UNIVERSITY OF NAIROBI

Department of Civil and Construction Engineering

GEOSYNTHETICS IN ROAD PAVEMENT DESIGN AND CONSTRUCTION IN KENYA

BY

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university.

Signed: **………………………………………………**Date: ………………………

Mr. Macharia Gacheru Paul - F56/82254/2015

This thesis has been submitted for examination with our approval as university supervisors.

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Prof. Sixtus K. Mwea

Signed: ………………………………………………Date: ………………………

Dr. Simpson N. Osano

DEDICATION

To my family, with love.

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Above all, thanks to God who for wisdom, good health and protection to undertake the tasks towards compilation of this document.

God bless you all.

ABSTRACT

In the past two decades, Kenya has been investing heavily towards infrastructure development. Infrastructure is at the heart of the country's goal of attaining its Vision 2030 of accelerating transformation into a rapidly industrializing middle-income nation by the year 2030.

Road construction costs, among other infrastructural development's costs, have been increasing rapidly. This can be attributed, partly, to the fast depletion of natural construction materials, and the increase in population density, which in turn shrinks the available land on which to place proposed infrastructural projects. The cost of land acquisition has skyrocketed. The design engineer is so often constrained to follow the available route alignment, despite the existing conditions, which are unsuitable at times.

The traffic loading on Kenyan roads has also increased. There has been the need to build roads that can accommodate higher axle loading, for long periods. At this point in time, alternative construction materials that guarantee a reduction in costs of construction and life-cycle costs, and at the same time accommodate the increased loading on our roads, are highly welcome.

Geosynthetics provide varied possibilities. The applicability of geosynthetics in road pavements, considering the cost approach, was addressed in this research. Geosynthetic reinforcement of the base, or subbase courses, was looked into, and the recommended practice introduced. The cost savings that are derived by using geosynthetics was also addressed, and also the sustainability of using geosynthetics in road pavement design and construction.

It was established that there are geosynthetic materials in the Kenyan market that can be used to reinforce road pavements. Analysis of the reinforcement possibility showed that placing a geotextile below the subbase or base of the pavement will yield substantive savings in costs of construction and eventual life-cycle costs. This is in addition to other associated savings in reduced pollution and shortened construction period.

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LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
BCR	Base Course Reduction
CBR	California Bearing Ratio
EAGM	European Association of Geosynthetic Manufacturers
EE and EC	Embodied Energy and Embodied Carbon
ESAL	Equivalent Standard Axle Loading
FHWA	Federal Highway Administration
FWD	Falling Weight Deflectometer
ICE	Inventory of Carbon and Energy
ISO	International Organization for Standardization
KEBS	Kenya Bureau of Standards
Kshs	Kenya Shillings
LCA	Life Cycle Analysis
LCR	Layer Coefficient Ratio
M-E	Mechanistic-Empirical
MEPDG	Mechanistic-Empirical Pavement Design Guide
PE and PP	Polyethylene and Polypropylene
PSI	Present Serviceability Index
Psi	Pound per Square Inch
RDM	Road Design Manual (Kenya)
TBR	Traffic Benefit Ratio
TRB	Transport Research Board
USCS	Unified Soil Classification System
UV	Ultraviolet

1.0 INTRODUCTION

1.1 Background

In designing road pavements, pavement engineers endeavour to deliver structures that will meet users’ present needs, and without rapidly becoming obsolete. The structures also need to be safe, and economical to construct and maintain. In Kenya, in the past, the initial cost of the project and the maintenance costs have not been put into consideration.

Geosynthetics have permitted innovative pavement designs that can better meet all aimed objectives. There is a belief that regularization limits opportunities for inventive solutions. However, innovation must pave the way to the adoption of appropriate technology, or its standardization (state of the practice). From experience, in Kenya, the move from innovative technologies to the state of practice by transportation and regulating agencies lags behind that in other engineering communities. This can be owed to our economic strength, knowing that innovation always seems to be costly until the technology becomes the standard of practice. The biggest role, however, is played by governmental conservatism, where many will prefer to stick to what is known.

With regard to geosynthetics, pavement engineers need to be more willing to consider the new materials in applications such as geosynthetic-reinforced pavement structures. Doing so will allow the innovation to become the state of practice, which in turn will lead to reduced project costs.

This study investigated the possibilities of incorporating geosynthetics in the design of road pavements in Kenya to achieve durable pavements and in a cost-beneficial way. The study is in five chapters with the first chapter introducing and giving a background into the study, the second chapter reviews existing literature on similar studies and reviews existing theory on the study. The third chapter covers the methodology used in acquisition of data and data collected while chapter four discusses and analyses results of the study. The final chapter gives conclusion and recommendations on the study. Other information on the study are the references and appendices, which form part of the thesis.

1.2 Terminologies

A geosynthetic refers to "a planar product manufactured from polymeric material used with soil, rock, earth, or other geotechnical engineering related material as an integral part of a man-made project, structure, or system." (ASTM, 1997).

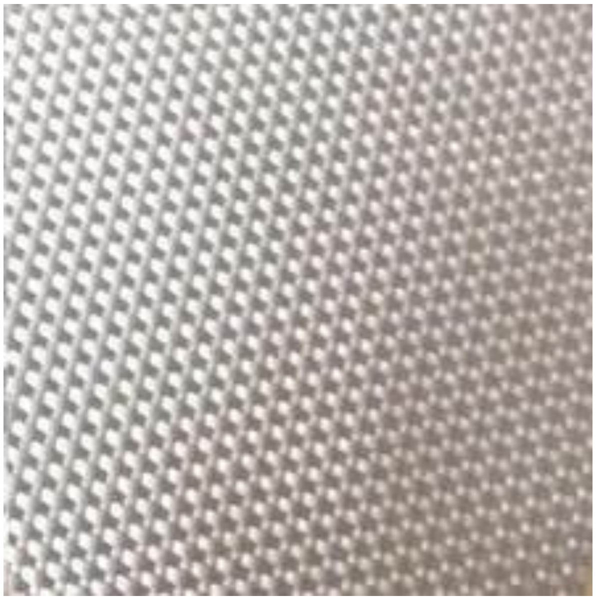
Bathurst (2009) largely classified geosynthetics into classes centred on technique of their production. The section below gives the brief descriptions of geosynthetics that are commonly used in road construction.

Geotextiles refer to continuous sheets of woven, non-woven, knitted or stitch-bonded fibres, which are usually flexible and permeable, and usually take the form of a fabric. Plate 1.1 and 1.2 show the two forms of geotextiles.

Geogrids are geosynthetic materials with an open web-like appearance, whose major use is the strengthening of soil materials.

Geomembranes refer to continuous elastic sheets made from one or several synthetic materials.

Geocomposites refer to geosynthetics manufactured from an amalgamation of two or more geosynthetic material types.

 **Plate 1.1:** Non-woven geotextile (Source: Author, 2017)	 **Plate 1.2:** Woven geotextile (Source: Author, 2017)

1.3 Problem Statement

Pavement design in Kenya is guided by the Road Design Manual Part III (Ministry of Transport and Communication, 1987), which follows the traditional catalogue system. The pavement structures are mainly composed of natural materials. These natural materials include gravels and crushed stone. Their sources are being depleted fast due to the continuous use and the lack of substitute materials. This means natural construction material sources are usually located further from the project roads, hence long haulage distances, increasing the cost of construction of roads and pollution of the environment.

Moreover, owing to the scarcity of good quality, natural construction materials used is usually compromised, and thus the durability of our roads is usually low. The premature failures encountered on our roads can be owed, to a better part, to a lack of creative innovations by the design engineers, thereby lacking alternative materials to counter the fast depletion of our natural resources.

Due to population growth, land availability has reduced. Many times, when design engineers are faced by very poor insitu materials along proposed projects, the design manual requires that either the alignment be changed, or the poor material is cut away and replaced with good quality material. Both options result in high overall construction cost.

Geosynthetic reinforcement of pavements is becoming a recommended practice because of the emphasis being placed in this area by the geosynthetics industry. Unfortunately, relatively little information is available to assist the designer with the appropriate usage of geosynthetic materials for pavement reinforcement applications.

The plates 1.3 - 1.6 demonstrate the state of some sampled roads, and some of these problems could be solved if the revolutionary technology of geosynthetics was incorporated in pavement design.

Figure 1.1 and Table 1.1 show the problems encountered on the Lamu-Garissa road, a sample road for this research, which also reflects the situation on many Kenyan roads. Figure 1.1 shows the thick recommended pavement structure for the road, which is expensive to construct. Table 1.1 shows the poor insitu material on the proposed alignment, meaning that an extra cost will be incurred to cart away the poor soil and replace it with good quality material for the formation.

However, incorporating a geosynthetic in the pavement structure of this road could lead to a thinner pavement structure, and enable construction over the poor insitu material.

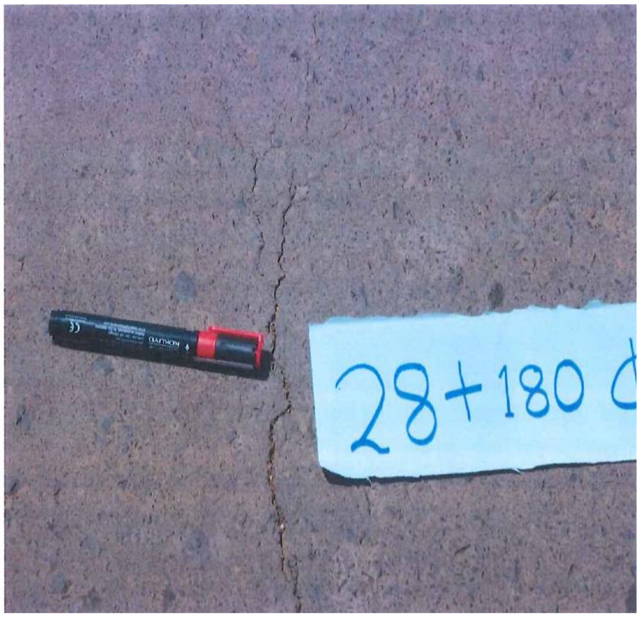


Plate 1.3: Longitudinal reflective crack in surfacing - Sigalagala-Butere Road (Source: Author, 2015)

Plate 1.4: Ravelling of surfacing and pothole - Sigalagala-Butere Road (Source: Author, 2015)

Plate 1.4: Potholed section of a Limuru township Road (Source: Author, 2016)

Plate 1.6: Rutting on Timboroa – Eldoret Road (Source: Kipyator F. K., 2013)

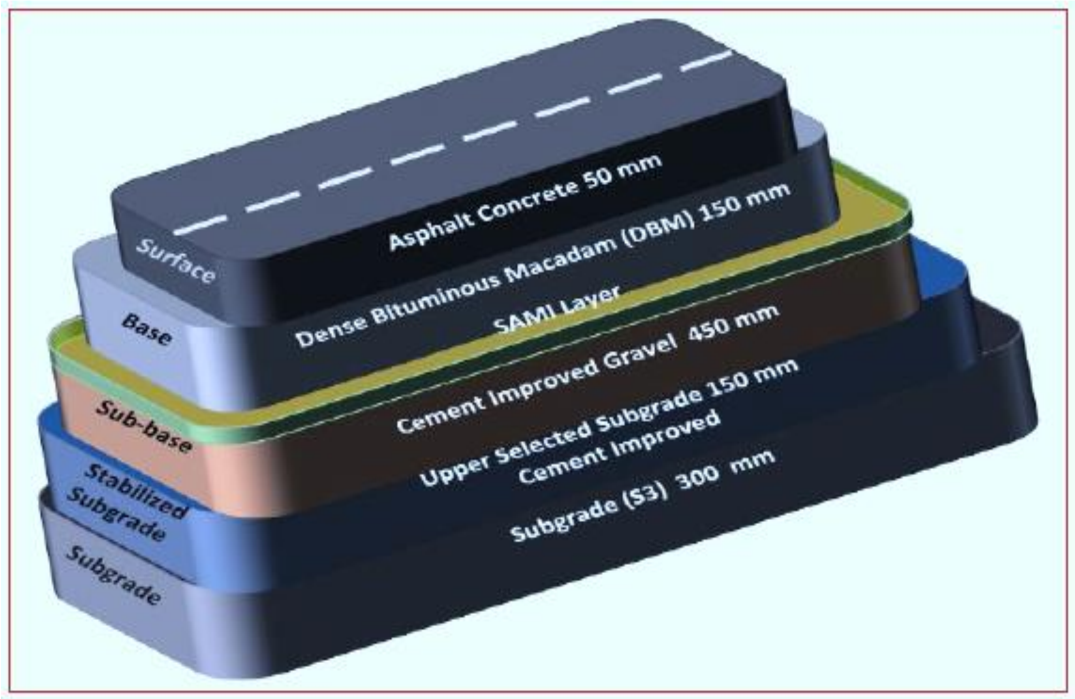


Figure 1.1: A thick pavement structure recommended for construction on Lamu-Garissa Road. (Source: Sai Consulting Engineers Pvt., 2015)

Table 1.1: Homogenous sections along the Lamu-Garissa road. Predominant insitu material was of poor strength, and not suitable for road formation. (Source: Sai Consulting Engineers Pvt., 2015)

No.	Chainage (KMs)	Average CBR value
1	0+000 – 4+500	14
2	4+500 – 15+500	6
3	15+500 – 32+500	15
4	32+500 – 38+500	3
5	38+500 – 44+500	12
6	44+500 – 75+000	3
7	75+500 – 100+500	1
8	100+500 – 249+500	3

1.4 Objectives of the study

This study was aimed at:

a) Establishing the mechanical properties of geosynthetics that can be justifiably used in flexible pavements to achieve economical pavement structures.
b) Establishing the cost savings that can be achieved by incorporating geosynthetics in the design and construction of flexible pavements.

1.5 Research Questions

This study sought to answer the following:

a) Are there mechanical properties of geosynthetics that can be used in flexible pavements to achieve economical pavement structures?
b) Are there cost savings that can be attained by incorporating geosynthetics in the design and construction of flexible pavements?

1.6 Justification of the study

Road construction costs have been increasing rapidly. The fast depletion of natural construction materials and high cost of land acquisition are some of the factors contributing to the high costs of construction. The traffic loading on Kenyan roads has also increased. There has been the need to build roads that can accommodate higher axle loading, for long periods. Now, alternative construction materials that guarantee a reduction in costs of construction and life-cycle costs, and at the same time accommodate the increased loading on our roads, are highly welcome, and this study seeks to introduce the use of geosynthetics in road pavements in Kenya in a cost saving approach.

1.7 Scope of the study

This research was limited to the use of geotextile type of geosynthetic as a reinforcement in road pavement design and construction. It involved laboratory testing to determine the mechanical properties of the geotextile. The research also investigated the effects of incorporating a geosynthetic in a sample road pavement structure. Here, designs with and without incorporating a geosynthetic were compared in terms of load carrying, life and cost.

2.0 LITERATURE REVIEW

2.1 Introduction

This chapter highlights the relevant literature and other studies carried out in the area including academic papers, theses, dissertations, books, journals and credible internet information by various institutions and personalities. It evaluates and correlates their findings that could be useful for further study on the same topic.

2.2 History of Geosynthetics

Beckham and Mills, (1935), made the first reference to a textile material being utilised for geosynthetic application. A woven cotton fabric was used to separate and stabilize the soil subgrade of an unpaved road. It was reported that after eight years, the fabric had degraded so much due to soil microorganisms that it could hardly be recognized. Termed by numerous names over the later decades, such as filter fabrics, synthetic fabrics, road rugs, or construction cloth, the name "geosynthetics" is currently used worldwide.

2.3 Nature of Geosynthetics

Geosynthetics are a well-known family of geo-materials used extensively in civil engineering applications. Many polymers used in ordinary life constitute the geosynthetics. The most common are polyolefin and polyester (Koerner, 2016). The geotextile and geogrid types of geosynthetics are briefly discussed in subsections below, along with their specific applications.

2.3.1 Geotextiles

Wovens and nonwovens make up the two main geotextile types. Nonwovens are made using either staple fibres (measuring about 25mm to 100mm in length) or continuous filaments that are arbitrarily dispersed in layers against a moving belt to make up a felt-like "web". The web is passed through a needle loom that interlocks the filaments. The nonwovens are normally used for drainage and stabilization applications (Geosynthetic Materials Association, 2002). Woven geotextiles are made by weaving of yarns. The Figure 2.1 shows the manufacture process of non-woven geotextiles.

