University of Nairobi

Department of Civil and Construction Engineering

Pavement Evaluation of Mbagathi Road, Kenya.

Submitted by:

Adoyo Felix Otieno

A thesis submitted in partial fulfillment for the Degree of Master of Science in Civil Engineering in the department of Civil and Construction Engineering, University of Nairobi.

October 2012

Declaration

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

4/11/2012

Adoyo Felix Otieno

Reg. F56/65073/2010

This thesis research has been examined with my approval as university supervisor

5/11/2012

Professor S. K. Mwea

Abstract

Mbagathi Road has been open to traffic for six years and yet various distress features have been observed despite the fact that most concrete roads are expected to operate for over twenty (20) years without any major maintenance and without exhibiting any distresses. The objectives of this research was to determine the relationship in the observed pattern of deterioration of Mbagathi Road with the performance of concrete slabs forming part of Mbagathi Way, to conduct a pavement condition survey and to determine magnitude and pattern of deflection of pavement slabs.

This thesis describes a literature review, studies on concrete road deflections, pavement condition survey, traffic loading on Mbagathi Road and analysis of results that provides baseline information on the performance of Mbagathi Road.

The assumption by Westergaard of infinite or semi-infinite slab was in tandem with this research and hence the applicability of these equations is not in doubt. This research concurred with other researchers who observed that as a/l increase, finite element stresses and deflections become progressively higher than Westergaard's. In addition, the pattern of observed deflections were similar the progression of Westergaard's deflections.

It was found that Mbagathi Road is weaker than the ideal Westergaard assumption. However, despite the fact that high noise levels were observed on Mbagathi Road, the determination of homogenous section through pavement condition surveys and measurement of pavement deflections yielded correlated results. Pavement deflections were directly proportional to the overall pavement condition and drainage conditions influenced, to a large extent, the overall pavement condition in terms of the occurrence of distresses. Homogeneity of concrete influences the degree pavement deflections while the performance of joints indicated performance of concrete pavements.

Despite the observed weaknesses, Mbagathi Road is expected to survive its intended life without major deterioration, special attention must be paid to drainage conditions which were found to indicate eminent failure of the pavement. Resealing of observed cracks will reduce percolation of water into the pavement layers and hence prolong the life of the pavement.

Acknowledgement

Special thanks to Prof. S.K. Mwea for his helpful guidance and encouragement throughout this research. Prof. Gichaga J. Francis whose lectures on pavement evaluation inspired me to undertake this research is greatly appreciated. Prof. Mbeche O.O. is appreciated for his guidance on research methodology and for presentation guidelines.

Special gratitude The Chief Engineer, Ministry of Roads, (Materials Department) and Eng. Wanyiri for offering guidance and conducting deflection measurements and concrete strength tests. Special thanks to Albert Ndege who helped in data analysis.

Thanks to the following staff members of Civil and Construction department of the University of Nairobi whose comments and opinions helped to shape up this research: Dr. Mumenya S. Wanjiku, Eng. D.M. Wanjau, Eng. D.O. Koteng' and Prof. Nyangeri E. Nyanchaga.

Special thanks to my dear wife for contribution in preparation of this research and emotional support throughout the entire duration of the thesis and to my daughter Nicole for her valuable encouragement.

Special appreciation to all the second year data collection enumerators from Kenya Polytechnic University College of The University of Nairobi for taking time and effort that resulted in the success of this research.

Dedication

This work is dedicated my loving mother Penina Adhiambo Nyakiti for all the sacrifices she made in my education. May the Almighty Father reward you according to his bountiful promise.

Table of Contents

List of tables

List of Figures

List of Appendices

List of Abbreviations

AASHTO – American Association of State and Highway Transportation Officials

ADT – Average Daily Traffic

CBR – California Bearing Ratio

CRCP – Continuously Reinforced Concrete Pavements

EACPA - East Africa Cement Producers Association

EUPAVE- European Concrete Paving Association

FWD - Falling Weight Deflectometer

JCP – Jointed Concrete Pavements

KURA - Kenya Urban Roads Authority

LHS – Left Hand Side (Langata road to Ngong road side)

RHS – Right Hand Side (Ngong road to Langata road side)

M.O.R –Ministry of Roads

NCDOT-North Carolina Department of Transportation

NDT – Non Destructive Test

PCA – Portland Cement Association

SANRA-South African National Roads Agency Limited

RDC- Radius of Curvature

UNON - United Nations Office in Nairobi

WTIC- Wisconsin Transportation Information Centre

CHAPTER 1

INTRODUCTION

1.1. Background Introduction

Roads constitute a major part of a nation's infrastructure. In Kenya, The Roads Act, 2007 established various authorities for the management and administration of roads in the country. Among the authorities that were created by the Roads Act of 2007, Kenya Urban Roads Authority, KURA, has the responsibility of management, development, rehabilitation and maintenance of all public roads in the cities and municipalities in Kenya. Mbagathi Road, being in Nairobi City, is managed by KURA (Kenya Roads Board, 2007). The overall mission of KURA is to professionally provide quality, safe and adequate urban roads network that satisfies stakeholder needs (KURA, 2011).

There has been little interest in constructing concrete pavements in Kenya owing to the high costs of construction and the lack of expertise to build them compared to asphalt roads. While no locally developed guidelines exist on the design and performance of concrete roads, the current Kenyan Road Design Manual is undergoing revision to incorporate, among other issues, the design manual for concrete roads (Kenya National Assembly, 2007). Pilot concrete road trials that have been constructed in Kenya include the reconstruction of 6km of Mbagathi Road in August 2006 (the cement being donated by Bamburi Cement Company and reconstruction of the Gilgil 200m long by 22m wide weighbridge facility near Naivasha using Europen Union grant.

Research has shown that concrete roads, though expensive to construct, incur little maintenance cost and can last several years without maintenance. Heavily trafficked roads are able to function comparatively well when constructed of concrete and driving on concrete roads is safer than on asphalt roads due to increased visibility at night owing to its pale colour. Vehicles travelling on concrete surfaces require in general less energy for propulsion than asphalt resulting in fuel savings between 10-20%. However, traffic noise and the relative difficulty of repairing concrete roads compared to asphalt is a major disadvantage (EUPAVE, 2009).

Mbagathi road is not the first concrete pavement in Kenya but is the first concrete road that the Government has taken ownership of. The project involved white-topping funded by the Government through proceeds from Road Maintenance Levy Fund. The project involved overlay of the 6km dual carriageway through provision of 205mm thick dowel jointed concrete pavement, construction of access and cross culverts, construction of a new footbridge, construction of 3m footpaths in concrete paving blocks and the provision of street lights.

1.2. Description of the Study Area

Mbagathi Road is located in Nairobi City, the capital city of Kenya and covers an area of 696 km^2 at an elevation of 1,661m with an estimated population of 3,138,295 and population density of 4,509 persons/km^2 (CBS, 2009) making it be the most populated city in East Africa. Nairobi is also the headquarters for the UN in Africa & Middle East, the United Nations Office in Nairobi (UNON).

Mbagathi Road is approximately 6km dual carriageway and starts at Langata Road (C58) roundabout, passing next to Nyayo Highrise estate, Kenyatta Market and ends at Ngong road (C60) roundabout at City mortuary next to Kenyatta National Hospital. Mbagathi Road was initially designed as a flexible pavement in 1970s and the main works executed between the year 2005 and 2006 comprised rehabilitation of the carriageway with cement concrete overlay on the following existing pavement layers:

- AC Wearing course: 80mm
- Gravel sub-base - 50mm
- Hand-packed stone base – 300mm

Overlay design was carried out for two typical sections (M.O.R.P.W, 2006). :

i. Sections with failed surfacing only where the surface was patched with Asphaltic Concrete Type 1.

ii. Completely failed sections which exhibited complete pavement failure. The existing failed pavement was entirely removed and a 300mm hand packed stone base was provided.

1.3. Statement of the Research Problem

Concrete roads can last over 20 years without any major maintenance (EUPAVE, 2009). However, Mbagathi road has lasted 5 years and yet observations that have been made on the road have shown widespread deterioration of concrete pavement slabs and joints. Among other defects, the following have been observed:

- Cracking of pavement slabs as shown is Figure 1.1.
- Widening of the joints due to infiltration of particulates and water into joints as shown is Figure 1.2.
- Ponding of water was observed in a section next to the bridge due to rains and poor drainage.
- Damaged kerbs and polished outer lanes on sections of the road as shown is Figure 1.3.

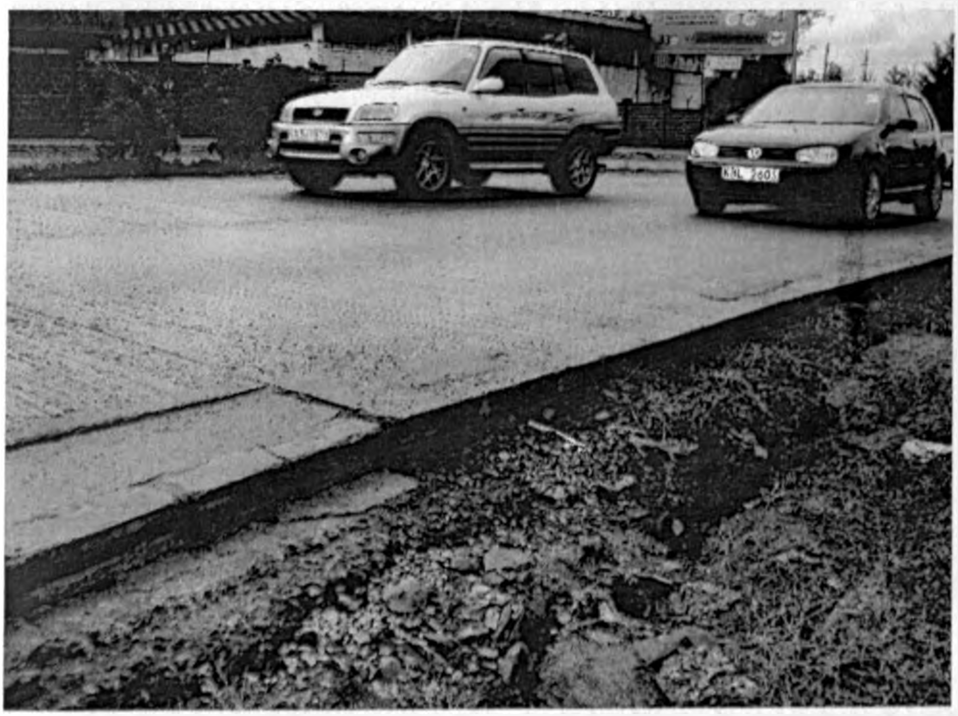


Fig. 1.1: Pavement cracking of concrete slabs at Mbagathi Way

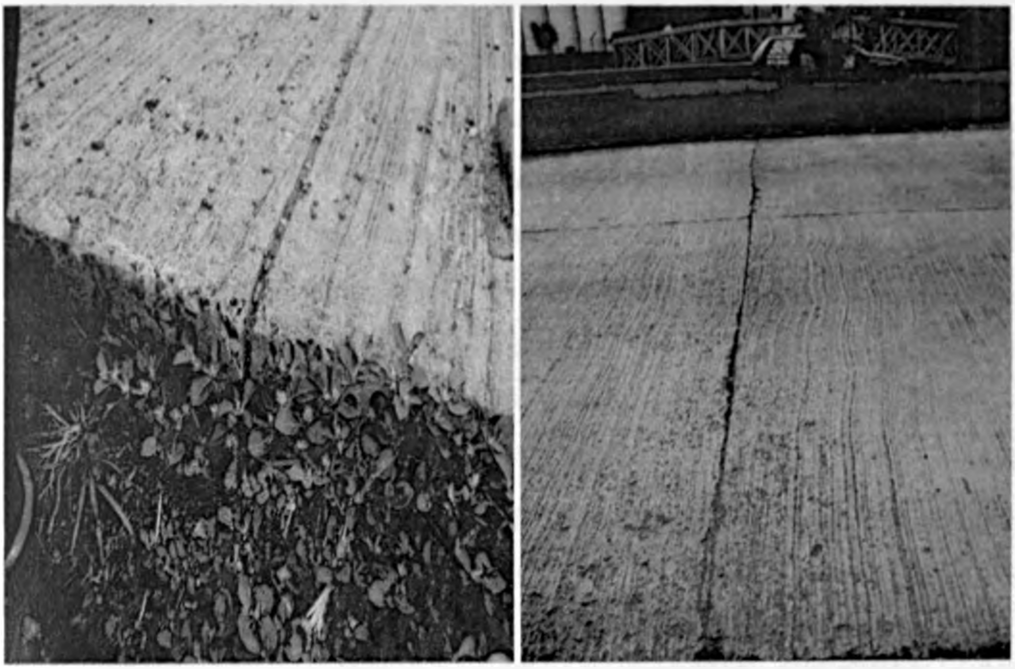


Fig. 1.2: Widening and failure of joints at Mbagathi Way

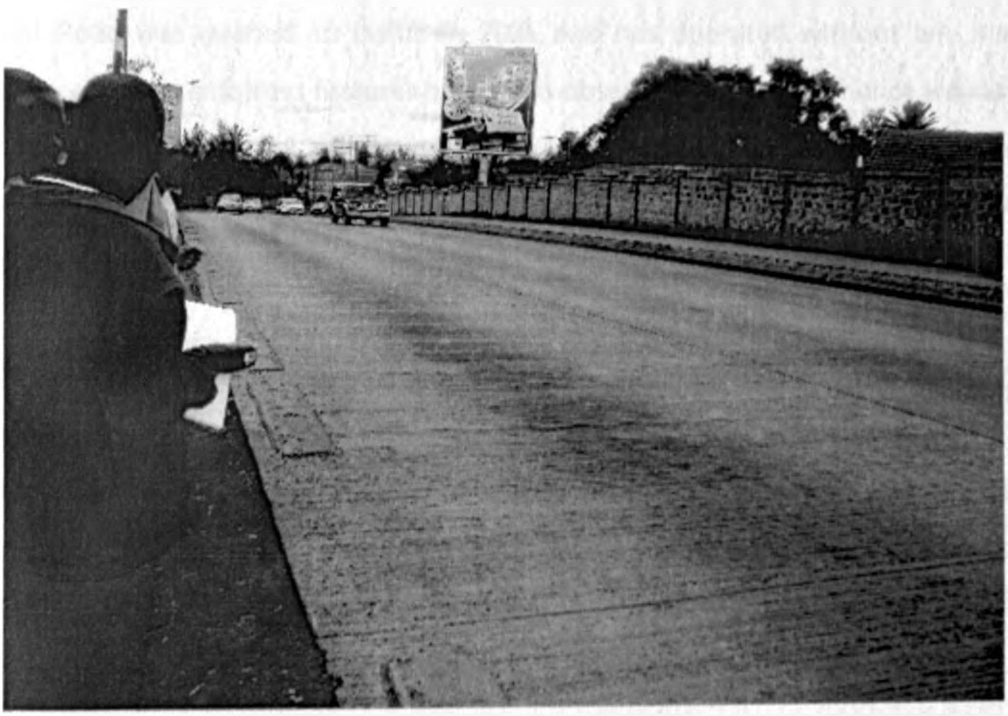


Fig. 1.3: Damaged kerbs and polished outer lane at Mbagathi Way

1.4. Research Objectives

This research will be based on the following objectives.

i. To determine the relationship in the observed deterioration of Mbagathi Road with the performance of concrete slabs forming part of Mbagathi Way.

ii. To conduct a pavement condition survey and hence investigate the causes of the following observed defects on Mbagathi Way

   a. Failure and Widening of joints

   b. Cracking of concrete pavement slabs

   c. Water ponding along sections of the road

iii. To determine magnitude and pattern of deflection of pavement slabs and dowel joints on Mbagathi Road as a measure of the performance of the road and further to determine the value of initial deflections that will form the basis of further research.

1.5. Justification of the Study

Mbagathi Road was opened to traffic in 2006 and has operated without any major maintenance whereas distress features have been observed on the road hence indicating deterioration. An evaluation of distresses on Mbagathi Road provides insights into methods on improving the design and construction of rigid pavements in the region and forms a basis for future research on the road.

Mbagathi Road project was implemented through co-operation between the Ministry of Roads and cement producers in order to show engineers that roads constructed of concrete would perform better than flexible pavements. However, since its construction there has not been any documented evaluation of the road despite it having been the first concrete pavement which the government actively participated. This evaluation has expanded knowledge and expertise on Mbagathi Road and rigid pavements in Kenya.

Owing to scarce pertinent data on evaluation and performance of concrete pavements in Kenya and given the several roads in Kenya which would ordinarily be constructed on concrete for example roads forming the northern corridor due to heavy truck loads, this research has provided data on performance of rigid pavements in Kenya and methodologies to be applied for evaluation of rigid pavements for other researchers and highway engineers.

Improvement to infrastructure is key to the realization on Kenya Vision 2030 and Nairobi Metropolis plans. Infrastructure is one of the four pillars of vision 2030 and hence knowledge on performance of concrete roads is paramount in decision making for road improvements and new construction (Ministry of Nairobi Metropolitan Development, 2008). Economic appraisal with cost-benefit analyses will be better understood when comparing several improvement alternatives with clear performance indices for the alternatives. When one of the alternatives is concrete roads, this research is useful for performance indices of rigid pavements.

1.6. Scope and Limitation of Study

This study was conducted within the following scope:

i. Deflection measurements using Falling Weight Deflectometer at 100m intervals along Mbagathi Road.
ii. Pavement condition survey of Mbagathi Road.
iii. Determination of traffic loading on Mbagathi Road by conducting a 7-day traffic survey.
iv. Determination of in situ concrete slab homogeneity by non-destructive methods.

Deflection study was limited to initial baseline investigation upon which further research will be based. The determination of stresses in the pavement was limited to interior stresses only.

Traffic loading was carried out using the assumption of no overloading. Actual axle loading surveys were out of the scope of this study and hence legal limits of vehicle equivalence factors have been employed in traffic analysis.

CHAPTER 2

LITERATURE REVIEW

2.1. Mbagathi Road Concrete Overlay Construction Project

Literature covering Mbagathi Road concrete overlay construction project have been adopted from the publications in Table 2.1 below.

Table 2.1: Summary of publications on Mbagathi Road Concrete Overlay Construction

No.	Title of publication	Date of publication
1	Memorandum of Understanding between the Ministry of Roads & Public Works and East Africa Cement Producers Association	2005
2	Ministry of Roads and Public Works; contract no. 0431; contract document for rehabilitation of Mbagathi Way	2005
3	Siyenza Engineers; Engineer's Report; Mbagathi Road Rehabilitation Project; Dowel Jointed Concrete Pavement	2005
4	Ministry of Roads and Public Works, Materials Testing and Research Department; Pavement Evaluation Report for Mbagathi Way; Report no. MB 665	2002

Mbagathi Road white-topping was carried out following a memorandum of understanding between the Ministry of Roads & Public Works and East Africa Cement Producers Association which resulted in an agreement to jointly fund the project. A steering committee on concrete roads composed of professional engineers in both the public and private sectors in 2001 identified Mbagathi Road as a suitable trial section for rehabilitation of roads using cement. The MoU was signed on 13th October 2005 and EACPA agreed to provide 4300 Tons of cement at a cost of Kenyan Shillings 44 Million and to procure and meet the cost of consultants for execution of the project at a cost of Kenyan Shillings 5 million.

The works executed in the project included:

i. Trimming of potholes and milling of surface to spoil
ii. Restoration of spalled edges and sealing of cracks
iii. Construction of access and cross culverts
iv. Patching of the surface
v. Provision of 205mm thick dowel jointed concrete pavement
vi. Construction of a new footbridge
vii. Construction of footpaths in concrete paving blocks
viii. Provision of street lights

The overlay was initially designed as 220mm thick using The American Concrete Pavement Association design guidelines and Benkelman deflection beam analysis. A review and optimization of the design was carried out using The South African ConPave modeling program. The concrete slab was designed as unreinforced concrete slab with transverse contraction joints at 4m spacing.

A crack was induced at the transverse joints by an initial saw cut at ¼ depth 4 hours after concrete placing. The joint was later trimmed to incorporate a backing rod and allow placement of joint sealant to prevent ingress of water and other particulates. Load transfer at the joints was enhanced by use of 450mm long R25 bars placed at mid depth, spaced at 300mm and debonded on one side of the joint. Adjoining lanes were tied together with 750mm long Y12 longitudinal bars spaced at 400mm.

The other design parameters were:

i. Daily truck volume – 400 trucks per day per lane
ii. 10 million Equivalent Standard Axles over 20 year period (T3).

The concrete was designed for a Flexural strength of 4.2MPa translating to nominal compressive strength of 35MPa with maximum aggregate size of 20mm. The concrete was designed bearing in mind the 16km haulage distance from EPCO batching plant and hence a retarding plasticizer was incorporated in the mix to increase workability at low water to cement ratio and also retard the initial setting of cement given the haulage distance. Slump requirements were 80mm at the batching plant and 65mm at the site.

The concrete mix proportions were:

i. 400 kg CEM 1 42.5
ii. 800 kg 20mm aggregates
iii. 530 kg 20mm aggregates
iv. 450 kg river sand
v. Water-cement ratio 0.42

The cost comparison of whitetopping option for Mbagathi Road was 30% more than conventional asphalt overlay in terms of cost.

Extra works that affected the original programme

This section has been reviewed from contract progress reports especially report number 8 (M.O.R.P.W, 2006). Extra works that affected the original programme include the following:

i. Extra cross pipe culverts
ii. Box culverts
iii. Widening of carriageway to provide concrete pavement edge support.
iv. Subsoil drains to enhance drainage of concrete pavement
v. Service ducts
vi. Grated open drains on accesses to estates
vii. Change of footbridge beam from steel to concrete beams.

The carriageway width was increased from 7m to 8m in order to cater for the installation of kerbs in order to avoid edge loading. However, the installed kerbs fell off from the pavement due to poor bonding with the hardened concrete. Currently, Mbagathi Road does not have kerbs except for tarmac shoulders.

2.2. Pavement Condition Survey

Pavement Condition Survey involves visual inspection to identify pavement distress features such as cracks and potholes, pavement distortions (such as rutting and corrugations) and edge failure. Gichaga & Parker recommend that this must be supplemented by quantitative techniques such as straight-edge, crack and roughness measurements (Gichaga & Parker, 1988).

The North Carolina Pavement Condition Survey Manual recommends that for divided highways, each direction of travel shall be rated as a separate section and that the rater shall evaluate the most distressed lane, generally the outside lane, in each direction. Each direction of travel (each lane) shall total 100% of the section. The ADT for each direction shall be the total (two-way) ADT for the highway (NCDOT, 2008).

Kenya Road Design Manual Part V (M.O.R. & P.W, 1988) recommends that during pavement condition survey, the following inputs are investigated:

i. Structural performance
ii. Axle load distribution

2.2.1. Pavement behaviour and deterioration mechanisms

The modes of pavement deterioration may be classified into three main categories:

i. fracture
ii. distortion and
iii. disintegration

Deterioration of rigid pavements involves cracking originating from the base or surfacing mainly caused by excessive tensile strain at the bottom of bound layers due to insufficient thickness, inadequate support or fatigue (M.O.R. & P.W, 1988).

The possible causes and deterioration mechanisms for rigid pavement layers have been illustrated in Table 2.2 showing that most defects affect the surfacing and road base.

