potholes. This translates into safe highways that require less maintenance, with less disruption for the traveling public and commercial truckers [17].

A long-lasting concrete pavement does not require rehabilitation or reconstruction as often, and therefore consumes less raw materials in the long run. This longevity impacts our environment in other ways as well. Energy savings are realized, since rehabilitation and reconstruction efforts consume energy. Also, congestion is reduced (with accompanying energy savings and reduction in vehicle pollutants) by employing long-lasting concrete pavements because of fewer construction zones impeding traffic flow. Because of this longevity, concrete pavements have the potential to help society address the challenges of sustainable development in numerous ways.

Ultimately, all these environmental and social benefits add up to greater long-term economic benefits to the public [17].

2.9.2.2 The Cost-Effective Advantage

Life Cycle Cost Analysis (LCCA) is a forward-looking decision framework that helps governments assess the lifetime costs of a roadway, rather than merely considering the initial construction costs [30]. When LCCA is applied, concrete pavement is, in many cases, less expensive than an asphalt surface of equivalent design as indicated in Fig. 2.3 [17].

LCCA is emerging as a policy component used in decision-making in some jurisdictions in Canada. The Cement Association of Canada urges governments at all levels to adopt LCCA in the tendering process, as a means of ensuring accountability in public infrastructure investments and assessing the true cost of a highway over time [43].

In 2009, concrete paved roads enjoyed $65,000 initial cost advantage over asphalt paved roads for one mile two lane roads as shown in Fig. 2.2 [44]. According to the PCA initial construction cost of cement concrete pavements are less than that of asphalt concrete pavements since 2008 onwards.

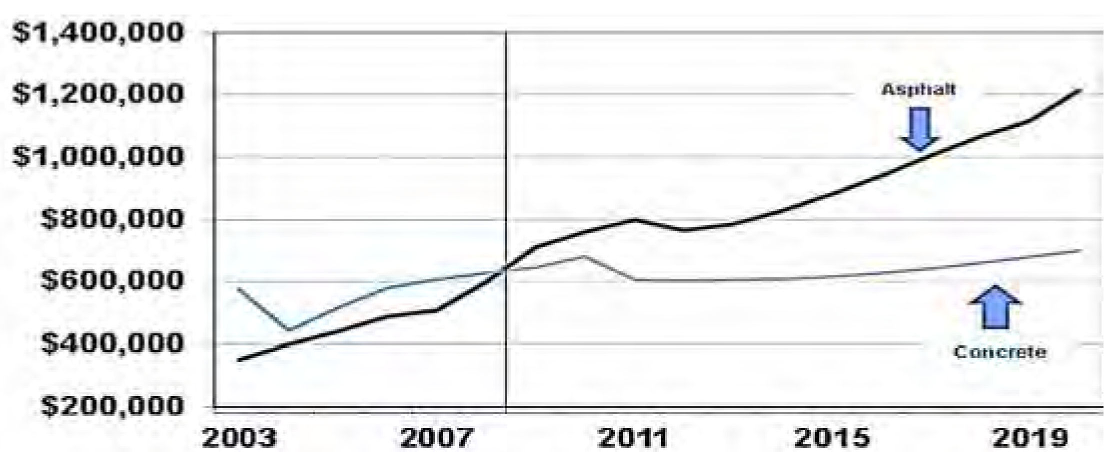

Figure 2-2 Initial Bid Concrete vs. Asphalt Paving Costs ($) per Two Lane Road Mile - Urban;

Source: PCA estimates using WisPAV (Wisconsin DOT paving cost software).

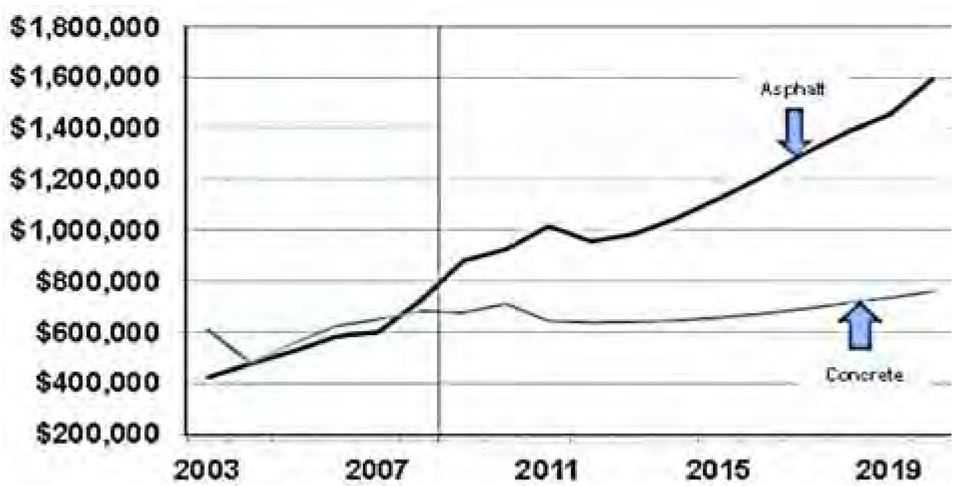

Figure 2-3 Life Cycle Concrete vs. Asphalt Paving Costs ($)/Two Lane Road/Mile (Urban);

Source: PCA estimates using WisPAV (Wisconsin DOT paving cost software).

2.9.2.3 A True Alternative Leading To Better Prices

A long-term commitment from governments to the use of rigid concrete pavements will lead to lower costs through increased competition between concrete and asphalt road builders. Data from the American Concrete Pavement Association confirms that American states truly committed to building concrete highways create competition between the concrete and asphalt paving industries resulting in lower unit costs for both concrete and asphalt highways [45].

2.9.2.4 Price Stability

Concrete is produced in Ethiopia using both locally available aggregates and in home manufactured cement that are less dependent on the supply of oil. While the pricing of asphalt materials fluctuates with the world price of oil, the pricing of concrete remains relatively stable and hoping become even lower than before.

If we examine the price adjustment of materials used in road construction projects, it is clear that imported materials such as heating oil and bitumen are entirely dependent on the international market price of crude oil and that this is subject to powerful fluctuations, particularly in periods of energy scarcity. Cement on the other hand is a locally produced construction material and in consequence its price is more stable, although of course it is to some extent affected by energy prices.

In certain countries such as Turkey the market situation for cement and bitumen binders is different than in most other West European countries. There the initial investment cost for a concrete road is lower than for an equivalent bituminous road before 2008. Furthermore when the maintenance costs are added to the equation the differences become exceptionally high [46].

2.9.2.5 Stands Up to Seasonal Stresses

Concrete highways have a strong track record in some of the coldest parts of Canada and the United States. Concrete mixes are tailored to specific applications and conditions; including cold weather and de-icing agents, to ensure strength and durability throughout the life of the highway. Thus concrete is not damaged by anti-icing agents normally used in winter. Furthermore, due to the way concrete pavements distribute vehicle loads, it is virtually unaffected by the seasonal weakening of the underlying granular bases and sub-grade [47].

According to Canadians' report, durability of Concrete is most evident during Canada's spring thaw season. Unlike some asphalt highways, springtime weight restrictions are not necessary on concrete highways. A study by the American Association of State Highway Officials (AASHO) showed that 61 percent of asphalt roads tested failed during spring conditions [47].

2.9.2.6 Reduced Lighting Cost

Lighting fixtures are important elements of most urban highway facilities. Enhanced nighttime visibility is intuitively related to improved traffic safety. In addition, because of the more reflective nature of concrete pavements, a specified luminance level can be achieved with fewer high-output lighting fixtures and standards. Ultimately, this translates to lower costs and lower energy consumption over time [17].

An industry report notes that concrete pavement reflects light in a diffuse manner, compared to the slightly spectral (somewhat mirror-like) reflectiveness of asphalt pavement. As a result, a concrete highway requires fewer lights per unit length of pavement to achieve the same level of illumination. The report concludes that the light color of concrete results in a cost-saving of up to 31 percent for night-lighting, , as indicated in Fig.2.4, including construction, energy consumption and maintenance, when compared with the lighting requirements of asphalt pavement [48].

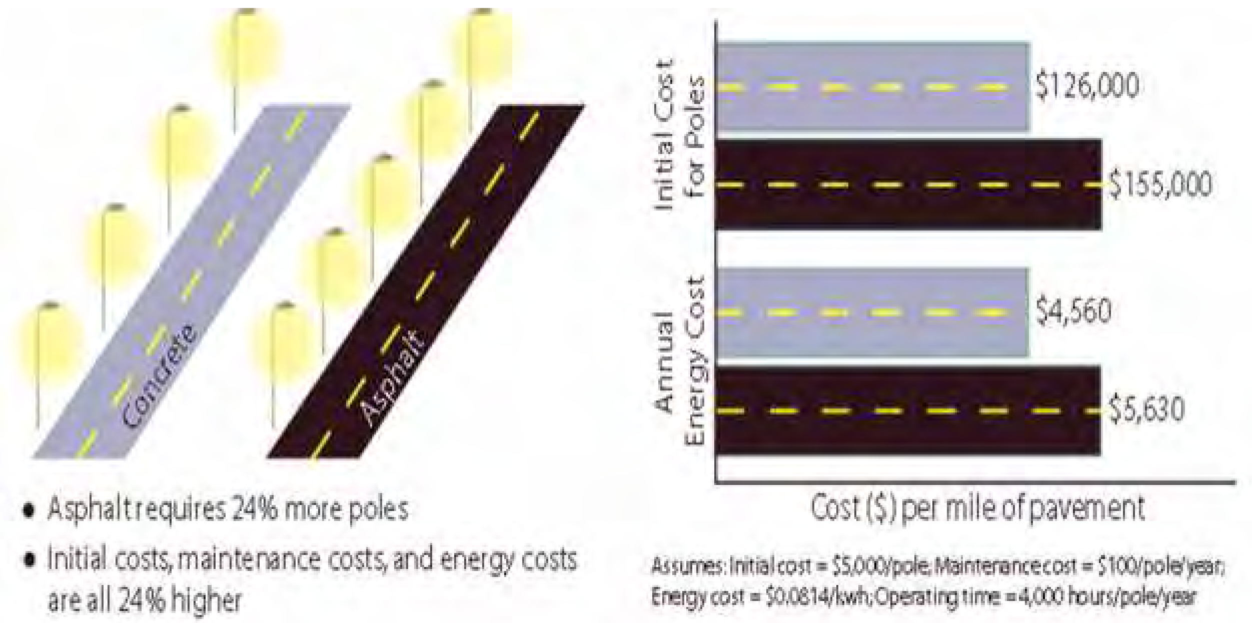

Figure 2-4 Energy cost comparison of pavement alternatives; Source: ACPA 2007 (Page 7)

2.9.2.7 Easy, Fast-Track Maintenance

The cement and concrete industries have developed methods for rapid maintenance and restoration of highways. ERA and/or AACRA can use pre-cast concrete pavement panels both for fast-track maintenance and reconstruction techniques and to minimize user delays [43]. Because maintained or reconstructed roads with this system facilitates to open the road for traffic immediately up on completion of tasks.

2.9.3 Environmental Benefits

2.9.3.1 Uses Less Energy

The Athena Sustainable Materials Institute compared equivalent concrete and asphalt pavement designs for a typical Canadian high-volume highway from a Life Cycle Analysis perspective [49]. The report revealed that over a 50-year period, the embodied primary energy required to construct, maintain and rehabilitate a highway is three times higher for the asphalt design than for its typical concrete equivalent pavement structure. According to the Canadian report, if one uses concrete shoulders and concrete restoration with no overlay as part of the Maintenance and Rehabilitation schedule, the primary embodied energy is 5.6 times higher for the asphalt option. Embodied primary energy is all of the energy required in bringing a material to its final product, including transportation [43].

2.9.3.2 Heavy Truck Fuel Savings and Reductions in Emissions

Profile stability is a term used to describe the ability of a pavement surface to resist deformation and deflection caused by sustained and repeated loading. Unlike asphalt pavement, which is viscoelastic and therefore sensitive to both temperature and loading, concrete pavement's rigid surface does not deform under heavy vehicle loading and therefore deflects less. This not only makes concrete pavement less susceptible to the formation of heavy-vehicle wheel ruts and the associated increased hydroplaning potential, it also positively impacts vehicle fuel consumption.

Fuel consumption is partly a function of the degree to which a pavement deflects in response to the load applied as the wheels of heavy vehicles traverse the surface. Any deflection absorbs some of the energy that would otherwise be available to propel the vehicle forward [17].

Extensive studies by the National Research Council of Canada confirm previous findings showing that fully loaded tractor-trailers consume less fuel traveling on concrete pavements than on asphalt pavements over a wide temperature range [43, 50]. When compared to asphalt, under actual road test conditions, reductions in fuel consumption on concrete pavement ranged from 0.8 to 6.9 percent. These results are statistically significant. CO_2 and other harmful emissions are also reduced.

To confirm the potential fuel savings in the Canadian climate, a year-long study was performed by the National Research Council of Canada (NRC) for the Cement Association of Canada. This study concluded an average of 11% fuel savings, as shown in Table 2.4 below, for trucks travelling on concrete roads [51, 52]. Table 2.2 below identifies the potential yearly savings for the maximum, minimum, and average percent diesel fuel saved in dollars, carbon dioxide, nitrogen oxides, and sulfur dioxide if one tractor-trailer unit traveled 160,000 km in a year [17]. Table 2.3 elaborates a yearly potential savings in fuel cost ($) for a typical major arterial highway of 100 km long and carries AADT of 20,000 with 15% trucks. From the results we can see that the average yearly fuel cost (ETB) saved is 31,460,000.00 which is equivalent to 3 km pavement construction cost with CRCP.

Table 2-2 Yearly potential savings in cost of fuel, CO_2, NO_X, and SO_2 per tractor trailer [17]

Fuel Savings (%)	**Fuel Saved (gal)**	**Fuel cost saved ($)**	**CO_2 (tons)**	**NO_x (kg)**	**SO_2 (kg)**
Min. = 0.80	549	435	1.66	16.9	2.18
Ave. = 3.85	2650	2100	8.06	82.6	10.4
Max. = 6.90	4,730	3,760	14.4	148	18.7

Table 2-3 Yearly potential savings in cost, CO_2, NO_x, and SO_2 for a typical major arterial highway of 100 km long & carries AADT of 20,000 with 15% trucks [17]

Fuel Savings (%)	**Fuel Saved (gal)**	**Fuel cost saved ($)**	**CO_2 (tons)**	**NO_x (kg)**	**SO_2 (kg)**
Minim. = 0.80	377,000	298,000	1,150	11,700	1,490
Ave. = 3.85	1,010,000	1,430,000	5,510	50,700	7,170
Max. = 6.90	3,250,000	2,570,000	9,880	102,000	12,800

Table 2-4 Estimated fuel savings when operating on concrete pavement compared to asphalt pavement

Source	**Vehicle Type**	**Fuel Savings**
Detroit Diesel Spec Manager™ Program	Trucks	8 – 17.5%
Dr. Zaniewski Study	Trucks	Up to 20%
NRC	Trucks	Average 11%

Source: Comparative research conducted by the National Research Council of Canada, Aug. 2000

2.9.3.3 Reusable and Recyclable

At the ultimate end of its fatigue life, concrete pavement can be crushed and reused in many ways, for example, as granular fill, sub-base material, or base course for new pavement. A 2005 study conducted by the Construction Materials Recycling Association revealed that about 130 million to 140 million tons of concrete were crushed and recycled in United States of America in 2004 [17].

2.9.3.4 Reduces Required Road Base Material

Compared to flexible asphalt pavement, rigid concrete pavement requires thinner granular sub-bases because it distributes the weight of vehicles more evenly over a larger area. Typically, in most cases, up to 50 percent less granular material is required for a concrete highway road base, reducing both costs and the use of scarce resources. An asphalt pavement is not as rigid and does not spread loads as widely. Therefore, asphalt pavements usually require more layers of base granular material at a greater thickness when compared to an equivalent concrete pavement design [17]. Furthermore, less hauling of granular material, results in significant fuel savings and associated emission reductions.

2.9.3.5 Makes Use of Industrial By-Products

In most concrete used for highways in North America, some of the Portland cement is replaced or supplemented with one or more industrial byproducts. These byproducts are often referred to as supplementary cementitious materials (SCMs). The three most commonly used SCMs are fly ash (byproduct of coal burning), slag cement or ground granulated blast furnace slag (byproduct of iron production), and silica fume (byproduct of silicon or ferrosilicon alloy manufacturing) [17].

Using SCMs in concrete pavement has several environmental benefits. First, recovering industrial byproducts avoids the use of virgin materials needed for cement manufacturing. Additionally, beneficial utilization reduces the amount disposed in landfills. More importantly, however, are the greenhouse gas and energy reductions achievable by using SCMs to replace a portion of Portland cement. CO_2 and energy savings are related to the percentage of SCM used in the concrete mixture design. Many state highway agencies in United States of America allow up to 25% of

Portland cement to be replaced with fly ash and 50% to be replaced with slag cement; some states even allow higher SCM replacement levels [17].

2.9.3.6 Reduces Urban Heat Island Effect

Large cities can be several degrees warmer than outlying areas in the summer, due to the heat absorbed by dark surfaces such as asphalt pavements. This temperature increase, known as the urban heat island effect, can be reduced by using concrete pavement because of its light colour and reflective properties [8].

The heat island effect can contribute significantly to energy consumption for air conditioning to cool urban buildings. This not only consumes energy and costs money; it also leads to higher emissions from power plants. One estimate is that the increase in temperature due to heat island effects accounts for 5 to 10% of peak urban electric demand for air conditioning use [53].

Paving urban roadways with concrete is an effective strategy to help mitigate urban heat island effects. With their higher albedo, concrete pavements reflect significantly more sunlight and are cooler than asphalt pavements. Research conducted at the Lawrence Berkeley National Laboratory suggests that, when exposed to sunlight, lighter-colored concrete pavements typically have surface temperatures approximately 12°C lower than darker-colored asphalt pavements [54].