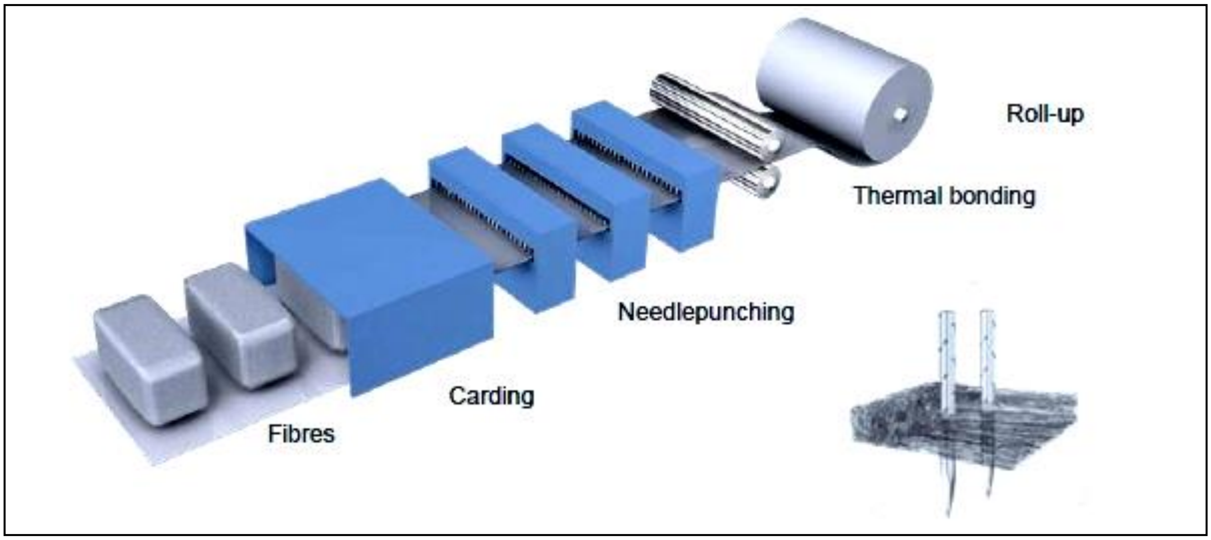


Figure 2.1: Diagram showing the manufacturing of non-woven geotextile (Source: Fibertex, www.fibretex.com, 2011)

2.3.2 Geogrids

Geogrids are composed of extruding and stretching high-density polyethylene or polypropylene made by weaving or knitting and coating high tenacity polyester yarns. Their grid like arrangement possesses apertures that enhance the contact with the soil. The tensile strength and stiffness of geogrids make them particularly effective as a soil reinforcement (GMA, 2002).

2.4 Key Properties and Behaviour of Geosynthetics

The geosynthetic characteristics essential for pavement design are centred on the properties required to carry the expected design traffic over the life of the pavement, and those required to survive against installation damage. The fundamental characteristics for geotextiles to achieve the reinforcement function are the tensile modulus and shear interaction (Christopher, 2016).

Sufficient interaction is required to transmit the target loading through the natural material to the reinforcement, whereas sufficient load-strain properties of the geotextile are essential to minimise horizontal movement of the natural material. Similarly, significant border shear resistance amid the geotextile and subgrade is necessary to minimise the strain level in the roadbed (Cuelho et al., 2014).

Strength is essential for the reinforcement. The optimal stresses on the roadbed are from pavement weight and vehicle loading, and usually little compared to the soil bearing capacity. The strength of geosynthetics is comparatively higher that this value. Nonetheless, the geotextile must survive construction damage, which is regularly higher than the reinforcement requirements. Therefore, geotextile survivability requires the geotextile to survive the construction work for it to succeed on its envisioned role (Christopher, 2016).

AASHTO (2014a) classifies geotextiles either as category one (high), category two (moderate) and category three (low) survivability based on their index properties (that is grab strength, California Bearing Ratio puncture resistance, and tear resistance). For stabilization functions, category one geotextiles are recommended for use.

2.5 Quality Control Testing of Geosynthetics

The mechanical behaviour tests are recognized in two classes: those dealing with load-extension properties, obtained using tensile tests, and those dealing with integrity properties, and usually obtained from tear propagation and puncture tests (Zanzinger, 2016).

2.5.1 Sampling and Specimen Preparation

Geosynthetics samples are obtained from the second fold of the roll and is usually cut over the full width of the roll. Normally, specimens are not taken closer than ten centimetres from the edge (ASTM D4354-99).

2.5.2 Tensile Behaviour

The tensile behaviour of geosynthetics provide soil reinforcement by improving the soil structural integrity. Therefore, the load-extension properties of the geosynthetic are of supreme significance to soil reinforcement applications. Tensile properties of geosynthetics are obtained using the small-width, grab and wide-width tests (Zanzinger, 2016).

2.5.2.1 Tensile Strength and Elongation

In the wide-width test, the specimen is firmly pinned and then slowly pulled to tear. Tensile strength measurements of are taken as the loading per unit width. The testing is carried out at strains of ten percent per minute in gauge length (ASTM D4595-11).

Since the testing rate has an effect on tensile strength, a common strain rate is normally fixed for all geotextiles. Wovens made from yarns with a ten percent break elongation are tested for thirty seconds, while those made from yarns with a break elongation of twenty percent are tested for one minute.

2.5.2.2 Tensile Stiffness

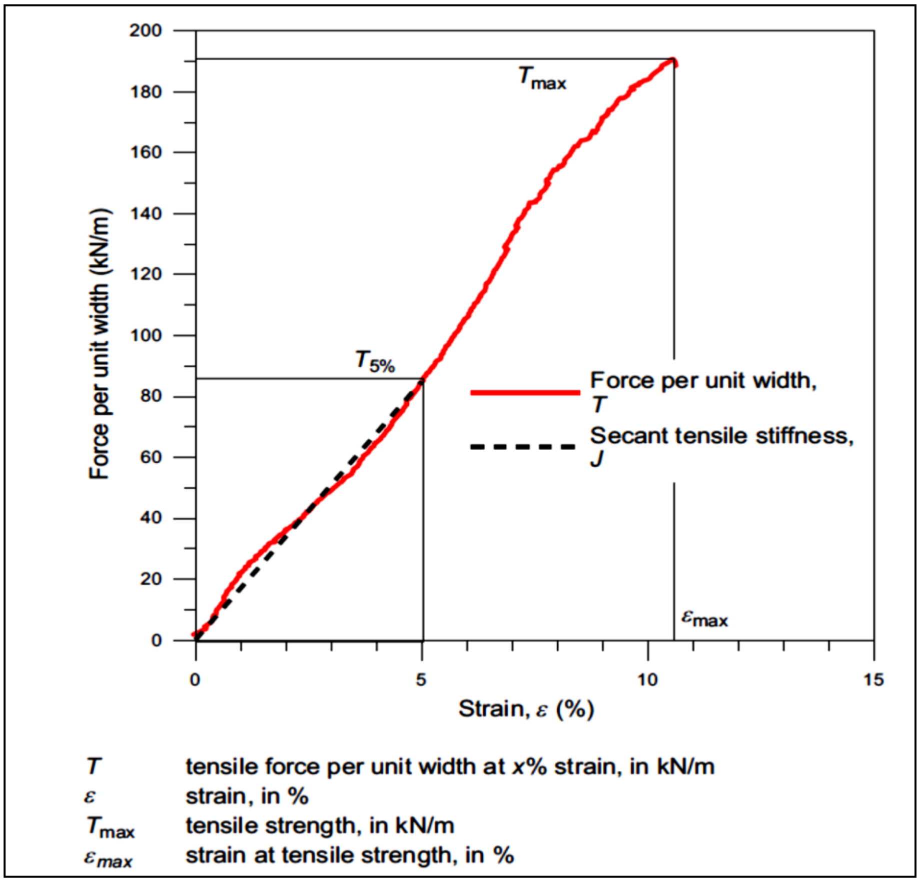
Better measurements of true tensile strength are obtained by wide-width tensile test, as compared to the small-width test. A load per unit width versus strain curve is used to present the test data, as shown in Figure 2.2, from which the modulus values are calculated using Equation 2.1. This is an index test for wovens.

$J = (T\,x100)/\varepsilon$…………………………*Equation 2.1*

Whereby;

J is the secant tensile stiffness, in kN/m, and

ε strain in percentage (Zanzinger, 2016).



T tensile force per unit width at x% strain, in kN/m
ε strain, in %
T_{max} tensile strength, in kN/m
ε_{max} strain at tensile strength, in %

Figure 2.2: Typical load/unit width against strain curve for wovens (Zanzinger, 2016).

2.5.3 Static Puncture Strength (California Bearing Ratio Test)

The California Bearing Ratio test (ASTM D6241-99) determines the requisite force to drive a flat plunger through a geotextile fixed in the midst of two immovable rings. The highest force and movement at tear are measured. With this, the tensile strength is computed (Zanzinger, 2016).

2.6 Application of Geosynthetics in Road Pavements

2.6.1 Separation Function

This function is attained by locating a flexible, porous geosynthetic in between unlike materials so that the strength and the working of the two materials can be enhanced. For instance, failure of road pavements constructed over soft roadbeds is often due to adulteration of the gravel base course with materials from the soft subgrade soils beneath it. The adulteration is attributed to:

(1) Penetration of the base into the weak subgrade due to localized bearing capacity failure under stresses induced by wheel loads, and

(2) Fine-grained soils intruding into the base due to subgrade weakening caused by excessive pore water pressure. The contamination of the subgrade causes insufficient structural support resulting to premature failure of the pavement. A geotextile, placed in between the base and the subgrade, acts as a separator, thereby preventing the subgrade and gravel base course from mixing (Zornberg and Barry, 2006). Geotextiles are usually used in the separation function. (Koerner, 2005). Figure 2.3(a) and 2.3(b) demonstrate the separation function of a geotextile.

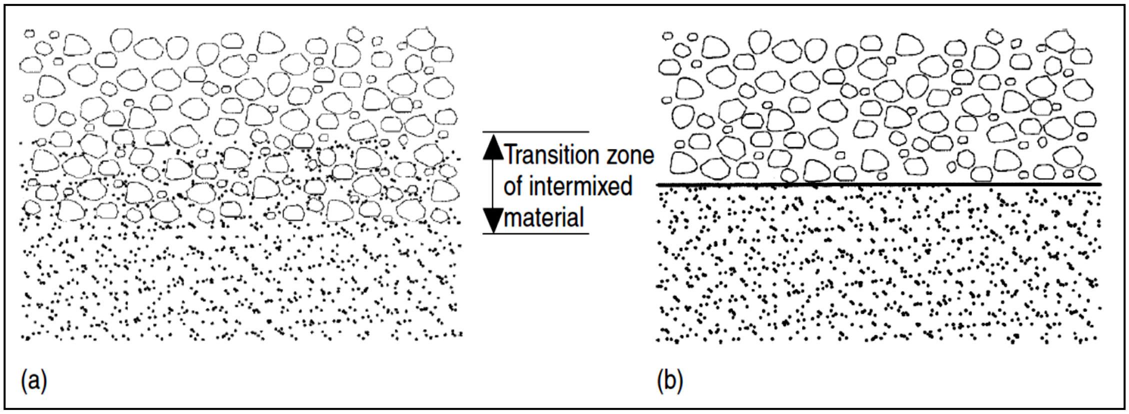


Figure 2.3: Separation function of a geotextile placed between road aggregate and soft saturated subgrade. (a) without geotextile and (b) with geotextile. (Zornberg and Barry, 2006).

2.6.2 Reinforcement Function

Geosynthetics, when used in reinforcement, are aimed at improving the construction and life cycle performance of paved, unpaved and rail roads. The enhancements are attained by their interaction with natural materials in the pavement, thereby improving its capacity and integrity over the design life. The success of geosynthetic reinforcement require collaboration with other geosynthetic functions such as separation and filtration (Christopher, 2016).

2.6.2.1 Reinforcement Mechanisms

Geotextiles reinforce poor subgrade soils to construct haulage tracks and providing a strong roadbed to support construction traffic (Christopher, 2016).

These improvements are provided by the following reinforcement mechanisms, and as shown in Figure 2.4:

(a) Lateral restraint of the base and/or subgrade through geotextile-soil interface shear resistance between the aggregate, soil, and the geosynthetic;

(b) Increase in the system-bearing capacity by compelling the potential-bearing capacity failure surface to develop along an alternative, higher shear-strength surface;

(c) Membrane support of the wheel loads (Holtz et al., 2008).

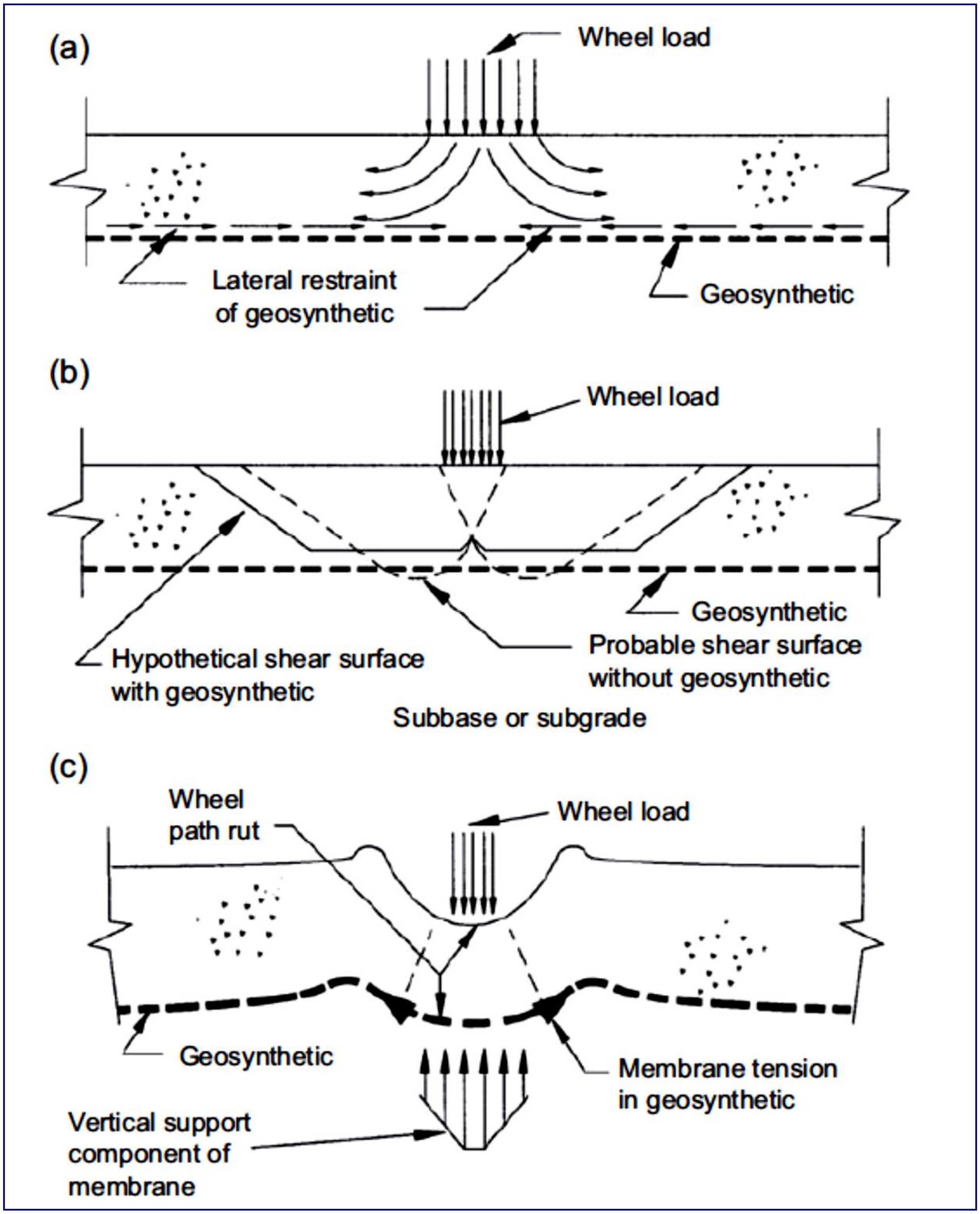


Figure 2.4: The reinforcement mechanism of geosynthetics: (a) lateral restraint, (b) increase in bearing capacity, and (c) membrane tension support (Holtz et al., 2008**).**

2.6.2.2 Reinforcement Mechanisms Limitations

The reinforcement influence of geotextile tend to reduce when introduced on stronger subgrade conditions and thicker pavement layers. With rutting of the subgrade of about 75-100 mm, the membrane tension support will not be developed. In addition, bearing capacity is not a problem for strong subgrades. Geotextile reinforcement is not important for subgrade soils with a CBR less than 3-4, (undrained cohesion, c_u approx. 90-120 kPa) and a resilient modulus M_R of not more than 30-40 MPa (Christopher, 2016).

Separation and lateral restraint reduce with stronger subgrades. Therefore, the normal effective performance limits are: (a) California Bearing Ratio ≤ 8 (b) Paved sections with base/subbase coarse layers ≤ 400 mm thick (c) Asphalt surface layers ≤ 75-100 mm thick (Christopher, 2016).

Substantial improvements in performance could be attained through pre-stressing the geosynthetic by rutting to about 25-50mm (Christopher and Lacina, 2008). For stronger soils, placing the geotextiles after proof rolling with a loaded truck (minimum axle load of 8 tonnes) is recommended.

2.6.3 Filtration Function

This encompasses the movement of water through the geotextile while retaining soil on its upper side. The geotextile must provide adequate hydraulic conductivity and soil retention. Additionally, the movement from side to side of the geotextile should not be diminished by clogging over the life of the pavement (Zornberg and Barry, 2006).

Certain geotextiles used for filtration function are comparatively thick and compressible. Therefore, geosynthetics are normally categorized by their permittivity, as defined by Equation 2.2:

$$\psi = k_n / t \text{ ……………………………} \textit{Equation 2.2}$$

Where;

ψ is the permittivity,
k_n is the hydraulic conductivity, and
t is the geotextile thickness at a specific normal pressure (Zornberg and Barry, 2006).

Larger flow of water require geotextiles with larger openings. However, enormous geotextile voids can lead to soil piping. In such case, the water velocity will then increase, thereby accelerating the process and eventual collapse of the soil structure. Therefore, a geotextile with small enough openings to retain the soil on the upper side of the fabric openings is recommended.