Table 2.2: Typical defects affecting rigid pavements;

TYPE OF DEFECT	LAYER (S) AFFECTED	DETERIORATION MECHANISM	POSSIBLE CAUSES
LONGITUDINAL CRACKING	B + S	Excessive and repeated loading - Fatigue	Insufficient thickness and/or excessive strength of base Excessive deformation of subgrade + subbase
LONGITUDINAL TRANSVERSE CRACKING	B + S	Thermal changes Shrinkage	Rigidity of the base and/or surfacing; excess cement/ or moisture; Poor cement treated base
TRANSVERSE CRACKING	B + S	Thermal changes Shrinkage	Rigidity of the base and/or surfacing; excess cement/ or moisture; Poor cement treated base; moisture changes
CRAZING	B + S	Excessive and repeated loading - Fatigue	Insufficient thickness and/or strength of the base. Advanced deformation of subgrade + subbase
DEPRESSION + CRACKING	SB + B + S SG + SB + B + S	Densification Settlement	Insufficient compaction or strength of SB Insufficient fill compaction; slip or Groundwater
FAULTING	B + S	Loading, Pumping Densification; Erosion	Insufficient strength of subbase and subgrade Lack of drainage and subgrade swelling

TYPE OF DEFECT	LAYER (S) AFFECTED	DETERIORATION MECHANISM	POSSIBLE CAUSES
POTHOLES	B + S	Disruption	Disintegration of surfacing and base combination of some of the above processes
EDGE SPALLING	B	Abrasion Loading	Poor bond between base and surfacing Lack of edge restraint, shoulder erosion

Legend:

S – Surfacing B – Base SB – Subbase SG - Subgrade

Adopted from Kenya Road Design Manual Part V (M.O.R & P.W, 1988)

2.2.2. Pavement Evaluation

Pavement evaluation includes both surface condition ratings and structural adequacy ratings.

A. Surface condition ratings – Kenyan Road Design Practice

The Kenya Road Design Manual part V rrecommends that condition assessment be based on one, or a combination of the following: -

i. Measurements of surface distress, showing locations and extent of each defect observed. Examples of defects are cracking, crazing, longitudinal deformation of the surface, depressions, upheavals, potholes, patching ravelling, and peeling, stripping and bleeding.

ii. Measurements of surface roughness using a towed bump integrator unit developed by the TRRL as a standard in Kenya.

iii. Subjective rating of the pavement riding quality and surface condition. A present day serviceability value may be obtained by either subjectively rating the pavement through visual observations (present serviceability rating) or by quantitative measurement of surface characteristics (present serviceability index).

B. Surface condition ratings – South African Road Design Practice

Visual assessment of concrete pavements is based on the type, degree and occurrence of distress features (SANRA, 1998). A visual condition index is then developed.

Table 2.3: Visual Condition Index;

Visual Rating	VERY GOOD	GOOD	FAIR	POOR	VERY POOR
Visual condition index	1	2	3	4	5

Source: SANRA, 1998.

Visual assessment looks at three broad types of assessment:

i. Surfacing assessment
ii. Functional assessment and
iii. Structural assessment

The texture of the pavement surface (riding quality) plays an important role in skid resistance and pavement drainage hence is essential for calculation of pavement condition index. Instrumental measurements can also be applied for skid resistance (SANRA, 1998).

The recommendations of the South African practice have been summarized in Tables 2.4 to 2.13 (SANRA, 1998).

Table 2.4: The extent and degree of joint spalling:

Extent	Degree	Description
Number of spalls per segment	Moderate	Spalling that extends between 20 and 50 mm wide on either slab edge, irrespective of the length of spalling.
	Severe	Spalling that extends between 50 and 200 mm wide on either slab edge, irrespective of the length of spalling.

Table 2.5: Degree and extent of joint seal condition

Degree	Description
1 (Good)	No damage to seal. New or functioning adequately.
3 (Fair)	Not functional i.e. sagging, protruding, not adhering to concrete or torn.
5 (Poor)	Dislodged from joint.
Extent	Not rated.

Table 2.6: The Degree and extent of faulting in JCP

Extent	Degree	Description
Record number of slabs with faulting per segment	Moderate	Between 5 and 10 mm.
	Severe	More than 10 mm.

Table 2.7: Degree and extent of cracking of slabs in JCP

Extent	Degree
Record the number of: JOINT ASSOCIATED CRACKED SLABS OR CRACKED SLABS OR SHATTERED SLABS	OPEN CRACKS – easily discernable from slow moving vehicle
	SPALLED CRACKS – cracks that have spalled more than 20 mm, irrespective of spall length.
	SEALED OR PATCHED CRACKS

Table 2.8: Degree and extent of blow-ups, failures and potholes in JCP

Degree	Not rated.
Extent	Record the number of defects occurring per segment.

Note: Unfilled core holes should be rated as potholes.

Table 2.9: Degree and extent of patching in JCP

Extent	Degree
Record the number of patches per segment	No defects. Concrete patches in good condition.
	With defects. Concrete patches that show signs of settlement, undulation, cracking and/or breaking up.
	Asphalt patch. Irrespective of condition.

Note: Filled core holes should not be rated as a patch.

Table 2.10: Degree and extent of pumping in JCP

Degree	Not rated.
Extent	Record the number of slabs per segment showing any signs of pumping.

Table 2.11: Description of degrees of overall pavement condition in JCP

Degree	Description
1 (Very Good)	Very few or no structural defects.
2 (Good)	Few structural defects.
3 (Fair)	General occurrences of which most are severe. Only local occurrence if degree is severe.
4 (Poor)	General occurrence of defects of which a large number is severe.
5 (Very Poor)	Many structural defects of which the majority is severe.

Note: Patches with no defect or sealed cracks do not influence overall condition.

Table 2.12: Description of degrees of shoulder conditions in JCP

Degree	Description
Very Good & Good (G)	Very few or no structural defects.
Fair(F)	Few structural defects (These defects are not large defects).
Poor & Very Poor	Many structural defects.
EXTENT	NOT RATED

Note: Paved shoulders < 1.0m form part of the rest of the pavement.

Table 2.13: Description of degrees of riding quality in JCP + CRCP

Degree	Description	Approx. psi'
1 (Very Good)	Ride very smooth and very comfortable. No unevenness of the road profile or uneven patching.	>3.5
2 (Good)	Ride smooth and comfortable. Slight unevenness of the road profile or uneven patching.	3.0
3 (Fair)	Ride fairly smooth and slightly uncomfortable. Intermittent moderate unevenness of the road profile or uneven patching.	2.5
4 (Poor)	Ride poor and uncomfortable. Frequent moderate unevenness of the road profile or frequent uneven patching. Comfortable when driving below speed limit.	2.0
5 (Very Poor)	Ride very poor and very uncomfortable. Extensive severe unevenness of the road profile or extensive uneven patching. Comfortable when driving below speed limit, road unsafe owing to severe unevenness.	<1.5

Legend:

PSI- Present Serviceability Index

C. **Comparison of South African and Kenya Surface condition rating practice**

The development of PSI and overall pavement evaluation in both the South African and Kenyan practice are both subjective and quantitative with minor differences. Therefore, pavement surface condition rating that incorporates the requirements of the South African and Kenyan rating practice presents a more unified approach towards pavement surface evaluation.

2.2.3 Structural Performance Evaluation of Rigid Pavements

Kenyan Road Design Manual Part V recommends that structural evaluation of a pavement be carried out through the following methods:

i. Measurement of the pavement's bearing capacity (from Benkelman beam deflection, dynaflect, falling weight deflectometer or similar surveys).
ii. Analyses of the characteristics of all pavement layers and subgrade through sampling and laboratory tests.

A. Use of deflection measurements for pavement evaluation

If a standard wheel load, tyre size and pressure, and test procedure are applied, measurement of the surface deflection will enable comparisons to be made between the stiffness of different pavements. It will also provide a means of monitoring the structural strength of pavements over a period of time (M.O.R. & P.W, 1988).

The deflection and curvature of a pavement system due to the load applied are influenced by the pavement modulus, thickness, load intensity and the overall structural integrity of the pavement system and therefore, the measurement of pavement deflection and its curvature at the road surface are considered as true indicators of pavement performance. It has been shown by several engineers that the load-deflection response of a pavement is an adequate representation of pavement performance and can be a most important tool for pavement analysis and evaluation (Mehta, 1990).

Kenyan Road Design Manual Part V recommends that high deflections always indicate structural deficiency whilst low deflections do not necessarily denote a satisfactory structural condition (M.O.R. & P.W, 1988). In circumstances where there is no historical traffic and deflection data or a deflection criterion curve, the evaluation is based largely upon an assessment of pavement condition, the prediction of the future deflection , and the 'life' of the overlay associated with this level of deflection (Smith & Jones, 1980).

Advantages of performing deflection measurements on rigid pavements

Deflection measurement is a simple, quick and non-destructive test.

- A deflection survey is therefore a practical means of identifying the various homogeneous sections of rigid pavements.
- Analysis of the deflection history of rigid pavements indicates the trend of pavement adequacy over time.

Limitations of performing deflection measurements on rigid pavements

- Deflections do not entirely account for the behaviour of rigid and semi-rigid pavement. Very low deflections can be measured on inadequate rigid or semi-rigid pavements (already fractured or about to break).
- Surface deflections do not necessarily measure absolute properties of the pavement structure; the deflection is a function of the strains in the pavement layers and the subgrade. It has value only when the characteristics of each pavement layer and the subgrade are known.

In this respect, it is stressed that deflections measured on thin pavements largely depend on the deformability of the subgrade (M.O.R. & P.W, 1988).

It therefore follows that: -

i. Low deflections may be measured on an inadequate or deteriorated pavement lying on a strong subgrade.

ii. Surface deflections depend on the subgrade strength, particularly on moisture content. Seasonal variations of subgrade moisture are reflected by seasonal variations in the deflections. It is then necessary to correlate deflection with the actual subgrade moisture content. It is also essential to measure the maximum deflection corresponding to the subgrade at its wettest (i.e. at the end of a rainy season).

It is necessary to obtain a sufficient number of readings to enable a meaningful statistical analysis to be made. In this respect, the following test patterns are recommended by Kenyan Road Design Manual Part V: -

- Feasibility study or routine survey: Testing at 100 - 250 m. intervals in each of the wheel paths
- Final design of a strengthening project: Testing at 50 m. intervals in each of the wheel paths.

Deflection testing methodologies

Two methods of testing are available:

i. Laboratory testing of core specimen obtained from the pavement structure.
ii. Non-destructive testing of the pavement surface. There are five general classes of Non-Destructive Testing equipment.
    a. Static Deflection Equipment.
    b. Automated Beam Deflection Equipment.
    c. Steady State Dynamic Deflection Equipment
    d. Impulse Deflection Equipment.
    e. Other Equipment.

Laboratory testing is time consuming and destructive to the pavement structure coupled with delays to traffic which usually inconveniences road users. Samples are usually disturbed upon acquisition from the field and must be remolded for laboratory testing. Hence, stiffness characteristics as measured in the laboratory may not be the same value of those in the field as it is difficult to simulate the exact state of stress in the laboratory by testing of pavement materials.

Static Deflection Equipment.

Measurement systems that determine the pavement response to slowly applied loads are generally termed as static deflection equipment. In static measurement systems, loads are applied by slowly driving to or away from a measurement point with a loaded wheel or applied by reacting against a stationary truck frame (Lytton, 1975). The most commonly used static deflection equipment is the Benkelman Beam and its various modifications. The Benkelman Beam requires a heavy load to create the measured deflection and the deflection profile measured by this device require multiple beams or multiple recordings at known distances as a vehicle moves from the center of the deflection basin. The disadvantage is the difficulty of obtaining a suitable immovable reference when making deflection measurements.

Automated Beam Deflection Equipment.

The La Croix Deflectograph and the Traveling Deflectometer is capable of making several hundred measurements daily.

Steady State Dynamic Deflection Equipment

Equipments which produce a sinusoidal vibration in the pavement with a dynamic force generator include the Dynaflect and the various models of the Road Rater.

Impulse Deflection Equipment.

Falling Weight Deflectometer falls under impulse deflection equipment.

Other Equipment.

Wave velocity equipment developed by the University of Texas Center for Transportation Research shows promise for determining the elastic modulus of layered systems. Laser technology and photogrammetric techniques are also being investigated to measure deflections under moving loads (Mehta, 1990).

The Falling Weight Deflectometer.

This section on Falling Weight Deflectometer has been adopted from research by College of Engineering and Technology, Ohio University; (Mehta, 1990)

The Falling Weight Deflectometer is a device which is used to generate and measure impulse pavement deflection. The Dynatest Model 8000 FWD is the most common FWD. It is manufactured in Denmark and distributed in the United States by Dynatest Consulting of Ojai, California and is widely used in the United States, Canada and other parts of the world. The whole system mounted on trailer weighs between 1323 and 1875 pounds depending on the weight of the falling mass used.

The FWD applies an impulse load by dropping masses from different heights. The system is equipped with four different mass levels weighing 50,100,200, and 300 kilograms. By varying the drop heights and mass levels, impulse load from 680 to 10,885 kilograms can be generated by FWD. Masses are raised hydraulically and released on an electronic signal. The drop heights range from 20 to 380 inches.

The mass is hydraulically lifted to a predetermined height and is then dropped onto a rubber contact, which results in a force impulse curve closely approximating a half sine wave. The force duration is 25 to 30 milliseconds and its peak magnitude is directly proportional to the drop height. The force impulse generated is transferred from the spring system to the loading plate through a configuration of three circular, symmetrically located tubular columns. These columns are connected to a plate which supports the springs at the top, and to a universal ball joint at the bottom. This ball joint is connected to an 11.8-inch diameter loading plate, and this loading plate rests on a 0.22-inch thick rubber pad which helps distribute the load evenly over the loading area.

The load is applied to the pavement surface through an 11.8-inch diameter loading plate and measured by load transducers. Deflections are measured by seven velocity transducers installed on a bar that is lowered automatically with the loading plate. The bar may have six-transducers located up to a radius of 90 inches from the center of the load plate. The six sensors are movable and may be placed at desired distance away from the center of the plate. The seventh sensor is located at the center of the plate. The velocity transducers are specifically designed to insure a linear response with the 25 to 30 millisecond rise time.

The entire operation of FWD is be controlled by one man sitting in front seat of the tow vehicle and it takes approximately 45 seconds to complete an entire test sequence. Heavy duty batteries mounted on the trailer supplies power to operate the trailer hydraulics while the computer is powered by a separate battery.

Other Rules Governing FWD Measurements

It is important for an NDT device to apply a loading condition (magnitude and duration) similar to that of the actual traffic. It is generally agreed that among all the currently available NDT devices, the Falling Weight Deflectometer (FWD) is the best device developed so far to simulate the magnitude and duration of actual moving loads (Lytton, 1989).

Deflection measurements should be made in both wheelpaths of the slow lane on dual carriageways and in both lanes of two lane carriageways. The deflections used both to check variability should be the largest reading from either wheelpath at each chainage.

Smith & Jones (1980) developed a simple and adequate check on variability of deflection measurements in the following way. Ten consecutive measured deflection values are considered as a group and their mean value is calculated. For this purpose, all the deflection values at the regular 100m spacing are used but only the maximum reading is taken from any one area tested on account of its surface distress or large deflection (Smith & Jones, 1980).

After all measurements have been made it is convenient to plot for each lane the maximum deflection (corrected for temperature effect) and the worst pavement surface condition ratings for each cross-section against chainage along the road. At least 20 measurements per kilometer spaced in such a way that they reflect the variation in pavement conditions should be made. At least 20 measurements per kilometer should be made on pavements which do not show any surface distress. If time is available measurements should be taken at closer intervals which may increase the accuracy of the method. Testing at 12m intervals is recommended for surveys in the United Kingdom (Smith & Jones, 1980).

Use of radius of curvature measurements

Kenyan Road Design Manual Part V recommends that on rigid pavements, the magnitude of surface deflection has little significance and the main structural indicator is the radius of curvature. In this regard, it is mandatory that radius of curvature (RDC) measurements are incorporated in all deflection survey work to provide a complete assessment and enhance the deductions as to the pavement condition.

High radii of curvature always indicate rigid base and surfacing, whereas low radii of curvature correspond to an unbound pavement. An "unbound" layer consists of either flexible material or broken rigid material. It is recommended that radii of curvature be measured simultaneously with the deflections. This has the advantage of providing a continual evaluation of the pavement structural condition.

2.2.4. Summary of procedure for pavement evaluation

Pavement evaluation process for routine survey or feasibility study can be summarized as shown on Table 2.14 below.

Table 2.14: Pavement evaluation process for routine survey or feasibility study

-Visual Assessment of the surface condition and drainage system. -Study of the design, construction records and maintenance history. -Deflection Survey: 4 points every 100 - 250 m. (four wheel paths). -Radius of Curvature: 4 points every 100 - 250 m. (four wheel paths). -Optional: Roughness Survey by Bump Integrator (outer wheel paths). -Optional: Core-Cutting for pavement structure and subgrade. - Check: if there is agreement between condition, structure and deflection - If Yes: Divide road into homogeneous sections. - If No: Further investigations to explain disagreement and define homogeneous sections.

Adopted from Kenya Road Design Manual Part V (M.O.R & P.W, 1988)

Table 2.15 shows the procedure for verifying the consistency of measured deflections with pavement surface condition, structural design and maintenance rate.

Table 2.15: Verification of the consistency of deflection with surface condition, structure design and maintenance rate

Deflection Level Case No.	Surface Condition	Structure Design	Maintenance Rate	Agreement Between Deflection and Other Criteria? Probable Cause of Disagreement Point to Check	Possible Use of Deflection for Sectioning and Choice of Remedial Measures
(1) High	Poor	Inadequate	Excessive	YES All factors in accordance	Deflection can be used for dividing the road into homogeneous sections and choice of corrective measures
(2) Low	Good	Adequate	Normal	YES All factors in accordance	Deflection can be used as an indicator. For flexible pavement, no corrective measures required
(3) High	Good	Inadequate		NO a) - Recent resealing has concealed surface distress Check resealing date. b)- New inadequate pavement, which carried light traffic	Deflection can be used for dividing the road into homogeneous sections and choice of corrective measures

(4) High	Poor	Adequate	Excessive	NO Probably one pavement layer is defective, not all layers Check layer by layer	Deflection can be used to define affected sections. Correction of deficiency may be independent of deflection
(5) Low	Poor	Inadequate	Excessive	NO Deflection not representative either dry season measurement Repeat survey in rainy season or pavement is not flexible	a) -Representative deflection can be used as in Case No. 1 b) - Deflection is not an indicator of structural condition
(6) Low	Poor	Adequate	Excessive	NO The surfacing is defective, the rest of the pavement is sound. Check the surface layer	Deflection is not related to surface deterioration.

Adopted from Kenya Road Design Manual Part V (1988)

2.3. Concrete Pavement Design, Construction and Performance

2.3.1. The history of concrete roads

Over 2000 years ago Romans built the forerunners of our modern concrete roads. The first modern concrete roads were constructed in the USA in the early 1890s. In Europe the interest for concrete as a road paving material started in the 1920s mainly in Germany and the Netherlands. Concrete and paving technology has developed and it is now possible to produce wear resistant concrete pavements causing limited noise when trafficked. Today, the use of concrete road pavements is common both in the USA and in several European countries such as Germany, Switzerland, Belgium, England and France, (European Commission, 1999).

In Africa, concrete roads are used in South Africa where standards have been developed for design, construction and performance of concrete roads.

2.3.2. Design of concrete roads

Concrete pavements are designed to act like a beam and use the bending strength of the slabs to carry the load. The design is based on the presumption of uniform support and cannot be expected to perform as "simply-supported" structures (WITC, 2002). Therefore load transfer across cracks and joints is important, especially on roads with heavy truck and bus traffic. Concrete pavements are stressed by variation in temperature, and to a lesser extent by moisture content, because of the volume changes that occur. Where concrete is exposed, the volume changes must be accommodated by expansion and contraction joints, the spacings of which are determined by the temperature variation range. The effects of temperature variations on concrete pavements are shown on figure 2.1.

Hairline and narrow cracks still have interlocked concrete aggregate and can effectively transfer loads. Because wide cracks and widely-spaced joints open up, they cannot transfer loads and must take higher edge loads. These higher edge loads can cause further cracking and deterioration along the joint or crack edges. Some concrete pavements use joints that have load transfer dowels. These are smooth steel bars placed across the joint. They transfer traffic loads between adjacent concrete slabs while allowing opening and closing of the joint. These bars can rust and sometimes cause problems. The corrosion causes forces on the concrete which lead to spalling, cracking and general joint deterioration. Epoxy coated dowels are now commonly used (WITC, 2002).

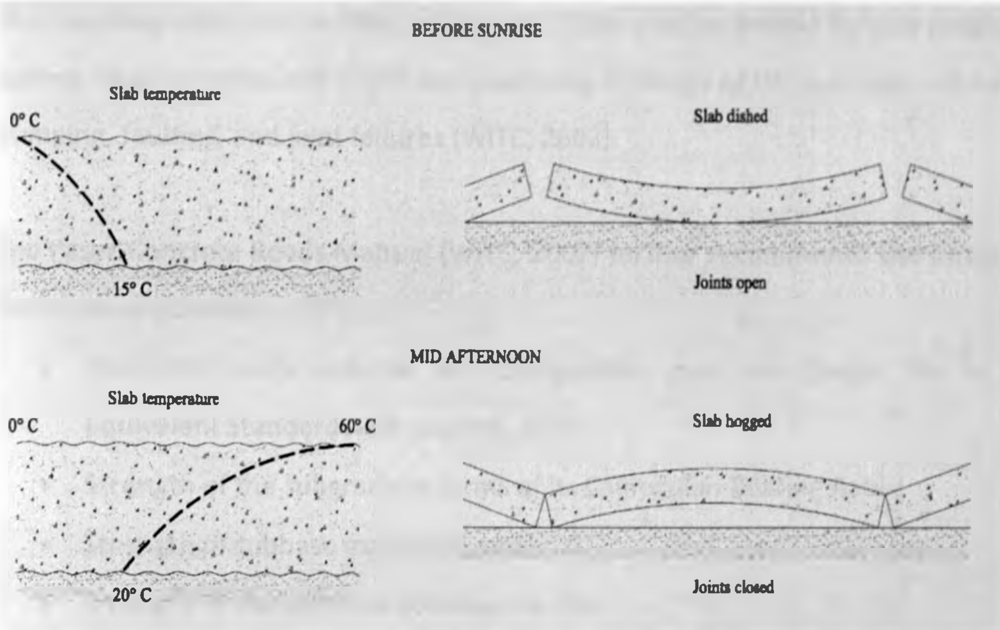


Figure 2.1: effects of temperature variations on concrete pavements

Three concrete pavements types are:

- Jointed Unreinforced Concrete Pavement (JUCP)
- Jointed Reinforced Concrete Pavement (JRCP) and
- Continuously Reinforced Concrete Pavement (CRCP)

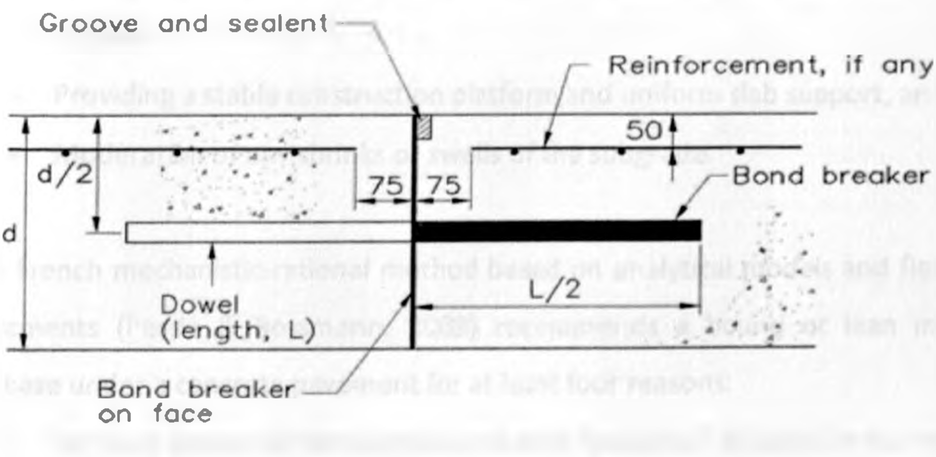


Fig. 2.2: Dowel Joint (Perrie & Rossmann, 2009)

Unsupported slab edges will deflect or bend under a load. If the supporting soil is saturated it can squeeze up through joints or cracks when the slab bends. This is called pumping. Eventually the loss of supporting soil through pumping creates voids under the slab. The slabs may then crack further under loads and result in further joint deterioration. Pumping can be detected by soil stains around pavement joints or cracks. The resulting voids can be filled with grout. Slabs can be leveled by slab jacking or mud jacking. Sealing cracks and joints and improving drainage of the sub-soils will help reduce pumping, faulting, and joint failures (WITC, 2002).