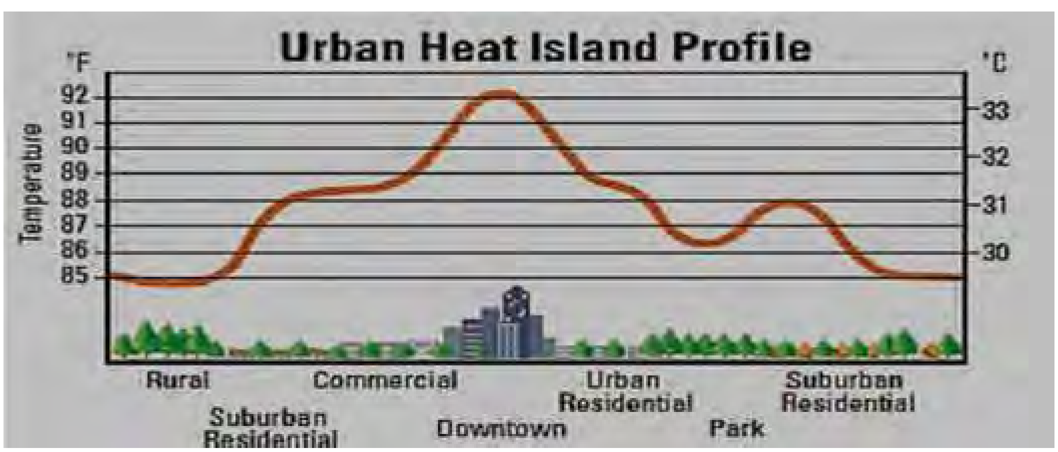

Figure 2-5 Illustration of an urban heat island profile; Source: EPA 2003

2.9.4 User Benefits

2.9.4.1 A Smooth and Comfortable Ride

Pavement smoothness affects both quietness and comfort on highways. Improvements in concrete paving equipment and construction techniques have helped contractors to construct smoother and quieter concrete pavements in recent years.

Nova Scotia Department of Transportation and Public Works five-year study on adjoining sections of asphalt and concrete pavement built in 1994 on their Highway 104, found that the concrete pavement section outperformed the adjoining asphalt pavement in both smoothness and riding comfort [55].

Data from the comparative study shows that although new asphalt pavement had a higher initial riding comfort index (RCI), it deteriorated over time to a lower level than adjoining concrete pavement. The study also demonstrated that the concrete pavement section maintained a smoother ride than the asphalt pavement over the same evaluation period. The values show that concrete pavement section retained most of its original smoothness, while the asphalt section showed increased roughness [55].

In a more recent study that evaluates pavement roughness in the Unites States, similar results were obtained, supporting the Nova Scotia findings described above. Long-term pavement performance data for Kansas roads show that roughness increased more quickly on asphalt roads than concrete roads (69.9 percent increase on asphalt sections over 8 years vs. 3.7 percent increase on concrete sections over 9 years) [55]. Significantly, this accelerated deterioration occurred on the asphalt sections although the concrete roads carried 3.5 times more truck traffic [56].

2.9.4.2 Quiet Surface Textures

One of the advantages of concrete pavements is that virtually any texture can be created during finishing operations, including textures that minimize tire–pavement noise while maintaining wet- and dry-weather friction for the life of the pavement. Research by the concrete paving industry is currently underway to identify optimal textures for low noise generation at the tire–pavement interface in a variety of circumstances. In North America, a significant amount of noise issues are related to existing transversely-tined concrete pavements. Consequently, some of the ongoing research is focused on identifying diamond grinding techniques for retexturing pavement to produce the "quietest" surface textures [17].

2.9.5 Safety Benefits

2.9.5.1 Less Potential for Hydroplaning

Hydroplaning is the loss of contact between vehicle tires and roadway surface that occurs when vehicles travel at high speeds on pavement surfaces with standing water. The non-rutting quality of concrete pavement reduces the potential for hydroplaning. Concrete pavement can be textured to create a roughened surface for good skid resistance, and grooved to help carry rainwater away from the road surface for improved traction as compared to asphalt pavement, thus providing safer roadways.

2.9.5.2 Better Night-Time Visibility

The light color of concrete results in better night-time visibility for motorists. It reflects light from vehicles and street lamps better than asphalt pavement, thus revealing potential hazards [8].

2.10 Economic Analysis Approach

2.10.1 Components of a Life Cycle Cost Analysis

Several economic analysis techniques can be used to assess pavement type options. The two most popular are the Net Present worth (NPW) method and the Internal Rate of Return method (IRR). The IRR method simply asks what rate of return makes the Net Present Worth equal to zero. In some countries, the Equivalent Uniform Annual Cost (EUAC) method is also common. The EUAC method is developed from the NPW so as to explain the average cost an agency will pay per year over the analysis period. All costs including initial construction and future maintenance are distributed equally. This method can be used to evaluate and compare options even though this value system may not seem realistic in times when little pavement action is required [57].

The economic evaluation has the following principal inputs:

- Base year traffic
- Existing road inventory and condition data
- Vehicle fleet and operating cost data
- Economic and traffic growth forecasts
- Project works and maintenance costs
- Project evaluation parameter

The principal outputs of the evaluation are indicators of economic viability:

- Net Present Value (NPV): discounted project benefits – discounted project costs
- Economic Internal Rate of Return (EIRR): the discount rate at which NPV = 0

Net present value method (present worth) method is based on the discounted cash flow technique. In this method, the stream of Cost/benefits associated with the project over an extended period of time is calculated and discounted at a selected discount rate to give the present value. Benefits are related as positive and costs are as negative and the net present value is found. Any project with a positive net present value is treated as acceptable. In comparing more than one project, a project with the highest net present value should be accepted. The internal rate of return is the discount rate which makes the discounted future benefits equal to the initial outlay. In other words, it is the discount rate which makes the stream of cash flows to zero. The minimum requirement of a project in terms of economic viability is to produce a positive NPV and an EIRR greater than the discount rate. In general, however, it is necessary to achieve more convincing results than the minimum requirements because of competing projects and limited funds [58].

LCCA is used to compare the relative long term costs of different pavement alternatives. LCCA allows the Engineer to objectively evaluate costs of two or more rehabilitation and/or new/reconstruction alternatives that may have significantly different initial costs and require very different levels of future preventive maintenance expenditures [58].

Life-cycle cost analysis procedure is desired when developing alternates, especially during the preliminary design stage. Life-cycle cost analyses are used for the prediction of future costs of proposed pavements over a given period of time, using the best available information as to total costs and predicted performance. Pavement designs will consider similar traffic and comparable age for the alternatives [59]. Factors considered in the economic analysis for comparison of the pavement type included initial construction cost, the expected maintenance costs, road-user delay costs, and the expected salvage value at the end of the analysis period [58].

Future costs are discounted to their present value, which allows comparison of different alternatives. Federal Highway Administration’s September 1998 Interim Technical Bulletin, Life Cycle Cost Analysis in Pavement Design, states that “good practice suggests conducting LCCA using constant dollars and real discount rates.” It goes on to say that “real discount rates reflect the true time value of money with no inflation premium and should be used in conjunction with no inflated dollar cost estimates of future investments” [59].

Several components make up the framework of a comprehensive life cycle cost analysis methodology. Inherent in the definition of life cycle cost analysis is the idea that all costs involved in a pavement’s construction, maintenance, rehabilitation, social and economic impacts, and any other costs that can be attributed to the use, care and maintenance of a pavement and highway section are captured and considered in the design decision process. Each component of a life cycle cost methodology is reduced and combined with other components in some way to produce a cost that is borne by some entity. The major costs included in the life cycle cost process are divided into two major categories: agency costs and user costs [13].

Different pavement types have different cost profiles over their lives. Initial construction costs of a pavement are often surpassed by the costs of operation. Whole-life costing analysis is used to identify the extent and timing of the costs involved and to help choose the most cost-effective pavement type. It uses net present worth (NPW) or net present value (NPV) for the assessment of future costs to provide a common basis of comparison of those costs [6].

2.10.1.1 Initial Cost

The initial costs have a major impact on the total PW. The initial costs are determined at year zero of the analysis period. Although numerous activities are performed during the construction, reconstruction or major rehabilitation of a pavement, only those activities that are specific to a pavement alternative should be included in the initial costs [57].

Comparing the initial cost of construction involves the calculation of material quantities to be provided in each pavement structure and multiplication by their unit prices. Material quantities are generally direct functions of their thicknesses in the structure. They are also functions of thicknesses of other layers and width of pavement and shoulders. The cost of in-place material in a pavement structure is not directly proportional to the volume required. Unit material price is dependent on material quantity to be provided, construction procedure employed, length of project, etc. Therefore, care should be taken to estimate quantities and true expected costs carefully. A 5 cm layer, for example may not be twice as expensive as a 2.5 cm layer because the labor involved in each operation is the same [4].

2.10.1.2 Maintenance and Rehabilitation Costs

All pavement types need maintenance, which can be periodic, preventive (routine) or corrective, during their service life. At a certain time, a pavement must be renewed. Maintenance and rehabilitation cost includes materials, equipment, staff salaries etc. The timing and amount of these activities vary from year to year. In Ethiopia, they are usually concentrated on the dry months, November to May. Cost data for preventive type maintenance are often not very easy to obtain or to predict.

The estimates of all costs which are essential to maintaining pavement investment at a desirable specified level of service, or at a specified rate of deteriorating service, is essential to a proper economic analysis. The level of maintenance, i.e., the type and extent of maintenance operations, determines the rate of loss of riding quality or serviceability index [4].

2.10.1.3 Salvage or Residual Value

Salvage or residual value is used by some agencies in economic evaluation. It can be significant in the case of pavements because it involves the value of reusable materials at the end of the design period. With the depletion of resources, such material can become increasingly important in the future, especially when used in a new pavement by reworking or reprocessing [4].

2.10.1.4 User Costs

User costs are not commonly used in pavement tendering processes due to the difficulty of calculating the values and the fact that they can overwhelm the Agencies' pavement costs. However, some agencies are beginning to use user costs in the United States and some Canadian DOTs are looking into this area too. Each alternative pavement strategy is associated with a number of indirect or non-agency costs which accrue to the road user and must be considered for a rational economic analysis. Such costs cannot be ignored because, similar to pavement costs, user costs are related to the roughness or serviceability history of the pavement [4].

The three main areas of user costs are as follows:

1. Vehicle Operating costs: Fuel consumption, Tier wear, Vehicle maintenance, Oil consumption, Vehicle depreciation and Parts replacement.
2. User Travel Time cost or delay cost
3. Accident or crash costs: Fatal Accidents, Non-fatal accidents and Property damage.

Each of the costs given above is a function of roughness level as well as vehicle speed resulting from such roughness level [4].

Delay of user costs are intended to cover the user cost associated with delays when the capacity of a roadway is reduced due to roadway construction and rehabilitation lane closures. These costs include things such as idling costs and delay of time costs as the vehicles slow down through the work zone or wait at construction zones and take longer route due to detour [60].

Accident costs are those costs attributed to motor vehicle accidents. These costs are normally considered when work zones are in effect during rehabilitation work. The costs are normally calculated by multiplying the estimated accident rate by the average cost per accident [60].

Travel time delay is normally the greatest component of user costs, since the value of time and the number of hours spent in work zone queues are multiplied to determine the total cost of travelers sitting in traffic. When motorists sit idle in vehicles longer than they would have under normal traffic conditions, the time lost is a cost borne by each individual passenger. However, this is a cost that must be considered when a decision is made as to the proper design for a highway project. Minimizing the disruption of traffic flow during each construction (and therefore, work zone) period throughout the analysis period is an important aspect of any highway project's design. The user costs associated with highway construction usually exceed the agency's construction costs by a substantial amount, particularly in urban areas [13].

Vehicle operating costs: Mostly as a result of increased fuel usage, wear on tires and other parts. Vehicle operating costs increase during maintenance periods. In service vehicle operating costs are a function of pavement serviceability level, which is often difficult to estimate [14].

User delay costs: User delay costs are connected with road users' time. Usually timesaving is mentioned as one of the key benefits in transportation projects [14].

User costs mostly increase during maintenance and rehabilitation periods, when traffic is completely shut down or diverted into other lanes. Time delay cost is mostly due to changes in speed. Speed changes are the additional cost of slowing from one speed to another and returning to the original speed. Time value depends on the vehicle type and the purpose of the trip. However, user delay costs are one of the most difficult and most controversial life-cycle cost analysis parameters: they are extremely difficult to calculate because it is necessary to put a monetary value on individuals' delay time [18].

2.10.1.5 Analysis Period

The analysis period refers to the time for which the economic analysis is to be conducted. The analysis period can include provision for periodic surface renewal or rehabilitation strategies which will extend the overall service life of a pavement structure to 30 or 50 years before complete reconstruction is required [4].

2.10.1.6 Discount Rate

Cash flow streams are converted to Net Present Worth (NPW) by using discount rates so that the economic worth of different alternatives can be compared. The discount rate used in an agency's cash flow calculations is a policy decision that may vary with the purpose of the analysis, the type of agency, and with the degree of risk and uncertainty.

2.10.1.7 Present Worth Method

The PW method involves conversion of all future costs to the present using an appropriate discount rate. All costs are predicted and are reduced to an equivalent single cost. Present-worth costs of the strategies provide a fair comparison basis, all other things being equal [4].

2.10.1.8 Traffic Analysis

The volume and composition of traffic has always been a major focus of pavement design due to the impact it has on determining the thickness of the pavement. Traffic has been traditionally described as the number of vehicles using the road in terms of the Average Annual Daily Traffic (AADT). In the 1993 AASHTO Design Guide, the traffic was described in terms of Equivalent Single Axle Loads (ESALs), which described the total damage caused by different vehicles in terms of the damage caused by 80 KN single axles [4].

The deterioration of paved roads is caused by traffic results from both the magnitude of the individual wheel loads and the number of times these loads are applied. Hence, to design a paved highway, it is necessary to consider not only the traffic volume or the total number of vehicles that will use the road but also to predict the number of repetitions of each axle load group (or wheel load group) during the design period. To convert the traffic volumes into cumulative equivalent standard axle loads (CESAL which is one design parameter in pavement design) equivalency factors are used [61].

2.10.2 Axle load surveys

Axle load surveys must be carried out to determine the axle load distribution of a sample of the heavy vehicles using the road. Data collected from these surveys are used to calculate the mean number of ESA for a typical vehicle in each class. These values are then used in conjunction with traffic forecasts to determine the predicted cumulative equivalent standard axles that the road will carry over its design life [62].

Once the axle load data has been gathered, it remains to be used to determine the mean equivalency factor for each class of vehicle. Computer programs may be used to assist with the analysis of the results from axle load surveys. The thickness of pavement is governed by the number of repetition of a standard vehicles or axle load usually the 80 KN single axle load. If the axle load is not 80 KN or by an equivalent axle load factor (EALF) the number of repetitions under each single- or multiple axle load must be multiplied by its EALF to obtain the equivalent effect based on 80 KN single axle load. A summation of the equivalent effect of all axle loads during the design period results in an equivalent single axle loads (ESAL) which is the single traffic parameter for the design purposes. This method is widely used in most countries for highway pavement design; ERA follows the producer of fixed vehicle for highway pavement design. The axle loads can be converted and compared using standard factors to determine the damaging power of different vehicle types. A vehicle's damaging power, or equivalency factor (EF), can be expressed as the number of equivalent standard axles (ESAs), in unit s of 80 KN. The design lives of pavements are expressed in terms of the ESAs they are designed to carry [62].

Finally, the cumulative ESAs over the design period (N) are calculated as the products of the cumulative one-directional traffic volume (T) for each class of vehicle by the mean equivalency factor for that class and added together for each direction. The higher of the two directional values should be used for design.

The relationship between a vehicle's EF and its axle loading is normally considered in terms of the axle mass measured in kilograms. The relationship takes the form as indicated in Eq. 2.1 below:

$$\text{Equivalency factor} = (\text{Axle}_i/8160)^{n} \quad \text{(Eq. 2.1)}$$

Where:

Axle_i = mass of axle i

n = a power factor

The power factor varies depending on the pavement construction type and subgrade but which can be assumed to have a value of 4.3 and the standard axle load is taken as 8160 kg with the summation taken over the number of axles on the vehicle in question [10].

3. RESEARCH DESIGN AND METHODOLOGY

As mentioned in section 1.3 of this research, the aim of the research was to identify the sustainable and economical pavement material in arterial roads of Ethiopia by making life cycle cost comparisons and economic analysis of Cement Concrete with Asphalt concrete pavement materials in selected representative roads of the country; considering asphalt pavement as a base case and project case of CCP for comparison. The research design and methodology followed towards this end are discussed as follows.

3.1 Literature Review

A comprehensive literature review was made to understand the previous efforts, practical situations which include the review of textbooks, design manuals, commercial websites, previous studies by different professionals in different countries, periodicals and academic journals, seminar, conference and research papers.

3.2 Main Research

In this research, it was decided to build a model based on LCCA methodology and test it by comparing asphalt and concrete pavements. The model will be tested using two traffic groups: $50*10^6$ ESA and $80*10^6$ ESA. For each traffic group, two pavement behavior scenarios will be built: one for asphalt pavement and the other for concrete pavement. The LCCA applied here includes all costs that are involved in the manufacture and use of the product during its lifetime; it was decided to compare alternatives by using the Present Worth method. A more detailed description of LCCA can be found in chapter 2.

The components of LCCA were divided into two categories, agencies' costs and user costs. Agencies' costs include initial construction, rehabilitation and maintenance costs. Others costs, such as engineering design and land acquisition, were not considered. User costs such as vehicles operating costs, accident costs, discomfort costs etc. were considered equal for both pavement types. The only user costs to be considered will be fuel consumption costs and straight light requirement costs, because other data for user costs are difficult to collect and quantify due to lack of availability.