2.6.4 Drainage Function

This is achieved by conveying water within the plane of the structure of the geosynthetic. Geotextiles and geocomposites are the geosynthetics used for the drainage purpose. They allow sufficient flow and minimal loss of soil over the design life.

Nonwoven geotextiles have substantial openings and allow flow of about of 0.01 - 0.1 litres/sec/metre width, while geocomposite allow twice the flow. As the geosynthetic thickness reduces with growing normal stress, the in-plane drainage of a geosynthetic is normally computed by its transmissivity, which is defined in Equation 2.3.

$$\theta = k_p * t \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation 2.3}$$

Where;

θ defines transmissivity,
k_p is hydraulic conductivity, and
t is the geotextile thickness at a specific pressure (Zornberg and Barry, 2006).

2.7 Designing with Geosynthetics

Geosynthetics reinforcement is used for various applications that including haulage tracks and working areas, tarmacked and untarmacked roads, and railroads.

2.7.1 Haulage tracks and working areas

Here, geosynthetics are used to ensure thickness reduction of the natural material needed to facilitate vehicles to access the site, minimise failure and improve the performance of the subgrade. Normally, these sites would require removal of clogged water, cutting away poor soil and filling in with suitable materials, or use of mechanical or cement/lime stabilization. Geosynthetics are an economical alternative (Collins and Holtz, 2005).

Stewart et al. (1977) developed the method used to design the roads (Forest Service method) which was centred on soil mechanics. The technique is appropriate for computing the natural material thickness sufficient to carry traffic loading over subgrades with a California Bearing Ratio of less than three (Christopher, 2016).

The following design steps select suitable performance requirements of geotextiles used for reinforcement (Christopher, 2016):

Step 1. Characterise the subgrade by establishing its California Bearing Ratio, the location of the groundwater table and the class of the soil.

Step 2. Relate characteristics to the subgrade properties that are optimum for use of geotextiles in pavements (Holtz et al., 2008), and establish whether or not a geotextile will be necessary:

Step 3. Establish the requirement for extra-borrowed natural material to take care of mixing at the base/subgrade interface. If the material is essential, compute its thickness, t_1, by use of the normal method as if geosynthetics were not there, and then half the thickness, which will account for the use of geosynthetic.

Step 4. Establish the extra natural material thickness, t_2, required to put in place a working area. The technique necessitates the usage of curves for material thickness against the design single tire pressure and the soil bearing capacity, as in *Figure 2*.5 (Stewart et al. (1977).

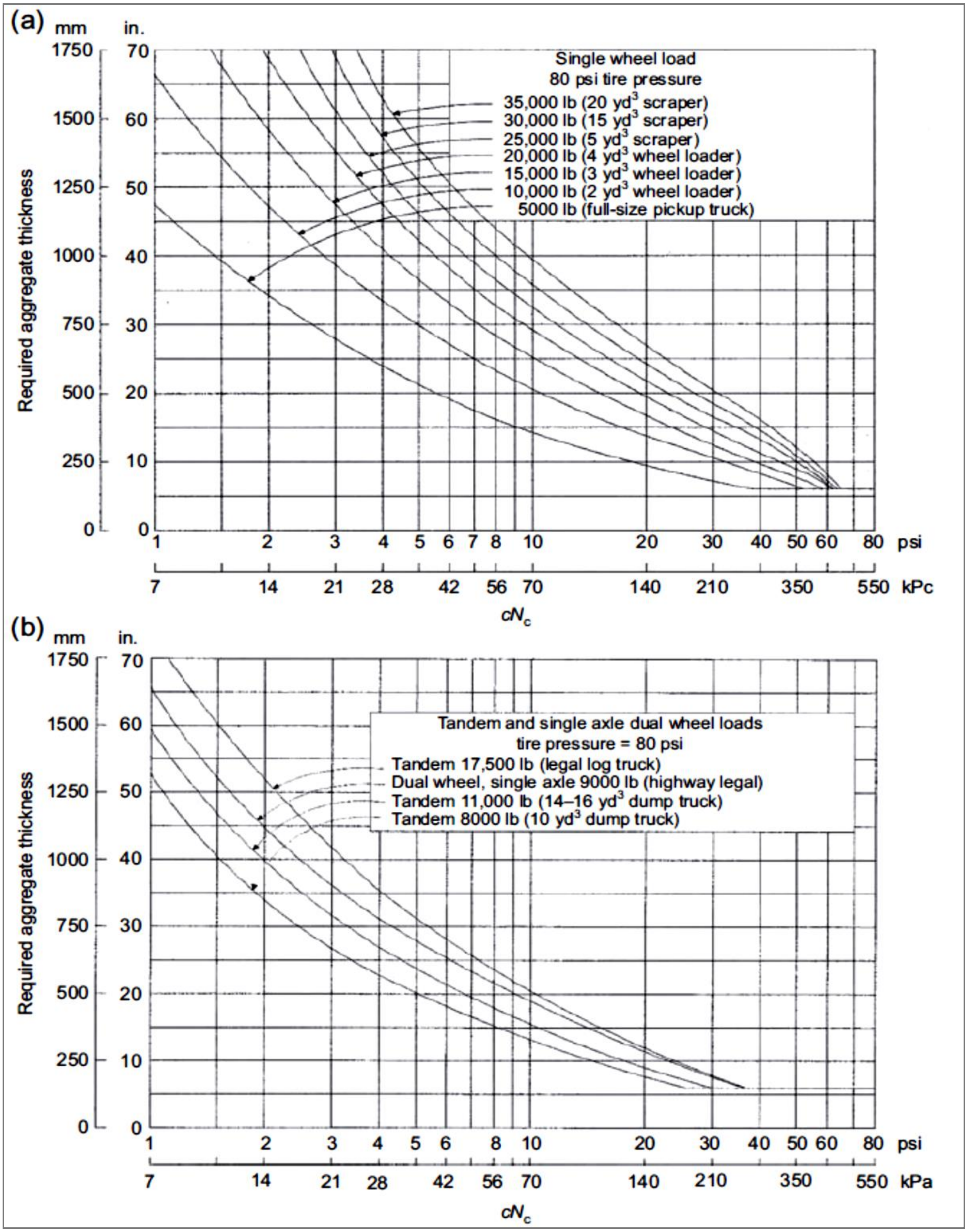


Figure 2.5: Curves for design with geosynthetics for (a) single and (b) dual wheel loads. (Source: Stewart et al., 1977).

Step 5. The higher value between t_2 and 50% t_1 is selected.

Step 6. The filtration conditions for the geosynthetic to be applied is determined. The important aspects are the apparent opening size (AOS), permeability (k), and permittivity (ψ) of the geosynthetic. These values are then related to a minimum required as in Equations 2.4 - 2.6.

$$AOS=D_{85\ subgrade}\ (Wovens)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 2.4$$

$$AOS=1.8D_{85\ subgrade}\ (Non\text{-}Wovens)\ \ldots\ldots\ldots\ldots\ldots Equation\ 2.5$$

$$K_{geosynthetic} > K_{soil}\ and\ \psi \geq 0.1\ s^{-1}\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 2.6$$

Step 7. Establish geosynthetic survival criteria. The geosynthetic must be able to survive against construction damage. AASHTO M288 gives properties for the geotextiles centred on the survival class shown in Table 2.1.

Step 8. Construction guidelines and specifications are then prepared, detailing the major conditions for installation, such as the sewing requirements, seam lap, construction sequencing and control of quality (Christopher, 2016).

Table 2.1: Geotextile Property Requirements for Reinforcement Applications (*Source: AASHTO, 2014a*)

Criteria	**ASTM Test**	**Units**	**Requirement**	
Survivability			Geotextile Class	
			Elongation	
			<50%	**>50%**
Grab strength	D4632-91	N	1400	900
Sewn seam strength	D4632-91	N	1260	810
Tear strength	D4533-91	N	500	350
Puncture strength	D6241-99	N	2750	1925

2.7.2 Paved and Unpaved Roads

Geotextile reinforcement can be introduced beneath the base course or within it to offer reinforcement to the layer. It increases structural support for the pavement, reduces deformation and improves pavement performance significantly. The traffic loading required to attain the same distress level is usually greater for reinforced pavements, compared to the unreinforced pavements of the similar thickness and design (Berg et al., 2000).

2.7.2.1 Selection and Design for Stabilization

The design-by-function approach, together with AASHTO M288, is used in the design of the geosynthetic for stabilization. The method assumes that the design of the pavement remains unchanged, and continues the same as in standard procedures. In its place, the geotextile substitutes additional material to be placed, while providing some added support (Holtz et al., 2008).

The pavement section can be designed using three options:

(1) Stabilization lift designed with some rutting (expected single tire pressure, N_c = 5.5-6) and zero allowance given for structural support.

(2) Stabilization material designed with minimal or zero rutting (N_c = 5) and use corresponding subgrade support of California Bearing Ratio of 3.

(3) Estimate corresponding subgrade support by carrying out elastic deflection tests or stiffness modulus test on geotextile-reinforced subgrade. Hence, adjust the design of the pavement and/or future sections be designed with same subgrade conditions founded on these subgrade modulus outcomes.

2.7.2.2 Selection and Design for Geotextile-Reinforced Pavement

There are two methods used to select and design the pavement with geotextile reinforcement. The first approach, an empirical method, is centred on the AASHTO Guide for Design of Pavement Structures (1993) and the AASHTO R50-09 (AASHTO, 2014b). The second approach uses methods outlined in AASHTO MEPDG-1 (2008), which integrate the reinforcement properties into the design model. The second method is also used for design without a geotextile renforcement.

Method 1. Empirical Design Method from AASHTO R50-09 and AASHTO 1993

These guides give procedures for designing geotextile-reinforced subbase/base layers in flexible pavements. The procedures, developed by Berg et al (2000), models the flexible pavement as a sequence of layers with a collective capacity to withstand a predetermined traffic loading (Christopher, 2016).

Either of the following factors put the structural input of geosynthetic reinforcement into consideration in the design:

(1) **Traffic Benefit Ratio (TBR):** is the ratio of the loading required to attain a particular failure condition in a geotextile-reinforced pavement to the loading required to reach the same failure condition in an unreinforced section;

(2) **Base course reduction (BCR):** is the percentage reduction in the base or subbase material thickness of a reinforced pavement as compared to an unreinforced pavement, for the same traffic loading to attain a particular failure condition;

(3) **Layer Coefficient Ratio (LCR):** is a modifier applicable to the layer coefficient of the base or subbase layer. It is a back calculated value normally based on the traffic loading required to attain a specified failure state on a reinforced pavement as opposed to an unreinforced one, with maintained geometry.

Pavement design is carried out bearing in mind the serviceability of the pavement defined by extents of roughness and distresses such as cracking and rutting (AASHTO, 1993). The traffic loading at which the lasting deformation at the surface reaches a specific value (allowable rut depth) defines the load-carrying capacity of a pavement. The traffic loading is computed using in Equation 2.7.

$$\log_{10}(W_{18}) = Z_R S_o + 9.36 \log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2-1.5}\right]}{0.4+\frac{1094}{(SN+1)^{5.19}}} + 2.32 \log_{10} M_R - 8.07 \quad \text{……}\textit{Equation 2.7}$$

Whereby;

$\mathbf{W_{18}}$ = traffic loading (ESALs);

$\mathbf{Z_R}$ = standard normal deviate;

$\mathbf{S_o}$ = standard deviation;

SN = structural number;

ΔPSI = change in present serviceability index; and

$\mathbf{M_R}$ = resilient modulus of subgrade or base in pound per square inch (psi).

The following steps are used in designing geotextile base/subbase reinforcement for flexible pavements (Berg et al., 2000):

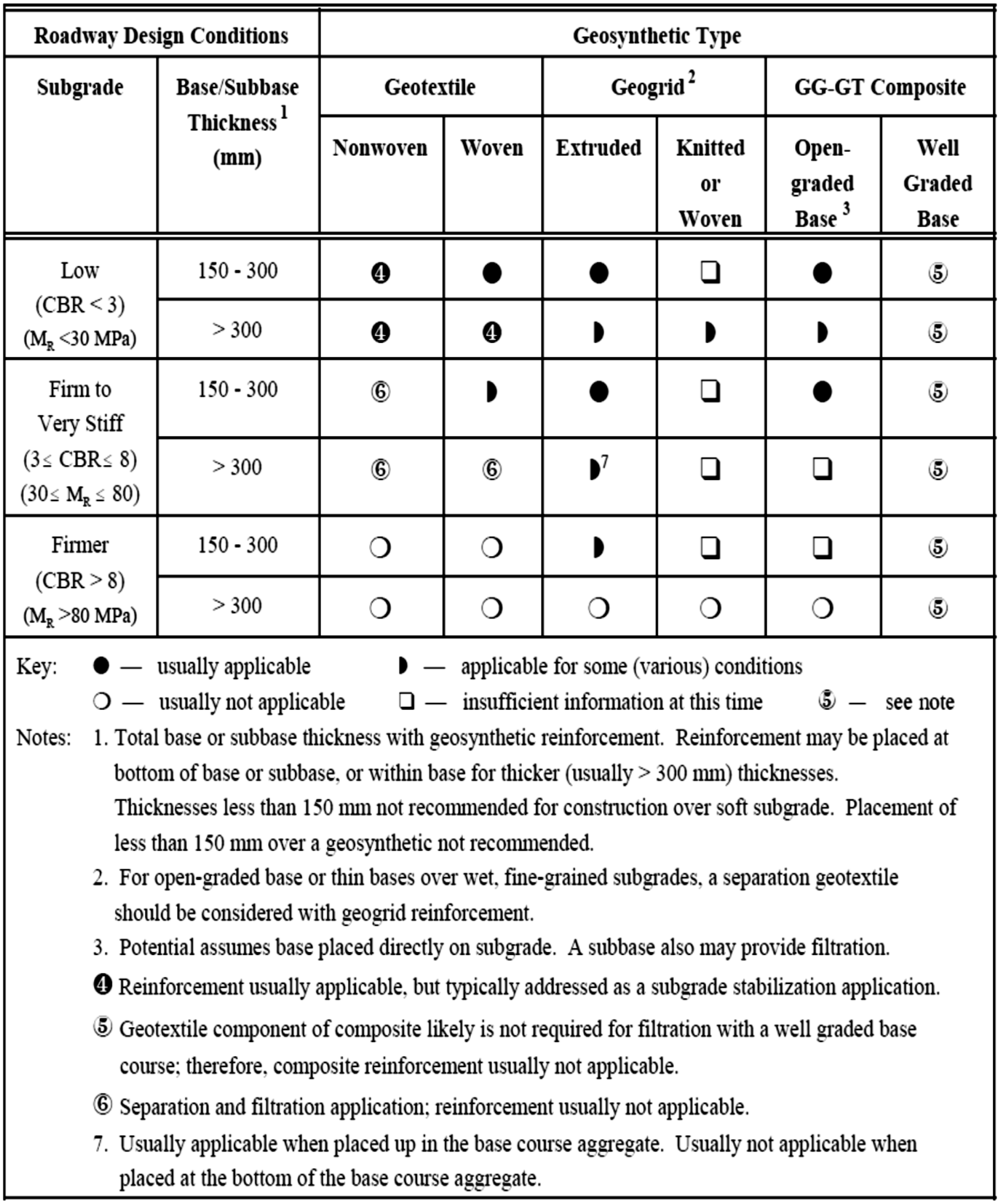
(1) **Preliminary determination of applicability of a geotextile.** Determine the strength of the subgrade, pavement layer thickness necessary for unreinforced segment, properties of base/subbase materials, seasonal variance in moisture regimes, reinforcing mechanisms, and value addition by geosynthetics.

(2) **Reinforced pavement design.** By a conventional technique, the unreinforced pavement design is carried out, without a geotextile.

(3) **Examine the potential benefits of incorporating geosynthetics as reinforcement.** Necessitates defining potential and target benefits for the project. Table 2.2 was provided by Berg et al. (2000), cataloguing geotextiles to be used for reinforcement functions, based on the road design conditions.

(4) **Outline reinforcement benefits by TBR or BCR.** Target benefits include (i) extension performance time; (ii) reduction of subbase or base thickness; or (iii) Both extension of performance period and reduction of thickness. Determine if there is need define either a TBR or a BCR.

Table 2.2: Criteria for use of geotextiles for reinforcement functions (Berg et al. (2000)



Roadway Design Conditions		Geosynthetic Type					
Subgrade	Base/Subbase Thickness^1 (mm)	Geotextile		Geogrid^2		GG-GT Composite	
		Nonwoven	Woven	Extruded	Knitted or Woven	Open-graded Base^3	Well Graded Base
Low (CBR < 3) (M_R <30 MPa)	150 - 300	❹	●	●	☐	●	⑤
	> 300	❹	❹	◗	◗	◗	⑤
Firm to Very Stiff ($3 \leq$ CBR ≤ 8) ($30 \leq M_R \leq 80$)	150 - 300	⑥	◗	●	☐	●	⑤
	> 300	⑥	⑥	◗^{7}	☐	☐	⑤
Firmer (CBR > 8) (M_R >80 MPa)	150 - 300	○	○	◗	☐	☐	⑤
	> 300	○	○	○	○	○	⑤

Key: ● — usually applicable ◗ — applicable for some (various) conditions

○ — usually not applicable ☐ — insufficient information at this time ⑤ — see note

Notes: 1. Total base or subbase thickness with geosynthetic reinforcement. Reinforcement may be placed at bottom of base or subbase, or within base for thicker (usually > 300 mm) thicknesses. Thicknesses less than 150 mm not recommended for construction over soft subgrade. Placement of less than 150 mm over a geosynthetic not recommended.