The Paser Concrete Roads Manual (WITC, 2002) further recommends the design method based on assessments of the:

- Predicted traffic volume and composition over the design life in terms of Equivalent Standard Axle Loading, ESAL;
- Strength of the subgrade in terms of its Californian Bearing Ratio;
- Strength of subbase materials; and
- Strength of the concrete forming the slab.

The structure of concrete pavements is shown in Figures 2.3 and 2.4. The foundation consists of the roadbed and, if the roadbed is weak (CBR < 15), a capping layer comprising selected fill is required which serves to protect the subgrade during the construction period (M.O.R. & P.W, 1988). The functions of the subbase include the following:

- Acting as a free-draining layer and prevent 'pumping' of water at joints and edges of slabs.
- Providing a stable construction platform and uniform slab support, and
- Moderation of any shrinks or swells of the subgrade.

The French mechanistic-rational method based on analytical models and field testing of pavements (Perrie & Rossmann, 2009) recommends a bound or lean mix concrete subbase under a concrete pavement for at least four reasons:

- To resist erosion of the subbase and limit "pumping" at joints or slab edges;

- To provide uniform support under the concrete pavement;
- To reduce deflection at joints and enhance load transfer across joints;
- To assist in the control of shrinkage and swelling of subgrade soils.

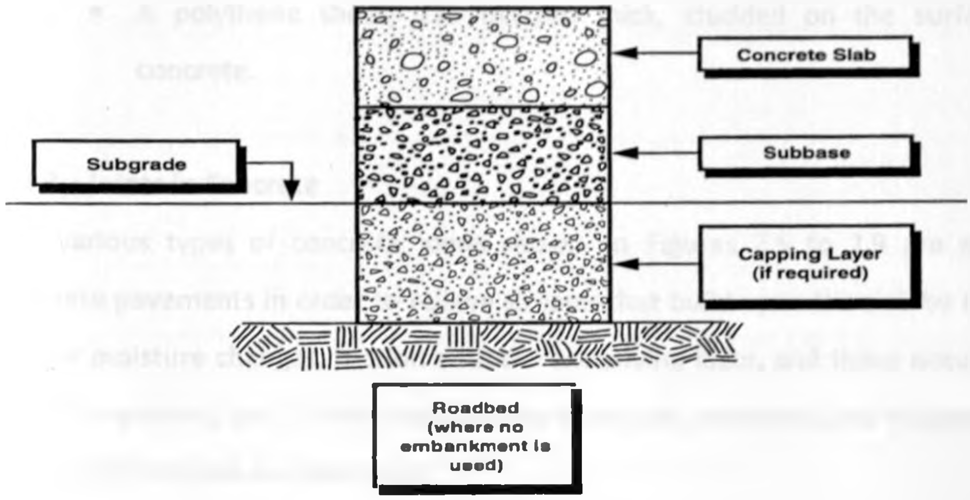
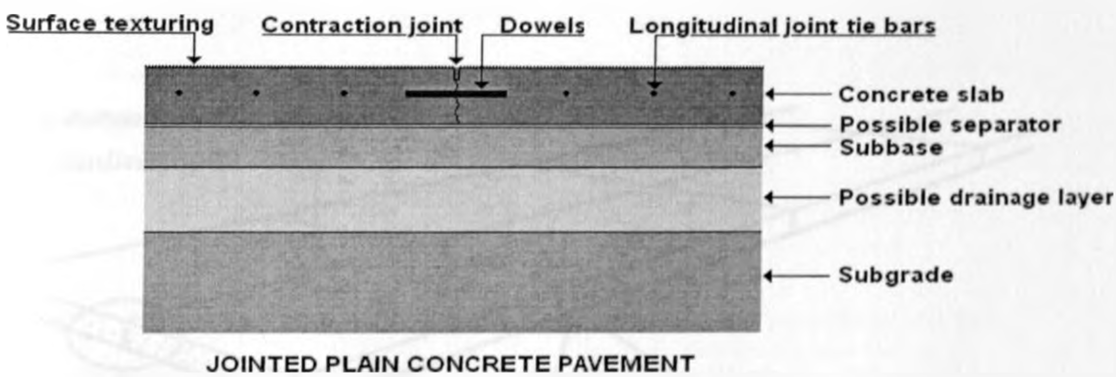


Fig. 2.3: The structure of concrete pavements



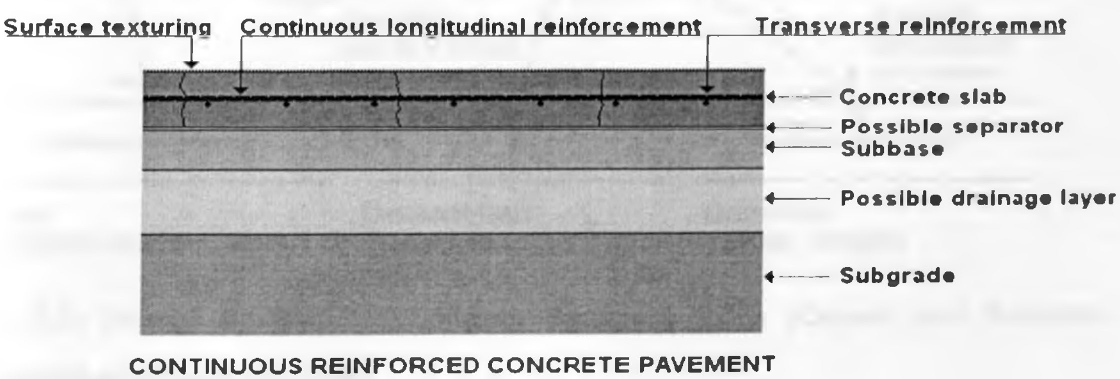


Fig. 2.4: The structure of concrete pavements (Perrie & Rossmann, 2009)

In the French mechanistic-rational method, a separator is installed to prevent the reflection of shrinkage cracks developed from the subbase to the surface. This separator can be either:

- A bitumen emulsion powdered with a little fine sand or
- A polythene sheet, 125 microns thick, studded on the surface of lean concrete.

2.3.3. Joints in Concrete

The various types of concrete joints shown on Figures 2.5 to 2.9 are necessary in concrete pavements in order to relieve stresses that build up in the slab by temperature and/or moisture changes, friction with the underlying layer, and those necessary at the end of a working day. In directional terms there are transverse and longitudinal joints and four joint types are fabricated:

- Contraction and Expansion joints
- Warping joints
- Construction joints

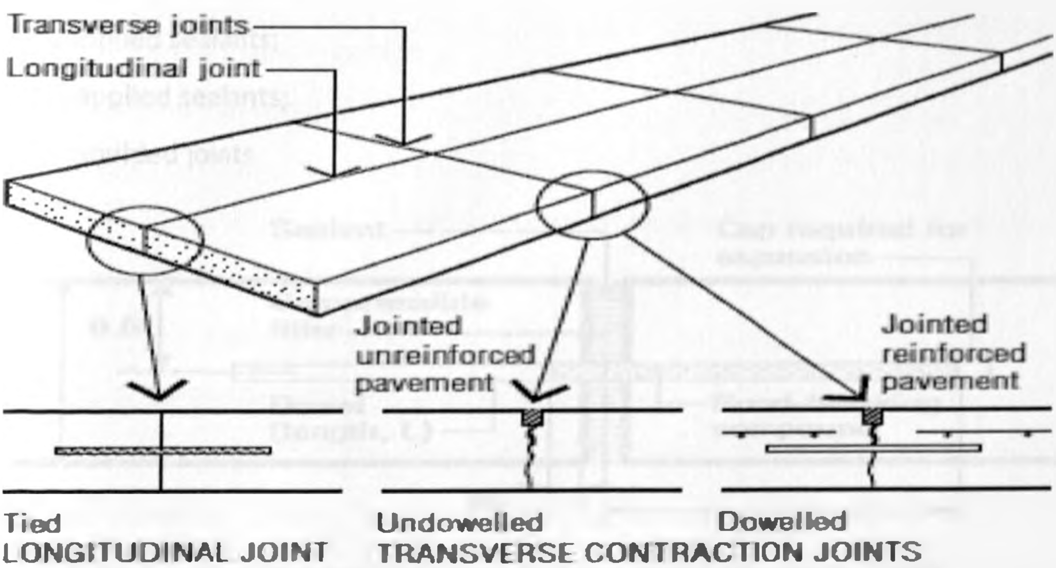


Fig 2.5: Jointed Unreinforced Concrete Pavement joints (Cement and Concrete Association of Australia, 2004)

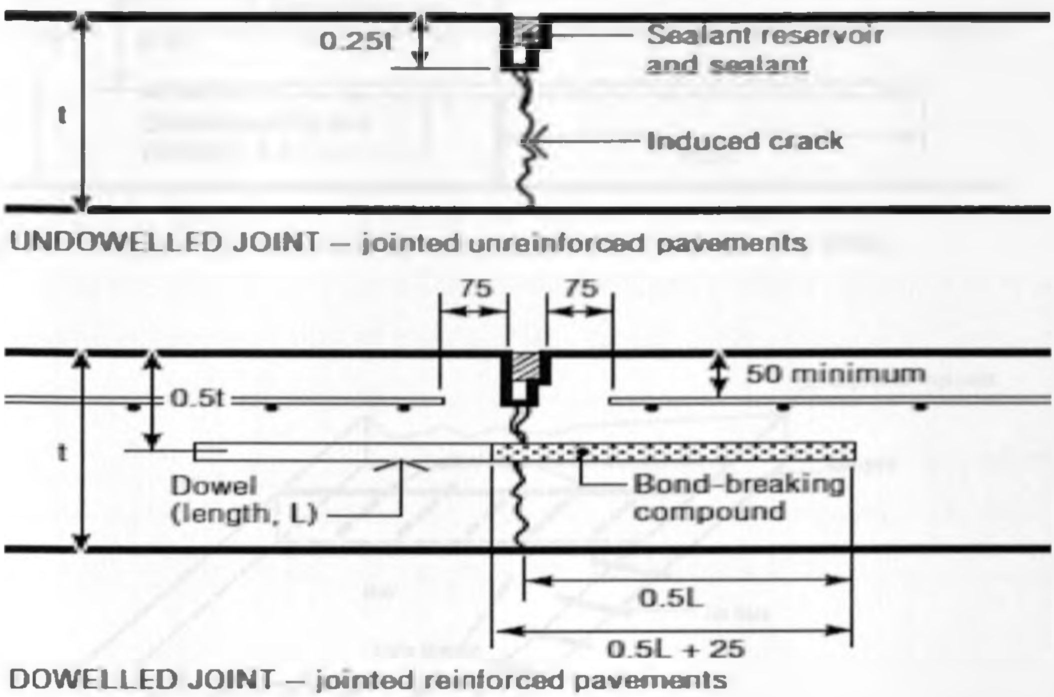


Fig 2.6: Dowelled and un-dowelled Concrete Pavement Joints (Cement and Concrete Association of Australia, 2004)

Transverse and longitudinal joints must be sealed with any of the following products in order to be waterproof:

- Hot applied sealants;
- Cold applied sealants;
- Pre-moulded joints.

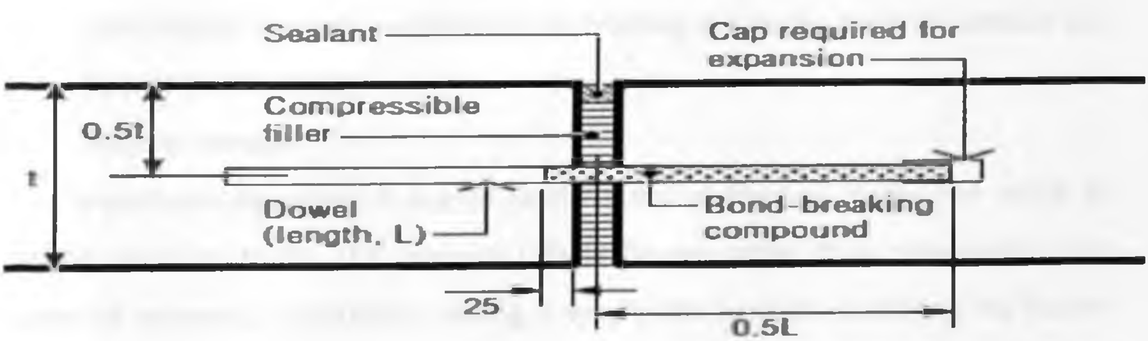


Fig 2.7: Joint sealing (Cement and Concrete Association of Australia, 2004)

Transverse joints are installed with dowel bars and longitudinal joints with tie bars as illustrated in Figures 2.6, 2.7 and 2.8.

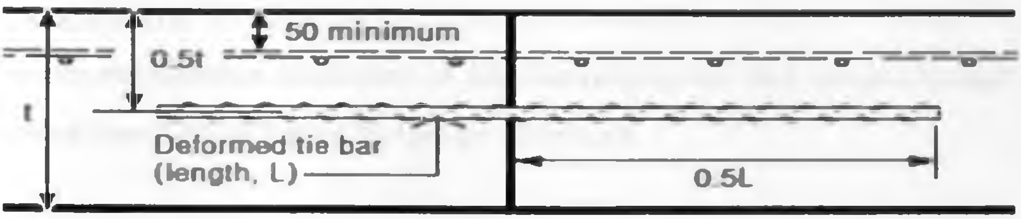


Fig. 2.8: Tied joint (Cement and Concrete Association of Australia, 2004)

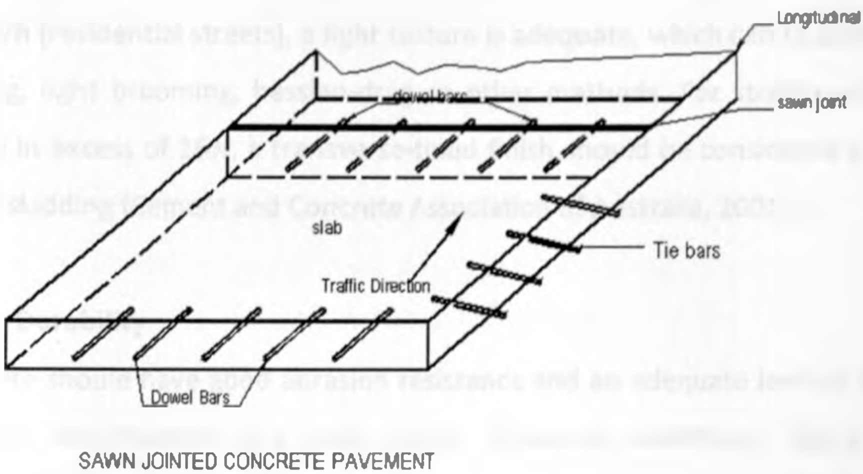


Fig. 2.9: Dowel and tie bars

2.3.4. Technical issues in concrete

A. Concrete strength

The strength of concrete used in pavements is usually specified in one of two ways:

i. Compressive strength —measured by crushing a cylinder along its vertical axis (test KS 02-595-1986).

ii. Flexural strength

When a concrete pavement is loaded to the point of fracture, under the action of wheeled vehicular traffic, the concrete fails in flexure rather than compression. For reasons of economy, compression testing is usually the basis for specifying the flexure requirement (Cement and Concrete Association of Australia, 2001). Compressive strength can be converted to flexural strength using Equation 1.

$$Flexural\ strength\ (MPa) = c\ x\ \sqrt{Compressive\ strength}$$ ....Equation 1

Where, c ≈ 0.75.

Cement and Concrete Association of Australia recommend that Flexural Strength values ranging from 3.8 to 4.5 after 28 days are acceptable.

B. Skid resistance

Aggregate surfaces generally have a lower skid resistance compared with mortar surfaces containing a high percentage of silica sand. For streets subject to traffic at speeds up to 70 km/h (residential streets), a light texture is adequate, which can be achieved by wood floating, light brooming, hessian-drag or other methods. For streets with longitudinal grades in excess of 16%, a transverse-tined finish should be considered to minimise the risk of skidding (Cement and Concrete Association of Australia, 2001).

C. Durability

Concrete should have good abrasion resistance and an adequate level of impermeability to resist deterioration and wear under in-service conditions. Taking measures to maximise the design strength of the concrete will also improve its durability. These include:

i. Use of good quality concrete;
ii. Proper placing and compaction, and
iii. Proper curing (starting immediately after the concrete has been finished).

D. Workability

Workability is measured using the slump cone test (KS 02-595-1986). To control workability the tendency is always to increase the added water but it is crucial to keep the water to cement ratio below 0.5 otherwise the concrete will have insufficient strength and durability.

E. Quality of materials for concrete production

Materials for concrete production need to conform to the following standards.

- Cement: The cement should conform to KS EAS 18-1.
- Water: The water used for concrete preparation should be potable and should ideally conform to the requirements of BS EN 1008.

- Aggregate: The quality of aggregates for concrete production should conform to KS 95 2003.

F. Construction practices

Placement, compaction, finishing and curing of concrete have a major influence on its strength and durability. The importance of compaction, finishing and curing in particular are often overlooked. Thorough compaction (by surface and/or immersion vibrators) particularly around reinforcement and in the corners of formwork minimises the number of air voids in the hardened concrete hence optimising concrete strength and reducing the risk of corrosion of reinforcement and spalling of the concrete. The strength of concrete falls rapidly as the number of air voids increases. For example a 2% reduction below maximum density reduces the strength by about 10%. If concrete contains 5% of air voids, its strength is likely to be about 30% below that of fully compacted concrete (Cement and Concrete Association of Australia, 2001).

G. Curing methods

Curing methods can be split into two groups:

i. those that offset water loss, for example continuous fine water spraying; or
ii. those that control water loss from the concrete by sealing the surface, for example covering with plastic sheeting or coating the concrete with a membrane curing compound (such as a water-based or wax emulsion, which can be brushed, sprayed or rolled onto the surface of the pavement).

H. Putting the concrete pavement into service

Unlike other paving materials, the rate of strength gain of concrete is time-dependent and it must be protected from traffic until adequate strength has been achieved to resist the imposed load stresses. As a general rule the pavement should not be trafficked until it has gained 60% of its specified 28-day thickness-design strength; usually seven days after placing. If earlier trafficking is necessary the specified strength grade of the concrete could be increased, and a variety of techniques can be used to attain the necessary strength in the required time. These include accelerators, thermal curing, use of hot water and vacuum de-watering (Cement and Concrete Association of Australia, 2001).

2.4. Pavement Modeling

Two basic approaches have been used to calculate deflection of rigid pavement namely elastic layered theory and plate theories. In each of these theories, researchers have developed certain models to meet specific requirements of the pavement systems being evaluated. Finite element, finite difference and other numerical analysis techniques have been applied to both of the above procedures, for the analysis of rigid pavements.

Elastic theory is a unified approach that can be applied for both flexible and rigid pavements as opposed to plate theories which can only be applied for rigid pavements. The use of plate load test to determine composite k value is possible and has been conducted by Portland Cement Association, PCA and AASHTO using full-scale tests. However, this approach has obvious limitations in practical applications, such as the high cost and the long time required (Bagus, 2009). Elastic theories will be used in this research and be discussed in the proceeding section.

2.4.1. Elastic-Layered Theory

In the elastic-layered theory, the term "elastic " means that the stiffness of the layer is independent of the rate at which the load is applied and is constant throughout a range of load magnitude. Again in this theory the soil is assumed to be an elastic, isotropic, semi-infinite body. In a layered linear elastic model of a pavement, each layer is characterized by its Young's modulus of elasticity, E, and Poisson's ratio, μ. Reasonable values of Poisson's ratio are assumed for different pavement materials, and these are generally within a narrow range. The majority of works, which treats the subgrade as a semi-infinite, elastic half-space uses axisymmetric models. Hence it can be only used for the interior loading case i.e., the applied load is away from the pavement edge (Mehta, 1990).

Boussinesq Circa in 1885 did the first work assuming the characterization of supporting layers in pavement system as elastic solids through the assumption of the soil to be linearly elastic, isotropic, homogeneous solid of infinite extent in both horizontal directions. Boussinesq considered the case of an elastic, isotropic, homogenous and infinite half pace with the assumption that elastic properties are identical in every direction under uniform circular loading (Gichaga & Parker, 1988). Equations 2 and 3 show the stress relationships as considered by Boussinesq.

$б_z = P \{1 - z^3 / (a^2 + z^2)^{3/2}\}$ ....Equation 2

$б_x = б_y = P/2 \{(1 + 2\mu) - 2(1 + \mu)/ (a^2 + z^2)^{1/2} + z^3 / (a^2 + z^2)^{3/2}$ ....Equation 3

Where;

P = Applied surface pressure

$б_x = б_y$ = Horizontal stress on vertical axis of loading

$б_z$ = Vertical stress along the vertical axis of loading

a = Radius of applied circle of loading

z = Distance of the point from the surface

μ = Poisson's ratio

In the mid-1940's Burmister applied the elastic solids concept of Boussinesq to two and three layer systems for the analysis of stresses and deflections in flexible pavements. In his work, Burmister found that stiff upper layers reduce stresses and deflections in the subgrade from those predicted by Boussinesq. This reduction is proportional to the ratio of the elastic moduli (Mehta, 1990). Deflections are derived using Equation 4.

$\Delta = 1.5pa\, F_w / E_2$ ....Equation 4

Where;

Δ = Vertical deflection in inches

P = Intensity of applied loading or the contact pressure

A = Radius of circular area of loading

E1 = Modulus of elasticity of the top layer of the pavement structure

E2 = Modulus of elasticity of the lower layer of the pavement structure

Fw = Displacement factor which depends on the thickness of the top layer and the ratio E_1/E_2 (Ranges from 0.02 to 1.0 for ratios of E_1/E_2 between about 10000 and 2 respectively).

The following assumptions were taken into account (Burmister, 1943; 1945a):

i. Each layer is homogenous, isotropic, and linearly elastic with an elastic modulus E and a Poisson ratio μ;
ii. The surface layer is weightless and infinite in extent in the horizontal direction, but finite in vertical direction. The subgrade is infinite in extent in both horizontal and vertical directions;
iii. The surface layer should be free of shearing stress and normal stress beyond the surface loading. The subgrade should be free of stress and displacement at infinite depth; and
iv. Continuity conditions at layer interfaces are satisfied.