3.2.1 Data Collection

Traffic data were collected from ERA's historic data from annual inventories. We took initial traffic data (AADT) from those inventories for each specific road segment.

Construction material, labor and machinery unit costs were taken from current market values during the time of data collection, November 2014.

3.2.2 Analysis Period

Experience in the US shows the life of concrete pavement is often more than 20 years, while the life of asphalt pavement in Ethiopia is around 15 to 20 years, depending, of course, on traffic intensity and type of surfacing applied. The Federal Highway Administration (FHWA) recommends an analysis period of at least 35 years [9]. An analysis period of 40 years was chosen for this research so that it could include full design period for concrete pavement, depending on the traffic level.

3.2.3 Discount Rate

Discount rate is used to convert the future benefits and costs of projects to present value. The higher the discount rate, the lower the net present worth of future costs will be. Thus, higher rates render initially expensive projects less profitable, while lower rates render them more so. A discount rate of 10% was used in this study as recommended by Ministry of Finance for evaluation of project feasibilities in Ethiopia.

3.2.4 Traffic Analysis and Pavement Design

Traffic analysis and forecast were conducted using the applicable trend of traffic projection practices of the country. Two different traffic classes were selected for equivalent pavement design works for the two alternative pavement types.

Assessment was made on the existing pavement design type selection practices and conditions in our country in relation to international practices. Equivalent pavement design works were carried out for the two pavement alternatives using different traffic volumes based on the traffic analysis data.

3.2.5 Project Data Used

A 1 km length and 7.3 m width representative arterial road were chosen from the five out let roads at the out skirts of Addis for the two alternative pavement options.

3.2.6 Data Analysis

It is the part and parcel of the main research to integrate and make analysis of the collected and computed data to come in to picture of this research. Hence, the following core tasks were carried out in the data analysis scheme.

- The Present Worth method was used for cost comparison and economic analysis purpose.
- Initial cost estimates were carried out for each alternative pavement structure based on current market rates of each specific cost components.
- Life cycle maintenance and rehabilitation costs were adopted from international practices with some modifications to be suited for our specific country.
- User benefits and sustainability issues were assessed in this study.
- Cost comparison and economic analysis of concrete and asphalt pavement roads were conducted.
- The results were presented in Tables and graphical form and interpretation and discussion were made on the research findings.

Based on the findings conclusions are drawn and recommendations are forwarded.

4. RESULTS AND DISCUSSIONS

4.1 Introduction

The economic evaluation compares the costs of the proposed projects with the major monetized benefits resulting from the projects to provide an indication of their value for money as currently layout. Factors considered in the economic analysis for comparison of the pavement type included initial construction costs, the expected maintenance costs and some road-user benefits in the analysis period [63].

Many factors influence in the selection of the type of pavement to build. Some of the main factors include: traffic, soil characteristics, climate/weather, construction considerations, recycling and cost comparison. There are also secondary factors such as: performance of similar pavements in the area, conservation of materials and energy, availability of local materials, traffic safety, traffic noise mitigation, experimental features and local preference [64].

More recent studies conducted by the Asphalt and Concrete industry bring insights on how to apply LCCA methodology to compare pavement types. However, each industry defends the type of pavement of its preference [64].

The objective of the economic evaluation is to establish the value for money of the proposed projects as currently laid down using clearly defined inputs and specified criteria of viability. Wherever possible, data freshly collected for the projects has been used and the evaluation methodology follows internationally established best practices.

The projects have been taken from the five out lets of Addis and 1km length is taken from each section having its own component evaluation parameters to identify the relative sources of costs and benefits.

The economic evaluation has the following principal inputs:

- Design life
- Base year traffic

- Existing road inventory and condition data
- Economic and traffic growth forecasts
- Pavement design for the two alternatives
- Vehicle fleet and operating cost data
- Project works and maintenance costs
- Project evaluation parameters

The principal outputs of the evaluation are indicators of economic viability:

- Net Present Value (NPV): discounted project benefits – discounted project costs
- Net Present Value/Cost (NPV/C): NPV / discounted scheme costs
- Economic Internal Rate of Return (EIRR): the discount rate at which NPV = 0

The minimum requirement of a project in terms of economic viability is to produce a positive NPV and an EIRR greater than the discount rate. In general, however, it is necessary to achieve more convincing results than the minimum requirements because of competing projects and limited funds. But the researcher used NPV or Present Worth (PW/PV) method for this research as Life Cycle Cost (LCC) comparison is the main component of the study and the pavement with less LCC output is concluded to be the feasible pavement option. Sustainability is also one of the evaluation tools for this research.

4.2 Design life

Determining an appropriate design period is the first step towards pavement design. Many factors may influence this decision, including budget constraints. However, the designer should follow certain guidelines in choosing an appropriate design period, taking into account the conditions governing the project. Some of the points to consider include [5]:

- Functional importance of the road
- Traffic volume
- Location and terrain of the project
- Financial constraints
- Difficulty in forecasting traffic

Usually it is economical to construct roads with longer design periods for important roads and for roads with high traffic volume. Where rehabilitation would cause major inconvenience to road users, a longer period may be used. For roads in difficult locations and terrain where regular maintenance proves to be costly and time consuming because of poor access and non-availability of nearby construction material sources, a longer design period is also appropriate [5].

Difficulties in traffic forecasting may also influence the design period. When accurate traffic estimates cannot be made, it may be advisable to reduce the design period to avoid costly overdesign and to adopt a stage construction strategy to cater for unexpected traffic growth [63].

It is common practice to design concrete pavements for 40 years or more. In this research the selected design life and analysis period is 40 years. Given that the required slab thickness varies linearly with the logarithm of the cumulated number of ESAs. This possibility of designing rigid pavements for more than twice the maximum design life of flexible pavements and the lower associated maintenance costs, make them generally more economical in the long term [10].

4.3 Road Network Data

4.3.1 Road Network Engineering Input

Some models like HDM-4 bases it’s modelling on road sections of homogeneous traffic. Where traffic levels change significantly, for example at a major settlement or junction, it is necessary to have a change of section. A series of sections make up a link within HDM-4. The road sections for the evaluation have been identified, on the basis of traffic, and are summarized in Table 4.1 below which indicates that 1km ideal section is chosen from each out let arterial roads around Addis. Each has its own uniform traffic data (homogeneous section).

Table 4-1 Arterial roads originated from Addis Ababa (representative homogeneous sections)

Route No.	Description	Representative Length (km)
1	AA - D/Brehan	1.0
2	AA - Commando	1.0

3	AA - Dukem	1.0
4	AA - Ambo	1.0
5	AA - Ghion	1.0

Source: selected by The Researcher (each to be Homogenous sections)

The input requirements reflect its reliance on reliable highway engineering data, in particular regarding road construction, condition and maintenance. The construction period for each representative road section is set to be one year (start of 2015 – end of 2015) and the analysis period is 40 years (2016 – 2055) with the discount rate of 10% as shown in Table 4.2. The other engineering requirements where they are included directly as part of the road network data can be summarised as follows:

- Road inventory/geometric data;
- Road construction and maintenance history;
- Road structure;
- Road condition.

Table 4-2 Summary of Assumed time horizon and Discount rate

Construction period	1year (start of 2015- end of 2015)
Analysis period	40 years (start of 2016- end of 2055)
Discount rate	10% (annually)

4.3.2 Road Sections Inventory and Geometries

Information of the Project Roads subject for analysis is provided in Table 4.3 below containing the main data on existing geometry and condition of the road sections: Addis Ababa - (Commando, Ambo, D/Berhan, Dukem, Ghion) out-lets. All listed arterial roads consist of two lane two way carriageway Asphalt roads of 7.0 m width. The roughness measurements and some other data are based on assumptions & field survey reports.

Table 4-3 Condition survey results of representative road sections

Description	Length	Carriage way width	Number of lanes	Shoulder width	Wearing type	Wearing thickness	Road Base (mm)	Sub-base (mm)	Sub grade (CBR %)	IRI (m/km)	Mean rut (mm)	AADT 2013
AA-Commando	1 km	7 m	2	1.5m	AC	100	200	250	7	7.6	3.27	1,947
AA-Ambo	1 km	7 m	2	1.5 m	AC	100	200	250	7	7.85	1.94	1,954
AA-Ghion	1 km	7 m	2	1.5 m	AC	100	200	250	7	8.43	2.0	3,111
AA- Dukem	1 km	7 m	2	1.5 m	AC	100	200	250	7	12.5	4.0	14,502
AA-D/Berhan	1 km	7 m	2	1.5 m	AC	100	200	250	7	8	1.5	1,778

Source: Real conditions with some modifications and assumptions by the researcher for uniformity of projects & ERA Pavement Maintenance Budget Report 2007 EC.

4.3.3 Construction, Maintenance History and Existing Road Condition

The roads were constructed in the RSDPs from 1997 to 2010 and subsequent maintenance has been confined to minor repairs where necessary and routine maintenance.

As the project alternative is to do something type (two new construction alternatives) condition survey data of the existing road condition is not as much importance.

4.4 Traffic Projection Based on Historic Data

In general, future travel is determined by the availability of fuel, growth in population, land use and other economic factors. Highway travel results from passenger demand and freight movements. Passenger travel on highways is mainly conducted by automobiles; station wagons; light, medium and large buses, while freight is hauled by small, medium and heavy trucks.

Traffic forecasting is at best approximate. Traffic is generated as a result of the interaction of a number of contributory factors. Forecasts of traffic have therefore to be dependent on the forecasts of factors such as population, gross domestic product, vehicle ownership, agricultural output, fuel consumption etc. Future pattern of change in these factors can be estimated with a limited degree of accuracy and hence the forecasting of future traffic levels cannot be precise.

Empirical evidence reveals that traffic growth is not correlated to changes in the major economic indicators of the immediate project influence area. In view of this, future traffic projections incorporate analysis of some of the key socio-economic characteristics and rate of change expected during the study period. This however, requires assumptions concerning the elasticity of road transport demand with respect to changes in the overall economy, i.e., economic growth.

Finally, the researcher has adopted the method of Elasticity to forecast future traffic. Hence, the researcher has preferred to assess elasticity of transport demand to estimate future traffic in the project roads.

4.4.1 Elasticity of Transport Demand

This method of long-term traffic forecasting incorporates analyses of some of the key socio-economic characteristics in the road influence area and their anticipated rates of change during the study period, these characteristics being taken as indicators for the future growth of traffic.

The growth rates for normal traffic obtained from this approach take account of the following factors, which affect future traffic levels:

- The prospective growth in the economy,
- The estimated elasticity of demand for transport, and
- Change in the structure of the vehicle fleet, if any.

It must be noted that the growth in agriculture and manufacturing sectors affect the growth of freight vehicles, while growth in population and income level affects growth of passenger vehicles. This method thus incorporates the perspective growth imagined in the national economy and the changes in transport demand elasticises over a period of time as the basic data input.

4.4.2 National Gross Domestic Product (GDP)

The main income development of the country for the last decade or so is shown in Table 4.4. The table shows average annual rates of growth of income and income per head for the period from 2000/1-2013/14. In the period 2000/01, the country witnessed a fairly high growth rate of 8.3% pa, followed by two years of marginal to negative growth rates due to drought. However, the GDP has well recovered from 2003/04 onwards, registering an average growth rate of 10.89% pa. The overall GDP growth rate during the period of 2000-2013 has been recorded at 9% pa.

Table 4-4 GDP, Population and per capita income Development (10^6, ETB)

Year	GDP at constant market price	Change (%)	Population	% Change	GDP per Capita	Change (%)
2000/01	72,181.10	8.3	64.1	0.8	1125.72	7.4
2001/02	73,274.44	1.5	65.9	2.8	1112.07	-1.2
2002/03	71,690.92	-2.2	67.7	2.7	1059.42	-4.7
2003/04	81,421.07	13.6	66.6	-1.6	1223.33	15.5
2004/05	91,044.09	11.8	67.9	1.9	1341.84	9.7
2005/06	100,908.38	10.8	73.1	7.7	1381.30	2.9
2006/07	112,468.46	11.5	74.8	2.4	1504.05	8.9
2007/08	124,602.19	10.8	76.5	2.3	1628.55	8.3
2008/09	135,557.20	8.8	78.3	2.4	1730.21	6.2
2009/10	152,404.69	12.4	80.2	2.4	1899.67	9.8
2010/11	169,641.48	11.3	87.3	8.8	1943.59	2.3
2011/12	184,400.29	8.7	90.1	3.3	2046.04	5.3
2012/13	202,471.52	9.8	93.1	3.2	2175.92	6.3
2013/14	223,326.08	10.3	93.4	0.4	2391.49	9.9
Average rates	**2000/01 – 2013/14**	**9.0**		**3.0**		**6.5**

Sources: (a) MoFED 2014, (b) 1994 & 2007 Population Census and Annual Abstract of Statistics

According to IMF recent report (2014), Based on a partial financing of the Growth and Transformation Plan (GTP I), real GDP growth is projected at 8.2% in 2013/14, 8.5% in the following two years, and to slightly tamp down to 8.0% until 2018/19 and to remain at 6.5% in the outer years. MoFED on the other hand, has set a medium term (GTP: 2010/11 - 2014/15) target rate of growth of at least 11% although very favorable circumstances would be required for this to be sustainable into the longer term one. Bearing in mind that GDP projections have to be made for 40 years period from the year 2016, and based on the sources supporting the medium and long term economic development forecasts as described above, the researcher has considered moderate estimates for the first period of 10 years at7.1% and an average of 6.5% for the next 30 years period as shown in Table 4.5.

In line with the above discussion, three set of scenarios are considered for estimating annual GDP growth in Ethiopia (to be in turn used for estimating the future traffic demand) as follows:

1. **Low**: stagnant to slow growth in the Ethiopian and regional economy.
2. **Medium**: moderate growth in Ethiopian and regional economy as a result of continued government commitment to poverty reduction and a supportive policy environment.
3. **High**: Relatively high growth in Ethiopian economy and assuming that there are no significant shocks (domestic or foreign) to affect the economy.

The growth rates adopted in this study take into account the fact that the economy in the country shall stabilize and maintain a slower rate of growth.

Table 4-5 Expected GDP Growth in Ethiopia; Based on IMF's Forecast

Period	National GDP Growth (% pa.)		
	Low	Medium	High
2016 - 2025	6.5	7.1	8.0
2026 - 2055	6.0	6.5	7

4.4.3 Transportation Demand Elasticity With Respect to GDP

Empirical evidence has long established that demand for transport tends to expand at somewhat faster rate than the economic growth rate as measured by national GDPs. The growth in traffic is typically about 2% per annum higher than the growth in the economy to support and serve this growth. Considering this as high scenario the following elasticity relating to road transport demand to income is reasonably consistent with international experience with the indications offered by the Ethiopian data.

Findings drawn from international studies generally suggest transport demand elasticity as found between 1 and 2. In Ethiopia, detailed empirical evidence have not yet been established and/or made available providing reasonable estimates of income elasticity of demand for transport. Some general forms of estimates, which may be taken as indicative, are however suggested by few studies.

The Network Analysis Study (2003) provides an estimate of income elasticity of demand for transport of different vehicles categories. Based on the findings of the study, estimates of income elasticity have been derived (with adjustments) for this study under consideration to estimate traffic growth rates. Generally, elasticity of demand for transport with respect to economic growth is assumed initially to reflect recent trends, but to decline over time as indicted in Table 4.6.

Table 4-6 Income Elasticity of Demand for Transport

Vehicle Type	**Income Elasticity**	
	2016-2025	**2026-2055**
Passenger Transport		
Passenger cars/4WD	1.4	1.2
Small Buses	1.2	1.1
Large Buses	1.1	1.1
Passenger Transport total	**1.23**	**1.13**
Freight Transport		
Small Trucks	1.1	1.0
Medium Trucks	1.1	1.0
Heavy Trucks	1.2	1.1
Articulated/truck & trailer	1.4	1.2
Freight Transport	**1.2**	**1.08**

Source: From feasibility Studies Under ERA with some Adjustments

In specifying forecasted traffic growth rates for the projection of stream of freight traffic using the road in the future, a simple model has been used that combines the effect of GDP growth on travel demand for freight vehicles. On the other hand, forecasted growth rates for passenger traffic were computed using a model that combines the effect on travel demand of population growth and of changes in per capita incomes. Two models of the following forms were, therefore, applied:

$$\Delta T = e\,(\Delta GDP) \quad \text{(Eq. 4.1)}$$

Where:

ΔT = the change in freight transport

ΔGDP = the change in GDP

e = the income elasticity for freight travel demand. And

$$\Delta T = \Delta P + e\,(\Delta C) \quad \text{(Eq. 4.2)}$$

Where:

ΔT = the change in passenger transport

ΔP = the change in population

ΔC = the change in per capita income

e = the income elasticity for passenger travel demand.

Based on the model relationship specified above, estimate of forecasted traffic growth rates for passenger and freight vehicles category (for three scenarios) are presented in Tables, Table 4.7 to Table 4.9, below corresponding to the forecast traffic growth periods.

Table 4-7 Average Annual Traffic Growth-Low Scenario

Period	National GDP (%)	Population Growth (%)	Growth Per Capita (%)	Elasticity of Vehicles		Average Annual Traffic Growth (%)	
				Pass.	Freight	Pass.	Freight
2016-2025	6	2.4	3.3	1.23	1.2	6.92	6.78
2026-2055	5.5	2.4	2.8	1.13	1.08	5.89	5.68
Average Over the Period						**6.40**	**6.23**

Table 4-8 Average Annual Traffic Growth-Medium Scenario

Period	National GDP (%)	Population Growth (%)	Growth Per Capita (%)	Elasticity of Vehicles		Average Annual Traffic Growth (%)	
				Pass.	Freight	Pass.	Freight
2016-2025	7.1	2.4	4.8	1.23	1.2	8.52	8.34
2026-2055	6.5	2.4	4	1.13	1.08	7.13	6.87
Average Over the Period						7.83	7.61

Table 4-9 Average Annual Traffic Growth-High Scenario

Period	National GDP (%)	Population Growth (%)	Growth Per Capita (%)	Elasticity of Vehicles		Average Annual Traffic Growth (%)	
				Pass.	Freight	Pass.	Freight
2016-2025	8	2.4	5.8	1.23	1.2	9.69	9.48
2026-2055	7	2.4	5.3	1.13	1.08	8.15	7.84
Average over Period						**8.92**	**8.66**

Thus, by considering medium growth scenario with some modifications in comparison to consultants' recent feasibility studies, the following traffic growth rates are adopted for traffic forecasting as summarized and presented in Table 4.10.