2. For open-graded base or thin bases over wet, fine-grained subgrades, a separation geotextile should be considered with geogrid reinforcement.

3. Potential assumes base placed directly on subgrade. A subbase also may provide filtration.

❹ Reinforcement usually applicable, but typically addressed as a subgrade stabilization application.

⑤ Geotextile component of composite likely is not required for filtration with a well graded base course; therefore, composite reinforcement usually not applicable.

⑥ Separation and filtration application; reinforcement usually not applicable.

7. Usually applicable when placed up in the base course aggregate. Usually not applicable when placed at the bottom of the base course aggregate.

(5) Design of reinforced pavement section.

1) Design for extension of performance period of the pavement;

a) Design with the use of TBR

TBR is applied to calculate the effective years before rehabilitation, and for the unreinforced pavement, it is given by Equation 2.8.

$$Years\ before\ Rehab = \frac{W_{18}}{ESALs/year}$$ *……………………Equation 2.8*

Where;

W18 = allowable trafficking (ESALs);

ESALs = Equivalent Standard Axle Loads.

For a reinforced pavement, the TBR is used to calculate a modified number of equivalent standard axle load applications. Equation 2.9 gives the equivalent reinforced value.

$$(W_{18})_R = W_{18}\ x\ TBR$$ *……………………………..Equation 2.9*

Using this value, the time before maintenance is calculated using Equation 2.10.

$$Years\ before\ Rehab = \frac{(W_{18})_R}{ESALs/year}$$ *tion 2.10*

b) Design using an LCR

Here, the LCR is applied to work out the prolonged effective period. The subbase/base layer LCR is used in the structural number Equation 2.11:

$$SN = a_1 D_1 + LCR\ a_2 D_2 m_2 + a_3 D_3 m_3$$ *………. Equation 2.11*

Where;

SN = structural number;
a_i = i^{th} layer coefficient;
D_i = i^{th} layer thickness (inches), and;
m_i = i^{th} layer drainage coefficient.
LCR = Layer Coefficient Ratio

With the subbase/base layer thickness maintained, the structural number of the reinforced pavement is improved. A bigger structural number ensures a protracted pavement design life.

2) **Design for reduction of natural material subbase/base thickness;**

a) **Design using a BCR**

The reinforced subbase/base layer thickness, $D_{2(R)}$, is calculated using Equation 2.12.

$$D_{2\,(R)} = D_{2\,(UNREINF)}\ x\ (1 - BCR) \quad \text{…………………… Equation 2.12}$$

b) **Design with a TBR ratio**

Here, the TBR is applied to compute a modified structural number, SN_R. The reinforced structural number is calculated with the $(W_{18})_R$ in the pavement design equation. The reinforced layer thickness is then calculated using Equation 2.13.

$$D_{2(R)} = \frac{SN_R - a_1\ D_1}{a_2\ m_2} \quad \text{…………………..… Equation 2.13}$$

3) **Design for combination of extension of performance period and reduction of base thickness.** Both benefits can be achieved simultaneously by going for a base course thickness bigger than $D_{2\ (R)}$ and less than D_2, thereby resulting in a performance period between the unreinforced and reinforced case.

(6) Cost-benefit analysis. Preliminary and life cycle costs and the intangible benefits for the different design possibilities are listed. Then the costs and benefits of all options are compared, and the most economical option is selected and carried into the final design.

Intangible benefits of reinforcement that cannot be quantified by monetary value should be taken care of in the design, such as minimised disturbance of the subgrade by construction traffic and better reliability of the pavement (for design centred on TBR).

(7) Prepare specifications, bidding documents and drawings for the various design options.

(8) Monitor construction and document performance

Method 2. Mechanistic-Empirical (M-E) design method for design with and without a geotextile renforcement

The important components of the Mechanistic-Empirical Pavement Design Guide technique are:

(1) A systematic model is used to compute the critical responses of the pavement, and;

(2) Damage models or empirical performance relates the critical responses to the overall distress and damage levels (Christopher, 2016).

The main procedures of the Mechanistic-Empirical Pavement Design Guide are:

a) Selection of the pavement structure, that is the pavement layers, the material types and layer thicknesses;

b) Description of climate regimes, traffic composition and nature of materials for the specific project location;

c) Mechanistic model analysis for the pavement structure;

d) Critical responses (stresses and strains) computation;

e) Overall damage and distress assessment in reference to pre-set standards (AASHTO, 2008).

The technique necessitates numerous repetitions allowing for different pavement structures. The design is usually considered complete when the levels of distress are within the tolerable levels for the design life of the structure for a specific section.

The Mechanistic-Empirical Method (M-E) of design and analysis is primarily based on the mechanics of the individual pavement materials (normally used in different layers) that relates inputs such as tyre load and contact stresses (as well as environmental stresses) to pavement responses such as stresses and strains (Huang, 1993). The schematic diagram of M-E design procedure is as shown in Figure 2.6.

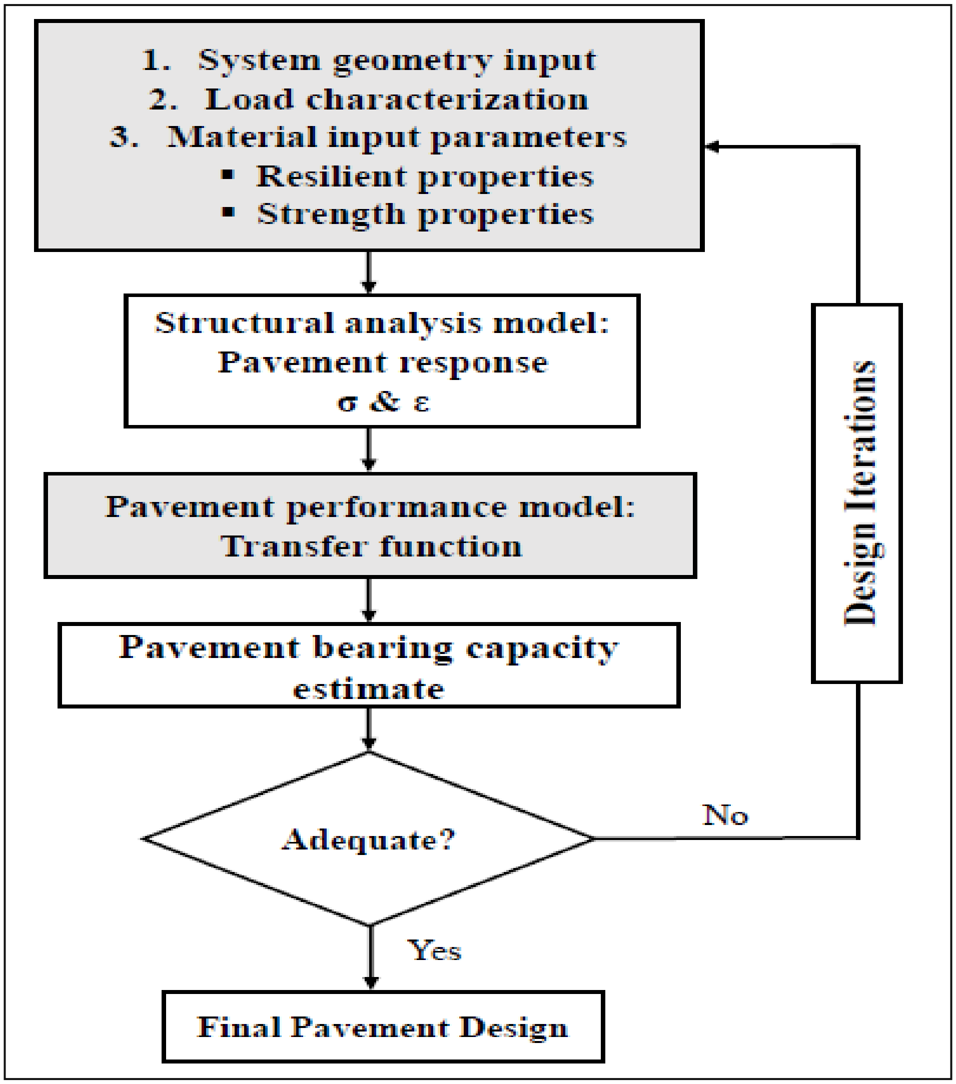


Figure 2.6: Schematic Diagram of a Mechanistic-Empirical design procedure (Theyse and Muthen, 2000)

The Mechanistic Empirical (M-E) design method uses a layered elastic theory model to calculate stresses and strains in the pavement structure, under a predefined standard axle load. The Mechanistic-Empirical Pavement Analysis Design Software (mePADS) uses selected failure criteria (transfer functions) to relate the stress/strain condition to the number of pre-defined standard axle loads that can be sustained at that stress/strain level before a certain terminal condition in the pavement is reached. The transfer functions used in the analysis converts stresses and strains to number of axles (Theyse and Muthen, 2000).

The software requires design input such as layer thickness, material properties and layer stiffness (Resilient Modulus). *me*PADS software contains a Mechanistic-Empirical design method, using layered elastic theory combined with South African transfer functions that is an adaptation of the MEPDG of AASHTO 2002 and 2007 versions.

2.8 Economic Considerations

The cost-benefit ratio of incorporating geosynthetic in a road pavement includes:

a) Direct savings by replacement or reduction of select soil materials;

b) Direct savings by simplicity in installation and improved construction time;

c) Reduced life-cycle cost by enhanced performance as determined by increased effective life or minimal maintenance;

d) Better sustainability by preserving the environment as compared to alternative designs (Christopher, 2016).

Geosynthetics are characteristically a cheaper substitute to other roadbed stabilization procedures such as cutting away and filling in with select natural materials, use of thicker material layers, or chemical treatment. When related to using thicker gravel alone, a geotextile will normally reduce the gravel thickness by 20-40% (Christopher, 2016).

An enhanced pavement performance is crucial to savings on cost provided by geosynthetics used for subbase/base reinforcement. Many researches have attempted to compute the cost-benefit life-cycle ratio of using geosynthetics in road pavements (Yang, 2006). The geosynthetic prolongs the life of a pavement by a minimum of 5% besides covering the cost of the geosynthetic (Christopher, 2016).

2.9 Sustainability Aspects of Using Geosynthetics

Sustainability development refers to the ‘development that meets the present needs without compromising the ability of future generations to meet their own needs’ (Brundtland, 1987). The use of carbon dioxide (CO_2) emission has been widely accepted as a pointer of sustainability of a construction project (Dixon et al, 2016)

WRAP (2010) noted that the use of geosynthetics could reduce the volume of borrowed fill. This would provide carbon dioxide savings from Embodied Carbon (EC) emission of hauled fill material and from transporting during cut and fill operations. Raja et al. (2015) developed EC data for geotextiles as shown in Table 2.3.

Table 2.3: Embodied Carbon for Geotextile materials (Raja et al., 2015)

Geotextile Type	**Polymer Embodied Carbon (tCO_2e/t)**	**Conversion of Granules to fibres (tCO_2e/t)**	**Average manufacturing carbon emissions (tCO_2e/t)**	**Total Embodied Carbon (tCO_2e/t)**
Nonwoven geotextile (needle-punched)	1.983	0.241	0.053	2.28
Nonwoven geotextile (thermally bonded/ needle-punched)			0.189	2.42

Raja et al. (2015) noted that to achieve the optimum sustainability from a geosynthetic-based construction solution, the geosynthetics appropriately used in the design and the polymer be efficiently used in producing a material that can attain the design criteria.

2.10 Literature Summary

The various reviewed literature show that there is a recommended practice for design of a pavement while incorporating geotextile as a base/subbase reinforcement. The literature also show that there a possibility of making significant savings by incorporating the geotextile on a road pavement. However, none of the studies quantified the cost benefits in monetary terms, especially the construction material savings owing to reduced thickness of reinforced pavements. This study sought to quantify the possible cost benefits, as well as establishing the quality of the locally available geotextile materials.

3.0 METHODOLOGY

3.1 Introduction

This chapter details the mode of data collection and presents the various data collected for analysis. It summarizes the primary and secondary data collected for the study.

3.2 Research Design

This study was intended to evaluate the applicability of geosynthetics in the design and construction of flexible pavements in Kenyan roads. To achieve the objectives of the study, the Lamu-Garissa road (250 Km in length) was used as a sample road. The road is of major economic influence in Kenya and its immediate Northern and Eastern border countries. It is part of the Vision 2030 flagship projects – The LAPSSET Corridor.

The project is located on the east side of River Tana, in the counties of Garissa, Tana River and Lamu. Design reports by Sai Consulting Engineers Pvt (2015) showed that construction materials; especially gravel material and hardstone were scarce. In addition, the predominant alignment materials were found to be of poor strength, and needed to be replaced by borrowed, good quality subgrade materials. With available good quality pavement material being far from the project road, the associated costs meant that the overall project cost was expected to be very high.

The possibility of incorporating geosynthetics in the pavement of this road was studied. Two designs were carried out, one incorporating geosynthetic reinforcement, and the other without a geosynthetic. For the design without geosynthetic reinforcement, M-E design was applied, with the South African mePADS software used to model the pavement and to determine the expected resourceful life of the pavement. For the design with geosynthetic reinforcement, guidelines provided by AASHTO R50-09 (AASHTO 2014b) were used for the design of geosynthetic-reinforced base/subbase courses. The costs of both pavements were then computed and compared.

3.2.1 Data Collection

This section details the data collected, both primary and secondary, in their raw form. The data analysis will be presented in chapter 4.

The following data was collected and analysed in this study: -

a) Laboratory tests on geotextiles, done on samples from Geotextiles East Africa Ltd, Mombasa. The laboratory tests included: (1) Tensile strength elongation (wide width test); (2) Grab breaking load test, and (3) Static puncture force (CBR) Test. These tests were carried out in accordance with the ASTM standards, and the results were compared with the specifications given by the manufacturer. The obtained results were important to determine the properties that are applicable to pavement design in order to improve performance and save on cost.

b) Secondary data for traffic loading (axle loading) and available construction materials on Lamu-Garissa road, obtained from Kenya National Highways Authority, based on the detailed engineering design reports done and submitted by Sai Consulting Engineers in 2015. The data for the traffic loading for the sample road were used to design the pavement, both with and without geosynthetic reinforcement. The resulting pavement thicknesses were compared and the cost comparisons computed and compared. The results obtained were also compared with similar researches done worldwide, to relate the findings and conformance.

3.2.2 Design procedure using the South African mePADS software

3.2.2.1 Software Input Parameters

Pavement Structure

The Pavement Structure worksheet contained the following input boxes for defining the pavement system:

Number of Layers: defines the unique layers in the pavement structure. The maximum 5 layers were defined.

Material: Refers to the type of pavement material, according to the South African Material Classification in TRH4 (1996). The material types were selected from the drop-down list as:

- AC: Continuously Graded Asphalt Surfacing
- C1-C2: Lightly Cement Crushed Gravel
- Soils: In-situ or imported Subgrade material

Thickness: Layer thickness in mm. A rigid layer was assumed to exist at the bottom of the last layer, in which case the rigid layer was be assumed to exist at 1000 mm below the defined pavement.

E-modulus: The modulus of elasticity of the selected material in MPa were inserted.

Number of Phases: defines the number of design phases to be considered in the analysis, as a result of the multi-phase nature of cemented materials. The number of phases in the analysis were automatically selected depending on the number of cemented layers in the structure. The material codes, E-moduli and Poisson's ratio for each of the phases were also provided.

Climatic Region: Refers to rainfall region, which was dry.

Road Category: Defines the design reliability, which was taken as A, with 95% reliability.

Terminal Rut: Failure rut-depth criteria for subgrade rutting, taken as 20mm

Design Traffic Class (in standard axles), which was ES100, that is 30 000 000 to 100 000 000 axles

Loads and Evaluation Points

Design Location: The point at the pavement surface where the pavement design is to be carried out.

Load definition: The number, magnitude (kN and kPa) and position of wheel loads.

Stresses and Strains: The location in the pavement for evaluating stresses and strains. This analysis was done independently from the bearing capacity analysis and the results were reported on the "Stresses and Strains" worksheet.

Load Position Plot: shows a plan view of the loads defined in the system.

Design Parameters

The stress and strain parameters at critical points in the pavement were displayed on this worksheet. These parameters were used in the bearing capacity calculations. The parameters and critical points vary for different material types as follows:

Asphalt Layers: The horizontal tensile strain at the bottom of the layer controls the fatigue life of the layer.

Cemented Layers: The horizontal tensile strain at the bottom of the layer controls the fatigue life of the layer, while the vertical compressive stress at the top of the layer defines the crushing life.

Granular Layers: The principal stresses at the middle of the layer controls the shearing capacity of the layer.

Soil (Subgrade) Layers: The vertical compressive strain at the top of the layer controls the rutting life of the layer.

3.2.2.2 Software Output Parameters

Pavement Life: The worksheet displays the main design outputs of the software. The worksheet becomes visible once a successful design has been completed after the 'Calculate' button has been clicked

Layer Bearing Capacity: The bearing capacity (in terms of the defined load) of the layers at the selected design reliability was shown in the table and the figure. The design traffic class (in terms of Standard Axles) was also shown as lines on the bar chart. The bearing capacity was calculated using transfer functions, specially formulated for the material type.

Approximate Pavement Life Distribution: The distribution of pavement lifes obtained by varying the design reliability input in the transfer functions.

Crushing in cemented layers: The bearing capacity of the cemented layers with respect to failure by crushing.

Cemented Life: The effective duration of the cemented life phase of the cemented layer.