Rosy software and MS excel were utilized for this research and have been detailed in Appendix IV. In this computer program, the values of moduli for the pavement layers are inputed and the program calculates a deflection basin. The calculated deflection basin is compared with the deflection basin measured by the Non Destructive Testing equipment and the moduli values resulting from the best fit between the calculated and measured deflection basins are assumed to be the correct in-situ moduli values for that pavement.

<u>Strengths on Elastic Layered Theory</u>

i. Through the use of elastic-layered computer programs, it is possible to characterize the pavement as a multi-layered system which is a more realistic representation of the pavement system and the use of a composite subgrade modulus, k, employed with plate theory.
ii. Elastic-layered theory is the single, unifying procedure which is best suited for both flexible and rigid pavement design and pavement evaluation philosophies.
iii. The characterization of the pavement materials with fundamental properties, which may be verified in the laboratory, is an added advantage over the reliance on a single, field determined modulus.

Despite the several strengths exhibited by elastic-layered theories, it is not possible to analyse joints. Mehta also found that the theory is not applicable for pavement evaluation under edge or corner loadings.

2.4.2. Computation of Stresses in concrete pavements

The works of Harold Malcom Westergaard between 1888 to 1950 has been at the heart of slab-on-grade pavement design since 1920s. Westergaard equations are available for interior, edge and corner regions with the assumption of infinite or semi-infinite slab dimensions. The solutions for interior stresses by Westergaard and other researchers have been given in the literature below.

A. Solutions for Interior stress

Westergaard assumed uniform distribution of pressure over the area of a small circle of radius, a. (Westergaard, 1926). Ioannides, Thompson and Berenberg modified Westergaard's equations to account for the effect of finite size of the loaded area and is satisfactorily applicable when a < l^{π} (Ioannides et al, 1984). Further research by Scott (Scott, 1981) recommends the use of ordinary theory as opposed to special theory.

Maximum bending stress and deflections by ordinary Westergaard theory is given by Equations 5 and 6;

$$\text{Stress, } \sigma_i = \left\{ \frac{[\,3P\,(1+\mu)\,]}{2\pi h^2} \right\} \left(\ln \frac{2l}{a} + 0.5 - \tau \right) + \left\{ \frac{[\,3P\,(1+\mu)\,]}{64\pi h^2} \right\} [\,(\,l/a\,)^2\,] \text{ ....Equation 5}$$

$$\text{Maximum deflection, } \delta_i = \left(\frac{P}{8kl^2} \right) \left\{ 1 + \left(\frac{1}{2\pi} \right) \left[\ln\left(\frac{a}{2l} \right) + \tau - \frac{5}{4} \right] \left(\frac{a}{2l} \right)^2 \right\} \text{ ....Equation 6}$$

Where;

P = Total applied loading

E = Young's modulus of concrete slab

μ = Poisson's ratio of concrete slab.

h = Concrete slab thickness.

k = modulus of subgrade reaction

a = Radius of circular load.

l = radius of relative stiffness give by $l = \left\{ \frac{Eh^3}{[12(1-\mu^2)k]} \right\}^{1/4}$ ....Equation 7

ɩ = Euler's Constant (ɩ = 0.577 215 664 90)

Ioannides, Thompson and Berenberg further observed that Westergaard's equations agree with finite element results for a loaded area whore radius, a is 0.1 times the radius of relative stiffness. As a/l increase, finite element stresses become progressively higher than Westergaard's.

B. Slab size requirements for Westergaard responses based on Finite Element Method.

Ioannides, Thompson and Berenberg proposed slab size ratio of at least 5.0 for infinite slab deflections and 3.5 for infinite bending stress. Their conclusions are summarised in Table. 2.16.

Table 2.16: Slab size requirements for Westergaard responses

Load Placement	**L/l Values for**	
	Maximum deflection	**Maximum bending stress**
Interior	8.0	3.5
Edge	8.0	5.0
Corner	5.0	4.0

Legend:

L=Least slab dimension l=radius of relative stiffness.

(Source: Ioannides et al, 1984)

2.4.3. Backcalculation of in-situ elastic modulus

One method of identifying the failure of a pavement structure before the end of its designed life (generally attributed due to the loss of strength in one or more layers in the pavements system) is to evaluate material properties of existing in-service pavement. This is achieved by recording the pavement's deflection under several magnitudes of loading on the surface, and then using this deflection data to predict in-situ layer stiffnesses.

Rosy software and MS excel analysis model has been proposed for use in back calculation of two essential parameters of the pavement system:

i. Modulus of elasticity of the top layer and
ii. Modulus of elasticity of subgrade.

The back calculated moduli, are then used to compare predicted pavement deflections with measured deflections. The moduli values that result in the best fit between the predicted and the measured deflection are assumed to be correct in-situ moduli values for that pavement system.

2.4.4. Regression Model

Simple Regression is often used by researchers to determine an equation which will predict a desired dependent variable. The accuracy of the equation to estimate the dependent variable is indicated by the coefficient of determination, R^2. If R^2 is large (close to one), most of the variability is accounted for by the relationship. If R^2 is close to zero, the regression equation does not represent the relationship. The R^2 statistic is often the most meaningful statistics that can be computed, since it gives a measure of the usefulness of the prediction (Mehta, 1990).

The use of regression method to backcalculate k value allows almost instantaneous computation of the moduli once the measured deflections are known (Fwa and Chandrasegaran, 2001; Harichandran et al., 1994).

2.4.5. Similar studies on Evaluation of concrete pavements

Fwa and Chandrasegaran (2001) backcalculated the radius of relative stiffness (*l*) based on the dimensionless ratios of measured deflections at different points of the deflection basins. Having computed *l*, the k value was determined as a function of *l*, the measured deflections, and the applied load, P using the relationships in Equation 8.

$l = f_1 (d_1, d_2, d_3, d_4, d_5, d_6, d_7)$

$k = f_2 (l, P, d_1, d_2, d_3, d_4, d_5, d_6, d_7)$ ....Equation 8

Where;

d_1, d_2, d_3, d_4, d_5, d_6 and d_7 are the measured deflections at radial distances of 0, 300, 600, 900, 1200, 1500 and 1800 mm respectively from the center of loading.

Other studies on rigid pavement evaluation through condition surveys and use of deflections measurements were conducted by: Mehta (1990), Scott (1981), Berenberg & Ioannides (1989), Bagus (2009), Bulman & Smith (1977) Harichandran et. al (1994) and Gunter (2009). The use of equation 8 is widely agreed among the researchers and will be explored in this research.

2.4.6. Conclusion on literature review

Regressions should be performed on the maximum central deflection data obtained from the fieldwork at Mbagathi Road to enable backcalculation of in-situ moduli as was carried out by Mehta (1990) and other researchers discussed in section 2.4.4. Using stress relationships in section 2.4.2, interior stresses and deflections can be calculated and compared to the collected deflection data.

<u>Gaps in theory</u>

The analysis of deflection measurements based on elastic layer theory for edge and corner loadings is not proven and hence was not carried out in this research.

CHAPTER 3

METHODOLOGY

3.1. Introduction

The methodology that was employed in this research was based on the following objectives:

i. Assessment of structural strength of the pavement
ii. Assessment of existing traffic loading on Mbagathi Way
iii. Evaluation of deflections on the road

3.2. Data Collection

Data collection was accomplished through conducting site visits over the entire period of the research in order to collect relevant data. The site visit concentrated on, among other things, the following topics;

i. Determination of traffic loading on Mbagathi road was done by conducting traffic counts of at two locations on Mbagathi Road. Classified traffic counts were performed at two sections of Mbagathi road for between 12th and 18th March 2012 at the overhead bridge at chainage 1200m and next to Mbagathi Mosque at chainage 2350m. Traffic counts were limited to commercial traffic only. The average daily traffic was computed from the data which consisted of five day 12-hr count and two day 24-hr counts on 14th March 2012 and 17th March 2012. The 12-hr counts were converted to 24-hr counts. Traffic counts were based on the methodology provided by Overseas Road Note 40 (TRL, 2004).

   Traffic data were converted into equivalent standard axles using legal limits of vehicle equivalence factors in Kenya. Cumulative ESA was based on the average GDP growth rate between 1961 and 2010. Traffic data was analysed for 15 years remaining life of the road as designed assuming that 80% of the commercial vehicles use slow traffic (outer) lanes.

ii. Non-destructive concrete strength tests using ultrasonic testing equipment. Ultrasonic tests were conducted in January 2012 on sections of Mbagathi Road where cracking was observed to determine the depths of cracks and hence homogeneity of concrete pavement slabs. The methodology for homogeneity testing is detailed in Appendix I.

iii. Falling Weight Deflectometer (FWD) testing of concrete slabs on both directions over the entire length of Mbagathi road at 100m intervals. FWD measurements were carried out on 30th January 2012. The methodology for carrying out deflection measurements using FWD is described in Section 2.2.3.

iv. Pavement Condition Survey of Mbagathi Road was performed in November 2011, January 2012 and March 2012. The methodology for pavement condition survey is based on a unified approach encompassing the South African and Kenyan practice as detailed in section 2.2.2. Appendix II describes the methodology for the determination of determining present serviceability ratings.

3.3. Expected outputs from the research

i. Pavement Condition Index – The pavement condition index (PCI) is a numerical value that represents the surface condition of the pavement. It was used in this study to measure the structural performance of the concrete pavement. The PCI can range from 0-100, with 0 being the worst score (failed), and 100 being the best score (good). (ASTM Standard D6433, 2003 & ASTM Standard D6433, 2007).

   Table 3.1 shows the range of PCI values based on ASTM D6433 Pavement Condition Index (PCI) Rating Scale for 2003 and 2007 versions. Mbagathi Road will be rated on this scale.

ii. The graphical relationship between PCI and ESALs at the 2 chosen points along Mbagathi Way. In his research, Gunter found that PCI has an inverse relationship to stress (Gunter, 2009).

iii. Values of initial pavement deflections of Mbagathi Road that will be useful for further research on the relationship between various pavement strength parameters and concrete pavement deflections.

- Elastic Modulus of the concrete pavement layers, E.
- Modulus of Subgrade Reaction, k
- Load Transfer at Cracks and Joints and
- Potential for the presence of voids beneath the surface of concrete slabs.

Table 3.1: ASTM D6433 Pavement Condition Index (PCI) Rating Scale for 2003 and 2007 versions.

Rating	ASTM D6433-2003	ASTM D6433-2007
85-100	Excellent	Good
70-85	Very good	Satisfactory
55-70	Good	Fair
40-55	Fair	Poor
25-40	Poor	Very poor
10-25	Very poor	Serious
0-10	Failed	Failed

Adopted from ASTM Standard D6433, 2003 and ASTM Standard D6433, 2007.

3.4. Existing pavement structure

The existing pavement structure is shown in Appendix III showing road cross sections and details at different chainages.

CHAPTER 4

RESULTS AND ANALYSIS

4.1. Measurement of Pavement Deflections.

The average drop time during deflection testing was 912 micro seconds at an average air temperature of 28^{0}C and surface temperature of 22^{0}C. The average applied pressure during testing was 700KPa and normalised to 707KPa for ease of analysis of the observed deflections. The average FWD deflections for the entire testing are summarised in Figure 4.1 for each geophone and detailed in Appendix IV.

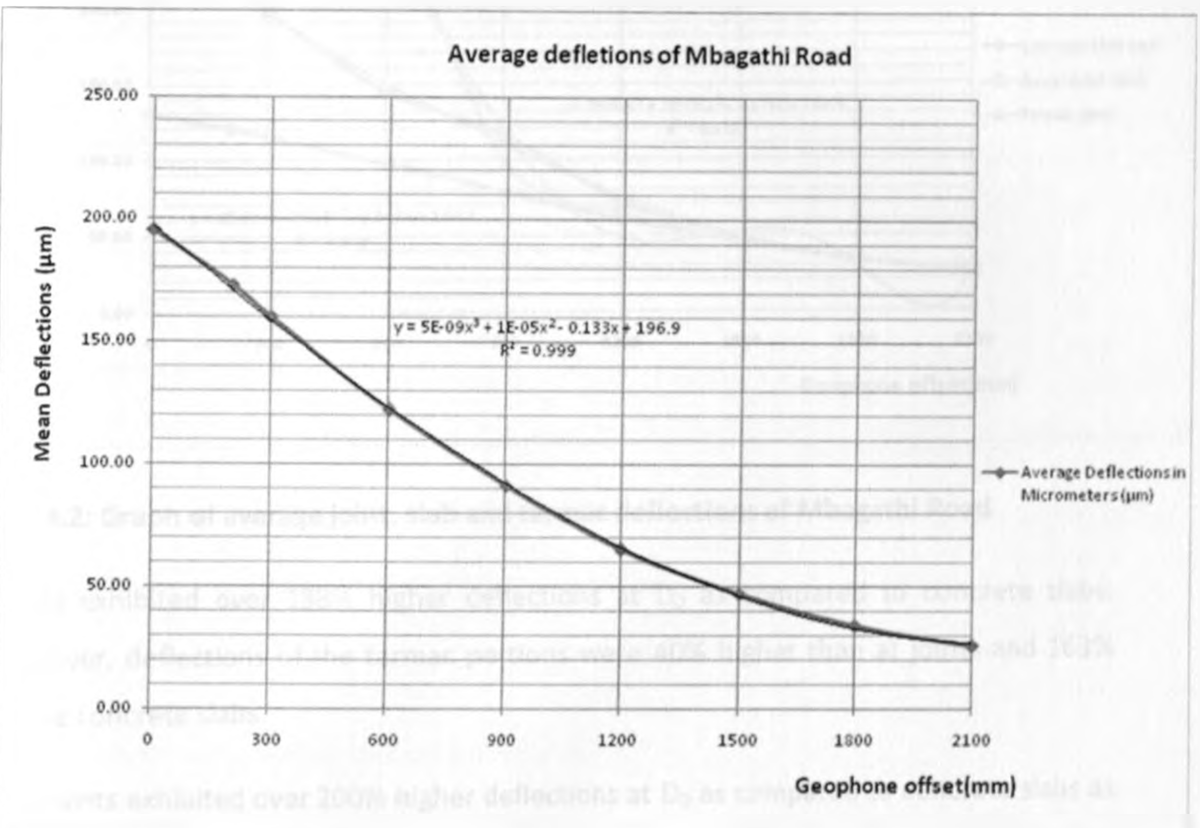


Fig. 4.1: Average FWD deflections of Mbagathi Road

4.1.1. Joint and Slab Deflections

Figures 4.2 summarises slab and joint deflections for concrete and tarmac sections tested on Mbagathi Road. Average deflections shown in Figure 4.2 represent the deflections for different chainages for both directions of testing and averaged for each geophone. Lines of best fit are indicated with the equation of the curve and the goodness of fit (R^2).

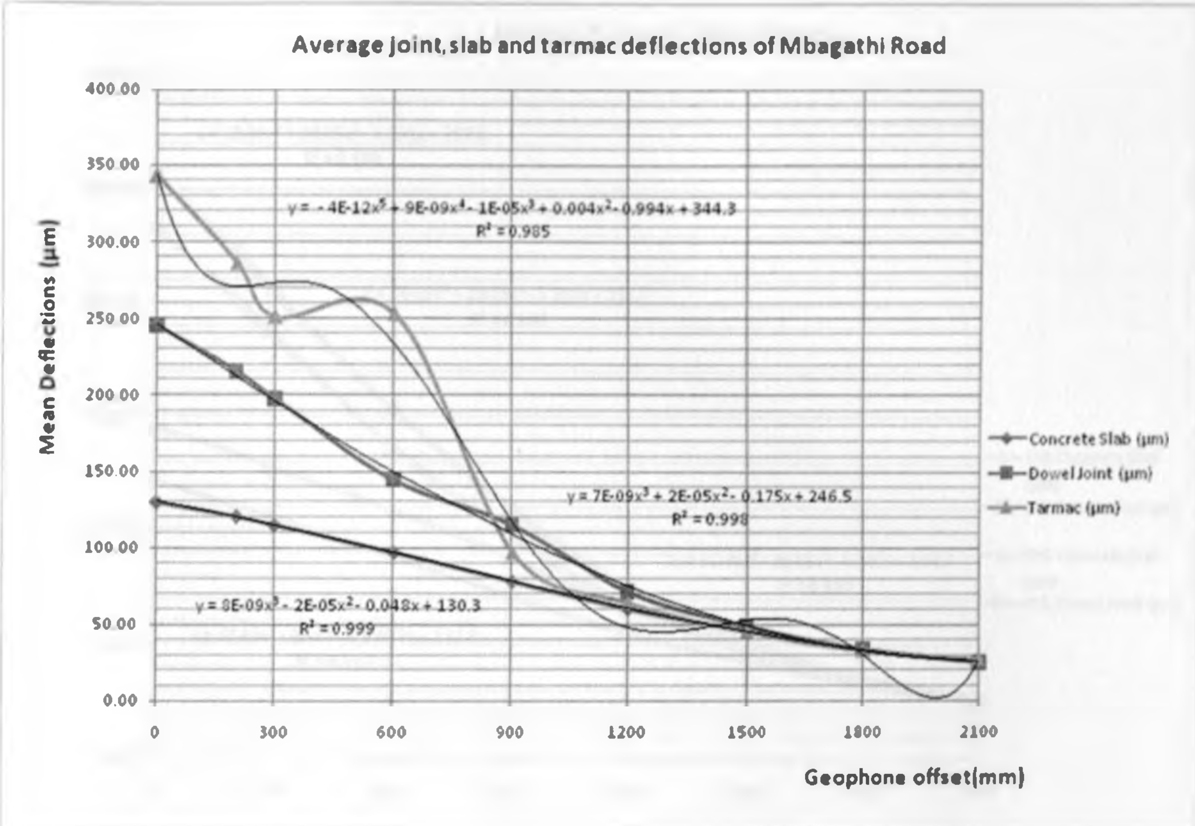


Fig. 4.2: Graph of average joint, slab and tarmac deflections of Mbagathi Road

Joints exhibited over 188% higher deflections at D_0 as compared to concrete slabs. However, deflections of the tarmac portions were 40% higher than at joints and 163% above concrete slabs.

LHS joints exhibited over 200% higher deflections at D_0 as compared to concrete slabs as shown in Fig. 4.3. Tarmac portions recorded 30% higher deflections as compared to joints and 183% above deflections of concrete slabs. However, higher deflections were reported in chainage 660, 1756 and 2354m.

RHS joint deflections were 160% that of pavement slabs at D_0. The deflections were randomly spread across the tested areas making sectioning not possible. However, higher deflections were reported in 700, 1267 and the section between 1890 and 2100m.

The LHS slabs exhibited 20% higher deflections while joints exhibited 10% lower deflections than RHS. The average RHS and LHS Deflections on Mbagathi Road are shown graphically in Figure 4.3.

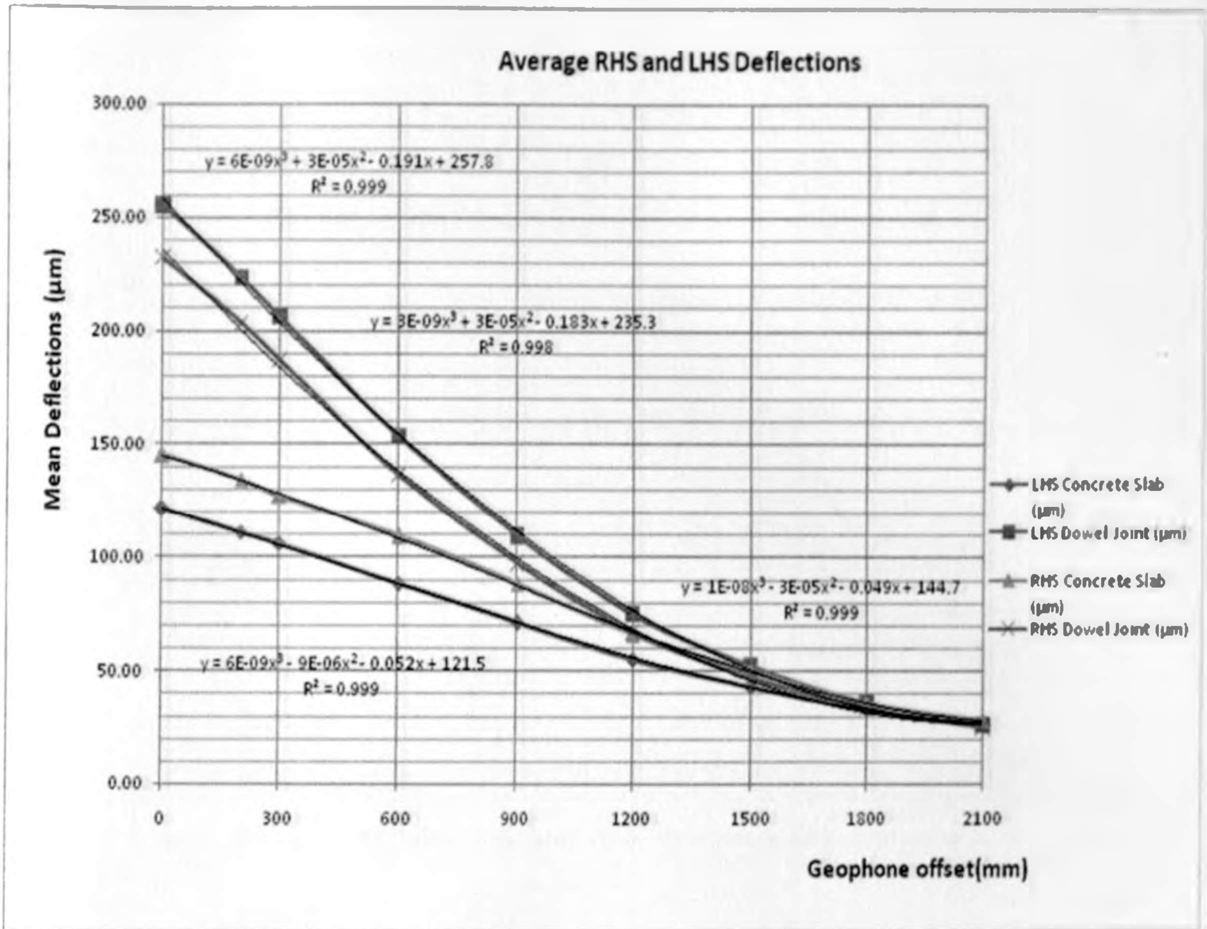


Fig. 4.3: Average RHS and LHS Deflections on Mbagathi Road

4.1.2. Analysis of Pavement Deflection Results

The analysis of pavement deflections for RHS and LHS are shown in the following Figures 4.4, 4.5, 4.6 and 4.7. The observed concrete slab deflections were within the expected range of deflections of between 20µm and 250µm and hence are normal rigid pavements. Deflection of joints was outside this range owing to end discontinuities at joints.

The LHS slabs exhibited 20% higher deflections while joints exhibited 10% lower deflections than RHS. The average RHS and LHS Deflections on Mbagathi Road are shown graphically in Figure 4.3.