Table 4-10 Estimated Annual Traffic Growth Rates

Vehicle Type	Period in years	Growth rate pa (%)
Passenger vehicles (Car, 4WD, Buses)	2013 – 2025	6.5
	2026 – 2055	5.9
Freight vehicles (ST, MT, HT, TT)	2013 – 2025	6.12
	2026 – 2055	5.50

4.4.4 Baseline Traffic

Assuming that the construction of the road will be completed and opened for traffic by the year 2016, the baseline traffic is taken as the projected traffic volume of 2016. Thus, the baseline traffic $AADT_b$ is computed using the relation as follows in Eq. 4.3:

$AADT_b = AADT_o(1+r)^n$---(Eq. 4.3)

Where:

$AADT_b$= Baseline AADT ($AADT_{2016}$)

$AADT_o$= Normal AADT ($AADT_{2013}$)

r = growth rate (fraction)

n = number of years elapsed from the time of counting to the period of opening of the road opened to traffic

The baseline traffic volumes on each road are computed with Eq.4.3 above from ERA's historic traffic data up to 2013 and presented in the Tables (from Table 4.11 to Table 4.15) below.

Table 4-11 Baseline traffic on AA – D/Berhan

	Car	LR	MB	LB	ST	MT	HT	TT	Total
$AADT_{2013}$	103	182	529	120	203	327	242	70	1778
$AADT_{2016}$	124	220	639	145	243	391	289	84	2136

Table 4-12 Baseline traffic on Addis Ababa - Commando

	Car	LR	MB	LB	ST	MT	HT	TT	Total
$AADT_{2013}$	102	167	116	243	275	243	201	102	1947
$AADT_{2016}$	123	202	140	290	329	291	241	123	2340

Table 4-13 Baseline traffic on Addis Ababa - Dukem

	Car	LR	MB	LB	ST	MT	HT	TT	Total
$AADT_{2013}$	1560	2115	847	1829	2088	2238	1776	1560	14502
$AADT_{2016}$	1755	2379	1023	2172	2480	2680	2146	1755	17110

Table 4-14 Baseline traffic on Addis Ababa - Ambo

	Car	LR	MB	LB	ST	MT	HT	TT	Total
$AADT_{2013}$	79	363	628	73	46	318	233	214	1954
$AADT_{2016}$	89	408	759	89	54	377	279	259	2314

Table 4-15 Baseline traffic on Addis Ababa - Ghion

	Car	LR	MB	LB	ST	MT	HT	TT	Total
$AADT_{2013}$	279	436	815	199	267	552	358	207	3111
$AADT_{2016}$	314	490	984	241	317	655	429	250	3679

4.4.5 Traffic Projection

The Traffic growth projection was derived considering the Normal Traffic (before Project specific Developments), traffic diverted onto the Project road from other adjoining areas as the Project road become more competitive upon upgrading and also the traffic likely to be generated as a result of the reduced costs of transportation.

The total traffic anticipated in each year within the design period consists of the normal and generated traffics for this research considering that diverted traffic is zero in this scenario. The annual average daily traffic anticipated within the design period i.e. 2016 – 2055 is projected by using the following relation (Eq. 4.4):

$$AADT_n = AADT_b(1+r)^n \text{--- (Eq. 4.4)}$$

Where:

$AADT_n$ = Projected AADT on the n^{th} year

$AADT_b$ = Baseline AADT ($AADT_{2016}$)

r = growth rate (fraction)

n = period between the base year and the n^{th} year

For structural pavement design the cumulative traffic loading of each of the motorized vehicle classes over the design life of the road in one direction is required. For a given class, m, this is given by the following equation (Eq. 4.5):

$$T(m) = 0.5 \times 365 \times AADT(m)_b\,[(1+i/100)^N - 1]/(i/100) \text{--------------------------- (Eq. 4.5)}$$

Where

T (m) = the cumulative traffic of traffic class m

AADT $(m)_b$ = The AADT of traffic class m in the first year

N = the design period in years

i = the annual growth rate of traffic in percent

The projected AADTs over the design period are presented in the Tables in Appendix A. But the commutative design traffics of each class in one direction with Eq.4.5 and computed with equivalent axle load factor formula Eq. 4.6 are shown in Table 4.16 and Table 4.17. The equivalent factor in Table 4.16 is taken from the consultants' feasibility studies for road projects under ERA.

$$CESA = 0.5 * 365 * \sum_{i=2016}^{2055} AADT_i * EF \quad \text{-- (Eq. 4.6)}$$

Where:

CESA = cumulative equivalent standard axles

EF = Equivalence Factor

$AADT_i$ = Annual average daily traffic on the ith year

Table 4-16 Cumulative Traffic in the design lane of each road (10^6) with 10% generated traffic

Route Name	Car	4WD	MB	LB	ST	MT	HT	TT	Total
AA - D/Brehan	4	7	20	5	8	13	9	3	68
AA – Commando	4	6	4	9	11	9	8	4	56
AA – Dukem	56	76	33	69	79	86	69	56	524
AA – Ambo	3	13	24	3	2	12	9	8	74
AA- Ghion	10	16	31	8	10	21	14	8	118
EF	0.001	0.01	0.07	0.77	0.12	0.96	4.5	8.5	

Table 4-17 Cumulative equivalent standard axles on the design lane of each road

Route Name	Car	4WD	MB	LB	ST	MT	HT	TT	Total
AA - D/Berhan	-	-	1.43	2.46	0.93	6.25	41.59	22.83	**75.50**
AA – Commando	-	-	0.31	4.92	1.26	4.65	34.68	33.44	**79.27**
AA - Dukem	-	-	2.29	36.82	9.52	42.86	308.85	477.09	**877.41**
AA- Ambo	-	-	1.70	1.51	0.21	6.03	40.15	70.41	**120.00**
AA – Ghion	-	-	2.20	4.09	1.22	10.47	61.74	67.96	**147.68**

4.4.6 Traffic Classes for Flexible Pavement Design

Accurate estimates of cumulative traffic are difficult to achieve due to errors in the surveys and uncertainties with regard to traffic growth, axle loads and axle equivalencies. As long as the estimate of cumulative equivalent standard axles is close to the center of one of the ranges, any errors are unlikely to affect the choice of pavement design. However, if estimates of cumulative traffic are close to the boundaries of the traffic ranges in Table 4.18, then the basic traffic data and forecasts should be re-evaluated and sensitivity analyses carried out to ensure that the choice of traffic class is appropriate. Depending on the degree of accuracy achieved, if in doubt, selecting the next higher traffic class may be appropriate.

Table 4-18 Traffic classes for Flexible Pavement Design [63].

Traffic Classes (10^6 ESA)	
T1	< 0.3
T2	0.3 – 0.7
T3	0.7 – 1.5
T4	1.5 – 3.0
T5	3.0 – 6.0
T6	6.0 – 10
T7	10 - 17
T8	17 – 30
T9	30 – 50
T10*	50 – 80

* The T10 designs are suitable for traffic of $80*10^6$ ESAs and are considered ‘long life’ pavements.

4.4.7 Design CBR Determination

All pavements derive their ultimate support from the underlying subgrade. Thus, in addition to the volume of traffic, the strength of the subgrade materials is a key factor that affects the structural pavement design and performance. In this regard, laboratory tests should be conducted on subgrades to determine their swell factor, plasticity and strength characteristics (CBR values). The design CBR value of 2% is taken for this research comparison purpose so as to include the worst scenario of subgrade values for the selected routes as one set of comparison and 7% CBR value is also taken for the second set of comparison to evaluate the effect of subgrade strength variations on the two competing pavement alternatives. Table 4.19 shows sub-base and capping layer thickness requirements under cement concrete pavements in response to sub grade strength variations. 2% CBR is categorized under S1 and 7% is under S3. Subsequently, required thicknesses of sub-base and capping layers are known. Pavement thicknesses under flexible pavements will be computed using design catalog of ERA Design Manual 2013 Volume I.

Table 4-19 Thickness of Sub-base and Capping Layers Based on Subgrade Classes [10].

Subgrade Class	CBR range %	Sub-base (mm)	Capping (mm)
S1	2	200	400
S2	3,4	175	350
S3	5 - 8	150	250
S4	8 - 15	150	200
S5	15 - 30	175	0
S6	>30	0	0

4.4.8 Pavement Design

The traffic analysis results shown in Table 4.18 indicates that the design traffics from Route No. 3 to 5 are above $80*10^6$ ESAs which are out of our maximum design charts, ERA 2013, for flexible pavement design options. Therefore it is better to think about the requirement of two way multiple-lane roads like the new AA – Adama express way road. But for our cost comparison and economic analysis purpose, the researcher has selected two assumptions as discussed below.

1. CBR value of 7% (S3) and traffic class of $50*10^6$ ESAs (T9 for Flexible Pavement) are chosen for the design lane and computed for ACP and JRCP options.
2. CBR value of 2% (S1) and traffic class of $80*10^6$ ESAs (T10 for Flexible pavement) are chosen for the design lane and computed for ACP and CRCP options.

4.4.8.1 Flexible Pavement Design

Fig.4.1 is a design catalogue taken from ERA Pavement Design Manual 2013 of Volume I for the design of Flexible pavement options in respect to the above suggested subgrade and traffic classes. Accordingly, the combination of subgrade class (S3) and Traffic value (T9) results in 90 mm AC, 190 mm Bituminous Road Base (BRB), 175 mm Sub-Base (SB) and 150 mm capping layers. Similarly, the combination of S1 and T10 results in 90 mm AC, 220 mm BRB, 250 mm SB and 300 mm capping layers. The computed results are shown in Table 4.20.

4.4.8.2 Rigid Pavement Design

Fig. 4.2 and Fig. 4.3 are design charts for rigid pavement options taken from ERA Pavement Design Manual 2013 of Volume II for the design of rigid pavement options based on traffic classes and strength of concrete materials used. The design class of concrete is taken from alternatives suggested in ERA Pavement Design manual 2013, volume II and determined to be C-40 (40 MPa of the 28 days compressive strength) with tied shoulders.

The required slab thickness varies approximately linearly with the logarithm of the cumulative number of ESAs; therefore designing for longer periods requires relatively small additional slab thicknesses.

Based on the above discussions & the design chart of Fig.4.2, the design thickness of JRCP for the subgrade class (S3), traffic load of $50*10^6$ ESAs and reinforcement requirement of 600 mm/m^2 results in 220 mm JRCP, 150 mm SB and 250 mm capping layers. Additional slab thickness of 25 mm is required for this long life pavement design. Hence the thickness of JRCP becomes 245 mm.

In addition to the longitudinal reinforcement, JRCP pavements should be provided with transverse reinforcement consisting of 12 mm diameter steel bars at 600 mm spacing. Dowel bars of 25 mm in diameter, at 300 mm spacing and 400 mm long are required at the transversal joints. Tie bars of 12 mm diameter at 300 spacing and 1000 mm long are also required at longitudinal joints [10].

The design of CRCP (for S1 and $80*10^6$ ESAs) results in 225 mm CRCP (including 25 mm additional slab thickness for untied shoulder), 200 mm SB and 400 mm capping layers. Longitudinal reinforcement in CRCP pavements should be 0.6% of the concrete slab cross-sectional area, and consist of 16 mm diameter deformed steel bars. Transverse reinforcement should be provided at 600 mm spacing and consist of 12 mm diameter deformed steel bars to prevent the opening of any longitudinal cracks which may form. It is also required for ease of construction [10].

Table 4-20 Pavement Layer Thicknesses

Subgrade Class	**Traffic Class ESAs (10^6)**	**Asphalt Concrete Pavement Thickness (mm)**					**Cement Concrete Pavement Thickness (mm)**		
S3	**50**	AC	BRB	GB	SB	Capping	CCP	SB	Capping
		90	190	0	175	150	245	150	250
S1	**80**	90	220	0	250	300	225	200	400

Source: Design results by the Researcher

Subgrade class	T6 6 – 10	T7 10 – 17	T8 17 - 30	T9 30 - 50	T10 50 - 80
S1	90 130 200 300	90 150 225 300	90 170 250 300	90 190 250 300	90 220 250 300
S2	90 130 200 200	90 150 200 200	90 170 200 200	90 190 225 200	90 220 225 200
S3	90 130 150 150	90 150 150 150	90 170 175 150	90 190 175 150	90 220 175 150
S4	90 130 150	90 150 150	90 170 175	90 190 175	90 220 175
S5	90 130 100	90 150 100	90 170 100	90 190 100	90 220 100
S6	90 110	90 130	90 150	90 170	90 190

Figure 4-1 Flexible Pavement Design Catalogue, Chart D1 [61].

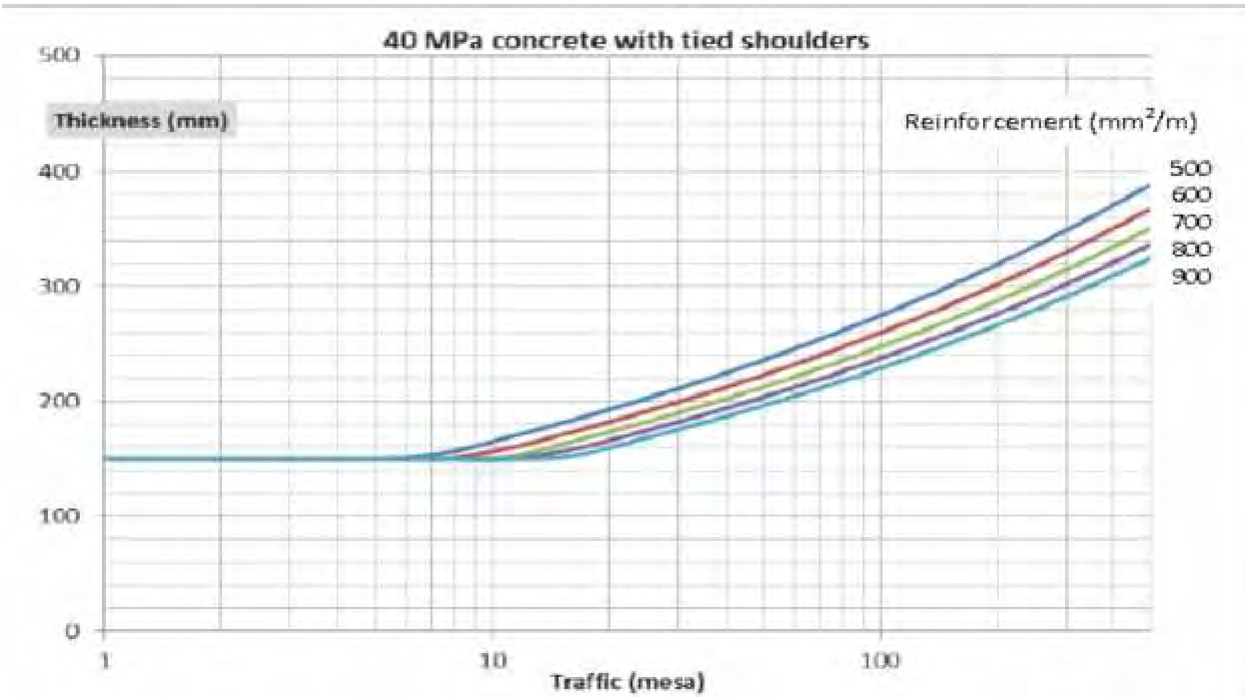

Figure 4-2 Design Thicknesses for JRCP (40 MPa concrete and tied shoulders) [10].

Figure 4-3: Design Thickness for CRCP with tied shoulders [10].

4.5 Vehicle Fleet and Operating Costs

It is also recommended that road user or vehicle operating costs (VOC) are also included in the life cycle cost analysis. This is because vehicle operating costs are the highest costs in a transport system and depend on the surface condition or roughness of the road. Smoother roads will save vehicle operating costs, which include fuel costs, spare part costs and other costs that affect the national economy [10].

A single vehicle fleet and VOC database has been developed for the stated road segments per individual vehicle classes. But as the model, HDM-4 software is not calibrated for our country especially for that of rigid pavement options, this research couldn't evaluate VOC and user delay cost effects during delays because of maintenance activities of the two pavement alternatives.

Thinking that night time maintenance activities will make user delay and vehicle operating costs minor differences on the two competing pavement alternatives, the researcher focuses on other economic parameters for the comparison purposes.

4.6 Economic Evaluation (LCCA)

The economic evaluation of competing alternatives is based on discounting the life-cycle costs and benefits to the present value of birrs. The economic analysis has no relationship to the financing of a project. Such financing considerations can either limit the number of feasible projects (on a network level basis) or limit the amount available for a particular project. The period of analysis should be chosen so that it is possible to forecast the factors involved in the analysis with a reasonable degree of reliability.