Calculation Table: Provides the transfer function outputs for a selected design reliability. This functionality is provided so that detailed information on the calculation procedure can be viewed.

Contour Plot: Provides a contour plot of the selected stress or strain parameter for a region in the pavement, on a vertical or horizontal plane.

3.3 Laboratory Testing

Material samples of geotextile were tested in the Kenya Bureau of Standards (KEBS) and Norken International Laboratories. The Table 3.1 and Appendix A show the material samples obtained and the tests conducted thereof. The plates 3.1 – 3.4 demonstrate how the tests were carried out.

Table 3.1: Materials Samples and Tests Conducted

Sample Description	Test Conducted	Test Procedure	Results	Specification (AASHTO, 2014a)	Remarks
Betatex (600 gsm)	Elongation at Break – *Cross Machine Direction*	ASTM D4632-91	86.3%	-	> 50%
	Elongation at Break – *Machine Direction*	ASTM D4632-91	73.0%	-	> 50%
	Grab Breaking Load – *Cross Machine Direction*	ASTM D4632-91	2215N	900N	Adequate
	Grab Breaking Load – *Machine Direction*	ASTM D4632-91	2687N	900N	Adequate
	Trapezoidal Tear – *Cross Machine Direction*	ASTM D4533-91	163N	350N	Inadequate
	Trapezoidal Tear – *Machine Direction*	ASTM D4533-91	184N	350N	Inadequate
	Puncture Strength	ASTM D6241-99	11384N	1925N	Adequate
Fibertex F32	Elongation at Break – *Cross Machine Direction*	ASTM D4632-91	56.6%	-	> 50%
	Elongation at Break – *Machine Direction*	ASTM D4632-91	48.3%	-	< 50%
	Grab Breaking Load – *Cross Machine Direction*	ASTM D4632-91	818N	900N	Inadequate
	Grab Breaking Load – *Machine Direction*	ASTM D4632-91	1031N	1400N	Inadequate
	Trapezoidal Tear – *Cross Machine Direction*	ASTM D4533-91	213N	350N	Inadequate
	Trapezoidal Tear – *Machine Direction*	ASTM D4533-91	291N	500N	Inadequate
	Puncture Strength	ASTM D6241-99	2785N	2750N	Adequate
Woven WG85	Elongation at Break	ASTM D4632-91	18.2%	-	< 50%
	Grab Breaking Load	ASTM D4632-91	2545N	1400N	Adequate

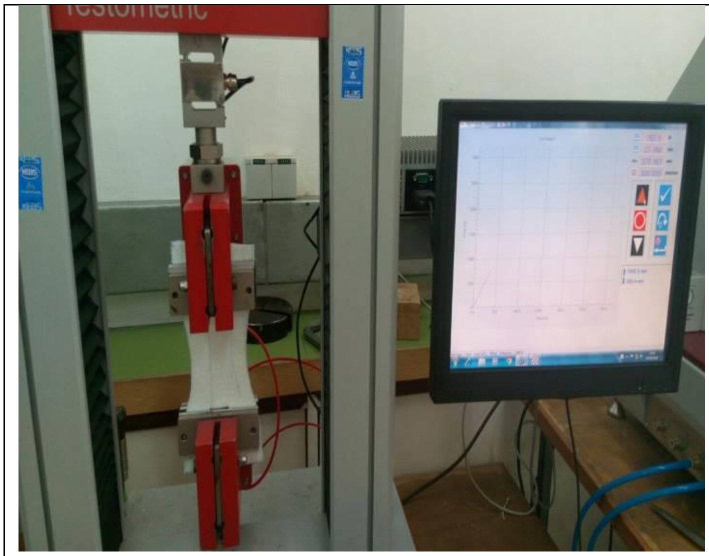


Plate 3.1: Grab Strength Testing

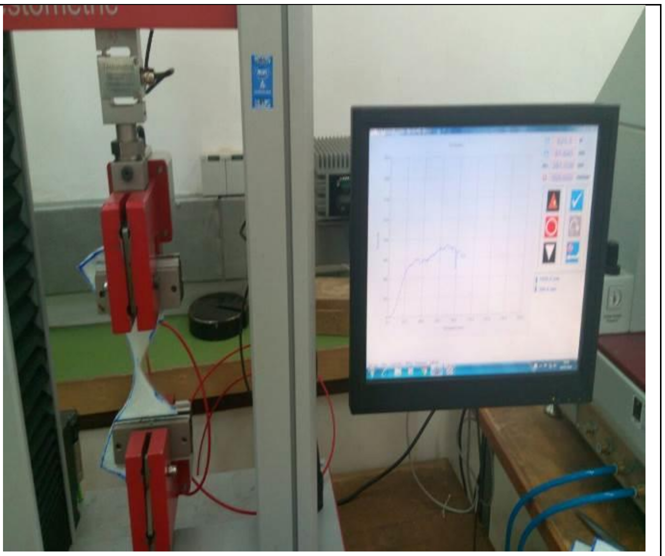


Plate 3.2: Trapezoidal Tear test

Plate 3.3: Static Puncture Strength test

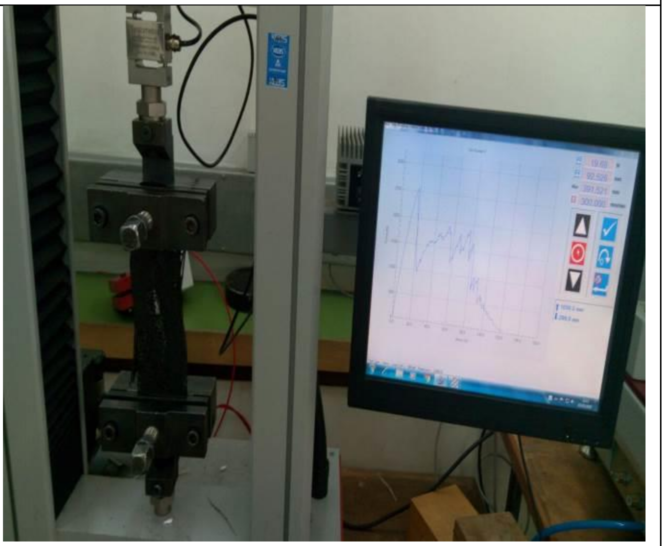


Plate 3.4: Trapezoidal Tear test

3.4 Pavement Loading

The Cumulative Numbers of Standard Axles (CNSA) used to determine the pavement loading class, in line with Kenya Road Design Manual (RDM), Part III (1987) were computed. The details of CNSA for twenty-year design period and corresponding traffic class are as shown in Table 3.2.

Table 3.2: Design Loading (Sai Consulting Engineers, 2015)

Design Life in Years (Projection Year)	Cumulative Numbers of Standard Axles (CNSA)	Traffic Class
20	75.9 Million	T0

The computed design loading exceeded what is provided for by the Kenyan Standard, as shown in the extract from the Kenyan manual in Table 3.3, and was therefore denoted as class T0.

Table 3.3: Traffic Classes

Traffic Class	Cumulative Numbers of Standard Axles (80 kN)
T1	25 – 60 Million
T2	10 - 25 Million
T3	3 – 10 Million
T4	1 - 3 Million
T5	0.25 – 1 Million

(Source: Kenya Road Design Manual, Part III, 1987)

3.5 Soils Along the Road Alignment

It was established from the test results that the predominant material found along the alignment was poor with medium to high plasticity and lower CBR strength in the range of 1 to 5, which can be classified as subgrade Class S1 in the Kenya Road Design Manual Part III (1987), as shown in the extract in Table 3.4. Therefore, the insitu materials were not suitable for use as subgrade. However, there were few small stretches along the alignment having good quality soil.

Table 3.4: Subgrade Classes

Subgrade Class	CBR Range	Median
S1	2 - 5	3.5
S2	5 -10	7.5

Subgrade Class	CBR Range	Median
S3	7 - 13	10
S4	10 - 18	14
S5	15 - 20	22.5
S6	> 30	

(Source: Kenya Road Design Manual, Part III, 1987)

Table 3.5 shows sections with uniform characteristics and were taken as homogenous sections. The sections between KMs 0+000-4+500; 15+500-32+500; and 38+500-44+500 were specially identified to have a higher quality subgrade than the rest of the alignment.

Table 3.5: Design Loading (Sai Consulting Engineers, 2015)

No.	Chainage (KMs)	Average CBR Value
1	0+000 – 4+500	14
2	4+500 – 15+500	6
3	15+500 – 38+500	15
4	32+500 – 38+500	3
5	38+500 – 44+500	12
6	44+500 – 75+000	3
7	75+500 – 100+500	1
8	100+500 – 249+500	3

3.6 Construction Materials

3.6.1 Natural Material (Gravel) Sources

Eighteen potential gravel sites were established. Laboratory testing results for samples taken from the possible borrow sources are as shown in Table 3.6. Laboratory Tests were also conducted on neat gravel material with cement and lime at 2%, 4% and 6% contents by weight. The results are as shown in Table 3.7.

Table 3.6: Laboratory Test Results on Gravel Borrow Samples (Sai Consulting Engineers, 2015)

No.	Reference	Gravel (%)	Sand (%)	Silt and Clay (%)	LL (%)	PL (%)	PI (%)	Linear Shrinkage	PM	MDD Kg/m3	OMC (%)	CBR (%) at 4-days soak	Swell (%)
1	Ms Prison	48	25	28	31	19	12	-	419	1869	12	33	0.2
2	Ms Kiongoni	58	17	25	35	20	15	-	408	1817	11	31	0.4
3	Ms Ndeu A	57	15	27	33	19	14	-	437	1796	13	22	0.3
4	Ms Ndeu B	56	16	29	41	18	23	11	723	2004	11	18	1.4
5	Ms Duwadeso	47	34	20	33	21	12	-	308	1952	10	29	0.3
6	Ms Masabubu	13	56	31	35	16	19	9	805	2001	9	6	1.9
7	Ms Walini	15	52	33	40	22	18	9	816	1969	9	10	1.6
8	Ms Nanich A	6	78	17	40	23	17	8	730	1563	16	12	1.3
9	Ms Nanich B	25	48	27	39	20	19	9	729	1929	9	21	0.9
10	Ms Abagandere	19	48	33	40	21	19	9	952	1900	9	11	1.0
11	Ms Kamuthe A	20	43	26	37	18	19	9	755	1975	8	14	1.2
12	Ms Kamuthe B	22	58	21	33	16	18	9	560	1749	8	17	1.4
13	Ms Warable A	25	47	27	41	24	17	8	639	1916	9	23	1.0
14	Ms Warable B	15	56	29	41	26	15	8	660	1970	7	16	1.2
15	Ms Dieso 1	65	23	12	41	25	16	7	284	2008	11	29	1.0
16	Ms Dieso 2	53	32	15	38	22	16	8	379	1983	10	42	1.1
17	Ms Km 242+000	49	34	16	48	34	13	6	242	1898	10	32	0.3
18	Ms Modika	34	42	24	43	24	18	9	502	2043	10	38	-

Table 3.7: Laboratory Test Results on Treated Gravel Borrow Samples (Sai Consulting Engineers, 2015)

No.	Reference	Liquid Limit (%)						Plasticity Index (%)						Plasticity Modulus						CBR (%)					
		2% L	4% L	6% L	2% C	4% C	6% C	2% L	4% L	6% L	2% C	4% C	6% C	2% L	4% L	6% L	2% C	4% C	6% C	2% L	4% L	6% L	2% C	4% C	6% C
1	Ms Prison	29.9	29.5	28.2	30.2	28.0	NP	7	5	3	5	3	NP	259	165	80	156	19	0	70	89	117	127	205	289
2	Ms Kiongoni	34.7	34.3	34.2	34.2	35.5	NP	10	7	4	6	4	NP	280	193	80	119	30	0	78	130	176	112	171	245
3	Ms Ndeu A	32.9	32.6	33.3	33.9	36.0	NP	10	8	6	6	8	NP	302	226	145	167	55	0	110	163	251	85	123	182
4	Ms Ndeu B	35.5	35.3	0.0	37.8	33.5	32.0	13	8	NP	15	13	7	410	303	NP	439	402	229	145	212	283	157	216	278
5	Ms Duwadeso	30.2	30.6	30.4	33.2	33.5	31.0	9	7	6	6	4	4	211	164	75	110	29	19	99	146	194	140	242	340
6	Ms Masabubu	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7	Ms Walini	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	Ms Nanich A	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	Ms Nanich B	33.9	30.4	26.5	37.9	35.4	29.0	12	7	5	13	9	6	488	199	40	494	176	31	382	243	275	177	234	269
10	Ms Abagandere	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
11	Ms Kamuthe A	36.0	25.8	0.0	33.7	34.2	32.7	14	14	0	15	13	7	429	224	0	504	397	397	196	586	0	177	288	364
12	Ms Kamuthe B	31.4	30.2	NP	36.5	32.7	37.0	11	6	NP	13	8	6	337	150	0	412	200	200	188	246	292	187	233	268
13	Ms Warable A	39.7	7.4	0.0	41.0	22.0	6.8	8	3	0	12	10	23	285	68	0	401	207	207	210	270	0	194	265	0
14	Ms Warable B	Extension of Warable A																							
15	Ms Dieso 1	40.6	NP	38.0	42.5	46.0	0.0	10	6	14	9	7	0	114	0	56	109	58	58	148	181	224	160	222	253
16	Ms Dieso 2	41.5	40.5	0.0	41.3	41.4	40.0	9	7	0	10	7	6	171	107	0	210	106	106	190	253	329	175	259	360
17	Ms Km 242+000	38.4	NP	NP	39.9	NP	NP	8	NP	NP	12	NP	NP	141	0	0	207	0	0	213	286	0	225	322	0
18	Ms Modika	40.8	NP	NP	41.8	NP	NP	11	NP	NP	14	NP	NP	257	0	0	315	0	0	160	192	227	201	262	288

NP = Non-Plastic

The Kenya Road Design Manual Part III (1987) gives the specifications of materials for base and subbase as shown in Table 3.8 and Table 3.9.

Table 3.8: Materials for Subbase (Kenya Road Design Manual, Part III, 1987 - Chart SB1 and SB2)

Material/Material Parameter	Specification
Natural Material	
CBR at 95% MDD (Modified AASHTO) and 4 days soak	Min. 30%
Plasticity Index	Max. 15
Plasticity Modulus	Max. 250
Cement and Lime Improved Material (Gravel)	
CBR of laboratory mix at 95% MDD (Modified AASHTO) and 7 days cure + 7 days soak	Min. 60%
Plasticity Index	Max. 15
Plasticity Modulus	Max. 250

Table 3.9: Materials for Base (Kenya Road Design Manual, Part III, 1987 - Chart B1 and B2)

Material/Material Parameter	Specification
Natural Material	
CBR at 95% MDD (Modified AASHTO) and 4 days soak	Min. 80%
Plasticity Index	Max. 15
Plasticity Modulus	Max. 250
Cement and Lime Improved Material (Gravel)	
CBR of laboratory mix at 95% MDD (Modified AASHTO) and 7 days cure + 7 days soak	Min. 160%
Plasticity Index	Max. 6
Plasticity Modulus	Max. 250

3.6.2 Hardstone Sources

Rock samples were taken to the laboratory and subjected to the tests including: (1) Aggregate Crushing Value (ACV); (2) Los Angeles Abrasion (LAA); and (3) Sodium Sulphate Soundness (SSS) tests, to determine suitability in line with specifications. The laboratory test results are as shown in Table 3.10.

Table 3.10: Test Results on Hardstone samples (Sai Consulting Engineers, 2015 and Standard Specification for Road and Bridge Construction, 1986)

Hardstone Source	Test	Lab Results	Suitability For Use as Concrete Aggregates	Suitability For Use for Asphalt Concrete
DEWADESO	L.A.A	20.2	Max. 50	Max. 30
	A.C.V	NOT TESTED	Max. 35	Max. 25
	S.S.S	0.5	Max. 12	Max. 12
	F.I.	30.8	Max. 40	Max. 20
	Bitumen Affinity	GOOD		
MWINGI	L.A.A	28.1	Max. 50	Max. 30
	A.C.V	21.9	Max. 35	Max. 25
	S.S.S	3.8	Max. 12	Max. 12
	F.I.	12	Max. 40	Max. 20
	Bitumen Affinity	GOOD		

3.6.3 Sand Sources

Adequate supply of good quality sand was readily available for exploitation along the seasonal rivers traversed by the alignment. The following potential sand sources were established and sampled for tests:

a) Juja Sand, 6km from Hindi (km 0+000)
b) Lagha at km 175+000
c) Lagha at km 180+000
d) Warable River Sand, 12km off Chainage km 217+500

The laboratory test results are as shown in Table 3.11.

Table 3.11: Test Results on Sand samples (Sai Consulting Engineers, 2015)

No.	Sand Source	Silt and Clay Content	Chloride Content	Sulphate Content	Organic Content
Specifications (Standard Specification for Road and Bridge Construction, 1986)		**3% Max by weight**	**0.05 Max**	**0.4 Max**	**Trace**
1	Juja Sand	0.5	Nil	Nil	0.15
2	Lagha at km 175+000	0.2	Nil	Nil	0.13
3	Lagha at km 180+000	Nil	Nil	Nil	0.2
4	Warable River Sand	1	Nil	Nil	0.18

3.6.4 Construction Water Sources

The River Tana, which is the only permanent river in the region, is about 10km from the start of the project road, and runs along the proposed route. It is one of the major sources of water in the area and will be a very good source of water for construction for the project road. There were also other possibilities of drilling boreholes at specific locations along the project road, to act as a substitute to the River Tana.