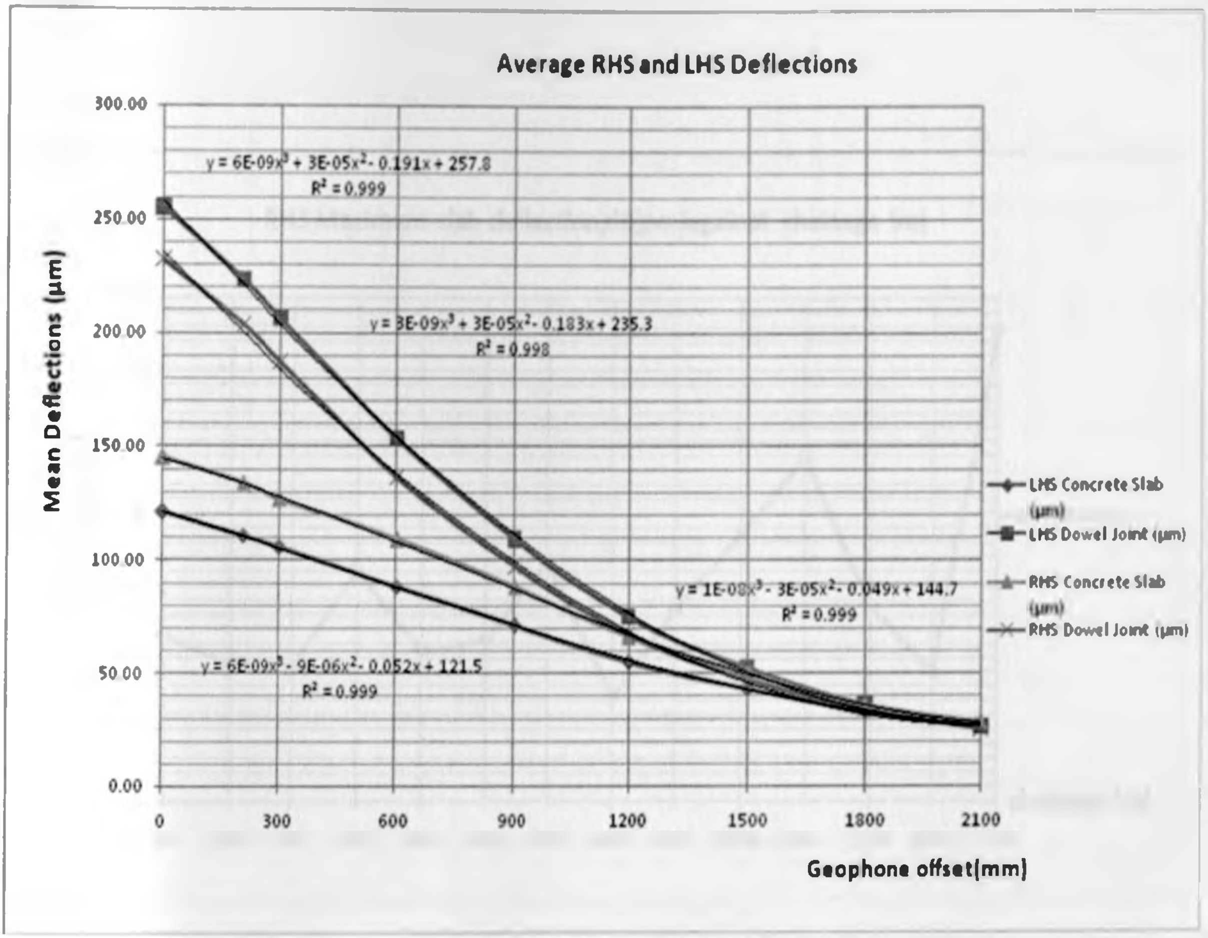


Fig. 4.3: Average RHS and LHS Deflections on Mbagathi Road

4.1.2. Analysis of Pavement Deflection Results

The analysis of pavement deflections for RHS and LHS are shown in the following Figures 4.4, 4.5, 4.6 and 4.7. The observed concrete slab deflections were within the expected range of deflections of between 20µm and 250µm and hence are normal rigid pavements. Deflection of joints was outside this range owing to end discontinuities at joints.

High RHS slab deflections were observed at chainages 700m, 1267m, the section 1700 to 2300 and at 2700m with low deflections at 500m, 1485m and 2500m. All joints exhibited deflections above 100μm with the highest at chainages 30m and the section 2400 to 3034m.

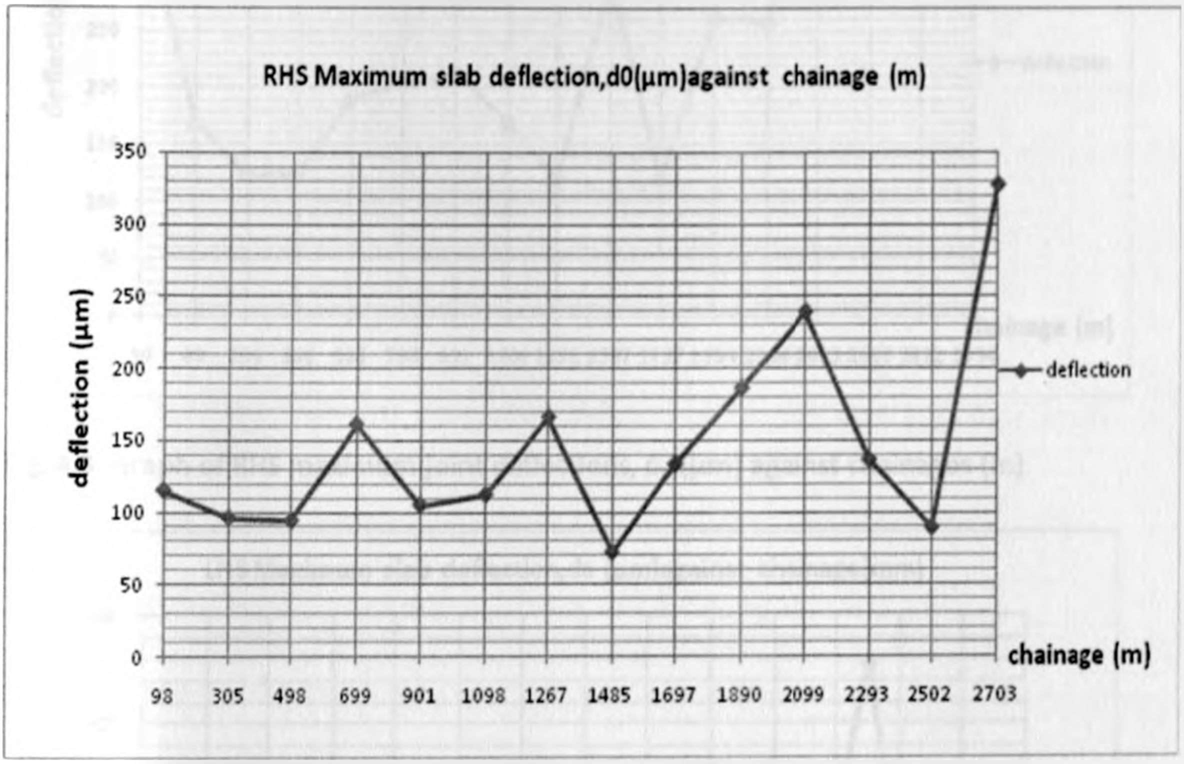


Fig. 4.4: Graph of RHS maximum slab deflections, d_o (μm) against chainages (m)

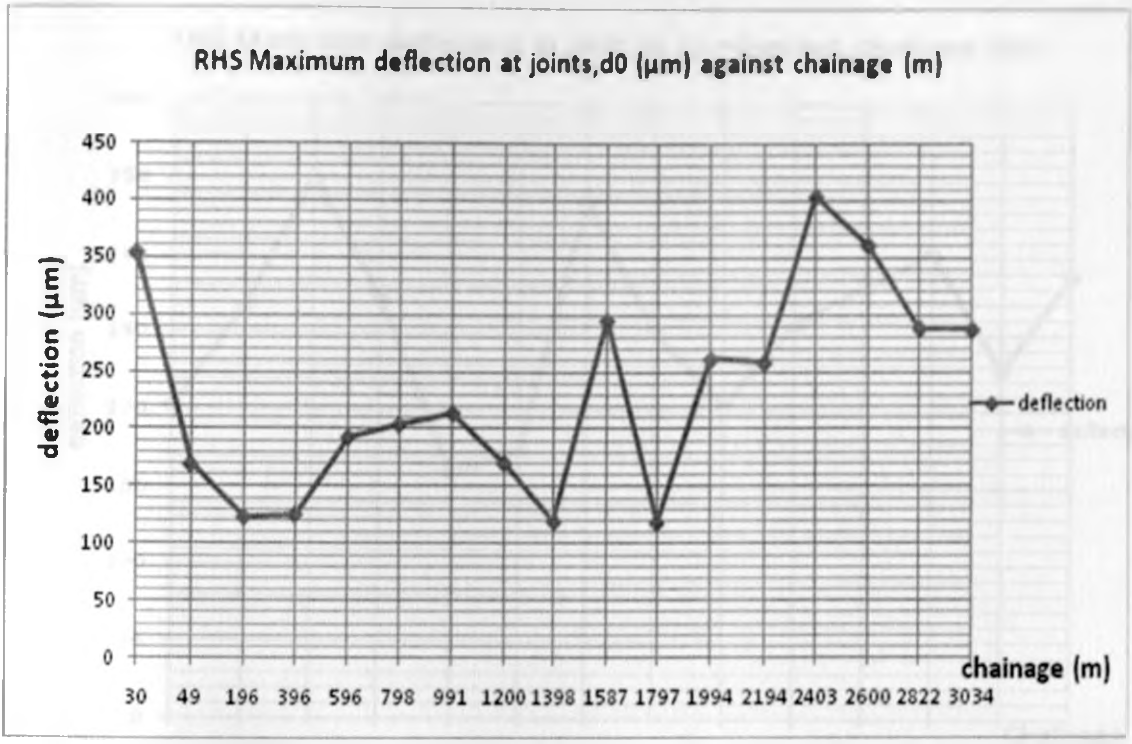


Fig. 4.5: Graph of RHS maximum joint deflections, d_o (μm) against chainages (m)

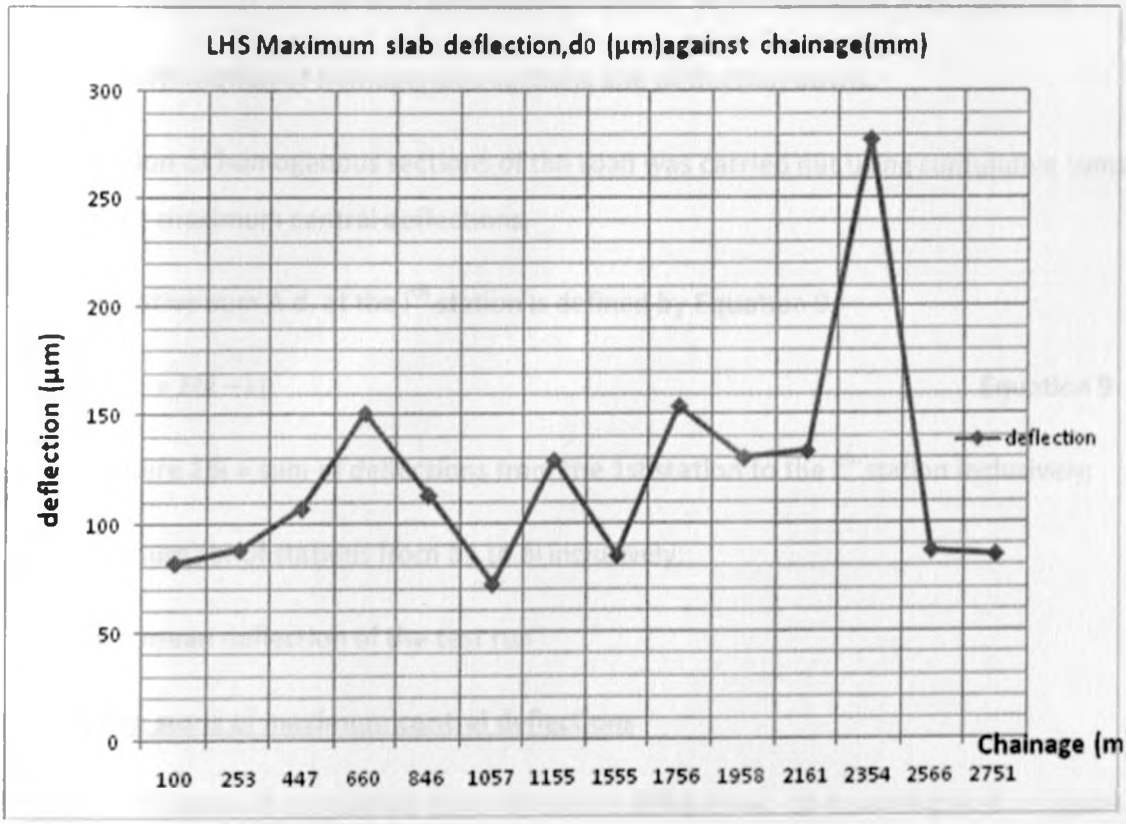


Fig. 4.6: Graph of LHS maximum slab deflections, d_o (μm) against chainages (m)

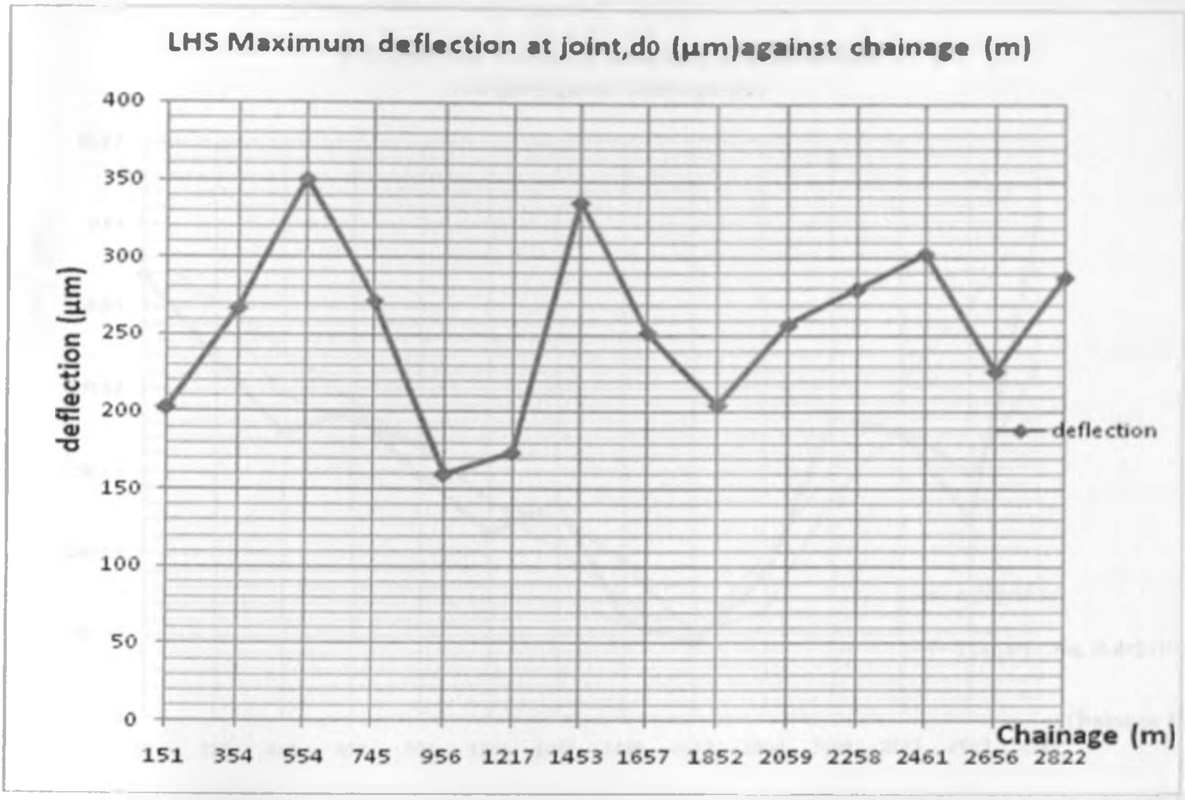


Fig. 4.7: Graph of LHS maximum deflections at joints, d_o (µm) against chainages (m)

4.1.3. Determination of homogenous sections and deflection bowls.

Identification of homogenous sections of the road was carried out using cumulative sums method for maximum central deflections.

The cumulative sum A.d. at the i^{th} station is defined by Equation 9.

A.d. = Σδi − i µ ....Equation 9

Where Σδi = sum of deflections from the 1st station to the i^{th} station inclusively;

i = number of stations from δ1 to δi inclusively;

µ = mean deflection of the test run

<u>**Cumulative sums of maximum central deflections**</u>

The determination of cumulative sums of central deflections, do is summarised in Figure 4.8 for RHS and Figure 4.9 for LHS shown below. Line of best fit with the equation of the curve and line of sectional classification are indicated.

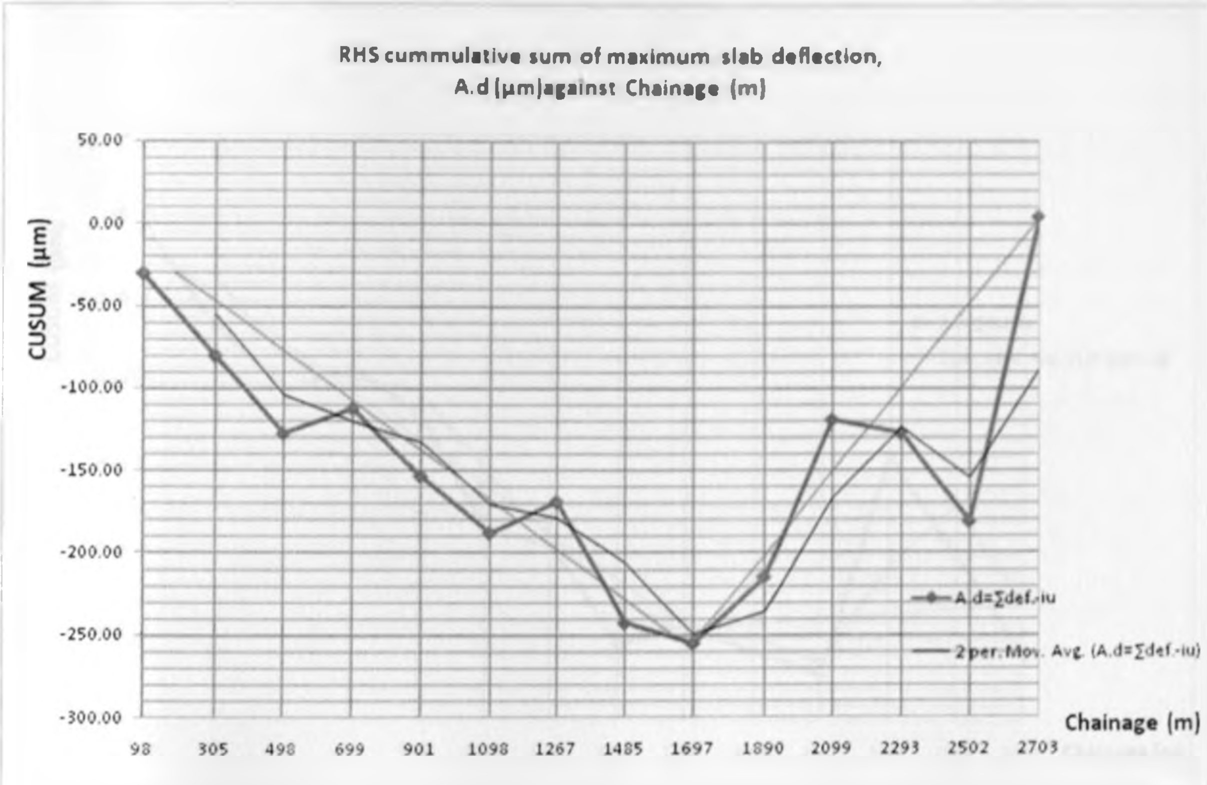


Fig. 4.8: Graph of RHS cumulative sum of maximum slab deflections (µm) against chainages (m)

The following homogenous sections were identified on the RHS:

i. Chainage 0.000m – 1697m
ii. Chainage 1697m – 2703m

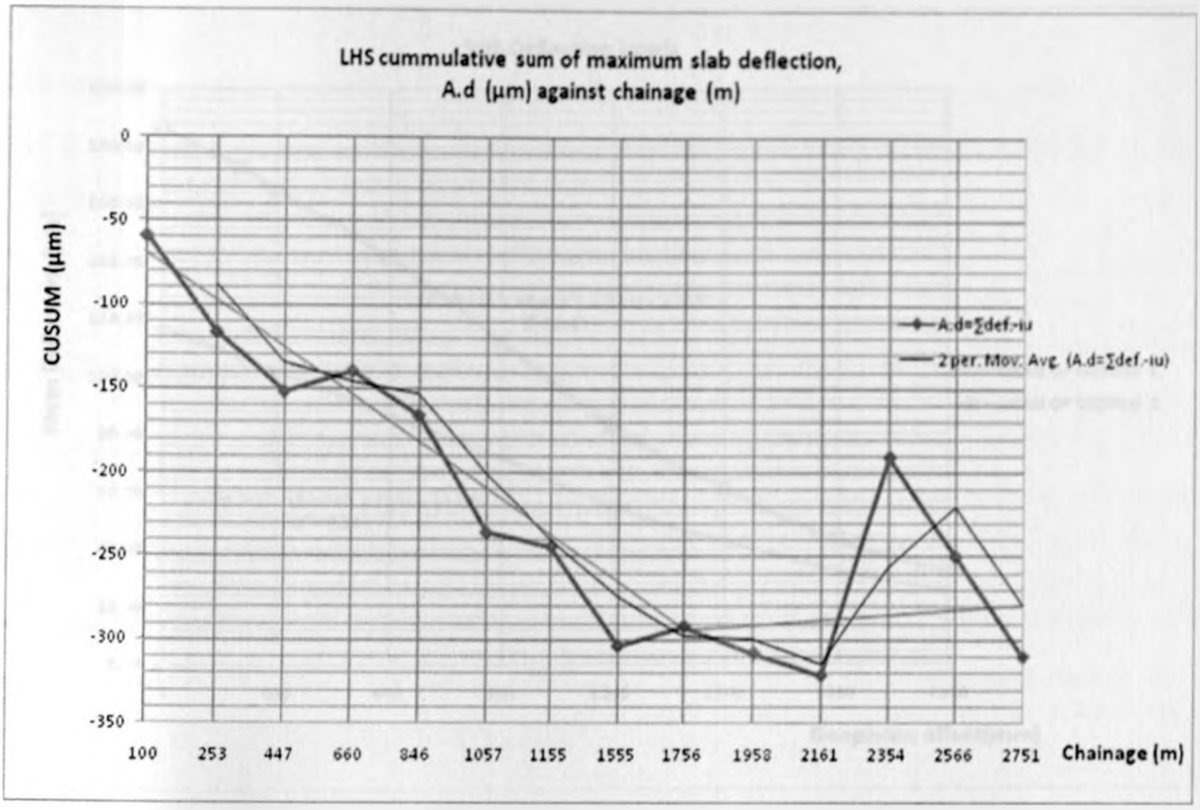


Fig. 4.9: Graph of LHS cumulative sum of maximum central slab deflections (μm) against chainages (m)

The following homogenous sections were identified on the LHS:

i. Chainage 0.000m – 1750m – section 1
ii. Chainage 1751m – 2751m – section 2

4.1.4 Transverse deflection bowls across pavement slabs

Deflections can be described by 3rd order polynomial with R^2=0.999 indicating a good degree of precision as shown in Figure 4.10 and 4.11. The mean slab deflections represent the deflections for different chainages in each defined section of testing and averaged for each geophone

RHS section 1 exhibited lower deflections as compared to section 2 indicating that section 1 has a stronger pavement structure as compared to section 2.