A general guideline for selecting the length of an analysis period is that it should not extend beyond the period of reliable forecasts. For long-term projects a range of 20 to 40 years is reasonable. The present worth (PW) of costs or benefits at future times beyond 40 years may not be significant, depending on the discount rate used. PW analysis is the best and most widely accepted method for LCC evaluations. The PW and equivalent uniform annual cost (EUAC) or simply annual cost methods are directly comparable. Using the PW method, the analysis period should be the same for all alternative design strategies. The PW method involves the discounting of all future sums to the present, using a selected discount rate and ignoring inflation. The PW factor for discounting either a future single cost or benefit is calculated using Eq. 4.6 below. It answers: how much a series of payments of M; "invested" for maintenance activities at the end of each of (n) periods at a discount rate (i), is worth today?

$$PW = M\{((1+i)^n-1)/(i(1+i)^n)\} \text{ --- (Eq. 4.6)}$$

Using the time value of money, the different costs occurring through the lifetime or analysis period of a project can be transferred to an equivalent cost at some reference year. For example, the present value of a pavement project will last (n) years, with an initial cost C; a yearly maintenance cost M; and a salvage value S is equal to P (PW) which is the life cycle cost of a pavement at present value. Hence, Eq.4.7 is used to calculate the life cycle cost of a pavement during the economic analysis period. For this research the salvage value (S) at the end of analysis period is assumed to be zero for simplicity and due to performance evaluation result data, at the end of analysis period, limitations in our country.

$$P = C+M\{((1+i)^n-1)/(i(1+i)^n)\}-S\{1/(1+i)^n\} \text{ ---------------------------- (Eq. 4.7)}$$

4.6.1 Initial Construction Costs

The initial costs have a major impact on the total NPW. The initial costs are determined at year zero of the analysis period. Although numerous activities are performed during the construction, reconstruction or major rehabilitation of a pavement, only those activities that are specific to a pavement alternative should be included in the initial costs [57].

By focusing on these activities, the researcher has concentrated on estimating the quantities and costs related to these activities. Data collection for basic material prices at the vicinity of the selected projects has been made and indicated in Table 4.21 below.

Table 4-21 List of Basic Materials Price for Cost Analysis (November 2014)

Average distance of the project from center of Addis Ababa is 15 km and unit price includes transport costs up to proposed projects sites			
Item	Material Description	Unit	Unit Price (ETB)
1	Cement (OPC)	Qtl.	300.00
2	Gas Oil (NOC)	Lts.	18.08

3	Lubricants	Kg.	100.00
4	Reinforcement Bar	Kg.	24.00
5	Nails	Kg.	30.00
6	Binding Wire	Kg.	25.00
7	Eucalyptus Ø12 cm, 4 m long	Pcs.	60.00
8	Lumber 2.5 cm	m^3	4000.00
9	Sand	m^3	450.00
10	Aggregate (20 mm)	m^3	550.00
11	Aggregate for AC (all sizes)	m^3	550.00
12	Bitumen grade 60/70 (NOC)	Kg.	36.00
13	Bitumen grade MC-30 (NOC)	Lts.	36.00

Initial costs per kilometer for the two equivalent pavement design alternatives at two different daily traffic loads of two way two lane 7.3 m carriage way width roads are computed by the researcher.

Unit rates are fixed based on cost break downs on new work items and unit rates of currently awarded projects of similar material type. Ready mix concrete and hot mix asphalt concrete supply prices by MIDROC Construction Ethiopia plc are also taken to compare the reasonability of cost breakdown analysis results made by the researcher. The two cost components discussed herein above are attached in Appendix C of this research.

Based on unit rates and cost break down component inputs to the designed pavement alternatives, initial costs are computed. The computed results shown in the tables from Table 4.22 to Table 4.25 indicate that rigid pavements have significant initial construction cost advantages in the two alternative traffic classes that are selected for this study. The initial cost savings are averagely 22.69% and 26.47% respectively for the two traffic and subgrade combinations, which means Ethiopia can have more length of paved roads with the limited financial budget if CCP is used instead of AC.

Table 4-22 Initial Pavement cost of JRCP at $50*10^6$ ESAs and S3

Description	Pavement layers	Amount	Unit	Quantity per km	Unit Rate (ETB)	Cost(ETB)
Surface	Cement Concrete	245 mm	m^3	1,788.5	4,200	7,511,700.00
	Reinforcement bars	600 mm^2/m	kg	46,318	37	1,713,768.96
Sub-base	Natural(crushed)	150 mm	m^3	1,200	280	336,000.00
Capping	Selected Material	250 mm	m^3	2,000	214.29	428,580.00
Joint Sealing , texturing and curing work (10% of pavement costs)						999,004.90
Total Initial cost per km						**10,989,053.86**

Table 4-23 Initial Pavement cost of AC at S3 and T9

Description	Pavement layers	Amount	Unit	Quantity per km	Unit Rate (ETB)	Cost (ETB)
Surface	AC	90 mm	m^2	7,300	838.34	6,119,882.00
Tack coat	RC-70	1 L/m^2	m^2	7,300	65	474,500.00
Prime coat	MC-30	1.2 L/m^2	m^2	7,300	55	401,500.00
Base layer	Bituminous Road Base	190 mm	m^3	1,387	4,250	5,894,750.00
Sub-Base	SB	175 mm	m^3	1,277.5	280	357,700.00
Sub-grade	Capping	150 mm	m^3	1,095	214.29	234,647.55
Total Initial cost per km						**13,482,979.55**

Table 4-24 Initial Pavement cost of CRCP at $80*10^6$ ESA & S1

Description	Pavement layers	Amount	Unit	Quantity Per km	Unit Rate (ETB)	Cost(ETB)
Surface	Cement Concrete	225 mm	m^3	1,642.5	4,200	6,898,500.00
	Reinforcement bar	$0.6\%/m^2$	kg	86,075.67	37	3,184,799.79
Sub-base	Natural(crushed)	200	m^3	1,600	280	448,000.00
Capping	Selected Material	400	m^3	3,200	214.29	685,728.00
Longitudinal Joint Sealing and curing work (5% of pavement layer costs)						560,851.39
Total Initial cost per km						**11,777,879.18**

Table 4-25 Initial Pavement cost of AC at S1 and T10

Description	Pavement layers	Application	Unit	Quantity per km	Unit Rate (ETB)	Cost (ETB)
Surface	AC	90 mm	m^2	7,300	838.34	6,119,882.00
Tack coat	RC-70	1 lit/m^2	m^2	7,300	65	474,500.00
Prime coat	MC-30	1.2 lit/m^2	m^2	7,300	55	401,500.00
Base course	Bituminous Road Base	220 mm	m^3	1,606	4,250	6,825,500.00
Sub-base	SB	250 mm	m^3	2,000	280	560,000.00
Subgrade	Capping	300 mm	m^3	2,400	214.29	514,296.00
Total Initial cost per km						**14,895,678.00**

4.6.2 Initial and Reconstruction Costs of ACP (on 20 years design life bases)

Alternatively, the selected roads can be designed for 20 years constructed with ACP (2016 – 2035) and reconstructed with revised design considering traffic projections (2036 – 2055). But the rigid pavement option is still for forty years (2016 – 2055) as before. When we compare construction costs, we have to evaluate the sum of initial construction and discounted reconstruction costs against initial cost of rigid pavement.

Traffic analysis and projections are made for the 20 years design period. Accordingly, traffic class of T8 (21.32 *10^6 ESA) is become the average value of the selected roads. Based on this and ERA 2013 Pavement Design Manual Catalogues Chart D1, flexible pavement layers are determined and associated costs are computed as indicated in Table 4.26. The computed results show that initial construction and discounted reconstruction costs of asphalt pavements are still far greater than the rigid pavement options.

Table 4-26 Initial construction and discounted reconstruction costs at different subgrade classes

At S3 and T8					
Pav't layer	Application	Unit	Qty per km	Rate (ETB)	Amount (ETB)
AC	90	m^2	7,300	838.34	6,119,882
Tack coat	1 lit/m^2	m^2	7,300	65	474,500.00
prime coats	1.2 lit/ m^2	m^2	7,300	55	401,500.00
BRB	170	m^3	1,241	4,250	5,274,250

SB	175	m^3	1,400	280	392,000.00
Capping	150	m^3	1,200	214.29	257,148
Total Initial cost per km					**12,919,280**
Discounted Reconstruction cost					**2,004,159.00**
Total Construction Cost per km					**14,923,439.00**
At S1 and T8					
Pavement Composition	Application	Unit	Quantity per km	Rate (ETB)	Amount (ETB)
AC	90	m^2	7,300	1,288.34	6,119,882
Tack Coat	1 lit/ m^2	m^2	7,300	65	474,500.00
Prime Coat	1.2 lit/ m^2	m^2	7,300	55	401,500.00
BRB	170	m^3	1,241	4,250	5,274,250
SB	250	m^3	2,000	280	560,000
Capping	300	m^3	2,400	214.29	514,296
Total Initial cost per km					**13,344,428**
Discounted Reconstruction cost					**2,214,147.62**
Total Construction Cost per km					**15,558,575.62**

4.6.3 Maintenance and Rehabilitation Costs

Table 4.27 gives details of the latest unit costs of asphalt and concrete road maintenance operations in Ethiopia as relevant to the current project. These have been based upon the Countries considerable experience of road maintenance and improvement projects in Ethiopia cross-referenced with recent relevant studies. Unit cost rates have been obtained for those operations anticipated for the study roads.

Unit cost rates for road improvements, including paving to AC/PCC standard, have been on a section-specific basis, the recommended treatment for each section varying slightly depending upon the depth of existing asphalt and the required depth of sub-base. These values are given in Table 4.27 below.

Table 4-27 Maintenance Operation Unit Costs for National Roads in Ethiopia

Operation	Unit	Unit cost (ETB)
Pothole Patching	m^2	1,158.50
Overlay	m^2	300
Mill & Over lay of	m^2	360

25 mm		
Mill & Rehabilitate with 40 mm AC	m^2	506.25
Reseal joints	m	228
Partial depth PCC repair	m^2	1,200
Full depth PCC repair	m^2	1,000
Texturizing	m^2	30
Routine maintenance	Km/year	26,000

Source: ERA Maintenance Schedule for 2007 E.C and partly adjusted

4.6.3.1 Maintenance of Asphalt Pavements

In a typical LCCA, two or more alternate choices are available for an initial pavement design or cross-section. Based on the initial pavement designs, the expected maintenance and rehabilitation over the design life are then determined and incorporated into a single, inflation adjusted, cost in order to evaluate and compare the different options in a fair and consistent manner. Table 4.28 discusses life time maintenance activities and related costs for 1 km road project. The major maintenance activity costs applied at different years of the analysis period are discounted in to Present Worth/Value using Eq. 4.8.

$P(M_a) = Ma*1/(1+i)^n$--(Eq. 4.8)

Where:

$P(M_a)$ = Present value of maintenance activity (M_i) at year n

M_a = Maintenance activity applied at activity "a"

i = Discount rate

Table 4-28 Maintenance and Rehabilitation cost for a conventional asphalt pavement

Year	Maintenance Activity	Unit	Unit cost (ETB)	Cost per km (ETB)	Present Worth (ETB)
5	Over lay of 25 mm AC, 5%	m^2	300	105,000	65,196.74
10	Mill & Over lay of 25 mm AC,	m^2	360	252,000	97,156.91

	10%				
15	Mill & Over lay of 25 mm, 15%	m^2	360	378,000	90,490.19
20	Mill & Rehabilitate with 40 mm AC	m^2	506.25	3,543,750	526,755.9
25	Over lay of 25 mm AC, 10%	m^2	300	210,000	19,382.16
30	Mill & Over lay of 25 mm AC, 15%	m^2	360	378,000	21,662.63
35	Mill & Over lay of 25 mm AC, 20%	m^2	360	504,000	17,934.39
Routine Maintenance		Km/year	26,000.	1,040,000	254,255.32
Total maintenance cost per km				**6,410,750**	**1,092,834.24**

4.6.3.2 Maintenance of Cement Concrete Pavements

Concrete pavements are often constructed for their long service life and the reduced level of maintenance expected due to their slower rate of deterioration.

For the maintenance and rehabilitation of concrete pavements, the most common activities include improving joint performance through resealing, partial depth repairs, and slab replacements with full depth repairs. On higher volume roadways, the smoothness of the roadway has more significance and some surface texturing is recommended to ensure an acceptable performance.

The recommended maintenance and rehabilitation plans are outlined in Table 4.29 and Table 4.30. These plans were developed to provide a consistent level of service in a cost effective manner. The maintenance and rehabilitation quantities provided are for a 1km length of roadway and will need to be adjusted for different section lengths.

Table 4-29 Rigid Major Arterial Road Pavement Preservation Plan (JRCP)

Year	Maintenance Activity Description	Unit	Unit Rate (ETB)	Cost/ km (ETB)	Present Value (ETB)
12	Reseal joints 25%	m	228	72,561	23,120.17
12	Partial depth CCP repair 2%	m^2	1,200	168,000	53,529.98
25	Partial depth CCP repair 5%	m^2	1,200	420,000	38,764.32
25	Full depth CCP repair	m^2	1,000	700,000	64,607.20

	10%				
25	Reseal joints 50%	m	228	145,122	13,394.18
25	Texturize 30%	m^2	30	63,000	5,814.65
Total Maintenance cost per km				**1,568,683**	**199,230.50**

Table 4-30 Rigid Major Arterial Road Pavement Preservation Plan (CRCP)

Year	Maintenance Activity Description	Unit	Unit Rate (ETB)	Cost/km (ETB)	Present Value (ETB)
12	Reseal joints 25%	m	228	57,000	18,161.96
12	Partial depth CCP repair 2%	m^2	1,200	168,000	53,529.98
25	Partial depth CCP repair 5%	m^2	1,200	420,000	38,764.32
25	Full depth CCP repair 10%	m^2	1,000	700,000	64,607.20
25	Reseal joints 50%	m	228	114,000	10,521.74
25	Texturize 30%	m^2	30	63,000	5,814.65
Total Maintenance cost per km				**1,522,000**	**191,399.84**

4.6.4 Life Cycle Costs of the Two Pavement Alternatives

Life cycle cost is the sum of initial construction costs and discounted life time maintenance or rehabilitation costs of the pavement during the analysis period of the two project alternatives. From the computed results of life cycle costs indicated in Table 4.31 below, cement concrete pavements have far better cost saving advantages by (> 30%) as compared to the asphalt concrete options.

Table 4-31 Life cycle costs of pavement alternatives

Item No.	Pavement type	Pavt. Constn. Cost (ETB)	Discounted Pavt. Maintenance cost (ETB)	Total Pavt. Life Cycle Cost/km (ETB)
1	JRCP ($50*10^6$ ESA)	10,989,053.86	199,230.50	11,188,284.36
2	AC ($50*10^6$ ESA)	13,482,979.55	1,092,834.24	14,575,813.79
3	CRCP ($80*10^6$ ESA)	11,777,879.18	191,399.84	11,969,279.02
4	AC ($80*10^6$ ESA)	14,895,678.00	1,092,834.24	15,988,512.24

4.6.5 Sensitivity (Risk) Analysis

The robustness of the project to reasonable changes in the main input assumptions has been tested by means of a sensitivity analysis. This includes examining the effects on the project's main cost component indicators of given changes in, among others, cement price changes and Bitumen price changes. The effects of changes of plus or minus 10% in the main input values are contemplated in this study. The detailed computation results are presented in Appendix D of the document.

Sensitivity analysis results (from Table 4.32 to 4.36) on the major cost components of the two alternative pavements indicate that there are no significant changes from original cost comparison results for cement price fluctuations on rigid pavements. But bitumen price fluctuations have significant effect on the initial cost of flexible pavements. Hence, bitumen is more sensitive and risky than cement as an alternative pavement material.

Therefore, rigid pavements are more feasible, less responsive for price changes on cement as compared to the competing flexible pavement which is more costly and sensitive to price changes on bitumen.

Table 4-32 Sensitivity Analysis 01 (when cost of Cement is increased by 10%)

Pavement type	Initial Cost	Remark
JRCP ($50*10^6$ ESA)	11,370,123.59	Initial Cost increased by 3.4% but still less than AC (T9)
CRCP ($80*10^6$ ESA)	12,111,933.81	Initial Cost increased by 2.4% but still less than AC (T10)

Table 4-33 Sensitivity Analysis 02 (when cost of Bitumen is decreased by 10%)

Pavement type	Initial Cost	Remark
AC (at T9)	12,896,023.05	Initial Cost decreased by 4.35% but still greater than JRCP
AC (at T10)	14,293,063.00	Initial Cost decreased by 4.05% but still greater than CRCP

Table 4-34 Sensitivity Analysis 03 (when cost of Cement is increased by 10% & Cost of Bitumen is decreased by 10%)

Pavement type	Initial Cost	Remark
JRCP	11,370,123.59	Initial Cost increased by 3.47% but still less than AC
AC (T9)	12,896,023.05	Initial Cost decreased by 4.35% but still greater than JRCP
CRCP	12,111,933.81	Initial Cost increased by 2.84% but still less than AC (T10)
AC (T10)	14,293,063.00	Initial Cost decreased by 4.05% but still greater than CRCP

Table 4-35 Sensitivity Analysis 04 (when cost of Bitumen is increased by 10%)

Pavement type	Initial Cost	Remark
AC (T9)	14,583,673.55	Initial Cost increased by 8.16% and far greater than JRCP
AC (T10)	16,089,447.00	Initial Cost increased by 8 % and far greater than CRCP

Table 4-36 Sensitivity Analysis 05 (when cost of Bitumen is increased by 10% & Cost of Cement is decreased by 10%)

Pavement type	Initial Cost	Remark
JRCP	10,610,732.45	Initial Cost decreased by 3.44% and much less than AC (T9)
AC (T9)	14,581,483.55	Initial Cost increased by 8.15% and far greater than JRCP
CRCP	11,446,233.79	Initial Cost decreased by 2.81% and much less than AC (T10)
AC (T10)	16,087,476.00	Initial Cost increased by 8% and far greater than CRCP

4.6.6 User Benefits of Concrete Pavement

4.6.6.1 Heavy Truck Fuel Savings and Reductions in Emissions

Profile stability is a term used to describe the ability of a pavement surface to resist deformation and deflection caused by sustained and repeated loading. Unlike asphalt pavement, which is viscoelastic and therefore sensitive to both temperature and loading, concrete pavement's rigid surface does not deform under heavy vehicle loading and therefore deflects less. This not only makes concrete pavement less susceptible to the formation of heavy-vehicle wheel ruts and the related increased hydroplaning potential, it also positively impacts vehicle fuel consumption [51].