4.0 RESULTS ANALYSIS AND DISCUSSION

4.1 Introduction

The collected data was analysed in this chapter and the designs carried out in response to the research objectives. The cost comparison done gives the possible cost savings that can be achieved when a geotextile is introduced in the flexible pavement structure.

4.2 Mechanical Properties of Geosynthetics

The test results, as shown in Table 3.1, give an indication that there are geotextile materials in the market that meet the minimum requirement for use as a reinforcement geosynthetic. The test results also showed consistency with specifications given by the geotextile manufacturers.

4.3 Properties of available Construction Materials

The analysis of the investigated materials along the project road as shown in Table 3.6 to Table 3.9 show that 5No. possible gravel borrow pits are adequate for use as a subbase layer prior to improvement with cement. When treated with minimal percentage of cement and/or lime, 14 No. borrow areas were found to be adequate for use as subbase material.

The analysis of the sample materials for adequacy as base materials found out that none of the borrow pits could be used as base material without improvement with cement or lime. When treated with cement and/or lime, 13 No. borrow areas were found to be adequate for use as base material with 4-6% cement or lime treatment.

4.4 Pavement Design Without a Geosynthetic

4.4.1 Design based on Kenyan Standards

The Kenya Road Design Manual, Part III (1987), proposes standard pavement structures based on the design subgrade strength class and the traffic loading to be accommodated. This criterion was as shown in Tables 3.3 and 3.4.

The project road was expected to carry 75.9 Million Equivalent Standard Axles (ESAs), which, as seen from Table 3.3, was above what the Kenyan Standard provides for. However, in this case, the catalogue system of the Kenya Design Manual gives an indication of the type of materials and thickness to use, and then a Mechanistic-Empirical Analysis simulation to determine the right thickness is applied.

The catalogue pavement structure options for the heaviest traffic in the Kenyan Standard, i.e. Traffic Class T1, and design Subgrade Class S3 are as shown in Table 4.1 and Table 4.2.

Table 4.1: Catalogue Pavement Structure Option 1 – Type 11

Layer No.	Pavement Layer	Material	Thickness (mm)
1	Wearing Course	Asphalt Concrete	50
2	Base	Dense Bitumen Macadam (DBM)	150
3	Subbase	Cement or Lime Improved Material (Base Quality)	275
4	Subgrade, S3		

(Source: Kenya Road Design Manual, Part III, 1987)

Table 4.2: Catalogue Pavement Structure Option 2 – Type 5

Layer No.	Pavement Layer	Material	Thickness (mm)
1	Wearing Course	Asphalt Concrete	100
2	Base	Cement Stabilised Gravel	150
3	Subbase	Cement or Lime Improved Material (Base Quality)	225
4	Subgrade, S3		

(Source: Kenya Road Design Manual, Part III, 1987)

In order to achieve a pavement to carry the projected traffic loading, the pavement structures given by the Kenyan Standards were modelled as shown in the section below to come up with modified options that will be able to sustain the loading for a design period of 20-years.

4.4.1.1 Modelling of Pavement Structure Option 1 – Type 11 (The Kenya Road Design Manual, Part III, 1987)

The pavement option 1 – Type 11 was modelled and the pavement bearing capacity distribution is as shown in Figure 4.1. The individual layer bearing capacities are shown in Figure 4.2. It was observed that the average bearing capacity was low, about eight million ESALs, with the base layer registering the lowest bearing capacity. The pavement life was expected to be short, given the expected traffic loading.

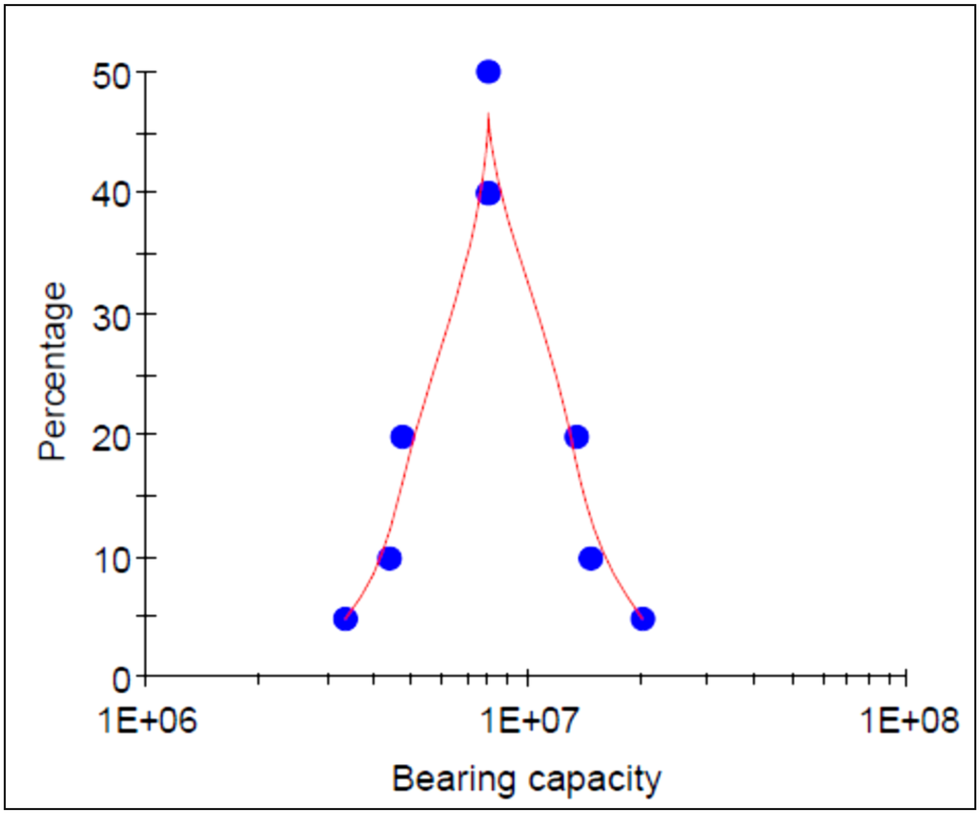


Figure 4.1: Approximate Pavement Bearing Capacity Distribution (in terms of Standard Axles)

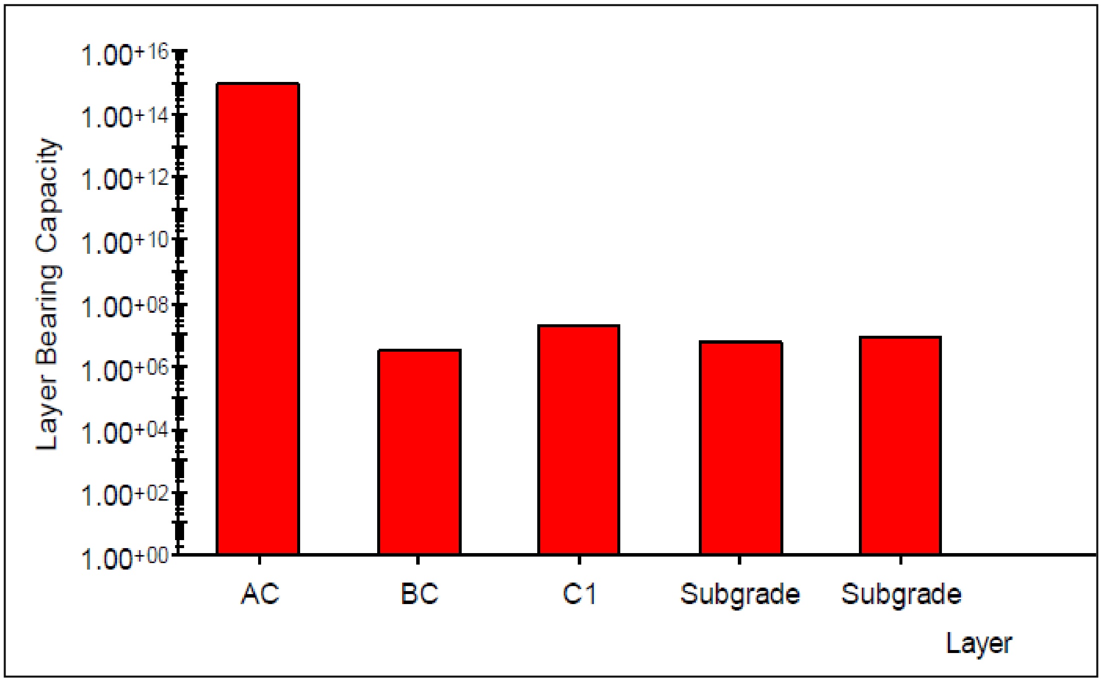


Figure 4.2: Estimated Layer Bearing Capacity (in terms of Standard Axles)

4.4.1.2 Modelling of Pavement Structure Option 2 – Type 5 (The Kenya Road Design Manual, Part III, 1987)

The pavement option 2 – Type 5 was modelled and the pavement bearing capacity distribution is as shown in Figure 4.3. The individual layer bearing capacities are shown in Figure 4.4.

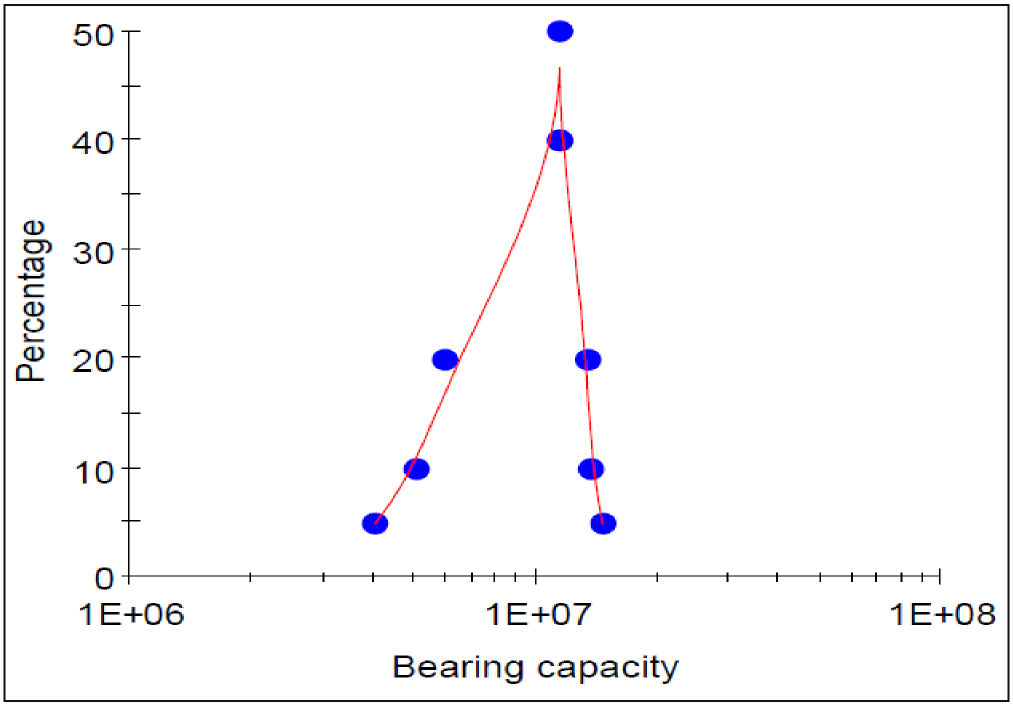


Figure 4.3: Approximate Pavement Bearing Capacity Distribution (in terms of Standard Axles)

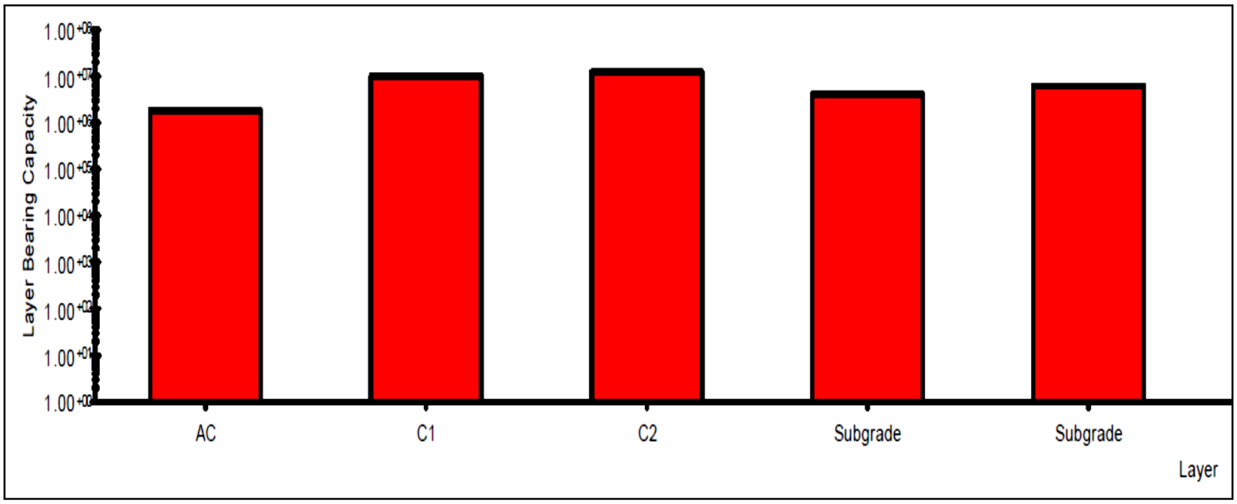


Figure 4.4: Estimated Layer Bearing Capacity (in terms of Standard Axles)

The pavements provided by the catalogues, i.e. options 1 (type 11) and option 2 (type 5), modelled on sections above, and shown on Figures 4.2-4.5, were found to have low bearing capacities to handle the expected traffic loading. However, taking into consideration that hardstone was scarce along the project road, while gravel was available was seen in Section 4.2 and Table 3.10, the pavement option 5 was chosen for further modification in order to increase the bearing capacity to handle expected traffic loading.

4.4.1.3 Modified Pavement Structure

Table 4.3 shows the modified pavement structure. The modified pavement structure option 2 – Type 5 was modelled and the pavement bearing capacity distribution is as shown in Figure 4.5. The individual layer bearing capacities are shown in Figure 4.6.

With the modified pavement layers and optimised material properties, it was observed that the average bearing capacity was adequate, above forty million ESALs, with each individual layer exhibiting high bearing capacities. The pavement life was expected to be able to carry the expected traffic for the design life, with routine maintenance.

Table 4.3: Modified Pavement Structure Option 2 – Type 5

Layer No.	Pavement Layer	Material	Thickness (mm)
1	Wearing Course	Asphalt Concrete	100
2	Base	Cement Stabilised Gravel	300
3	Subbase	Cement or Lime Improved Material (Base Quality)	450
4	Subgrade, S3	Selected subgrade	300

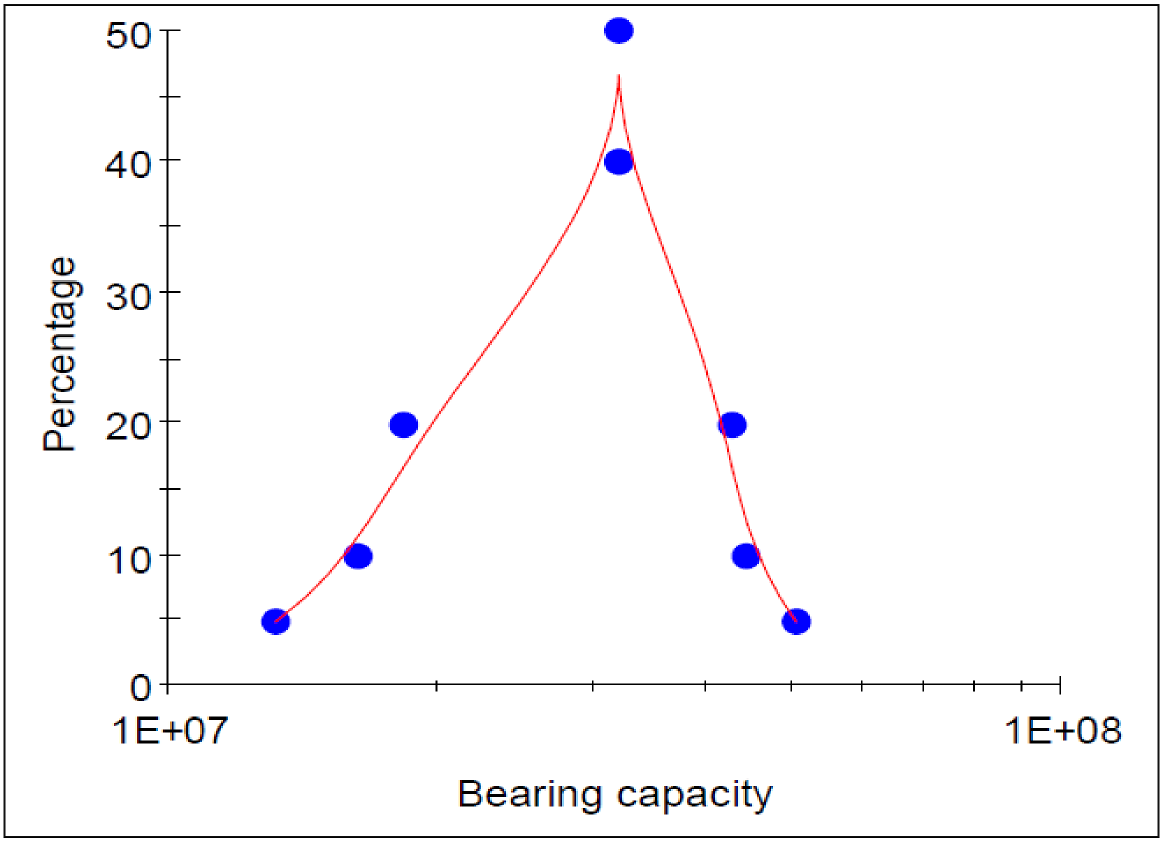


Figure 4.5: Approximate Pavement Bearing Capacity Distribution (in terms of Standard Axles)