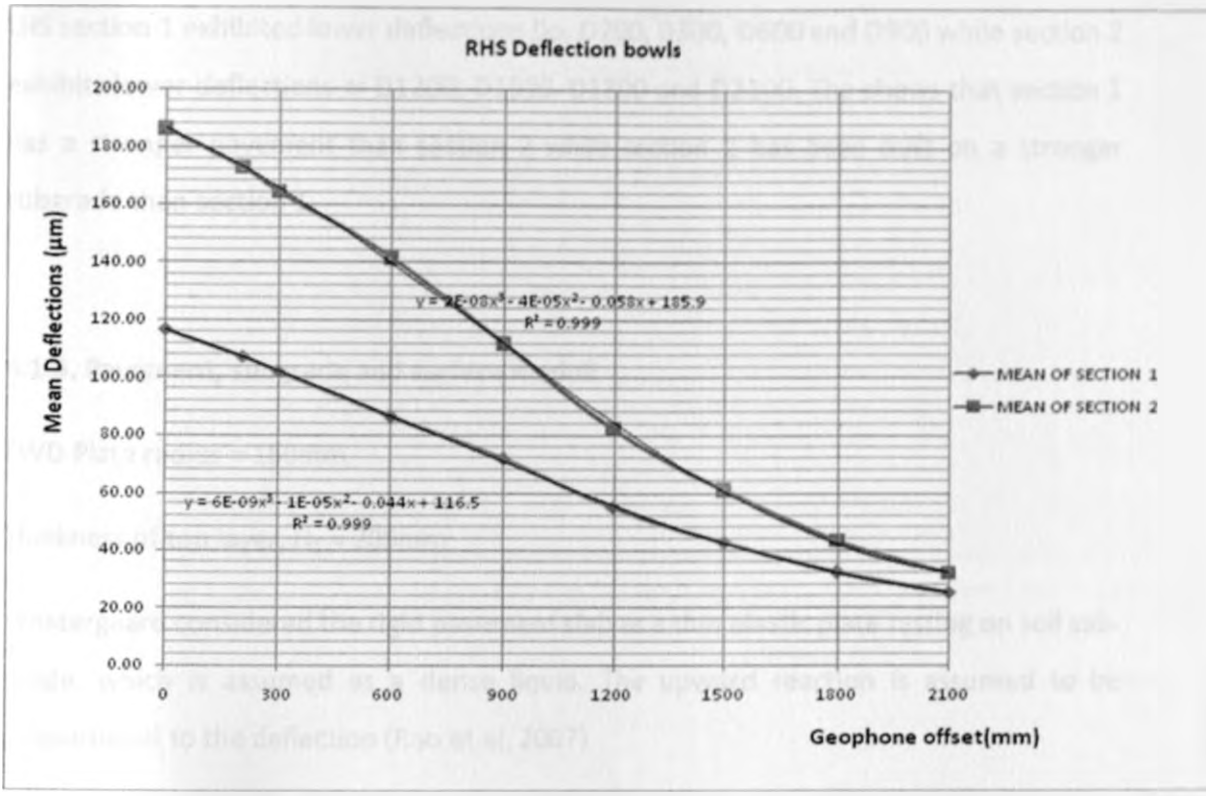


Fig. 4.10: Graph of RHS mean slab deflections (µm) against geophone distance (mm)

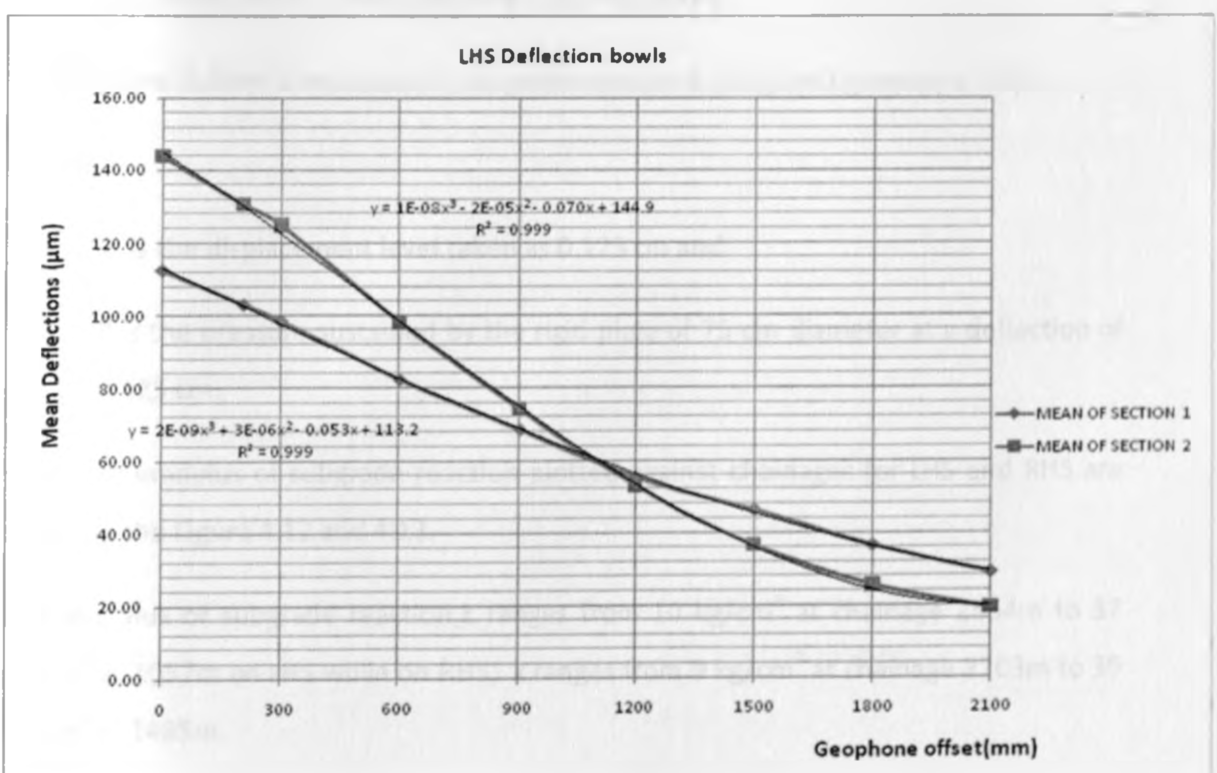


Fig. 4.11: Graph of LHS mean central slab deflections (µm) against geophone distance (mm)

LHS section 1 exhibited lower deflections Do, D200, D300, D600 and D900 while section 2 exhibits lower deflections at D1200, D1500, D1800 and D2100. The shows that section 1 has a stronger pavement than section 2 while section 2 has been built on a stronger subgrade than section 1.

4.1.5. Pavement, subgrade and surface moduli

FWD Plate radius = 150mm

Thickness of top layer, H_1 = 205mm

Westergaard considered the rigid pavement slab as a thin elastic plate resting on soil sub-grade, which is assumed as a dense liquid. The upward reaction is assumed to be proportional to the deflection (Rao et.al, 2007)

Pressure for 75mm dia. Plate = 4 x pressure for 150mm dia plate.

Normalised pressure for 75mm plate = 4 x 707 =2828 KPa.

Westergaard defined a modulus of sub-grade reaction K in kg/cm3 given by $K = P/\Delta$

Where;

> Δ is the displacement level taken as 0.125 cm and
>
> P is the pressure sustained by the rigid plate of 75 cm diameter at a deflection of 0.125 cm.

Values of modulus of subgrade reaction plotted against chainages for LHS and RHS are shown in the Figure 4.12 and 4.13.

The modulus of subgrade reaction,k ranges from 10 kg/cm^3 at chainage 2354m to 37 kg/cm^3 at 1057m on LHS while on RHS, k ranges from 9 kg/cm^3 at chainage 2703m to 39 kg/cm^3 at 1485m.

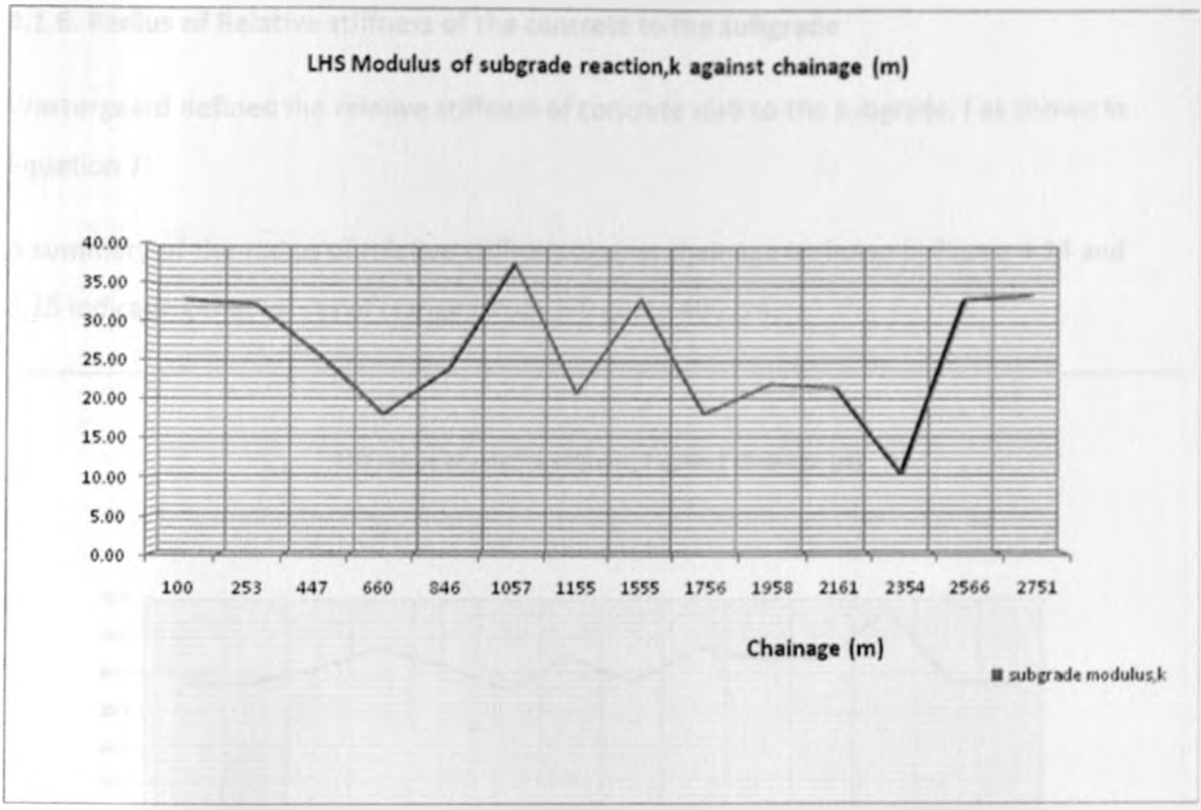


Fig. 4.12: Modulus of subgrade reaction, k (kg/cm3) against LHS chainage (m)

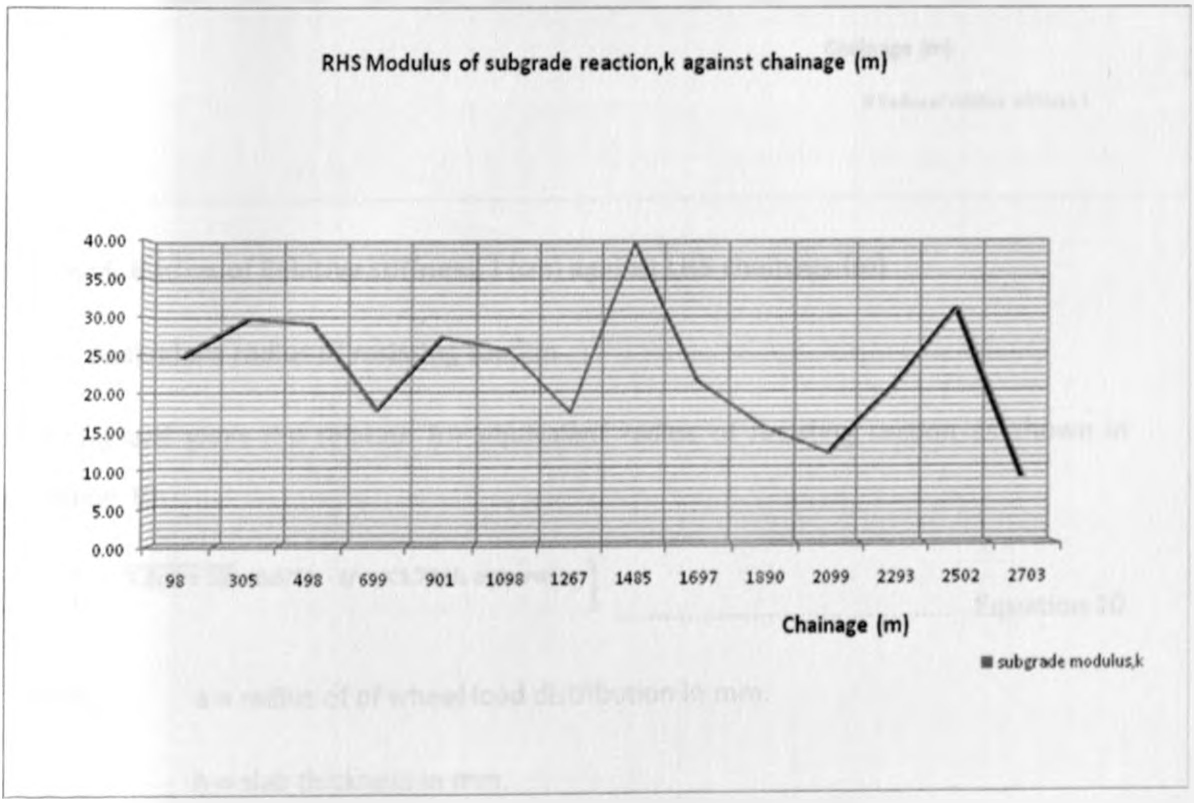


Fig. 4.13: Modulus of subgrade reaction, k (kg/cm3) against RHS chainage (m)

4.1.6. Radius of Relative stiffness of the concrete to the subgrade

Wastergaard defined the relative stiffness of concrete slab to the subgrade, *l* as shown in Equation 7:

A summary of the radius of relative stiffness against chainage is shown in Figure 4.14 and 4.15 indicating that values of *l* ranges from 270 cm to 400 cm.

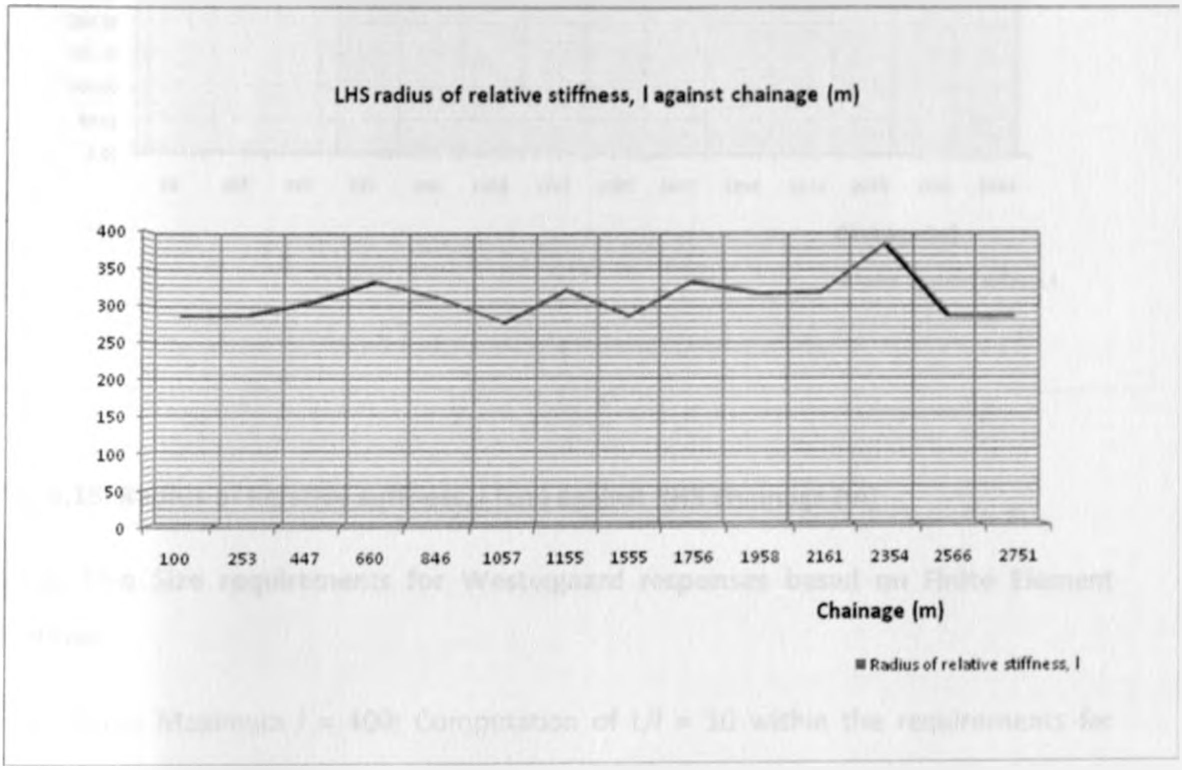


Fig. 4.14: Radius of Relative stiffness, l (cm) against LHS chainage (m)

4.1.7. Equivalent radius of resisting section

Westergaard gives the relation for equivalent radius of resisting section as shown in Equation 10.

$$b = \left\{ \begin{matrix} \sqrt{1.6a^2 + h^2} - 0.675h \quad if\ a < 1.724h\ otherwise \\ a \end{matrix} \right\}$$ ....Equation 10

Where; a = radius of of wheel load distribution in mm.

h = slab thickness in mm.

1.724h = 353 > 205 (h) and therefore, b = 140.96mm

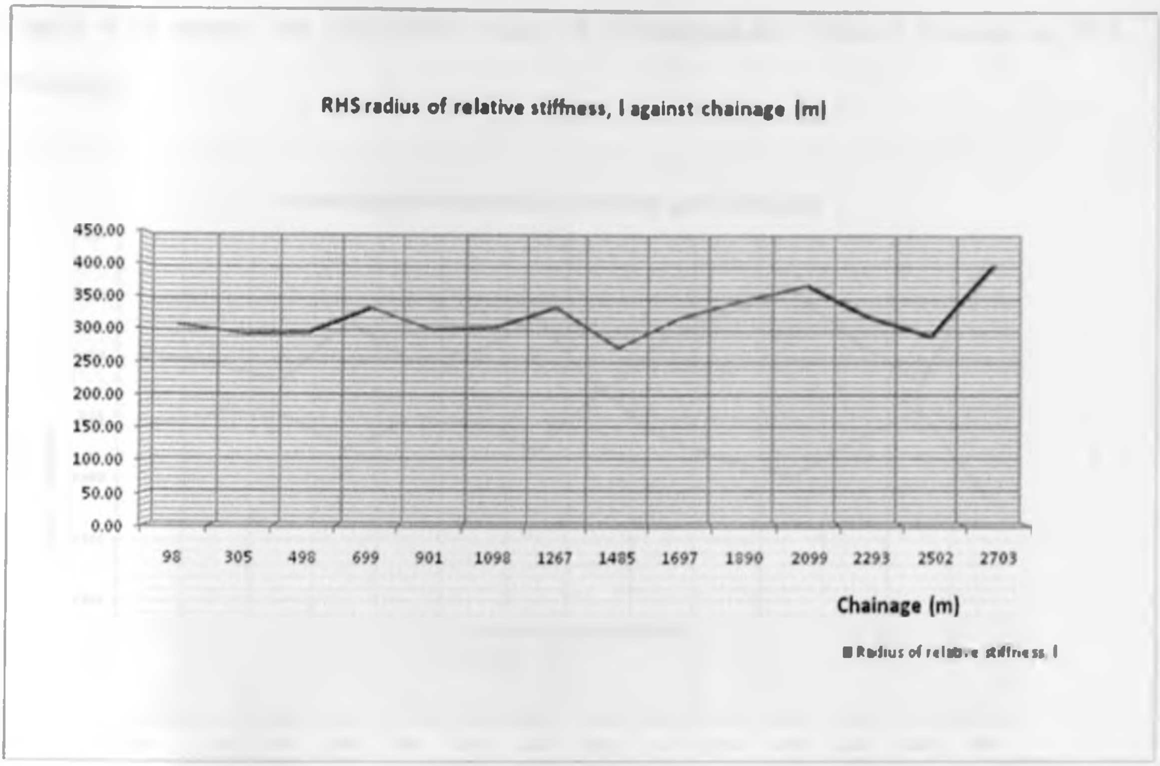


Fig. 4.15: Radius of Relative stiffness, l (cm) against RHS chainage (m)

4.1.8. Slab Size requirements for Westergaard responses based on Finite Element Method.

L=4000mm; Maximum l = 400; Computation of L/l = 10 within the requirements for infinite slab.

Therefore the pavement structure is considered infinite and Westergaard equations can be applied to calculate deflections and stresses.

4.1.9. Stresses and deflections in concrete slab.

Maximum interior bending stress by ordinary Westergaard theory is given by Equation 5;

Where; P= 707 KPa.; μ = 0.15; h = 205; a = 150mm; E =27 KN/mm^2

τ = Euler's Constant (τ = 0.577 215 664 90)

k = modulus of subgrade reaction (cm)

l = radius of relative stiffness given by Figures 4.14 and 4.15.

Figure 4.16 shows the calculated values of Westergaard's ordinary stresses at RHS chainage.

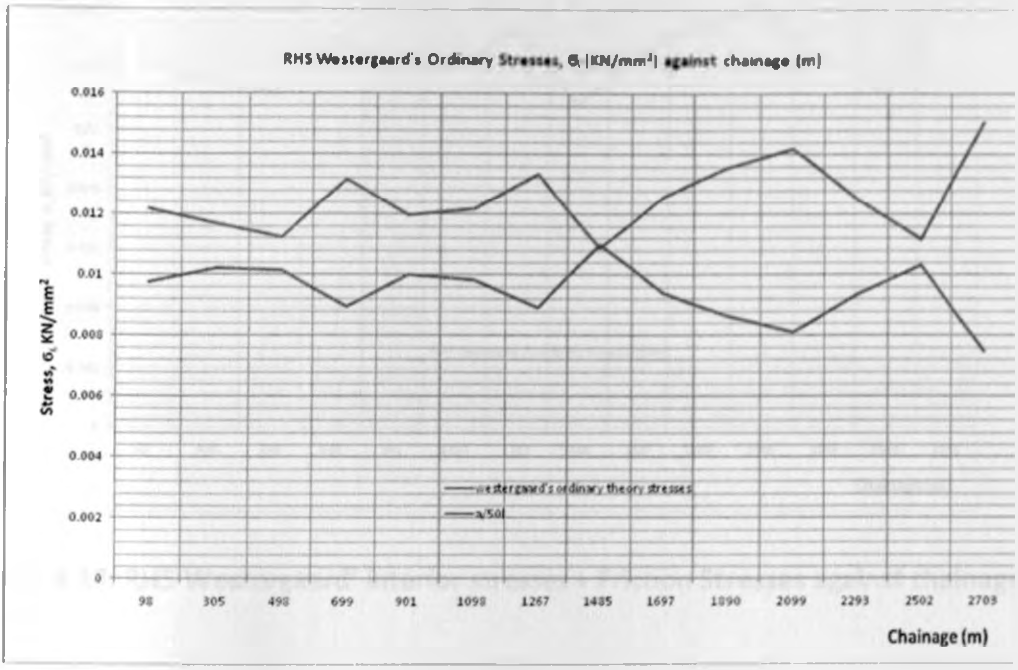


Fig. 4.16: RHS Westergaard interior stresses and a/50l against chainage

Westergaard's stresses are inversely proportional to a/l. Section 4.1.2 gives the results and analysis of deflections on Mbagathi Road.