The findings from different studies show that fuel consumption for heavy truck types' tractor tanker (semi-trailer and van semi-trailer) can be reduced an average of about 0.8% to 6.9% when traveling on concrete versus asphalt pavement, depending on truck type and vehicle speed [51]. These savings were used to calculate the potential economic and environmental benefits from tractor-trailers traveling on concrete pavement compared to asphalt pavement, as shown in Table 4.37. For the calculations, it is assumed that the tractor-trailer unit has an average engine fuel consumption of 0.5 liters per km) and that diesel fuel costs ETB 18.08 per liter. Table 4.38 also identifies the potential yearly savings for a major arterial highway that is 1 km long and carries 25,306 vehicles per day with 20.8% trucks (at the end of analysis period). Calculations assume the same tractor-trailer unit average engine diesel fuel consumption and diesel fuel cost used.

Table 4-37 Yearly potential savings in cost, CO_2, NO_x, and SO_2 for a typical major arterial highway [51]

Fuel savings (%)	Fuel saved (lit.)	Fuel cost saved (ETB)	CO_2 (t)	NO_x(kg)	SO_2 (kg)
Minimum = 0.8	7,684.93	138,943.46	23.44	238.50	30.37
Average = 3.85	36,983.71	668,665.42	112.59	1,158.55	146.50
Maximum = 6.9	66,282.49	1,198,387.37	2,014.99	20,802.50	2,610.51
Total saving in 40 yrs. With 3.85% (cost in present Value)	1,479,348.40	6,538,913.04	4,503.43	46,342.01	5,860.18

These environmental and economic savings can have significant down-stream implications to the public. The emission reductions result in a direct public health benefit. The cost of consumer goods likely will be affected as well because lower fuel consumption decreases transportation expenses, which, on average, comprise nearly one-fifth of the cost of a typical consumer item [20]. It should also be noted that the fuel cost saved is nearly 70% of the construction cost of CRCP at 80* 10^6 ESA computed in this research.

In the context of overall transportation sustainability, these fuel savings and pollutant reductions are enormous. In the case of greenhouse gases (CO_2) alone, the average savings realized by (1-km) long major arterial highway in Table 4.37 above over its 40-year design life (4,503.43 tons) are nearly seven times greater than the CO_2 emitted during the manufacture of cement used for the construction of the concrete pavement (CRCP=655 tons).

In another way, all of the CO_2 emitted during the manufacturing of cement used to construct a concrete highway pavement is compensated for during the first six years of service by virtue of the reduced pavement deflection and improved truck fuel efficiency. The remaining 34 years of service and the proportionate CO_2 savings are a further testament to the sustainability of concrete pavements.

4.6.6.2 Lower Construction Fuel Demand

The Federal Highway Administration (FHWA) reports on fuel usage for various elements of construction, including highway paving, in its Technical Advisory T 5080.3 on Price Adjustment Contract Provisions of this Technical Advisory shows that the fuel usage factor for asphalt pavements is 12 liters per metric ton, and for concrete pavements is 4.9 liters per cubic meter. However, as these fuel usage factors are reported in different units, it is somewhat difficult to make a direct comparison [62, 17].

Table 4.38 below converts these construction fuel usage factors to fuel required per km of roadway constructed for asphalt and concrete. The equivalently designed concrete and asphalt pavement thicknesses are presented for the computation of respective quantities of construction materials required for each option. This example ignores the fact that asphalt pavements typically require more layers of sub-base and capping materials at a greater thickness when compared to an equivalent concrete pavement.

Table 4-38 Construction fuel demand for asphalt versus concrete pavement

Traffic & Subgrade Classes	Pavement type	Thickness	Quantity	Fuel Demand per km (litter)	Fuel Saved (Litter)
T9 & S3	AC + BRB	280 mm	3,920 ton	47,040.00	(39,322.50)
T10 & S1	AC+BRB	310 mm	4,340 ton	52,080.00	(43,676.50)
$50*10^6$ & S3	JRCP	245 mm	1,715 m^3	8,403.50	43,676.50
$80*10^6$ & S1	CRCP	225 mm	1,575 m^3	7,717.50	39,322.50

Assumptions: Asphalt density = 2.0 KN/m3, Fuel usage: Asphalt 12 L/ton, Concrete 4.9 L/m3.

This means that if concrete pavements were placed instead of the roughly 2.29 million metric tons of asphalt placed each year (RSPD 16 years performance report estimation from the last three years pavement volume), the savings in diesel fuel from construction alone would amount to nearly 27.48 million liters. This saving is equivalent to the construction cost of 45 km road project ($50*10^6$ ESA) per year with Jointed Reinforced Concrete pavement (JRCP) based on the initial construction cost per km of this study.

In addition to the obvious economic benefits, there are enormous environmental advantages. The savings in diesel fuel eliminates the emission of approximately 61,575.56 metric tons of CO_2 into our atmosphere each year. To put this into perspective, the average passenger car emits about 4.5 metric tons of CO_2 annually [64]. The CO_2 savings realized by constructing concrete pavements instead of the 2.29 million metric tons of asphalt placed annually would be equivalent to taking 13,683.46 cars off the road.

4.6.6.3 Reduced Lighting Requirement

Lighting fixtures are important elements of most urban highway facilities. Enhanced nighttime visibility is intuitively related to improved traffic safety. A report comparing the environmental impacts of concrete pavements to asphalt pavements indicates that asphalt pavements require more lights per unit length to achieve the same illumination as concrete pavements [17]. The results suggest cost savings of as much as 31% in initial construction and annual energy costs for lighting concrete pavements versus lighting asphalt pavements.

Recently awarded tender values by AACRA for Straight lighting fixtures are about ETB 2.5 million per km. This indicates that if concrete pavement is used the initial construction cost saving could be reached to ETB 775,000 per km. With this analysis Table 4.39 illustrates more about saving per km for the analysis period.

Table 4-39 Total straight lighting cost saving per km for a typical urban road

Saving from initial construction	Saving from Lighting & Maintenance cost (40yrs discounted at 10%)	Total Present worth of saving
ETB 775,000	ETB 543,342.72	ETB 1.32 million

Assumes: Initial cost = 50,000/pole; Maintenance cost =1000/pole/year; Energy cost = 0.4/kwh; Operating time = 4,380 hours/pole/year; 200 watt lamp for each pole, 40m spacing between poles for AC pavements; all costs in ETB.

4.6.6.4 Heat Island Mitigation

The energy of sunlight that is not reflected off pavement surfaces is converted into thermal energy that increases the pavement's temperature. This, in turn, increases the temperature of the air around the pavement. In urban areas, the higher air temperature that occurs as a result of pavements and other surfaces absorbing the sun's heat is known as the "heat island effect." According to some researchers, downtown areas of North American cities are up to 5 °C warmer than surrounding suburban and rural areas, where natural vegetation cools the air through evapotranspiration [17].

The heat island effect can contribute significantly to energy consumption for air conditioning to cool urban buildings. This not only consumes energy and costs money; it also leads to higher emissions from power plants. One estimate is that the increase in temperature due to heat island effects accounts for 5 to 10% of peak urban electric demand for air conditioning use [65].

The estimate puts the cooling energy savings from cool surfaces and shade trees, when fully implemented, at $5 billion per year in the United States alone [65].

In this regard considerable projected energy savings could be achieved in the future if we replace asphalt roads of Federal and Regional cities with concrete pavement. But as a matter of awareness and majority of urban duelers are at lower standard of living, the urban heat island effect mitigation is not visible now.

4.7 Sustainability of Concrete Pavements

The basic definition of sustainability is the capacity to maintain a process or state of being into perpetuity, without exhausting the resources upon which it depends nor degrading the environment in which it operates. In the context of human activity, sustainability has been described as activity or development that meets the needs of the present without compromising the ability of future generations to meet their own needs [37].

Many municipalities are looking for ways to reduce the continuous repair and reconstruction of roads. Road users are demanding better performance from the roads they travel daily and are less tolerant of disruptions and the negative impact on our economy. The real cost of building a road goes well beyond the initial cost of construction. Decision-makers should include the cost of maintenance, rehabilitation, reconstruction and salvage costs, as well as the cost of traffic disruption to road users. Recognizing infrastructure as a valuable asset to the economic success of the country will lead to choosing concrete more frequently as a long-term paving solution.

Such long-lived concrete pavements have verified economic advantages in terms of life-cycle costs. In addition, they contribute directly to the system's sustainability in several important ways.

Concrete pavements do not require rehabilitation or reconstruction as often, and therefore consumes less raw materials in the long run. This longevity impacts our environment as well. Energy savings are realized, since rehabilitation and reconstruction efforts consume energy. Also, congestion is reduced (with accompanying energy savings and reduction in vehicle pollutants) by employing long-lasting concrete pavements because of fewer construction zones impeding traffic flow. Because of this longevity, concrete pavements have the potential to help society address the challenges of sustainable development in numerous ways. Ultimately, all these environmental and social benefits add up to greater long-term economic benefits to the public [17].

However, there are many other features of concrete pavements that also support the case for concrete pavements' sustainability. As mentioned before, these features all contribute to making concrete pavements an environmentally sensitive that [8]:

- The rigidity of concrete pavement means lower vehicle fuel consumption and emissions.
- Less fuel-intensive construction operations for concrete pavement result in enormous economic and CO_2 savings.
- Using industrial byproducts in concrete improves pavement longevity, saves money, reduces the need for disposal in landfills, and greatly reduces both energy use and generation of greenhouse gases.
- Concrete pavement's renewability and recyclability lead to improved longevity and reduced demand on non-renewable resources.
- The strength and rigidity of concrete means fewer and thinner required layers of sub-base materials.
- The light-colored and cool surface of concrete pavement leads to improved visibility, reduced lighting requirement, and reduced heat island effects.
- Concrete pavement's overall lower energy footprint means tremendous savings in energy over the life of the pavement facility.
- Pervious concrete pavements capture and filter pavement runoff and help improve storm water quality.
- Optimized surface textures can be formed on concrete pavements that result in long-lasting, quiet pavements.

Sustainable pavements require consideration of environmental, economic and social indicators and this could be associated with the idea of life cycle analysis. Sustainable solutions often require major investments: hence, one has to make use of life cycle analysis; thus, sustainability and life cycle analysis go hand in hand.

These benefits result in greater long-term cost-effectiveness to the public. As such, concrete pavements are the clear choice for environmentally sensitive and economically sustainable roadways; truly green highways, in more ways than one [17].

.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Cement concrete as an alternative pavement material over asphalt pavement in arterial roads of Ethiopia in relation to life cycle cost comparison and economic analysis were studied in this research and found the following conclusions;

1. The result of cost comparison between Cement concrete and Asphalt concrete pavements shows that Cement concrete pavement is by far economical in both initial cost and life cycle cost components.
2. Cement concrete pavement consumes less fuel during its construction operations than Asphalt concrete pavements, which means contributing in the reduction of carbon (CO_2) footprint.
3. Heavy fright trucks consume less fuel when driven on Cement concrete pavements as compared to Asphalt pavements due to its rigidity which have positive economic implications, reduces emissions and contribute in the conservation of non-renewable resources.
4. The longevity of Concrete pavements and its less maintenance requirement make it sustainable pavement material than asphalt concrete, as it requires frequent reconstruction and rehabilitation activities that consume nonrenewable raw materials like; fuel, road base material, sub-base material, aggregates for asphalt concrete, etc.
5. Cement concrete pavement also needs less straight lighting fixtures when it is constructed in Cities and Urban areas. In turn it contributes for national energy savings and saves hard currency demands to import those fixtures.
6. From the results of the study it is found to be Cement Concrete Pavement is more sustainable pavement construction material than Asphalt Concrete Pavement due to its improved longevity, utilization of industrial byproducts and recyclability lead reduced demand on non-renewable resources.
7. New asphalt concrete pavement is quieter than new cement concrete pavement; but cement concrete pavement retains its smoothness for longer as compared to asphalt pavement.

5.2 Recommendations

It should be emphasized that life cycle cost analysis is only a tool to assist those who make decisions concerning the selection of pavement types and not the decision itself. Moreover, this tool is not going to give an absolute answer as to which pavement to choose: rather, it helps to provide an overview of total cost during the life cycle and to give an idea of the traffic level at which concrete pavement could be considered as an option. There might be other grounds for selection than pure economic ones. Implementing agencies should create alternative bid system in maintaining competition on the pavement market in order to avoid monopoly of one type of pavement. In addition, environmental or other considerations, such as those that have been discussed above, might outweigh economic factors.

Hence, based on the research out comes; the following recommendations are included to be considered by beneficiaries' of this report.

1. Concrete pavement construction in our country is in its trial stage by local construction companies; but it needs serious attention to take in to consideration that foreign companies experienced in concrete pavement construction should participate in the trial construction roads for the sake of technology transfer and experience sharing.
2. Implementing Authorities, ERA and AACRA, should include cement concrete pavement alternatives in their feasibility studies as well as in their tendering stages of major arterial roads.
3. Cost breakdowns for each pavement alternative should be critically evaluated rather than taking unit rates of concrete for major structures of the same project.
4. Initially the researcher planned to use HDM-4 software for economic evaluation of the two pavement alternatives, but due to unavailability of calibrated data input systems for CCP the research is evaluated using excel sheets. Hence, Road economic evaluation models like HDM-4 should better be calibrated based on Ethiopia's specific realities and conditions for more reliable evaluation of pavement alternatives.

5.3 Further research is proposed in the following areas

1. Cement Concrete Pavement Design using Supplementary Cementious materials shall be studied to capture the full picture of its sustainability and Environmental Benefits.
2. User costs such as vehicle operating costs, accident costs, discomfort costs etc. were considered equal for both material types, mostly due to lack of information on these parameters, which require further studies using models like HDM-4.

6. REFERENCES

[1] **Ethiopian Roads Authority**, Sixteen Years Performance Assessment Report of RSDP (third year of Phase IV), October 2013, Addis Ababa, Ethiopia.

[2] **T. Akakin, et al**, Initial Cost Comparison of Rigid and Flexible Pavements: Under Different Traffic and Soil Conditions, Turkish Ready Mix Concrete Association, Research Paper, Turkey, 2009.

[3] **Shiraz Tayabji, et al,** Advanced High-Performance Materials for Highway Applications: A Report on the State of Technology, FHWA 2010

[4] **American Association of State Highway and Transportation Officials (AASHTO),** Guide for Design of Pavement Structures, Washington, D.C., 1993.

[5] **ACPA**, Life-Cycle Cost Analysis: A Guide for Comparing Alternate Pavement Designs, Illinois, 2002.

[6] **Organization for Economic Co-Operation and Development (OECD)**, Economic Evaluation of Long-Life Pavements, Research Paper Report, Paris, France, 2005.

[7] **FHWA**, Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) Web site: http://www.fhwa.dot.gov/crt/lifecycle/ca4prs.cfm, Washington, DC, 2009.

[8] **Tom Van Dam, et al**, Sustainable Concrete Pavements, A Manual of Practice, Iowa State University, 2012

[9] **Steven H. Kosmatka, et al,** Design and Control of Concrete Mixtures, EB001, 14th edition, Portland Cement Association, Book, Skokie, Illinois, USA, 2003.

[10] **Ethiopian Roads Authority**, ERA Pavement Design Manual Volume II, 2013

[11] **Department of Highways**, Analytical Design of New Flexible Pavements in Thailand, Pavement Technology Project, Thailand, 2001.

[12] **Yongyuth Taesiri and Poranic Jitareekul**, an Engineering Manual For Highway Pavement Design, Road and Pavement Design Branch Department of Highways, Bangkok, Thailand, August 2002.

[13] **William James Wilde, et al**, Life Cycle Cost Analysis of Portland Cement Concrete Pavements, Research Report, University of Texas, Austin, 1999.

[14] **Asta Guciute Scheving**, Life Cycle Cost Analysis of Asphalt and Cement Concrete Pavements, Thesis, Reykjavik University, Iceland, 2011.

[15] **Asphalt Pavement Alliance**, Pavement Type Selection Processes, Position Paper, Lexington, Kentucky, 2004.

[16] **Von Quintus, et al**, Expected Service Life and Performance Characteristics of HMA Pavement, Performance Report, Texas, 2005.

[17] **ACPA**, Green Highways, concrete pavement research and technology, special report, American Concrete Pavement Association, 2007.

[18] **Walls, J. and Smith, M.R**., Life-Cycle Cost Analysis in Pavement Design, In Search of Better Investment Decisions, U.S., Department of Transportation, Washington D.C., 1998.

[19] **U.S. Department of Transportation and FHWA**, Life–Cycle Cost Analysis Primer, Washington D.C., 2002.

[20] **Velado, M**, Life-Cycle Cost Analysis Procedures Manual, California Department of Transportation, Sacramento, California, 2007.

[21] **Taylor & Francis group**, Concrete Pavement Design, Construction, and Performance, Hand Book, London, 2006

[22] **Kejin Wang and ZhiGe**, Evaluating Properties of Blended Cements for Concrete Pavements, Iowa State University, 2003.

[23] **ACAA**, http://www.acaa-usa.org, American Coal Ash Association, 2009.

[24] **Slag Cement Association** (SCA), (http://www.slagcement.org, 2011.

[25] **Taylor, P. C**, "New Technologies for Sustainable Concrete", In Proceedings-Concrete for a Sustainable Environment, Concrete Society of Southern Africa, Johannesburg, SA, 2010.

[26] **Van Dam T.J**, Geopolymer Concrete: FHWA, Concrete Pavement Technology Program. Washington, D.C., 2010.

[27] **Federal Highway Administration (FHWA)**, Advanced High Performance Materials for Highway Applications, FHWA-HIF-10-002, Washington, D.C., 2010.