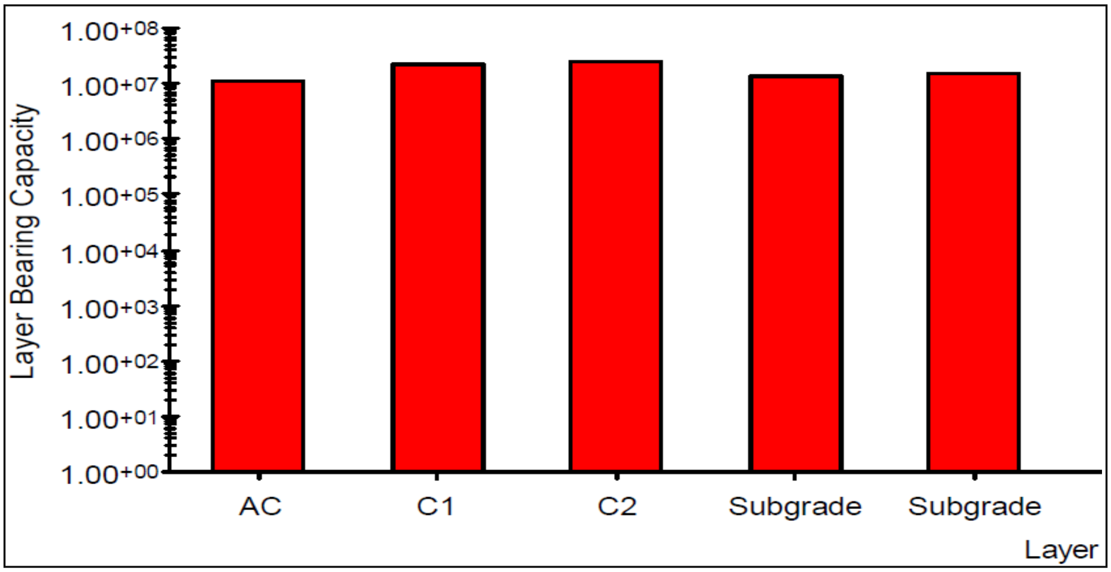


Figure 4.6: Estimated Layer Bearing Capacity (in terms of Standard Axles)

4.5 Pavement Design with a Geosynthetic

The modified pavement structure option 2 – Type 5 in Table 4.3 was used to design for geosynthetic reinforcement. The approach used was subbase/base reinforcement using a non-woven geotextile, placed at the bottom of the subbase/base to (1) increase the effective design life, and (2) attain same performance with a reduced pavement thickness.

4.5.1 Preliminary determination of application of Geotextile Reinforcement

The possible use of a geotextile as a reinforcement was primarily evaluated by scrutinizing the conditions of the road pavement in comparison to the conditions favourable or unfavourable to the use of geosynthetic reinforcement. Table 4.4 shows the initial assessment done on the insitu conditions.

Table 4.4: Review of Reinforcement Application Potential (AASHTO 2014(b))

Pavement Conditions		**Geotextile Type**		**Comment**
Subgrade	**Base Thickness (mm)**	**Nonwoven**	**Woven**	
Low (CBR < 3)	150 - 300	*Reinforcement Applicable*	*Reinforcement Applicable*	***Non-Woven geotextile most recommended for base reinforcement*** ***(1 ≤ CBR ≤ 5)***
	> 300	*Reinforcement Applicable*	*Reinforcement Applicable*	
Firm to very stiff (3 ≤ CBR ≤ 8)	150 - 300	*Separation and Filtration applicable*	*Reinforcement Applicable*	
	> 300	*Separation and Filtration applicable*	*Separation and Filtration applicable*	
Firmer (CBR > 8)	150 - 300	*Not Applicable*	*Not Applicable*	
	> 300	*Not Applicable*	*Not Applicable*	

4.5.2 Target Benefits of using geosynthetic reinforcement

The target benefits of using the geosynthetic reinforcement were then defined. For this design, the main target benefit was both extension of performance period and reduction of subbase/base thickness.

For this case, a Traffic Benefit Ratio (TBR) was defined, and applied to calculate the optimal traffic loading for the unreinforced pavement, as compared to the reinforced pavement for a specific rutting level. The TBR was determined using Figure 4.7 that was developed by Shukla (2002).

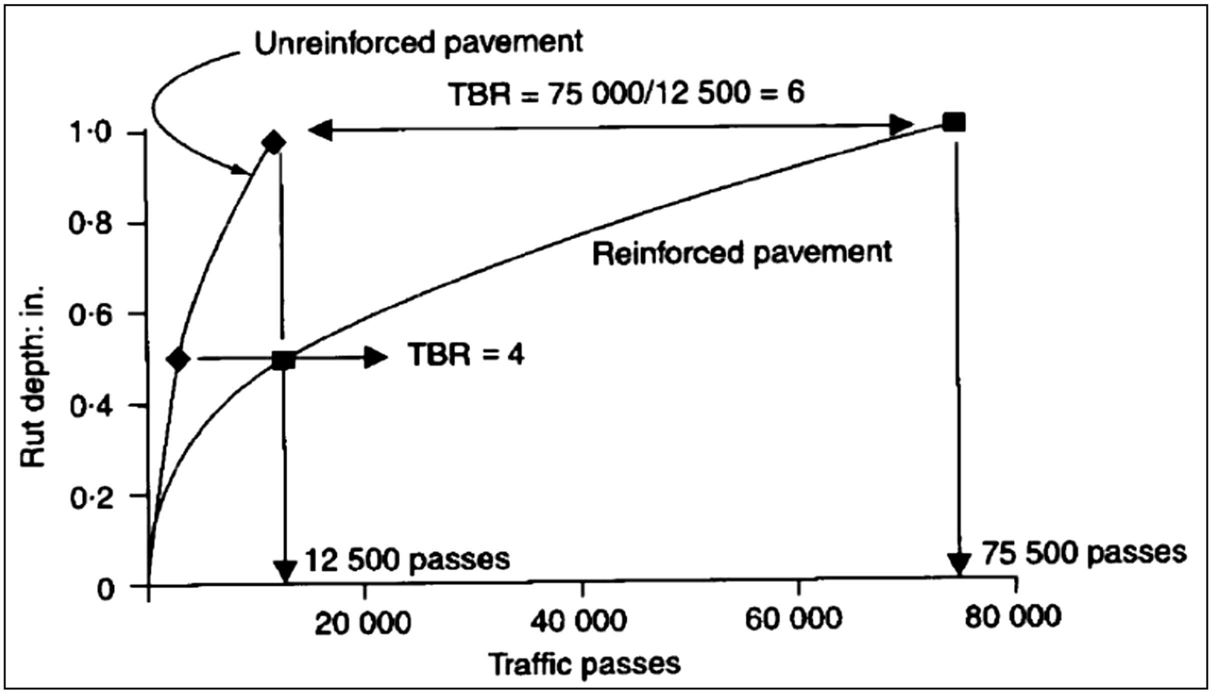


Figure 4.7: Characteristic TBR values for pavements to attain a specific rutting level (Shukla, 2002)

The Kenya Road Design Manual Part V (1988) defines the allowable rutting depths on flexible pavements that necessitates strengthening. For flexible pavements, when rut depths in the wheel path reaches 20mm, cracking is usual and water will penetrate the pavement which then deteriorates rapidly. Therefore, roads require major overlay or reconstruction when the mean rut depth in either wheel exceeds 20mm (0.79 inches) for trunk roads and 25mm (0.98 inches) for other roads. Figure 4.8 shows the determined TBR values. The Lamu-Garissa road is a major trunk road, and therefore a TBR value of 4.7 was adopted.

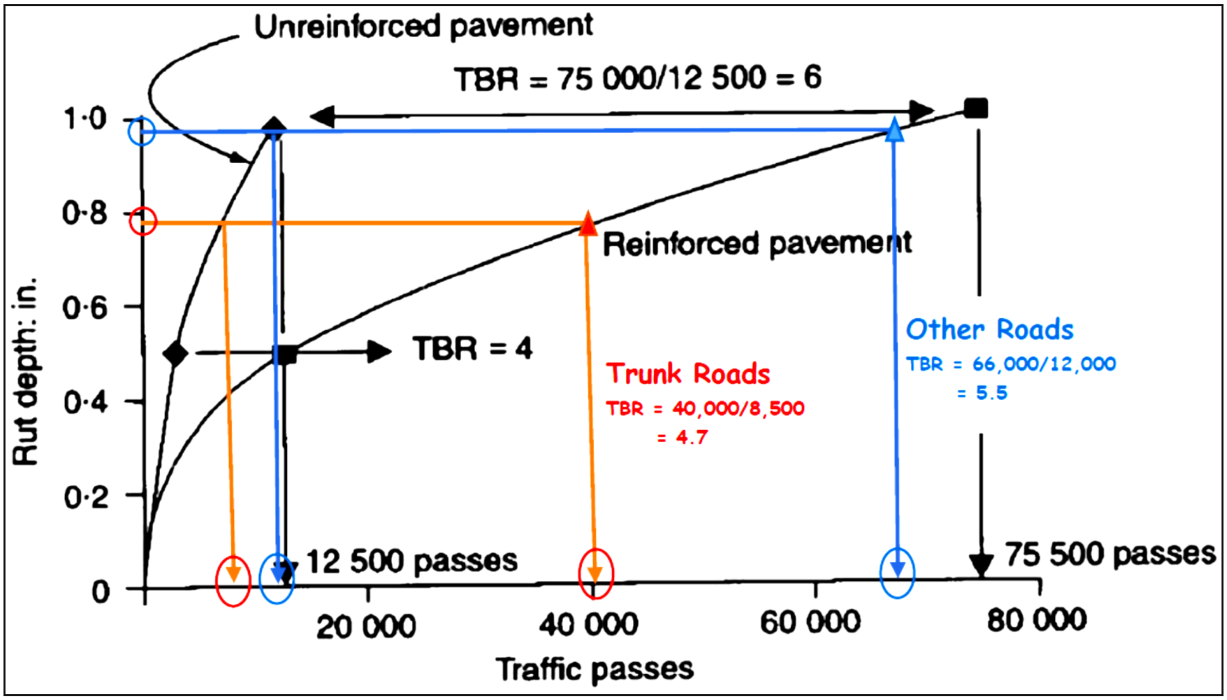


Figure 4.8: Determined TBR values based on provisions of Kenya Road Design Manual Part V (1988).

4.5.3 Reinforced Pavement Design

The design with a Traffic Benefit Ratio (TBR) for subbase/base reduction was carried out. An indirect computation was used, where the TBR was applied to calculate a modified structural number, SN_R. First, the TBR was used to compute $(W_{18})_R$ as shown in Equation 4.1. Then a reinforced structural number was calculated with the $(W_{18})_R$ in the pavement design equation, Equation 2.7. The reduced thickness of gravel layer, with the reinforcement, was then computed using Equation 2.13. The standard normal deviate (for a reliability of 95%) was taken as, based on Tables 4.5 and 4.6. The standard deviation (S_o) was taken as 0.49 (AASHTO, 1993).

$$(W_{18})_R = W_{18} \ x \ TBR \quad \text{…………………………} \textit{Equation 4.1}$$

Table 4.5: Suggested Levels of Reliability for Various Functional Classifications (AASHTO, 1993)

Functional Classification	Recommended Level of Reliability	
	Urban	Rural
Interstate and other Freeways	85 - 99.9	80 – 99.9
Principle Arterials	80 - 99	75 - 95
Collectors	80 - 95	75 - 95
Local	50 - 80	50 - 80

Table 4.6: Standard Normal Deviate (Z_R) Values Corresponding to Selected Levels of Reliability (AASHTO, 1993)

Reliability, R (%)	Standard Normal Deviate, Z_R
50	0.000
60	-0.253
70	-0.524
75	-0.674
80	-0.841
85	-1.037
90	-1.282
91	-1.340
92	-1.405
93	-1.476
94	-1.555
95	-1.645
96	-1.751
97	-1.881
98	-2.054
99	-2.327

The layer coefficients used were based on the provisions of AASHTO 1993, which were based on the elastic moduli M_R and were determined based on stress and strain calculations in a multi-layered pavement system.

The Appendices A, B and C present the charts used to obtain layer coefficients for asphalt layer and granular base and subbase respectively. Appendix A estimates the structural layer coefficient, a_1, of a dense-graded asphalt concrete surface course based on its elastic (resilient) modulus at 68°F (20°C). Appendix B estimates the structural layer coefficient, a_2, for a cement-treated base material from either its elastic modulus, E_{BS}, or, alternatively, its 7-day unconfined compressive strength. Appendix C estimates the structural layer coefficient, a_3, from one of four different laboratory results on a granular subbase material, including subbase resilient modulus, E_{SB}.

The drainage factors were used to treat the effects of certain levels of drainage on predicted pavement performance. Table 4.7 demonstrates the general definitions corresponding to different drainage levels from the pavement structure. Table 4.8 shows the drainage coefficients based on the quality of drainage and the exposure levels.

Table 4.7: Drainage Quality (AASHTO, 1993)

Quality of Drainage	Water Removed Within
Excellent	2 hours
Good	1 day
Fair	1 week
Poor	1 month
Very Poor	(water will not drain)

Table 4.8: Suggested m_i Values for Adjusting Structural Layer Coefficients of Unbound Base and Subbase Materials in Flexible Pavements (AASHTO, 1993)

Quality of Drainage	**Percent of Time Pavement Structure is Exposed to Moisture Levels Approaching Saturation**			
	< 1%	**1 to 5%**	**5 to 25%**	**>25%**
Excellent	1.40 – 1.35	1.35 – 1.30	1.30 – 1.20	1.20
Good	1.35 – 1.25	1.25 – 1.15	1.15 – 1.00	1.00
Fair	1.25 – 1.15	1.15 – 1.05	1.00 – 0.80	0.80
Poor	1.15 – 1.05	1.05 – 0.80	0.80 – 0.60	0.60
Very Poor	1.05 – 0.95	0.95 – 0.75	0.75 – 0.40	0.40

The serviceability of a road pavement is the ability to carry the traffic that use the roadway facility. The main measure of serviceability is the Present Serviceability Index (PSI), which ranges from 0 (poor roads) to 5 (excellent road). The allowable PSI or terminal serviceability index (p_t) selected is based on the lowest index that will be tolerated before rehabilitation, resurfacing, or reconstruction becomes necessary. An index of 2.5 was adopted for the major highway, based on the AASHO Road Test (AASHTO, 1993). The time at which the chosen pavement structure would reach its terminal serviceability depends on traffic volume and the original or initial serviceability (p_o), which was adopted as 4.2 (for a flexible pavement) (AASHTO, 1993).

Once p_t and p_o were established, the Equation 4.2 was applied to define the total change in serviceability index. A value of 1.7 was adopted.

$$\Delta \text{PSI} = p_o - p_t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation 4.2}$$

Where;

Δ PSI = total change in serviceability index;
p_t = terminal serviceability index;
p_o = initial serviceability index.

The subgrade resilient modulus is the characteristic of the soil that indicates the stiffness or elasticity of the soil under dynamic loading. It is also adjusted for seasonal variation from temperature. The effective resilient modulus was determined based on Equation 4.3 of fine-grained soils (Heukelom and Klomp, 1962). Taking the observed average CBR value of 3, MR value of 4,500 psi was obtained. These values were compared to suggested values of common subgrades from AASHTO shown in Tables 4.9 and 4.10.

$$M_{R\,(psi)} = 1500 \text{ x CBR} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation 4.3}$$

Where;

M

CBR = California Bearing Ratio;

Table 4.9: Subgrade Resilient Modulus Values (AASHTO, 1993)

Subgrade Material	Resilient Modulus (psi)
Gravels	10,000 – 12,000
Tills	10,0000
Sands	7,500 – 10,000
Silts	6,000 – 7,500
Clays	4,000 – 6,000

Table 4.10: Roadbed Resilient Modulus (AASHTO, 1993)

Type of soil	Subgrade Strength	Resilient Modulus (psi)	CBR
Silts and clays of high compressibility (liquid limit ≥ 50)	Very Low	1,000 – 2,700	3 or less
Fine grain soils with predominating silt and clay size particles (low compressibility, liquid limit < 50)	Low	2,700 – 4,000	3 to 5.5
Poorly graded sands and soils that are predominately sandy with moderate amounts of silts and clays (well drained)	Medium	4,000 – 5,700	5.5 to 12
Gravely soils, well graded sands, and sand gravel mixtures, free of plastic fines	High	> 5,700	> 12

Since the predominant subgrade soils were a mixture of clays, sand, gravel and at times boulders, a resilient modulus of 5,700 psi was adopted.

4.5.3.1 Base Reinforcement

Using Equation 4.4, the unreinforced structural number (SN) calculates to 6.70. Using Equation 4.1, where W_{18} was taken as 75.9 Million ESALs and TBR as 4.7, then $(W_{18})_R$ calculates to 356.73 Million ESALs.

$$SN = a_1D_1 + a_2D_2m_2 + a_3D_3m_3 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation 4.4}$$

Where;

SN = structural number;
$\mathbf{a_i}$ = i^{th} layer coefficient;
$\mathbf{D_i}$ = i^{th} layer thickness (inches), and;
$\mathbf{m_i}$ = i^{th} layer drainage coefficient.