Frictional stresses are given by Equation 11:

$$\sigma_f = \frac{WLf}{2 \times 10^4} \qquad \text{...Equation 11}$$

$= 24 \times 4 \times 1.5 / 2 \times 10^4$

$= 0.0072\ kN/m^2$

The total of frictional stresses and Westergaard's stresses at each chainage is shown in Figure 4.17.

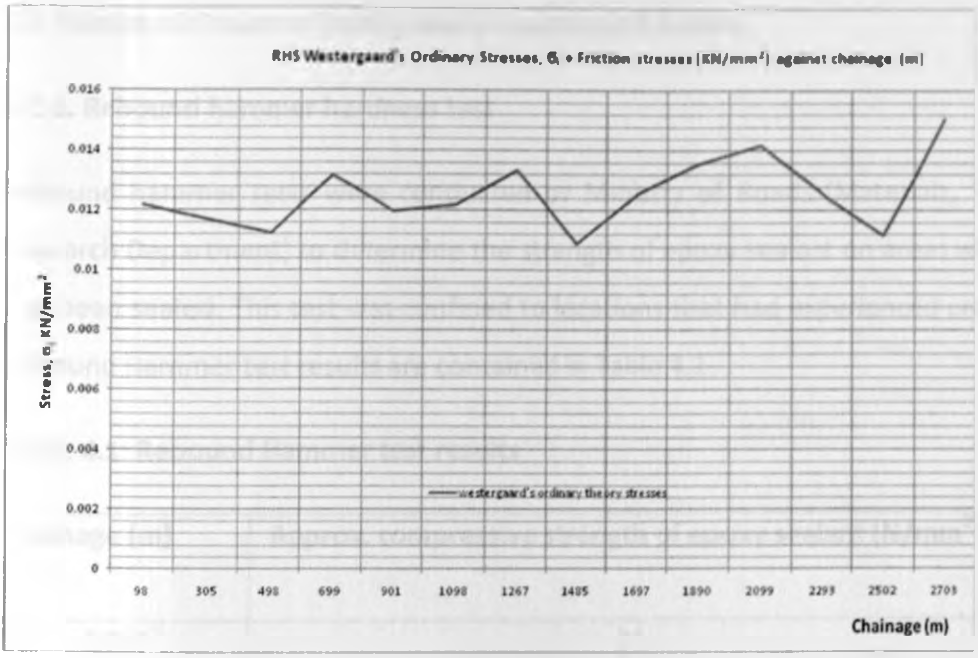


Fig. 4.17: RHS Westergaard' interior stresses + Friction Stresses against chainage

4.2. Results of Concrete Homogeneity and strength testing

4.2.1. Rebound hammer hardness test

Rebound hammer tests were conducted by Ministry of Roads (Materials, Testing and Research Department) to determine the strength of epoxy sealant on areas where cracks had been sealed. This test was confined to locations that had experienced cracking only. Rebound Hammer test results are contained in Table 4.1.

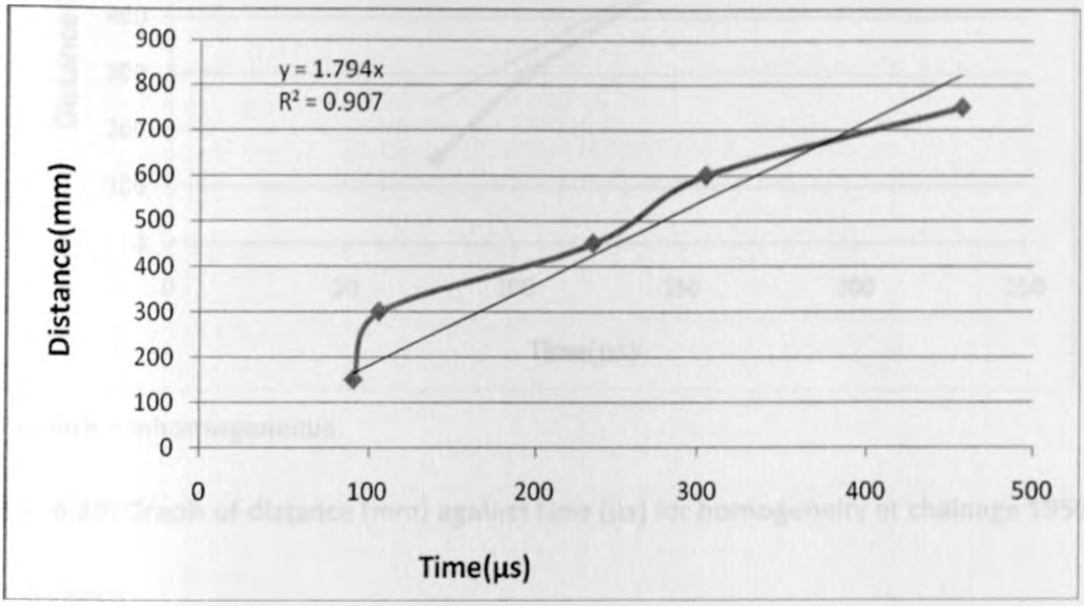
Table 4.1: Rebound Hammer test results

Chainage (m)	Approx. compressive strength of epoxy sealant (N/mm^2)
2650	31
2720	43
2660	49
2650	45
2420	41
2380	47
2300	43
2290	39
1950	31
Average	**41.2**

Compressive strength ranged between 31 and 49 which lie within the estimated range for concrete class 35/20. The sealant used has therefore sealed the cracks as required.

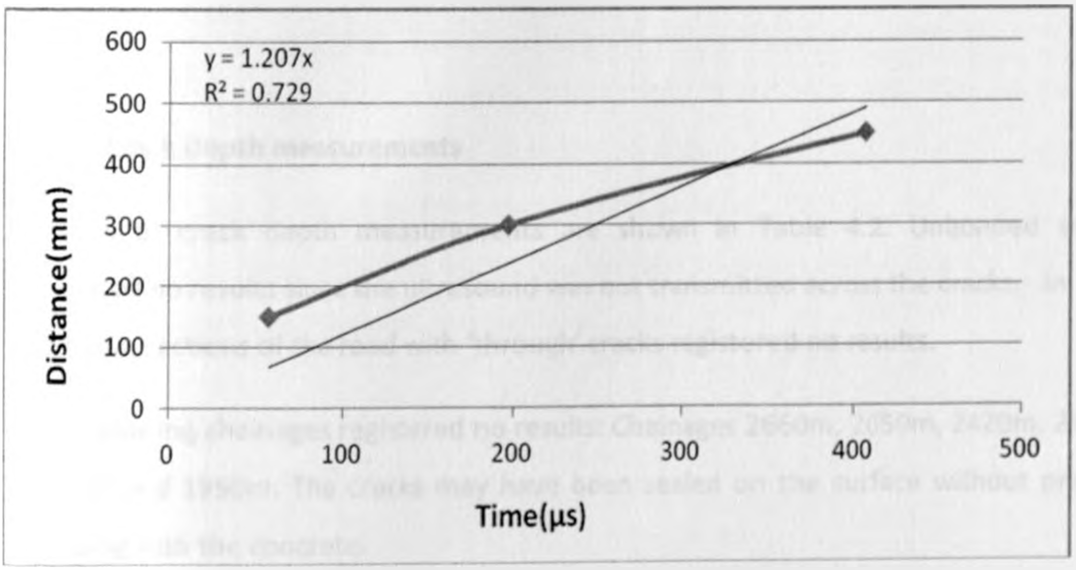
4.2.2. Concrete Homogeneity measurements

Concrete Homogeneity results are shown in Appendix I and Figures 4.18, 4.19 and 4.20. 85% of tested sections comprised homogenous concrete except chainages 2660m, 2300m and 1950m.



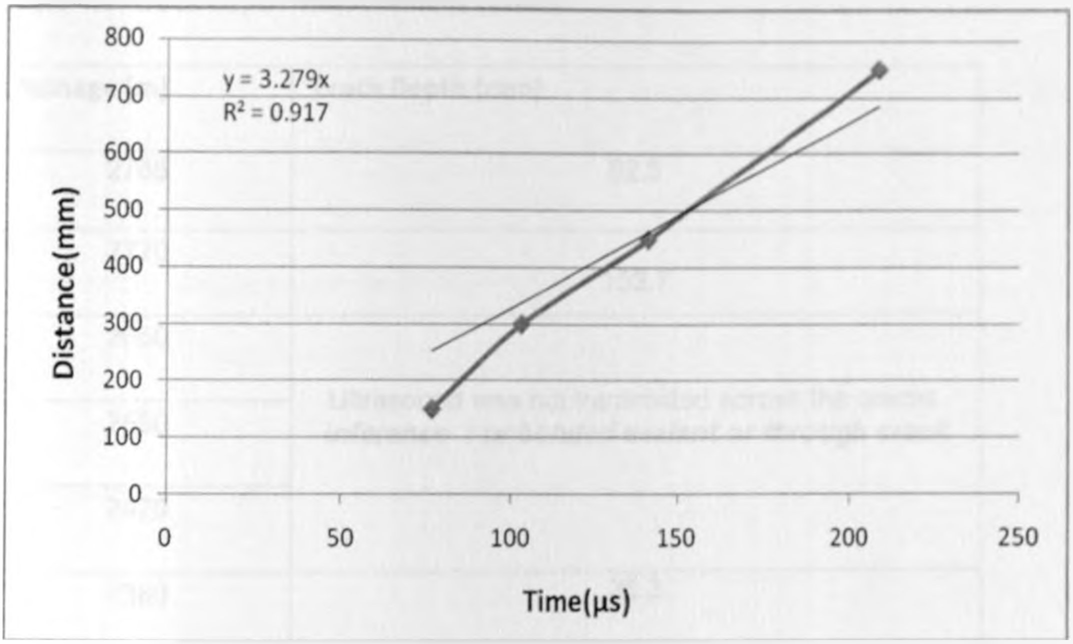
Remark – Inhomogeneous

Fig. 4.18: Graph of distance (mm) against time (μs) for homogeneity at chainage 2660m



Remark – Inhomogeneous

Fig. 4.19: Graph of distance (mm) against time (μs) for homogeneity at chainage 2300m



Remark – Inhomogeneous

Fig. 4.20: Graph of distance (mm) against time (µs) for homogeneity at chainage 1950m

<u>**Inference**</u>

From the graphs and velocity of sound, the concrete was fairly homogeneous for each panel an indication that no weak areas in the concrete that can be sources of failure within the current environment.

4.2.3. Crack Depth measurements

Results of crack depth measurements are shown in Table 4.2. Unbonded sealant indicated no results since the ultrasound was not transmitted across the cracks. In addition, sections of the road with 'through' cracks registered no results.

The following chainages registered no results: Chainages 2660m, 2650m, 2420m, 2300m, 2290m and 1950m. The cracks may have been sealed on the surface without properly bonding with the concrete.

Table 4.2: crack depth measurement results

Chainage (m)	Crack Depth (mm)
2765	82.3
2720	153.7
2660	Ultrasound was not transmitted across the cracks. ***inference : unbonded sealant or through crack***
2650	
2420	
2380	25.3
2300	Ultrasound was not transmitted across the crack. ***inference: : unbonded sealant or through crack***
2290	
1950	

4.2.4. Inspection of as-built pavement

An inspection of progress reports (report no. 8) indicate that the pavement was constructed to specification. Compressive strength of concrete according to materials testing results indicated concrete strength of between 36 and 49N/mm^2 for grade 35N/mm^2. Average concrete thickness ranged between 200mm and 230mm on the centerline with minimal discrepancies. It is therefore unlikely that pavement failure can result from concrete pavement strength or thickness.

4.3. Pavement Condition Survey

Based on pavement condition survey results, the occurrence of distress features resulted in classification of the pavement structure into two identical sections. Following this classification, the following homogenous sections were identified as shown in Table 4.3.

Table 4.3: Homogenous sections of Mbagathi Road

Section	Chainage as described on LHS
1	Chainage 0 to 1700m
2	Chainage 1700 to 3000m

4.3.1. Visual Condition of Surfacing

A. Degree and extent of joint spalling

The observed extent and degree of joint spalling is as summarized in Table 4.4 indicating a higher degree of moderate spalling at section 2 as compared to section 1. None of the joints were observed to have severe spalls over 50mm.

Table 4.4: Degree and extent of joint spalling

Section	Extent	Degree	Description
1	4 out of 25 slabs	Moderate	Spalling that extends between 20 and 50 mm wide on either slab edge, irrespective of the length of spalling.
2	15 out of 25 slabs	Moderate	Spalling that extends between 20 and 50 mm wide on either slab edge, irrespective of the length of spalling.

Percentage of joints indicating spalling defect = 50%.

The severity of joint spalling joints is illustrated in Figures 4.21, 4.22 for LHS effect and plates 4.23 and 4.24 for RHS effect.

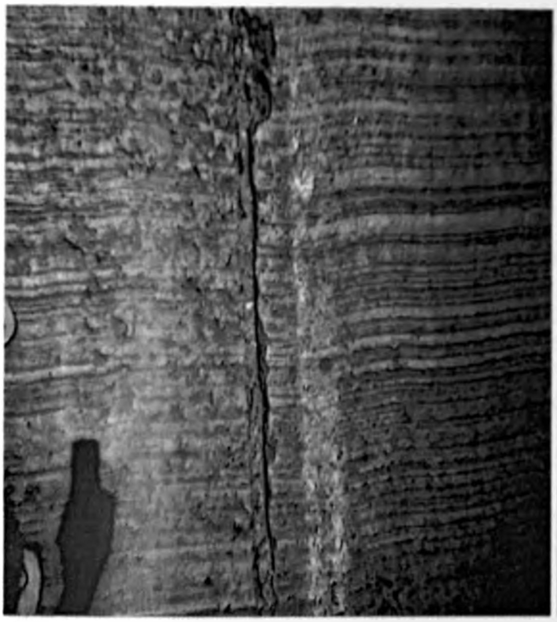



Fig. 4.21 and 4.22: Spalled joints at LHS chainage 2650m and 2350m

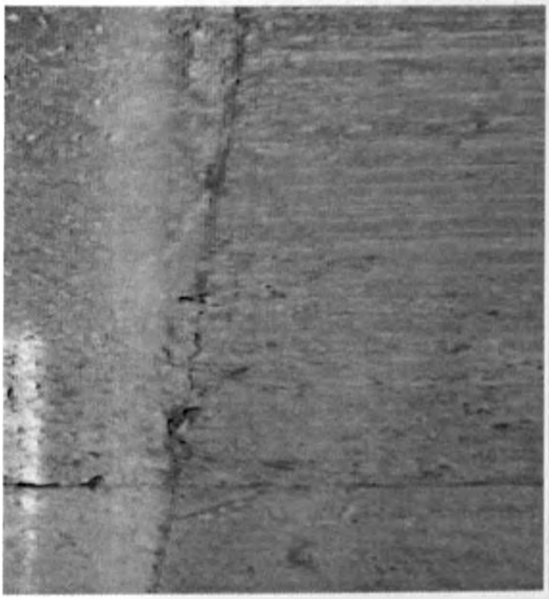



Fig. 4.23 and 4.24: Spalled joints at RHS chainage 2500m and 2600m

B. Joint Seal Condition

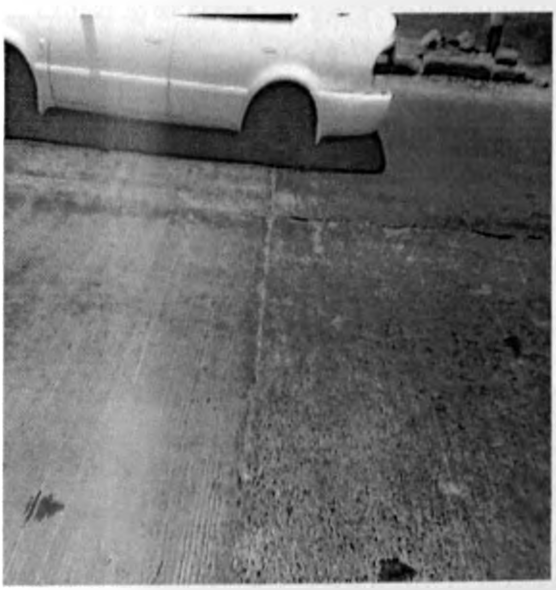
The damages that were observed include seals that extruded from joints and damaged and torn seals. Foreign matter was observed in both transverse and longitudinal joints. The degree and extent of joint seal performance is shown in Table 4.5.

Table 4.5: Degree of Joint Seal Performance on Mbagathi Road

Section	Degree	Description
1	3 (Fair)	Not functional i.e. sagging, protruding, not adhering to concrete or torn.
2	3 (Fair)	Not functional i.e. sagging, protruding, not adhering to concrete or torn.

C. Texture

The road surface texture was observed greater than 6mm deep on both sections. Loss of texture was recorded at chainage 1690 on LHS and on both RHS and LHS at chainage 2700m to 2800m. Figures 4.25 and 4.26 show the observed rough pavement texture.



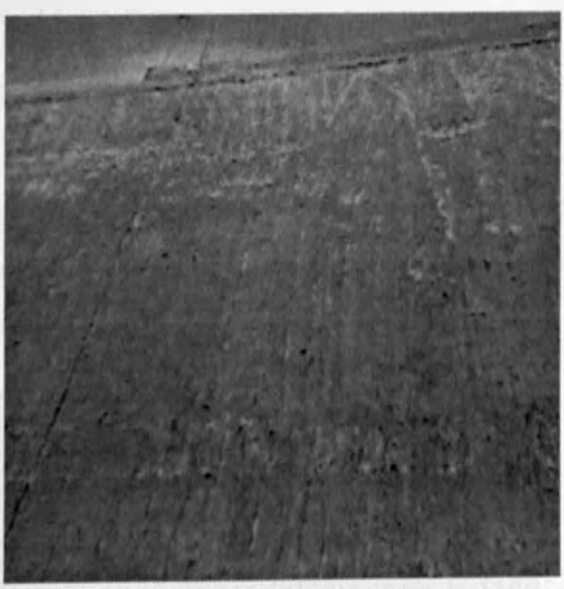


Fig. 4.25 and 4.26: Rough pavement texture

D. Faulting

Table 4.6 summarises the observed pattern of faulting on Mbagathi Road indicating moderate faulting of both longitudinal and transverse joints. Severe faults were not observed.

Table 4.6: Degree and extent of faulting on Mbagathi Road

Section	Extent	Degree	Description
1	9 out of 25 slabs per 100m from chainage 1300 to 1700m on LHS	Moderate	Between 5 and 10 mm.
	2 out of 25 slabs per 100m both sides on other sections	Moderate	Between 5 and 10 mm.
2	3 out of 25 slabs per 100m	Moderate	Between 5 and 10 mm.

Faulted area = 20% of entire road.

E. Cracking of slabs

Joint associated cracks were not observed. During the initial stages of the research in July 2011, cracked slabs with open cracks were observed between chainage 2700 to 3000m. However, the cracks were sealed in January 2012 using Sikadur epoxy sealant. The strength of the sealant that was used is indicated under concrete strength results. The degree and extent of cracking is shown in Table 4.7.

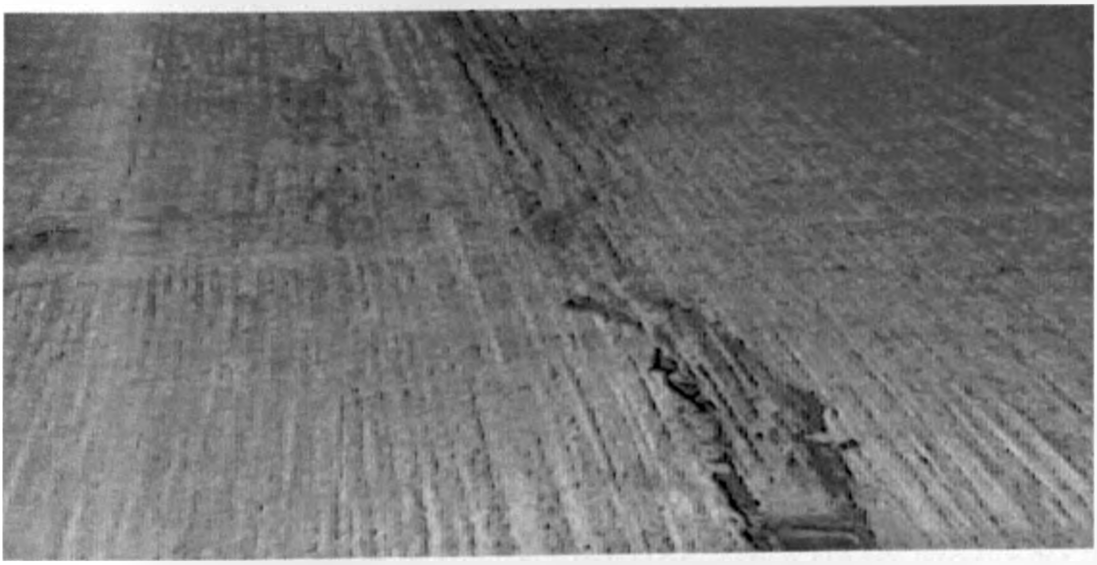


Fig. 4.27: Epoxy Sealed crack on Mbagathi Road

Table 4.7: Degree and extent of cracking on Mbagathi Road.

Section	Extent	Degree
1	Nil	N/A
2	15 out of 25 slabs per 100m from chainage 2700 to 3000m on both LHS and RHS.	OPEN CRACKS – easily discernable from slow moving vehicle in July 2011. SEALED CRACKS in March 2012.

The percentage of cracked area = 5% as at December 2011. This area has since been patched by January 2012 as illustrated in Figures 4.27 and 4.28.

Fig. 4.28: Recurring crack on epoxy sealed crack

F. Blow ups and potholes

The study revealed a low degree of occurrence of blow-ups and potholes as shown in Table 4.8 indicating a total of 7 blow ups over the entire road.

Table 4.8: Observed pattern of occurrence of potholes and blow-ups on Mbagathi Road.

Section	Extent of occurrence of potholes and blow-ups
1	5 blow ups over the entire section
2	2 blow ups over the entire section

The percentage area of the pavement affected by blowups < 1% of entire road.

Observed failures included failure and sections where cabbro or tarmac was joined to concrete as shown in figures 4.29 and 4.30. Roadside kerbs were observed to have fallen off resulting in edge loading of the pavement.