[28] **Morian, D., et al**, Use of Air-Cooled Blast Furnace Slag as Coarse Aggregate in Concrete Pavements, A Guide to Best Practice, Washington, D.C., FHWA, In publication, 2011.

[29] **Abiy Bekele**, Implementation of the AASHTO Pavement Design Procedures into Multi-Pave, Royal Institute of Technology, Stockholm, 2011.

[30] **Smith, K.D., and K.T. Hall**, Concrete Pavement Design Details and Construction Practices–State of the Art Technical Digest: Department of Transportation, National Highway Institute, U.S. Washington, D.C., 2001.

[31] **DARWin** Version 3.01, American Association of State Highway and Transportation Officials, Design Manual, 1997.

[32] **AASHTO MEPDG**, Mechanistic Empirical Pavement Design Guide, 2008.

[33] **Shields, S., and P. Taylor**, "Working a Double Lift, Two-Lift Paving Makes a Comeback in the U.S.", Roads and Bridges2009, www.roadsbridges.com/workingdouble- lift; accessed Dec 5, 2013.

[34] **Lane, B. and Kazmierowski, T**., Use of Innovative Pre-Cast Concrete Slab Repair Technology in Canada, Proceedings, 8th International Conference on Concrete Pavements, Volume II, : International Society for Concrete Pavements, Colorado Springs, 2005.

[35] **Covarrubias, et al**, Thin Concrete Pavements (TCP), www.siteresources.worldbank.org, TC Pavements Paper, Covarrubias 2007, accessed in Jan., 2014.

[36] **Cervantes, V., and J. Roesler,** Performance of Concrete Pavements with Optimized Slab Geometry, Research Report ICT-09-053 and Urbana IL: Illinois Center for Transportation, University of Illinois, 2009. (http://ict.illinois. edu/publications/report%20files/ICT-09-053.pdf; accessed Dec., 2013)

[37] **World Commission on the Environment and Development, United Nations (WCED)**, Our Common Future, The Report of the World Commission on Environment and Development, New York, NY, Oxford University Press, 1987.

[38] **U.S. EPA**, Annual Emissions and Fuel Consumption for an "Average" Passenger Car, EPA420-F-97-037, Washington, DC, 2003.

[39] **Carter, T. B,** Building a Sustainable Future: Minimizing the Environmental Impact of Cement Manufacturing and maximizing the Environmental Benefits of Cement Products. In KCI International Symposium on "Environment and Concrete" Hanyang University, Seoul, Korea, November 2006. KCI:Korea, 2006.

[40] **ACPA**, Subgrade and Sub-bases for Concrete Pavements. EB204P. Skokie, IL: American Concrete Pavement Association, 2007.

[41] **US Department of Transportation Federal Highways Administration** website, 2005. http://www.fhwa.dot.gov/policy/ohim/hs05/xls/hm12.xls accessed on December 2014.

[42] **ACPA,** Diamond Grinding Shines in California and Missouri. R&T Update, Number 7.01, Skokie, IL: American Concrete Pavement Association, 2006.

[43] **Taylor G.W., et al**, Effects of Pavement Structure on Vehicle Fuel Consumption – Phase III, prepared for Natural Resources Canada Action Plan 2000 on Climate Change and Cement Association of Canada, Research Paper, January 2006.

[44] **PCA**, Financial Benchmarking Report, 2011, Southeast Chapter American Concrete Pavement Association, "Who says..."Concrete Pavement Costs Too Much?" Count on Concrete Pavement, 2005.

[45] **L. Rens**, EUPAVE, European Concrete Paving Association, a Smart and Sustainable Choice, 2009.

[46] **American Concrete Pavement Association**, White topping - State of the Practice, Engineering Bulletin 210P

[47] **Gajda, J.W., et al**, A Comparison of Six Environmental Impacts of Portland Cement Concrete and Asphalt Cement Concrete Pavement, PCA R&D Serial No. 2068, Portland Cement Association, 1997.

[48] **The Athena Sustainable Materials Institute**, A Life Cycle Perspective on Concrete and Asphalt Roadways, Embodied Primary Energy and Global Warming Potential, Ottawa, September 2006.

[49] **Taylor G.W., et al**, Additional Analysis of the Effect of Pavement Structure on Truck Fuel Consumption, prepared for Government of Canada Action Plan 2000 on Climate Change, Concrete Roads Advisory Committee, Research Paper, 2002.

[50] **Portland Cement Association**, SN2437, Effect of Pavement Surface on Fuel Consumption, National Research Council of Canada, Centre for Surface Transportation Technology, Ottawa, Ontario, August 2000.

[51] **Taylor Consulting**, Additional Analysis of the Effect of Pavement Structure on Truck Fuel Consumption; Action Plan 2000 on Climate Change, Concrete Roads Advisory Committee, Government of Canada, 2002.

[52] **Pomerantz, M., B. Pon, et al**, The Effect of Pavements' Temperatures on Air Temperatures in Large Cities. Lawrence Berkeley National Laboratory Report LBL-43442. Berkeley, CA, 2000.

[53] **Nova Scotia Transportation and Public Works**, Asphalt Concrete Pavement and Portland Cement Concrete Pavement, Highway 104, Cumberland County, Year 5 of 5 Year Study Report, October 1999.

[54] The Transtec Group, Pavement Roughness Progression Case Study, July 2006.

[55] VDOT, Life Cycle Costs Analysis Pavement Options, Charlottesville, Materials Division / Virginia Transportation Research Council, 2002.

[56] Michigan Department of Transportation (**MDOT)**, Pavement Design and Selection Manual, 2012.

[57] Andrew J. Wimsatt, et al, Considerations for Rigid vs. Flexible Pavement Designs When Allowed as Alternate Bids Texas University, 2009

[58] Tim Smith, P.Eng. and Rico Fung, P.Eng., Review of Alternate Bid Tenders for Canadian Highway Construction Projects with Life Cycle Cost Component, Charlottetown, Prince Edward Island, 2006.

[59] Andrew J. Wimsatt, et al; Considerations for Rigid vs. Flexible Pavement Designs When Allowed as Alternate Bids: Technical Report, Texas Department of Transportation, Austin, Texas, 2009.

[60] Taylor & Francis, Concrete Pavement Design, Construction, and Performance, Book, 270 Madison Ave, New York, NY 10016, USA, 2008

[61] Ethiopian Roads Authority, ERA Pavement Design Manual Volume I, 2013

[62] Federal Highway Administration (FHWA), Development and Use of Price Adjustment Contract Provisions: Technical Advisory No. T 5080.3. Washington, DC, 1980.

[63] Mitchell, M., and Walker, R. The Economic of Pavement Type Selection, Department of Transportation, Pretoria, Design Manual, South Africa, 1985.

[64] EPA, Annual Emissions and Fuel Consumption for an “Average” Passenger Car, EPA420-F-97-037. Washington, DC: U.S. Environmental Protection Agency, Manual, 1997.

[65] Akbari, H., Energy Saving Potentials and Air Quality Benefits of Urban Heat Island Mitigation. In First International Conference on Passive and Low Energy Cooling for the Built Environment, Athens, Greece, May 17–24, 2005.

APPENDIX – A Traffic Data (From Era) and Traffic Analysis Results

Addis Ababa - Debre Berhan									
Year	**Car**	**4WD**	**MB**	**LB**	**ST**	**MT**	**HT**	**TT**	**Total**
2016	124	220	639	145	243	391	289	84	2,135
2017	132	234	681	154	259	416	308	89	
2018	141	250	725	164	276	443	328	95	
2019	150	266	772	175	294	472	349	101	
2020	160	283	822	187	313	503	372	108	
2021	170	301	875	199	333	536	396	115	
2022	181	321	932	212	355	571	422	123	
2023	193	342	993	225	378	608	449	131	
2024	205	364	1,058	240	402	647	478	139	
2025	219	388	1,126	256	428	689	509	148	
2026	233	413	1,199	272	456	734	542	158	
2027	246	437	1,270	288	483	777	574	167	
2028	261	463	1,345	305	512	823	608	177	
2029	276	490	1,425	323	542	872	644	187	
2030	293	519	1,509	342	574	923	682	198	
2031	310	550	1,598	363	608	978	723	210	
2032	328	582	1,692	384	643	1,035	765	222	
2033	348	617	1,792	407	681	1,096	810	236	
2034	368	653	1,897	431	722	1,161	858	249	
2035	390	692	2,009	456	764	1,230	909	264	
2036	413	733	2,128	483	809	1,302	962	280	
2037	437	776	2,253	511	857	1,379	1,019	296	
Com.	6,135	10,885	31,615	7,174	12,022	19,345	14,298	4,156	
EF	-	-	0.07	0.53	0.12	0.50	4.50	8.50	
10^6 ESA	**-**	**-**	**0.40**	**0.69**	**0.26**	**1.77**	**11.74**	**6.45**	**21.32**

2038	463	822	2,386	542	908	1,460	1,079	314	
2039	490	870	2,527	573	961	1,546	1,143	332	
2040	519	921	2,676	607	1,018	1,638	1,210	352	
2041	550	976	2,834	643	1,078	1,734	1,282	373	
2042	582	1,033	3,001	681	1,141	1,837	1,357	395	
2043	617	1,094	3,179	721	1,209	1,945	1,438	418	
2044	653	1,159	3,366	764	1,280	2,060	1,522	442	
2045	692	1,227	3,565	809	1,356	2,181	1,612	469	
2046	733	1,300	3,775	857	1,436	2,310	1,707	496	
2047	776	1,376	3,998	907	1,520	2,446	1,808	526	
2048	822	1,458	4,234	961	1,610	2,591	1,915	557	
2049	870	1,544	4,483	1,017	1,705	2,743	2,028	589	
2050	921	1,635	4,748	1,077	1,806	2,905	2,147	624	
2051	976	1,731	5,028	1,141	1,912	3,077	2,274	661	
2052	1,033	1,833	5,325	1,208	2,025	3,258	2,408	700	
2053	1,094	1,941	5,639	1,280	2,144	3,450	2,550	741	
2054	1,159	2,056	5,972	1,355	2,271	3,654	2,701	785	
2055	1,227	2,177	6,324	1,435	2,405	3,870	2,860	831	
	19,755	35,048	101,800	23,100	38,713	62,291	46,041	13,382	
Com.	21,730	38,553	111,980	25,410	42,584	68,520	50,645	14,720	
EF	-	-	0.07	0.53	0.12	0.50	4.50	8.50	
10^6 ESA	-	-	1.43	2.46	0.93	6.25	41.59	22.83	75.50

Addis Ababa - Commando									
Year	**Car**	**4WD**	**MB**	**LB**	**ST**	**MT**	**HT**	**TT**	**Total**
2016	123	202	140	290	329	291	241	123	2,340
2017	131	215	149	309	350	310	257	131	
2018	140	229	159	329	373	330	273	140	
2019	149	244	169	350	397	352	291	149	
2020	158	260	180	373	423	374	310	158	
2021	169	277	192	397	451	399	330	169	
2022	179	295	204	423	480	425	352	179	
2023	191	314	218	451	511	452	375	191	
2024	204	334	232	480	544	482	399	204	
2025	217	356	247	511	580	513	425	217	
2026	231	379	263	544	618	546	452	231	
2027	245	402	278	576	654	578	479	245	
2028	259	425	295	611	693	613	507	259	
2029	274	450	312	647	733	649	537	274	
2030	290	477	331	685	777	687	569	290	
2031	308	505	350	725	823	728	603	308	
2032	326	535	371	768	871	770	638	326	
2033	345	566	393	813	922	816	676	345	
2034	365	600	416	861	977	864	716	365	
2035	387	635	440	912	1,035	915	758	387	
2036	410	673	466	966	1,096	969	803	410	
2037	434	712	494	1,023	1,160	1,026	850	434	
Com.	6,085	9,994	6,927	14,348	16,277	14,397	11,923	6,085	
EF	-	-	0.07	0.53	0.12	0.50	4.50	8.50	
10^6 ESA	**-**	**-**	**0.09**	**1.39**	**0.36**	**1.31**	**9.79**	**9.44**	**22.38**

2038	459	754	523	1,083	1,229	1,087	900	459	
2039	486	799	554	1,147	1,301	1,151	953	486	
2040	515	846	586	1,215	1,378	1,219	1,009	515	
2041	546	896	621	1,286	1,459	1,291	1,069	546	
2042	578	949	658	1,362	1,545	1,367	1,132	578	
2043	612	1,005	696	1,443	1,637	1,448	1,199	612	
2044	648	1,064	737	1,528	1,733	1,533	1,270	648	
2045	686	1,127	781	1,618	1,835	1,623	1,344	686	
2046	727	1,193	827	1,713	1,944	1,719	1,424	727	
2047	770	1,264	876	1,814	2,058	1,821	1,508	770	
2048	815	1,338	928	1,921	2,180	1,928	1,597	815	
2049	863	1,417	982	2,035	2,308	2,042	1,691	863	
2050	914	1,501	1,040	2,155	2,445	2,162	1,791	914	
2051	968	1,589	1,102	2,282	2,589	2,290	1,896	968	
2052	1,025	1,683	1,167	2,417	2,741	2,425	2,008	1,025	
2053	1,085	1,783	1,235	2,559	2,903	2,568	2,127	1,085	
2054	1,149	1,888	1,308	2,710	3,075	2,719	2,252	1,149	
2055	1,217	1,999	1,386	2,870	3,256	2,880	2,385	1,217	
	19,595	32,181	22,304	46,200	52,413	46,360	38,394	19,595	
Com.	21,555	35,399	24,534	50,820	57,655	50,996	42,233	21,555	
EF	-	-	0.07	0.53	0.12	0.50	4.50	8.50	
10^6 ESA	-	-	0.31	4.92	1.26	4.65	34.68	33.44	79.27

Addis Ababa - Kaliti									
Year	**Car**	**4WD**	**MB**	**LB**	**ST**	**MT**	**HT**	**TT**	**Total**
2016	1,755	2,379	1,023	2,172	2,480	2,680	2,146	1,755	17,110
2017	1,869	2,534	1,089	2,313	2,641	2,854	2,285	1,869	
2018	1,991	2,698	1,160	2,464	2,813	3,040	2,434	1,991	
2019	2,120	2,874	1,236	2,624	2,996	3,237	2,592	2,120	
2020	2,258	3,061	1,316	2,794	3,190	3,448	2,761	2,258	
2021	2,405	3,259	1,402	2,976	3,398	3,672	2,940	2,405	
2022	2,561	3,471	1,493	3,169	3,619	3,911	3,131	2,561	
2023	2,727	3,697	1,590	3,375	3,854	4,165	3,335	2,727	
2024	2,905	3,937	1,693	3,595	4,104	4,435	3,552	2,905	
2025	3,093	4,193	1,803	3,828	4,371	4,724	3,782	3,093	
2026	3,294	4,466	1,920	4,077	4,655	5,031	4,028	3,294	
2027	3,489	4,729	2,034	4,318	4,930	5,328	4,266	3,489	
2028	3,695	5,008	2,154	4,572	5,221	5,642	4,518	3,695	
2029	3,913	5,304	2,281	4,842	5,529	5,975	4,784	3,913	
2030	4,143	5,617	2,415	5,128	5,855	6,327	5,067	4,143	
2031	4,388	5,948	2,558	5,430	6,201	6,701	5,365	4,388	
2032	4,647	6,299	2,709	5,751	6,566	7,096	5,682	4,647	
2033	4,921	6,671	2,868	6,090	6,954	7,515	6,017	4,921	
2034	5,211	7,064	3,038	6,449	7,364	7,958	6,372	5,211	
2035	5,519	7,481	3,217	6,830	7,799	8,427	6,748	5,519	
2036	5,844	7,922	3,407	7,233	8,259	8,925	7,146	5,844	
2037	6,189	8,390	3,608	7,660	8,746	9,451	7,568	6,189	
Com.	86,829	117,701	50,613	107,460	122,698	132,593	106,174	86,829	
EF	-	-	0.07	0.53	0.12	0.50	4.50	8.50	
10^6 ESA	**-**	**-**	**0.65**	**10.39**	**2.69**	**12.10**	**87.20**	**134.69**	**247.72**

2038	6,554	8,885	3,821	8,112	9,262	10,009	8,015	6,554	
2039	6,941	9,409	4,046	8,590	9,808	10,599	8,487	6,941	
2040	7,350	9,964	4,285	9,097	10,387	11,225	8,988	7,350	
2041	7,784	10,552	4,537	9,634	11,000	11,887	9,518	7,784	
2042	8,243	11,174	4,805	10,202	11,649	12,588	10,080	8,243	
2043	8,730	11,834	5,089	10,804	12,336	13,331	10,675	8,730	
2044	9,245	12,532	5,389	11,442	13,064	14,118	11,305	9,245	
2045	9,790	13,271	5,707	12,117	13,835	14,950	11,972	9,790	
2046	10,368	14,054	6,044	12,831	14,651	15,833	12,678	10,368	
2047	10,980	14,884	6,400	13,588	15,515	16,767	13,426	10,980	
2048	11,627	15,762	6,778	14,390	16,431	17,756	14,218	11,627	
2049	12,313	16,692	7,178	15,239	17,400	18,803	15,057	12,313	
2050	13,040	17,676	7,601	16,138	18,427	19,913	15,945	13,040	
2051	13,809	18,719	8,050	17,091	19,514	21,088	16,886	13,809	
2052	14,624	19,824	8,524	18,099	20,665	22,332	17,882	14,624	
2053	15,487	20,993	9,027	19,167	21,885	23,649	18,937	15,487	
2054	16,401	22,232	9,560	20,298	23,176	25,045	20,055	16,401	
2055	17,368	23,544	10,124	21,495	24,543	26,522	21,238	17,368	
	279,591	379,001	162,975	346,024	395,092	426,954	341,882	279,591	
Com.	307,550	416,902	179,273	380,626	434,601	469,649	376,070	307,550	
EF	-	-	0.07	0.53	0.12	0.50	4.50	8.50	
10^6 ESA	-	-	2.29	36.82	9.52	42.86	308.85	477.09	877.41