The Reinforced Structural Number (SN_R) was the computed using Equation 2.7, and a value of 9.12 was obtained. Using iterative indirect computations for the base thickness, it was found that a 300 mm geosynthetic stabilized base would function the same as a 557 mm unstabilized base. Thereby, by iterations, a reduced base thickness by 30% was adequate to carry the expected loading and therefore, a base of 210 mm, reinforced with a geotextile was proposed.

4.5.3.2 Subbase Reinforcement

Designing for subbase reinforcement, using the procedure as in section 4.4.3.1, it was found that a reinforced 450mm subbase thickness will function like an 887 mm thick unreinforced subbase, meaning that the subbase could be reduced by 32% owing to the geotextile reinforcement. Therefore, a 305 mm geotextile reinforced subbase was proposed.

4.5.3.3 Recommended Pavement Structures

The Table 4.11 shows the proposed pavement thickness options. Option 1 is for a reduced base course thickness, while option 2 is for a reduced subbase thickness.

Table 4.11: Pavement Options with Geotextile Reinforcement

Layer No.	Pavement Layer	Material	Option 1 - Thickness (mm)	Option 2 - Thickness (mm)
1	Wearing Course	Asphalt Concrete	100mm	100mm
2	Base	Cement Stabilised Gravel	210mm	300mm

Layer No.	Pavement Layer	Material	Option 1 - Thickness (mm)	Option 2 - Thickness (mm)
3	Subbase	Cement or Lime Improved Material (Base Quality)	450mm	305mm
4	Subgrade, S3	Selected subgrade	300mm	300mm

4.6 Cost Savings for Geotextile Reinforcement

The cost savings to be derived on materials only were then computed. Effective life costs and the benefits that could not be enumerated in Kenya Shillings amount were not computed. These benefits not computed included: minimal disturbance of the subgrade during construction; better reliability of pavement structure and reduced pollution. Life-cycle costs include construction costs, maintenance costs and rehabilitation costs.

The computed materials costs are as shown in Table 4.12, and the basis of cost calculation included:

(1) A construction width of eight (8) metres will be maintained.

(2) The subbase and base courses will be improved with 2% and 4% cement respectively.

(3) The reinforcement geotextile selected would be Bidim A5, with a unit cost of Kshs 276.00 per square metre, all costs inclusive.

(4) The unit prices of the pavement materials were taken as (Government of Kenya, 2017):

   (a) Borrowed fill in soft material and compaction – Kshs. 857.00 per m^3

   (b) Natural gravel for base/subbase – Kshs. 2,076.00 per m^3

   (c) Cement stabilization - Kshs. 4,053.00 per m^3

   (d) Cement mixing - Kshs. 3,805.00 per m^3

   (e) Hot mix asphalt concrete for surfacing - Kshs. 42,028.00 per m^3

Table 4.12: Summary of Material Costs

ESAL/Design Year	**75,885,762/2039**		
Design Option	**Unreinforced**	**Reduced Base Course Thickness**	**Reduced Subbase Course Thickness**
Pavement Option			
Asphalt Concrete Surface	100mm	100mm	100mm
Base Course	300mm	210mm	300mm
Subbase Course	450mm	450mm	305mm
Select Subgrade	300mm	300mm	300mm
Geotextile Reinforcement	None	Yes (Bidim A5)	Yes (Bidim A5)
In-Place Cost	n/a	Kshs. 276/ sq. m.	Kshs. 276/ sq. m.
TBR Value	n/a	4.7	4.7
BCR Value	n/a	30%	32%
Analysis Period (Yrs.)	20 Years		
Initial Construction Materials Costs (Kshs)	17,911,526,000.00	17,118,664,400.00	16,477,428,600.00
Cost Savings on Construction Materials (Kshs)	-	792,861,600.00	1,434,097,400.00
Percent Savings Compared to Unreinforced Design	-	4.4%	8.0%

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The analysis of the flexible pavement, both with and without a geotextile; and the testing of the locally available geotextiles give the following conclusions:

1) In Kenya, currently, there are geosynthetic materials in the market that can be used to reinforce flexible pavements, as they meet the mechanical property requirements for use in pavement reinforcement function.
2) Placing a geotextile below the subbase of the pavement will yield substantive savings in costs of construction and eventual life-cycle costs. This is in addition to other associated savings in reduced pollution and shortened construction period.

5.2 Recommendations

The following recommendations are made from the study:

1) The recommended practice for incorporation of geosynthetics in road pavements towards cost saving need to be further investigated with field trials in the local scenario, and performance studies be carried out and documented, towards adoption of the practice.
2) Dissemination of knowledge regarding usage of geosynthetics in road pavements is a key area that need to be addressed, and eventual incorporation of the geotextile-reinforced pavement specifications in the Kenya Road Design Manuals.
3) In addition, the cost benefits derived by incorporating a geotextile in a pavement, which include minimal disturbance of the subgrade during construction; better reliability of pavement structure and reduced pollution need to be studied and enumerated in monetary terms.
4) The possibility of reducing both the base and the subbase simultaneously by incorporating a geotextile in the pavement need to be investigated

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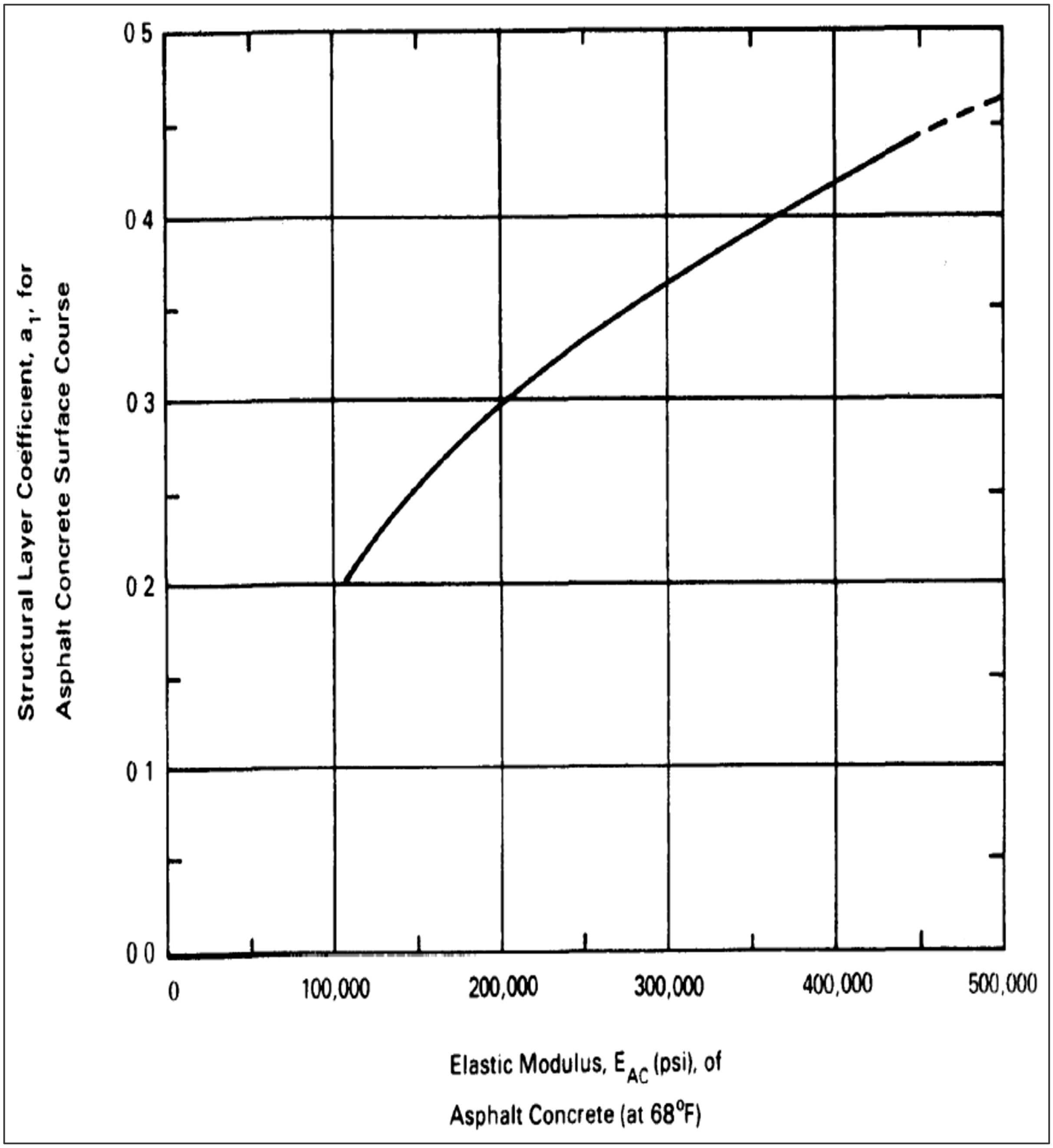
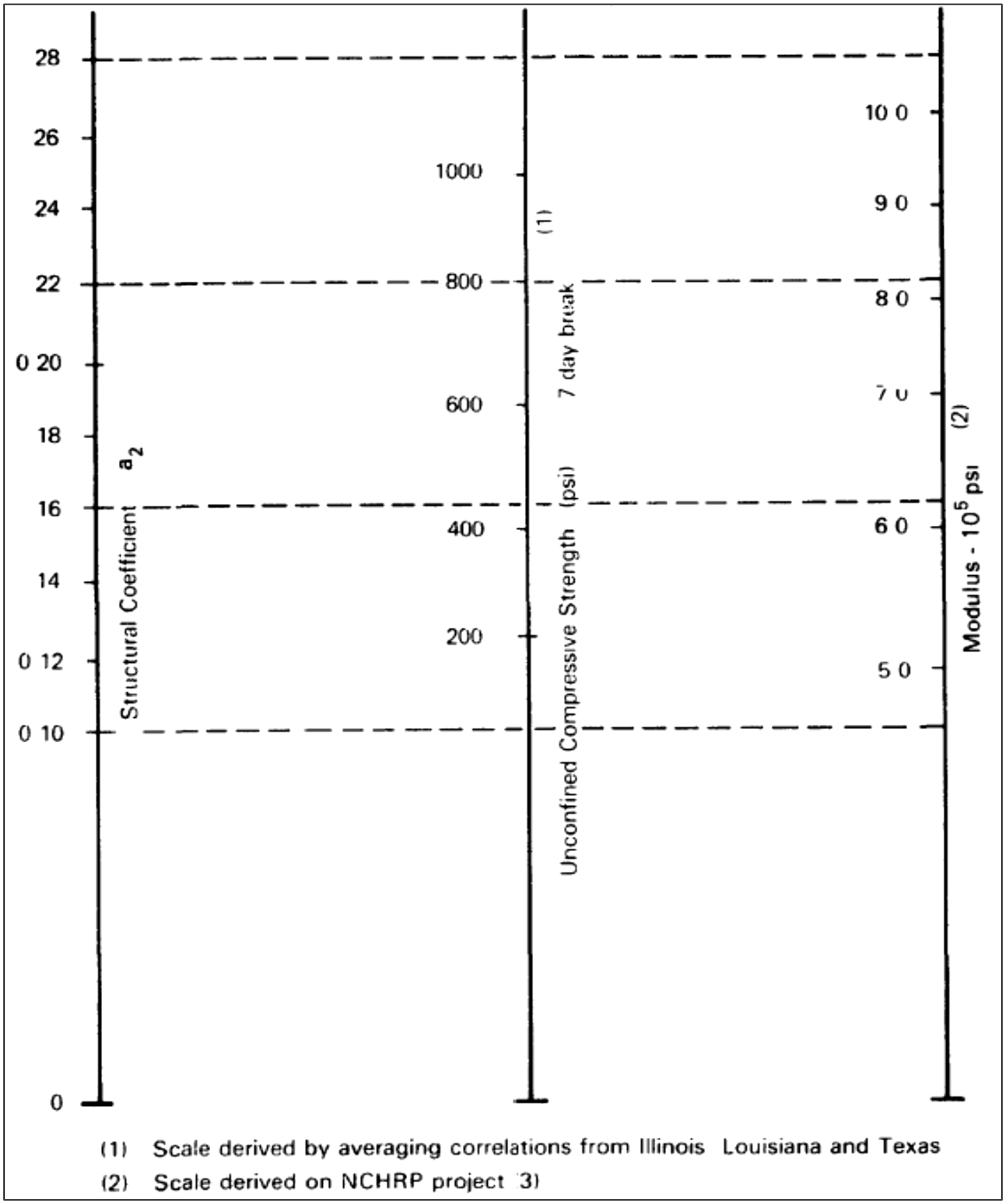
7.0 APPENDICES

7.1 Appendix A - Chart for Estimating Structural Layer Coefficient, a_1, of Dense Graded Asphalt Concrete based on the Elastic (Resilient) Modulus (AASHTO, 1993).



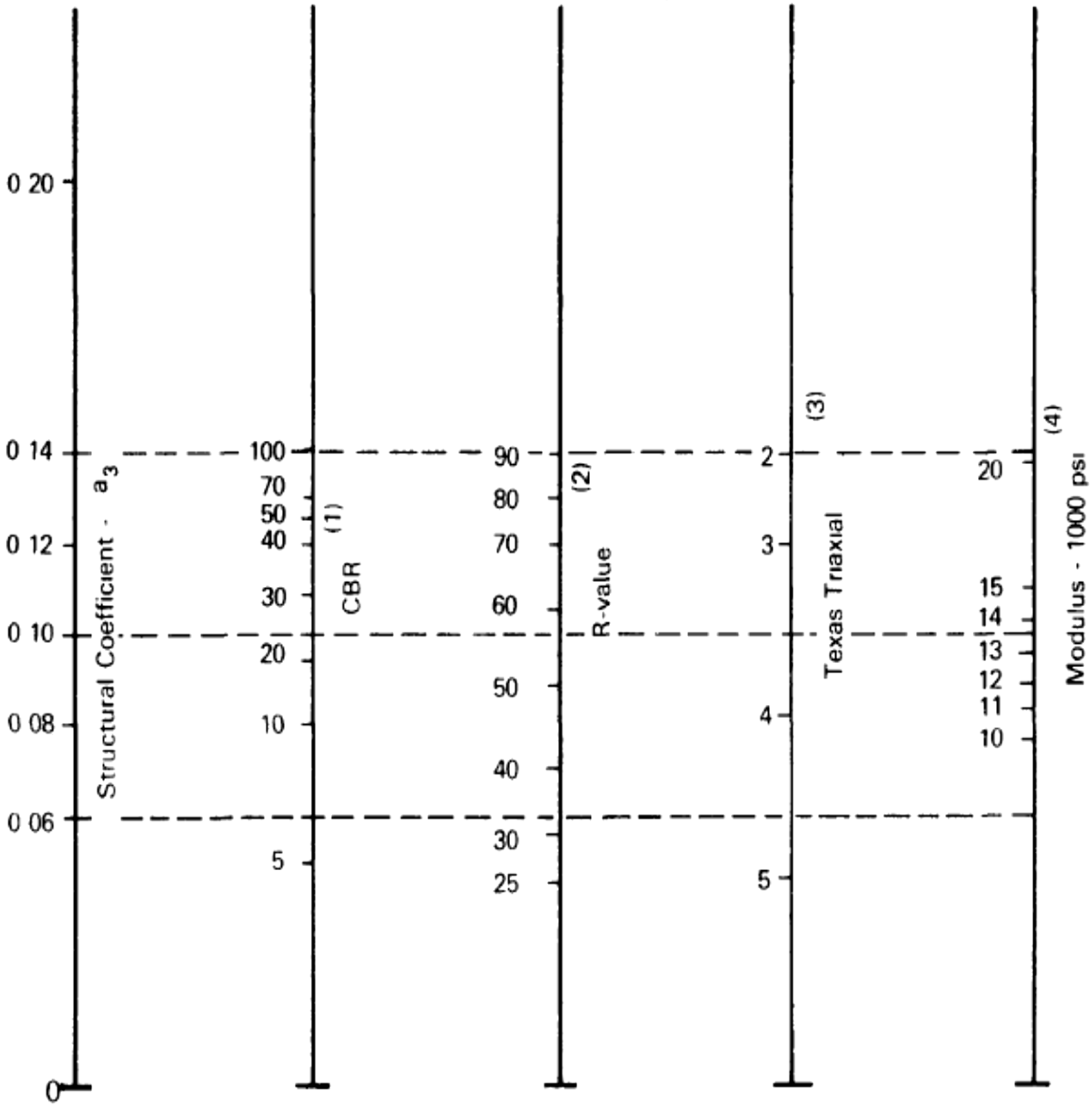
7.2 Appendix B - Chart for Estimating Structural Layer Coefficient, a2, of Cement-Treated Bases (AASHTO, 1993).



(1) Scale derived by averaging correlations from Illinois Louisiana and Texas

(2) Scale derived on NCHRP project 3)

7.3 Appendix C - Chart for Estimating Structural Layer Coefficient, a3, of Granular Subbase (AASHTO, 1993).



(1) Scale derived from correlations from Illinois

(2) Scale derived from correlations obtained from The Asphalt Institute, California, New Mexico and Wyoming

(3) Scale derived from correlations obtained from Texas

(4) Scale derived on NCHRP project *(3)*