Addis Ababa - Ambo									
Year	**Car**	**4WD**	**MB**	**LB**	**ST**	**MT**	**HT**	**TT**	**Total**
2016	89	408	759	89	54	377	279	259	2,314
2017	95	435	808	95	58	402	297	276	
2018	101	463	861	101	61	428	316	294	
2019	108	493	917	108	65	455	337	313	
2020	114	525	976	114	69	485	359	333	
2021	122	559	1,040	122	74	517	382	355	
2022	130	595	1,107	130	79	550	407	378	
2023	138	634	1,179	138	84	586	434	402	
2024	147	675	1,256	147	89	624	462	429	
2025	157	719	1,338	157	95	664	492	457	
2026	167	766	1,425	167	101	708	524	486	
2027	177	811	1,509	177	107	749	555	515	
2028	187	859	1,598	187	114	794	587	545	
2029	198	910	1,692	198	120	840	622	577	
2030	210	963	1,792	210	127	890	659	611	
2031	223	1,020	1,898	223	135	943	698	648	
2032	236	1,080	2,010	236	143	998	739	686	
2033	250	1,144	2,128	250	151	1,057	782	726	
2034	264	1,212	2,254	264	160	1,119	828	769	
2035	280	1,283	2,387	280	170	1,185	877	814	
2036	296	1,359	2,528	296	180	1,255	929	862	
2037	314	1,439	2,677	314	190	1,330	984	913	
Com.	4,403	20,186	37,552	4,403	2,672	18,652	13,804	12,814	
EF	-	-	0.07	0.53	0.12	0.50	4.50	8.50	
10^6 ESA	**-**	**-**	**0.48**	**0.43**	**0.06**	**1.70**	**11.34**	**19.88**	**33.88**

2038	332	1,524	2,835	332	202	1,408	1,042	967	
2039	352	1,614	3,002	352	214	1,491	1,103	1,024	
2040	373	1,709	3,179	373	226	1,579	1,169	1,085	
2041	395	1,810	3,366	395	240	1,672	1,237	1,149	
2042	418	1,916	3,565	418	254	1,771	1,310	1,217	
2043	443	2,029	3,775	443	269	1,875	1,388	1,288	
2044	469	2,149	3,998	469	284	1,986	1,470	1,364	
2045	496	2,276	4,234	496	301	2,103	1,556	1,445	
2046	526	2,410	4,484	526	319	2,227	1,648	1,530	
2047	557	2,553	4,748	557	338	2,359	1,745	1,620	
2048	590	2,703	5,029	590	358	2,498	1,848	1,716	
2049	624	2,863	5,325	624	379	2,645	1,958	1,817	
2050	661	3,032	5,640	661	401	2,801	2,073	1,924	
2051	700	3,210	5,972	700	425	2,966	2,195	2,038	
2052	742	3,400	6,325	742	450	3,141	2,325	2,158	
2053	785	3,600	6,698	785	477	3,327	2,462	2,286	
2054	832	3,813	7,093	832	505	3,523	2,607	2,420	
2055	881	4,038	7,511	881	534	3,731	2,761	2,563	
	14,179	64,999	120,917	14,179	8,603	60,060	44,448	41,262	
Com.	15,597	71,499	133,009	15,597	9,463	66,066	48,893	45,388	
EF	-	-	0.07	0.53	0.12	0.50	4.50	8.50	
10^6 ESA	-	-	**1.70**	**1.51**	**0.21**	**6.03**	**40.15**	**70.41**	**120**

Addis Ababa - Ghion									
Year	**Car**	**4WD**	**MB**	**LB**	**ST**	**MT**	**HT**	**TT**	**Total**
2016	314	490	984	241	317	655	429	250	3,679
2017	334	522	1,048	257	338	698	457	266	
2018	356	556	1,116	273	360	743	487	284	
2019	379	592	1,189	291	383	791	518	302	
2020	404	630	1,266	310	408	843	552	322	
2021	430	671	1,348	330	434	897	588	343	
2022	458	715	1,436	352	463	956	626	365	
2023	488	761	1,529	375	493	1,018	667	388	
2024	520	811	1,629	399	525	1,084	710	414	
2025	553	864	1,734	425	559	1,154	756	441	
2026	589	920	1,847	452	595	1,230	805	469	
2027	624	974	1,956	479	630	1,302	853	497	
2028	661	1,032	2,071	507	667	1,379	903	526	
2029	700	1,092	2,194	537	707	1,460	956	557	
2030	741	1,157	2,323	569	748	1,546	1,013	590	
2031	785	1,225	2,460	603	793	1,638	1,073	625	
2032	831	1,297	2,605	638	839	1,734	1,136	662	
2033	880	1,374	2,759	676	889	1,837	1,203	701	
2034	932	1,455	2,922	716	941	1,945	1,274	742	
2035	987	1,541	3,094	758	997	2,060	1,349	786	
2036	1,046	1,632	3,277	803	1,056	2,181	1,429	833	
2037	1,107	1,728	3,470	850	1,118	2,310	1,513	882	
Com.	15,535	24,243	48,683	11,923	15,684	32,406	21,225	12,369	
EF	-	-	0.07	0.53	0.12	0.50	4.50	8.50	

10^6 ESA	**-**	**-**	**0.62**	**1.15**	**0.34**	**2.96**	**17.43**	**19.19**	**41.69**
2038	1,173	1,830	3,675	900	1,184	2,446	1,602	934	
2039	1,242	1,938	3,892	953	1,254	2,591	1,697	989	
2040	1,315	2,052	4,121	1,009	1,328	2,743	1,797	1,047	
2041	1,393	2,173	4,364	1,069	1,406	2,905	1,903	1,109	
2042	1,475	2,302	4,622	1,132	1,489	3,077	2,015	1,174	
2043	1,562	2,437	4,895	1,199	1,577	3,258	2,134	1,244	
2044	1,654	2,581	5,183	1,270	1,670	3,450	2,260	1,317	
2045	1,752	2,733	5,489	1,344	1,768	3,654	2,393	1,395	
2046	1,855	2,895	5,813	1,424	1,873	3,870	2,534	1,477	
2047	1,964	3,066	6,156	1,508	1,983	4,098	2,684	1,564	
2048	2,080	3,246	6,519	1,597	2,100	4,340	2,842	1,656	
2049	2,203	3,438	6,904	1,691	2,224	4,596	3,010	1,754	
2050	2,333	3,641	7,311	1,791	2,355	4,867	3,188	1,858	
2051	2,471	3,856	7,743	1,896	2,494	5,154	3,376	1,967	
2052	2,616	4,083	8,199	2,008	2,641	5,458	3,575	2,083	
2053	2,771	4,324	8,683	2,127	2,797	5,780	3,786	2,206	
2054	2,934	4,579	9,196	2,252	2,962	6,121	4,009	2,336	
2055	3,107	4,849	9,738	2,385	3,137	6,482	4,246	2,474	
	50,024	78,062	156,762	38,394	50,502	104,349	68,345	39,828	
Com.	55,026	85,869	172,438	42,233	55,552	114,784	75,179	43,811	
EF	0	0	0.07	0.53	0.12	0.5	4.5	8.5	
10^6 ESA	**0.00**	**0.00**	**2.20**	**4.09**	**1.22**	**10.47**	**61.74**	**67.96**	**147.68**

APPENDIX – B Basic Materials Price

Basic Materials Price List for Cost Analysis (November 2014)						
Average Distance Of The Project Center From Addis Ababa 15.0km						
Item	Material Description	Unit	Unit Price in Birr at Addis Ababa	Transport cost	Total Cost	Remark
1	Cement	Qut.	275.00	0.00	275.00	Total cost is at project site
2	Gas Oil (NOC)	Lts.	18.08	0.00	18.08	"
3	Lubricants	Kg.	100.00	0.00	100.00	"
4	Reinforcement Bar	Kg.	20.88	0.00	20.88	"
5	Nails	Kg.	30.00	0.00	30.00	"
6	Binding Wire	Kg.	25.00	0.00	25.00	"
7	Eucalyptus Poles Ø12cm, 4 mts long	Pcs.	60.00	0.00	60.00	"
8	Lumber 2.5cm	m^3	4,000.00	0.00	4,000.00	"
9	Sand	m^3	450.00	0.00	450.00	"
10	Aggregate (20mm)	m^3	550.00	0.00	550.00	"
11	Aggregate for AC (all sizes)	m^3	550.00	0.00	550.00	"
12	Asphlat /Bitumen 60/70 or 40/50 (NOC)	Kg.	36.00	0.00	36.00	"
13	Bitumen grade MC-30 (NOC)	Lts.	36.00	0.00	36.00	"

Source: market survey by the researcher at different locations of Addis Ababa

Unit costs of ready mix concrete and hot mix asphalt supplies in the industry (MIDROC Construction Ethiopia); the unit price includes delivery casting or paving of the materials on site.

Item No.	Description	Unit	Unit Rate	Remark
1	C-30 Concrete	m^3	3,300	400 kg OPC is used for the mix
2	Asphalt Wearing Course	m^2	450	40 mm thick
3	Tack Coat	m^2	65	RC-70 cut back Bitumen applied at 1L/m^2
4	Asphalt Binding Course	m^2	550	50 mm thick
5	Prime Coat	m^2	55	MC-30 cut back Bitumen applied at 1L/m^2

APPENDIX – C Cost Break Down for C-40 Concrete

ANALYSIS OF COST BREAKDOWN FOR ONE METER CUBE C-40 CONCRETE

		Date:
Project:	A - B	Page No.:
Work Item:	Concrete Class C-40	
		Monthly Output
		Labor:
		Equipment:
		Resultant Taken: 15.00 m^3/d
		2.14 m^3/h

No.	D) Material Type	Qty. Per Measure	Unit Price	Cost Per Measure	E) Labor by Skills	No.	U.F.	Indexed Hourly Rate	Hourly Cost	F) Equipment Type	No.	U.F.	Hourly Rental Rate	Hourly Cost
1	Cement (OPC)	4.20	300.00	1260.00	Construction Forman	1	1.00	83.68	83.68	Concrete Mixer	1	1.00	30.00	30.00
2	Aggregate (20mm)	0.90	550.00	495.00	Mason & Carpentor	4	1.00	19.52	78.10	Concrete Vibrator	2	1.00	25.00	50.00
3	Sand	0.60	450.00	270.00	Bar bender II	1	1.00	16.74	16.74	Water Tanker	1	1.00	1.00	1.00
4	Form Work	0.14	348.66	49.86	Light Equ. Operator I	3	1.00	13.95	41.84	Dump Truck	2	0.25	200.00	100.00
					Laborers	20	1.00	8.22	164.35	Water Truck	2	1.00	250.00	500.00
					Heavy Truck Driver	2	0.25	16.74	8.37	Light Vehicle	1	0.50	500.00	250.00
					Light Vehicle Driver	1	0.50	11.16	5.58	Hand Tools	20	1.00	0.25	5.00
		Sub Total (A)	=	2074.86		Sub Total (B)		=	398.64		Sub Total (C)		=	936.00
Purchase+Fabic's+Transport+Waste+Store														

(D) Material

Unit Price=Sub Total (A) = 2074.86

(E) Manpower

Unit Cost = $\frac{\text{Sub Total(B)} = 398.64}{\text{Hourly output } 2.14}$ 186.03

(F) Equipment

Unit Cost = $\frac{\text{Sub Total(C)} = 936.00}{\text{Hourly output } 2.14}$ 436.80

Direct Cost = D+E+F = 2,697.69 Birr/M3

Remarks: Considering O.H. and Profit margin = 1.35 x 2,697.69 = **3,641.88**

UF - Utilization Factor

H.D.E - Heavy Duty Equipment

APPENDIX – D Sensitivity Analysis

D1 When cost of Cement increased by 10% and cost of Bitumen decreased by 10%

D1.1 Asphalt Concrete				
ERA Design Manual 2013 with S3 and T9				
Pavement Composition	Thickness (mm)	Qty/km	Rate (ETB)	Amount (ETB)
AC	90	7,300 m^2	780.61	5,698,453.00
Tack coats	1 lit/m^2	7,300 m^2	59.83	436,759.00
prime coats	1.2 lit/ m^2	7,300 m^2	51.08	372,884.00
Bituminous Road Base	190	1,387 m^3	4,178.5	5,795,579.50
SB	175	1,277.5 m^3	280	357,700.00
Capping	150	1,095 m^3	214.29	234,647.55
Total AC Cost				**12,896,023.05**
Original cost per km				**13,482,979.55**
Cost decreased by				**4.35%**

D1.2 Jointed Reinforced Concrete Pavement				
ERA Design Manual 2013 with S3 and $50*10^6$ ESAs				
Pavement Composition	Thickness (mm)	Qty/km	Rate (ETB)	Amount (ETB)
JRCP	245	1,788.5 m^3	4,393.69	7,858,127.03
SB	150	1,200 m^3	280	336,000.00
Capping	250	2,000 m^3	214.29	428,580.00
Rebar	600 mm^2/m	46,318 kg	37	1,713,768.96
Joint sealing, texturing, separation membrane and curing costs = 10% of pavement costs				1,033,647.60
Total JRCP Cost				**11,370,123.59**
Original cost per km				**10,989,053.86**
Cost increased by				**3.47%**

D1.3 Asphalt Concrete Pavement				
ERA Design Manual 2013 with S1 and T10				
Pavement Composition	Thickness (mm)	Qty/km	Rate (ETB)	Amount (ETB)
AC	90	7,300 m^2	780.61	5,698,453.00
Tack Coat	1lit/m^2	7,300 m^2	59.83	436,759.00
Prime Coat	1.2lit/m^2	7,300 m^2	51.08	372,884.00
Bituminous Road Base	220	1,606 m^3	4,178.5	6,710,671.00
SB	250	2,000 m^3	280	560,000.00
Capping	300	2,400 m^3	214.29	514,296.00
Total AC Cost				**14,293,063.00**
Original cost per km				**14,895,678.00**
Cost decreased by				**4.05%**

D1.4 Continuously Reinforced Concrete Pavement				
ERA Design Manual 2013 with S1 and $80*10^6$ ESAs				
Pavement Composition	Thickness (mm)	Qty/km	Rate (ETB)	Amount (ETB)
CRCP	225	1,642.5 m^3	4,393.69	7,216,647.27
SB	200	1,600 m^3	280	448,000.00
Capping	400	3,200 m^3	214.29	685,728.00
Rebar	0.6%/X-area	86,075.67 kg	37	3,184,799.79
Joint sealant, grinding and curing costs = 5% of pavement costs				576,758.75
Total CRCP Cost				**12,111,933.81**
Original cost per km				**11,777,879.18**
Cost increased by				**2.48%**

D2 When cost of Cement decreased by 10% and cost of Bitumen increased by 10%

D2.1 Asphalt Concrete Pavement				
ERA Design Manual 2013 with S3 and T9				
Pavement Composition	Thickness (mm)	Qty/km	Rate (ETB)	Amount (ETB)
AC	90	7,300 m^2	896.08	6,541,384.00
Tack coats	1 lit/m^2	7,300 m^2	71	518,300.00
prime coats	1.2 lit/m^2	7,300 m^2	60.8	443,840.00
Bituminous Road Base	190	1,387 m^3	4,676	6,485,612.00
SB	175	1,277.5 m^3	280	357,700.00
Capping	150	1,095 m^3	214.29	234,647.55
Total AC Cost				**14,581,483.55**
Original cost per km				**13,482,979.55**
Cost increased by				**8.15%**

D2.2 Jointed Reinforced Concrete Pavement				
ERA Design Manual 2013 with S3 and $50*10^6$ ESAs				
Pavement Composition	Thickness (mm)	Qty/km	Rate (ETB)	Amount (ETB)
JRCP	245	1,788.5 m^3	4,007.7	7,167,771.45
SB	150	1,200 m^3	280	336,000.00
Capping	250	2,000 m^3	214.29	428,580.00
Rebar	600$mm^{2/}$m	46,318 kg	37	1,713,768.96
Joint sealing, texturing, separation membrane and curing costs = 10% of pavement costs				964,612.04
Total JRCP Cost				**10,610,732.45**
Original cost per km				**10,989,053.86**
Cost decreased by				**3.44%**

D2.3 Asphalt Concrete Pavement				
ERA Design Manual 2013 with S1 and T10				
Pavement Composition	Thickness (mm)	Qty/km	Rate (ETB)	Amount (ETB)
AC	90	7,300 m^2	896.08	6,541,384.00
Tack Coat	1lit/m^2	7,300 m^2	71	518,300.00
Prime Coat	1.2lit/m^2	7,300 m^2	60.8	443,840.00
Bituminous Road Base	220	1,606 m^3	4,676	7,509,656.00
SB	250	2,000 m^3	280	560,000.00
Capping	300	2,400 m^3	214.29	514,296.00
Total AC Cost				**16,087,476.00**
Original cost per km				**14,895,678.00**
Cost increased by				**8.00%**

D2.4 Continuously Reinforced Concrete Pavement				
ERA Design Manual 2013 with S1 and 80*10^6 ESAs				
Pavement Composition	Thickness (mm)	Qty/km	Rate (ETB)	Amount (ETB)
CRCP	225	1,642.5 m^3	4,007.7	6,582,647.25
SB	200	1,600 m^3	280	448,000.00
Capping	400	3,200 m^3	214.29	685,728.00
Rebar	0.6%/X-area	86,075.67 kg	37	3,184,799.79
Joint sealant, grinding and curing costs = 5% of pavement costs				545,058.75
Total CRCP Cost				**11,446,233.79**
Original cost per km				**11,777,879.18**
Cost decreased by				**2.80%**

APPENDIX – E Typical 3-D Plan and Profiles of Rigid Pavements

E1 Jointed Unreinforced Concrete Pavement (3-D, Plan & Profile)