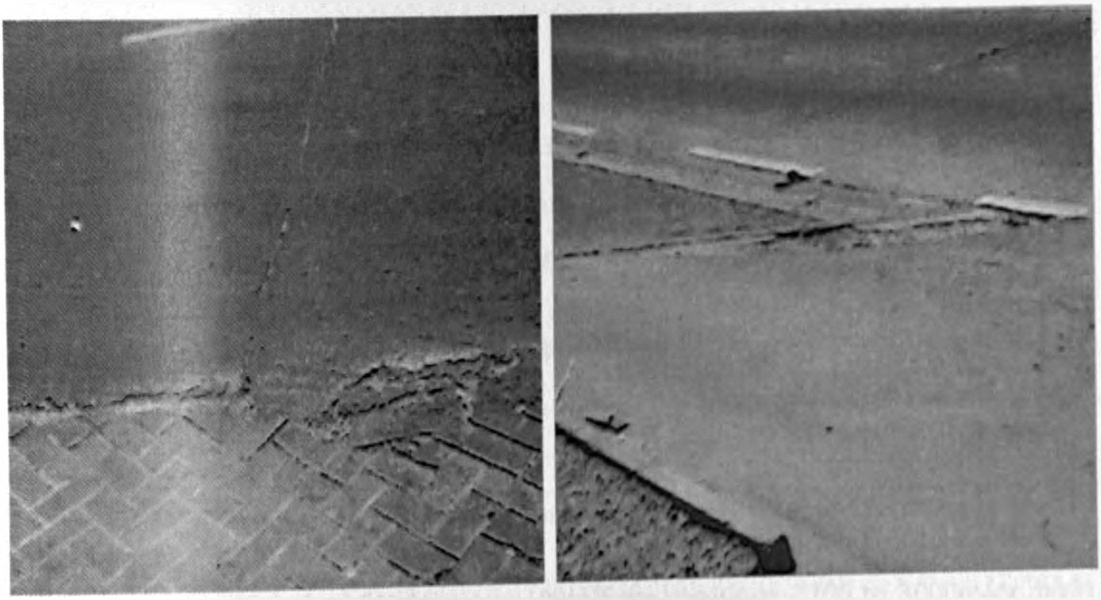


Fig. 4.29 and 4.30: Blow ups and failures between LHS chainage 2800m and RHS chainage 3000m

G. Patching

The road sections on chainages 2700 to 3000m had open cracks in July 2011 but were patched in January 2012. The patches are in good condition. The observed pattern of patching is shown in Table 4.9.

Table 4.9: Observed patching on Mbagathi Road

Section	Extent	Degree of patching
1	No patches	N/A
2	15 out of 25 slabs per 100m from chainage 2700 to 3000m on both LHS and RHS.	No defects. Concrete patches in good condition. Some sections have shown recurrent cracks.

The percentage of patched area = 5%

H. Pumping

Joint pumping was recorded at chainages 1300 to 1700 on LHS and 2700 to 3000m on both sides of the road. In the overall context, pumping was not severe. The observed extent of joint pumping is shown in Table 4.10.

Table 4.10: Extent of joint pumping on Mbagathi Road

Section	Extent of pumping
1	9 out of 25 slabs per 100m from chainage 1300 to 1700m on LHS
2	13 out of 25 slabs per 100m from chainage 2700 to 3000m on both LHS and RHS.

4.3.2 Assessment of functional features

A. Riding Quality

The observed degree of riding quality has been summarized in Table 4.11. Riding quality was rated as fair for section 1 and good for section 2.

Table 4.11: Degree of riding quality on Mbagathi Road.

Section	Degree	Description	Approx. psi'
1	3 (Fair)	The concrete surface is rough resulting in high noise levels. At chainage 1300 to 1350m, driving is very uncomfortable on both sides of the road due to poor interconnection of the tarmac and concrete sections. Tarmac sections are highly corrugated. On the RHS, an abrupt change of road level occurs making it easy to veer off the road.	2.0
2	2 (Good)	Ride smooth and comfortable. Slight unevenness of the road profile.	3.0

B. Skid Resistance

Mbagathi road exhibited a good degree of skid resistance as shown in Table 4.12.

Table 4.12: Degree Skid Resistance on Mbagathi Road.

Section	Degree	Description
1	Good.	Loss of texture observed at chainage 1690m
2	Good.	Water ponding was observed and could result in slippery surface at chainage 2600 to 2800m.

C. Drainage

Water ponding was observed and could result in slippery surface at chainage 2600 to 2800m. Clogged drains were observed along both sections of the road as shown in Figure 4.33. Destruction of drainage systems is illustrated in Figures 4.31, 4.32 and 4.34.

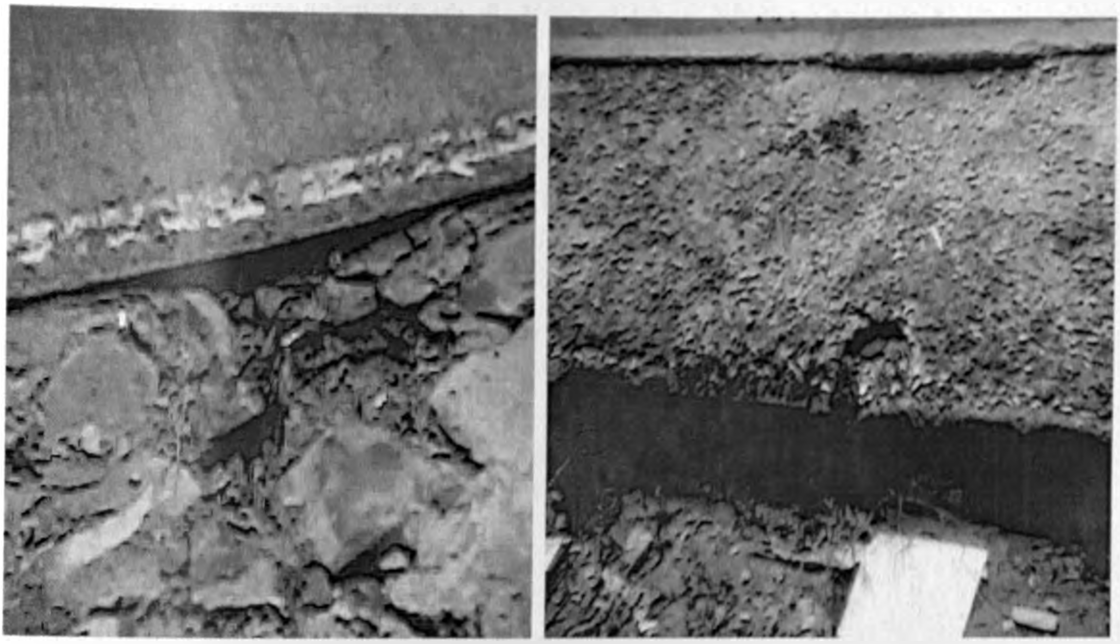


Fig. 4.31 and 4.32: Eroded edges of the pavement and kerbs falling off.

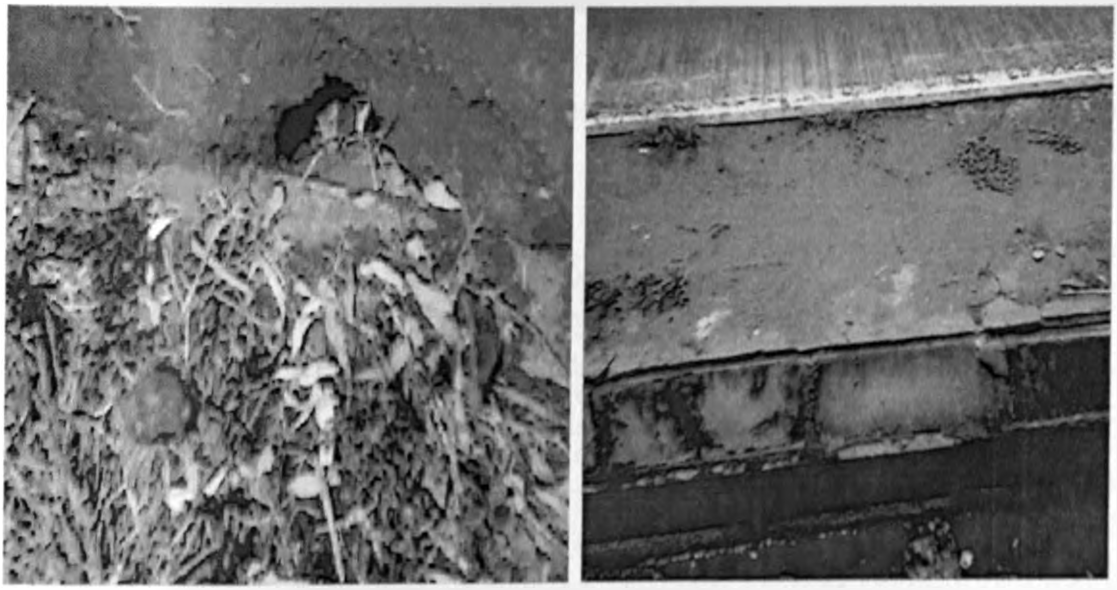


Fig. 4.33 and 4.34: Destruction of side drains at RHS chainage 1550m and 2300m.

D. Shoulders

Tarmac shoulders were observed to be in good condition except longitudinal cracks along chainage 1800 to 2300m as shown in Figure 4.35. Shoulders are generally 3m wide but some few sections are shorter than 3m up to 1m wide. A summary of degree of shoulder condition is contained in Table 4.13.

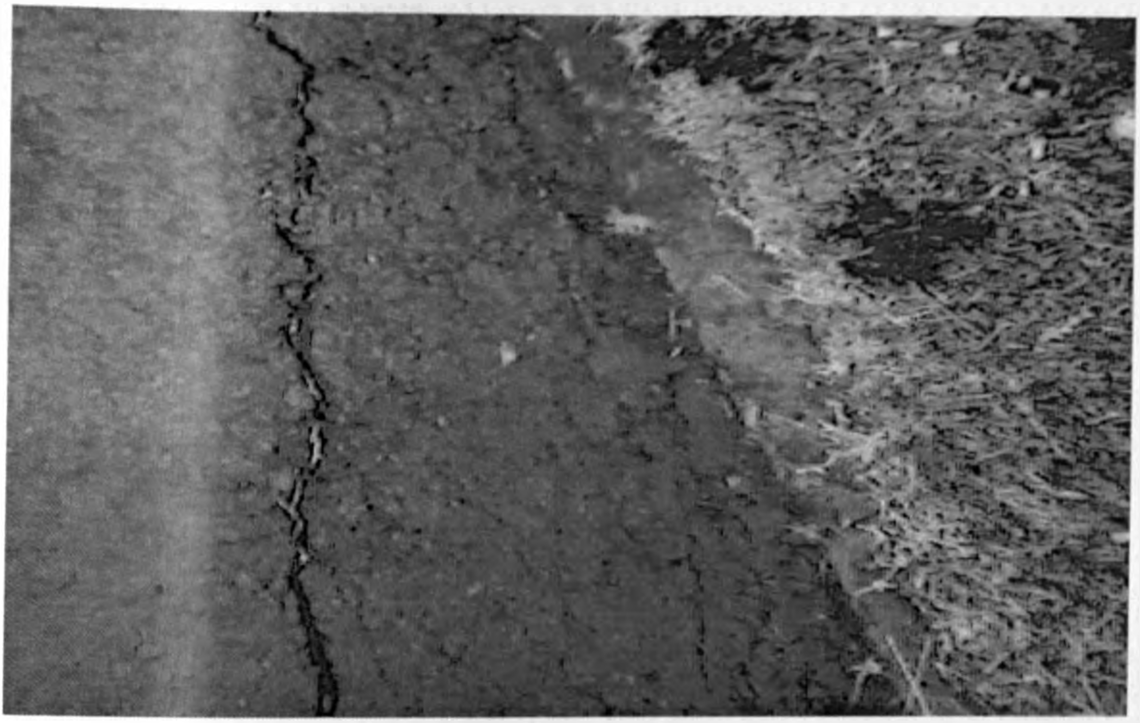


Fig. 4.35: Longitudinal crack at chainage 1800m extending to chainage 2300m on the walkway.

Table 4.13: Degree of Shoulder Condition on Mbagathi Road.

Section	Degree	Description
1	Good.	Very few structural defects
2	Good.	Longitudinal cracks at chainage 1800 to 2300m on both sides.

4.3.3. Overall Pavement Condition

Table 4.14 summarises the overall pavement condition of Mbagathi Road. The rating of overall pavement condition is based on all results of pavement condition survey.

Table 4.14: Overall Pavement Condition on Mbagathi Road.

Section	Degree	Description
1	Fair	General occurrence of structural defects. Corrugations at the bridge at chainage 1300m, widening of longitudinal and transverse joints at 1700m coupled with loss of texture and faulting.
2	Good.	Few structural defects. Widening of joints at chainage 2500m, joint seals that extrude from the joints between 1900 and 2600m, drainage failure at 2700m resulting into pumping, sealed cracks at 2800m.

The concrete surface is rough resulting in high noise levels on both sections.

4.3.4. Pavement Condition Index

The PCI values based on this research are shown on table 4.15 based on 2003 and 2007 ASTM D6433 Pavement Condition Index (PCI) Rating Scale.

Table 4.15: ASTM D6433 Pavement Condition Index (PCI) Rating Scale for Mbagathi Road based on 2003 and 2007 versions 2003 and 2007 versions.

Section	Rating	ASTM D6433-2003	ASTM D6433-2007
1	60%	Good	Fair
2	55%	Good	Fair

4.4. Classified Traffic Counts.

Classified traffic counts were performed at two sections of Mbagathi road for between 12th and 18th March 2012 at the overhead bridge at chainage 1200m and next to Mbagathi Mosque at chainage 2350m. Traffic counts were limited to commercial traffic only.

The average daily traffic was computed from the data which consisted of five day 12-hr count and two day 24-hr counts on 14th March 2012 and 17th March 2012. The 12-hr counts were converted to 24-hr counts. The results are shown in Table 4.16 and 4.17.

Table 4.16: Average daily commercial Traffic for Mbagathi Road Bridge

Vehicle Type	Mon	Tue	Wed	Thur	Fri	Sat	Sun	Totals	ADT
Bus	217	289	364	240	368	184	115	1,777	254
MGV	768	857	744	415	727	246	173	3,930	561
HGV	180	188	170	91	201	80	21	931	133
A-HGV	67	60	106	51	110	31	10	435	62
Total	**1,232**	**1,394**	**1,384**	**797**	**1,406**	**541**	**319**	**7,073**	**1,010**

Table 4.17: Average daily commercial Traffic at the mosque

Vehicle Type	Mon	Tue	Wed	Thur	Fri	Sat	Sun	Totals	ADT
Bus	623	629	609	407	691	253	145	3,357	480
MGV	474	472	620	390	604	245	188	2,993	428
HGV	119	143	138	109	165	66	24	764	109
A-HGV	58	53	88	66	127	24	26	442	63
Total	**1,274**	**1,297**	**1,455**	**972**	**1,587**	**588**	**383**	**7,556**	**1,080**

The average number of commercial vehicles per day was recorded to be less than 2,000 commercial vehicles per day hence the total commercial traffic in one direction was used as recommended by Kenya Road Design Manual Part III.

4.4.1. Vehicle Equivalence Factors

The average vehicle equivalence factors have been derived from the maximum legal limits for vehicular loadings. The legal limits for equivalence factors are shown in table 4.18.

The vehicle classes considered were:

i. Buses (B); passenger vehicles with more than 18 passengers;
ii. Medium Goods Vehicles (MGV); with 2 axles and un-laden weight above 1.5 tons;
iii. Heavy Goods Vehicles (HGV); vehicles having three or four rigid axles; and,
iv. Articulated Heavy Goods Vehicles (AHGV); vehicles with 3 or more articulated axles.

Table 4.18: Legal Limits of Vehicle Equivalence Factors in Kenya.

Vehicle Type	Maximum E.F based on legal limit
Bus	3.4
Heavy Goods Vehicle	3.4
Medium Goods Vehicle	3.0
Articulated Heavy Goods Vehicle	6.8

4.4.2. Design daily Equivalent Standard Axles

The design daily equivalent standard axles (DESA) were calculated by summing up product of average vehicle equivalence factors (VEF) and the average daily traffic (ADT) for both directions for each vehicle type. DESA for the most heavily loaded road section (at the mosque) was adopted for design. The Design daily Equivalent Standard Axles are shown in Table 4.19. Assuming that slow traffic lanes will carry 80% of commercial vehicles, the design traffic loading is 2,972 daily equivalent standards axles.

Table 4.19: Design daily Equivalent Standard Axles

Vehicle Type	V.E.F	Design ADT	DESA
Bus	3.4	480	1632
Heavy Goods Vehicle	3.4	109	370.6
Medium Goods Vehicle	3.0	428	1284
Articulated Heavy Goods Vehicle	6.8	63	428.4
Total		**1,080**	**3,715**

4.4.3. Annual Traffic Growth Rate

Annual trends in traffic growth can be estimated from the growth rate of Gross Domestic Product, GDP (Kenya Road Design Manual, Part III). The annual growth rate of GDP between the years 1961 to 2011 is given in Table 4.18. The average growth in GDP = 4.51% rounded off to 5.0%. the annual GDP growth rate in Kenya from 1961 to 2010 is summarized in Table 4.20.

Table 4.20: Annual GDP Growth Rate from 1961 to 2010.

Year	GDP Growth rate (%)	Year	GDP Growth rate (%)	Year	GDP Growth rate (%)
1961	-7.8	1978	6.9	1995	4.4
1962	9.5	1979	7.6	1996	4.1
1963	8.8	1980	5.6	1997	0.5
1964	5.0	1981	3.8	1998	3.3
1965	2.0	1982	1.5	1999	2.5
1966	14.7	1983	1.3	2000	0.6
1967	3.4	1984	1.8	2001	3.8
1968	8.0	1985	4.3	2002	0.5
1969	8.0	1986	7.2	2003	2.9
1970	-4.7	1987	5.9	2004	5.1
1971	22.2	1988	6.2	2005	5.9
1972	17.1	1989	4.7	2006	6.3
1973	5.9	1990	4.2	2007	7.0
1974	4.1	1991	1.4	2008	1.6
1975	0.9	1992	-0.8	2009	2.6
1976	2.2	1993	0.4	2010	5.3
1977	9.5	1994	2.6	**MEAN**	**4.5%**

Source: World Bank data bank, 2012.

4.4.4. Cumulative Equivalent Standard Axles, CESA

The cumulative Equivalent Standard Axles, CESA over a chosen design period, n is obtained by Equation 12.

$$CESA = 365\ x\ T\ x\ \frac{((1+r)^n - 1)}{r} \quad \text{.......Equation 12}$$

Where:

T – The design daily Equivalent Standard Axles (DESA) for base year (2012);

r – Annual traffic growth rate (5%) expressed as a decimal fraction; and,

n – Design period in years; taken as 15 years to take into account the fact that this study is being undertaken 5 years after the concrete road was open to traffic.

Seasonal correction factor = 1.0.

CESA = 23.42 x 10^6 ESA. Traffic class T2.

4.5. Design of Mbagathi road by Thickness Design Method.

Based on the design of Mbagathi Road based on 15 year remaining life, the following results are obtained.

Assuming subgrade CBR > 30; (white-topping)

Subbase thickness = 150mm and no capping layer required.

Concrete slab thickness = 200mm for JUCP.

Therefore provided 205mm thick slab is adequate for the remaining life of the pavement.

Summary:

Thickness design method indicates that the road will survive its remaining life without major deterioration. However, special attention must be paid to drainage conditions which indicated failure of the pavement.

CHAPTER 5

DISCUSSION AND CONCLUSION

5.1. Construction of Mbagathi Road

An inspection of progress reports (report no. 8) indicate that the pavement was constructed to specification. Compressive strength of concrete according to materials testing results indicated concrete strength of between 36 and $49N/mm^2$ for grade $35N/mm^2$. Average concrete thickness ranged between 200mm and 230mm on the centerline with minimal discrepancies. It is therefore unlikely that pavement failure can result from concrete pavement strength or thickness. Other factors that may initiate deterioration will therefore be discussed further in proceeding sub-topics.

5.2. Stresses of Mbagathi Road

The assumption by Westergaard of infinite or semi-infinite slab based on *L/l* ratio was in tandem with this research and hence applicable to this study.

The comparison of Westergaard's and actual deflections on Mbagathi Road is as shown in Figure 5.1. This research concurs with Ioannides, Thompson and Berenberg who observed that as a/l increase, finite element stresses and deflections become progressively higher than Westergaard's. In all sections, values of a/l are higher than 0.1 where according to with Ioannides, Thompson and Berenberg, Westergaard's equations would agree with finite element results. The pattern of observed deflections are similar the progression of Westergaard's deflections.

However, Ioannides, Thompson and Berenberg did not indicate the amount of difference as a/l progresses. The relationship between a/l and the RHS Westergaard's stresses at different chainages is shown in Figure 4.13. As a/l increases, Westergaard's stresses reduce while the progression of Westergaard's stresses for a/l between 0.37 and 0.55 is shown in Figure 5.2. This concurs with the findings of several researchers since an increase in a/l shows a stronger pavement and hence lower stresses. The radius of load application results in larger area over which the load is applied.

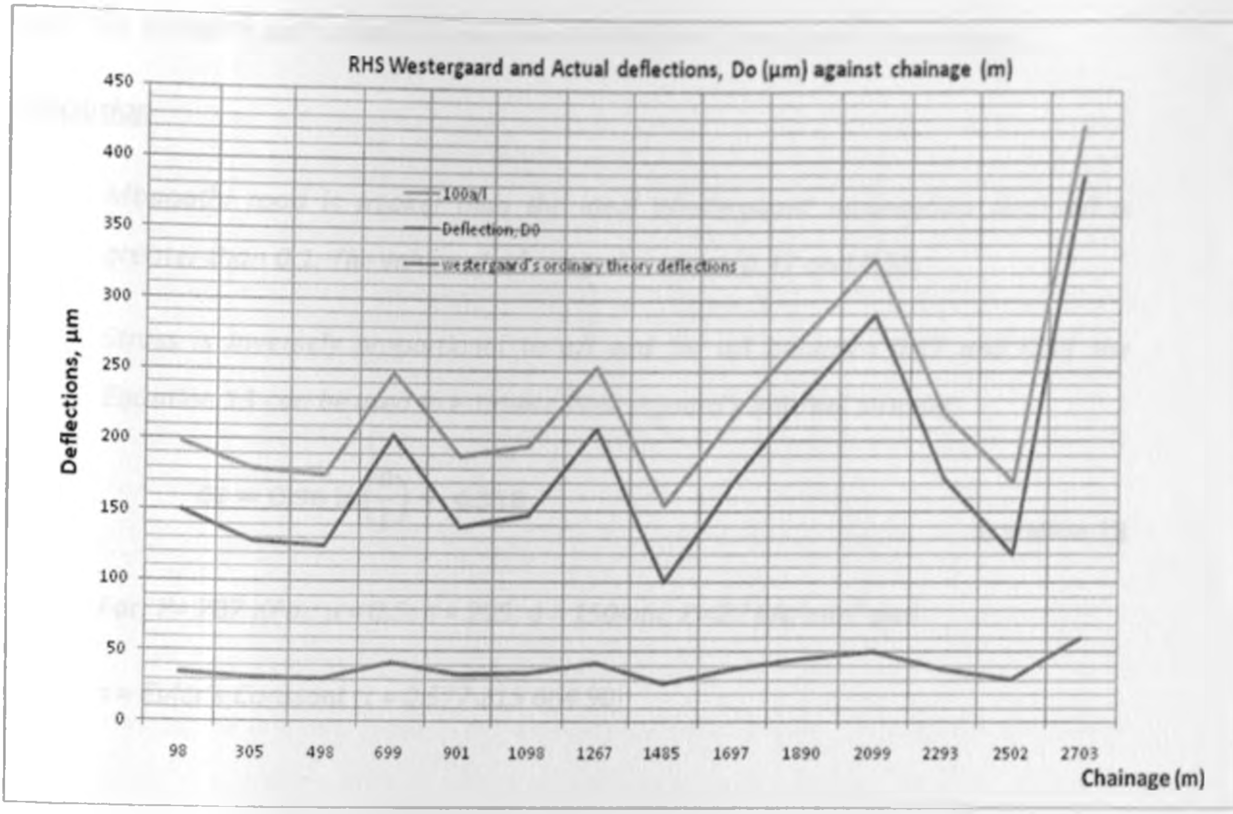


Fig. 5.1: RHS Westergaard and actual deflections against chainage.

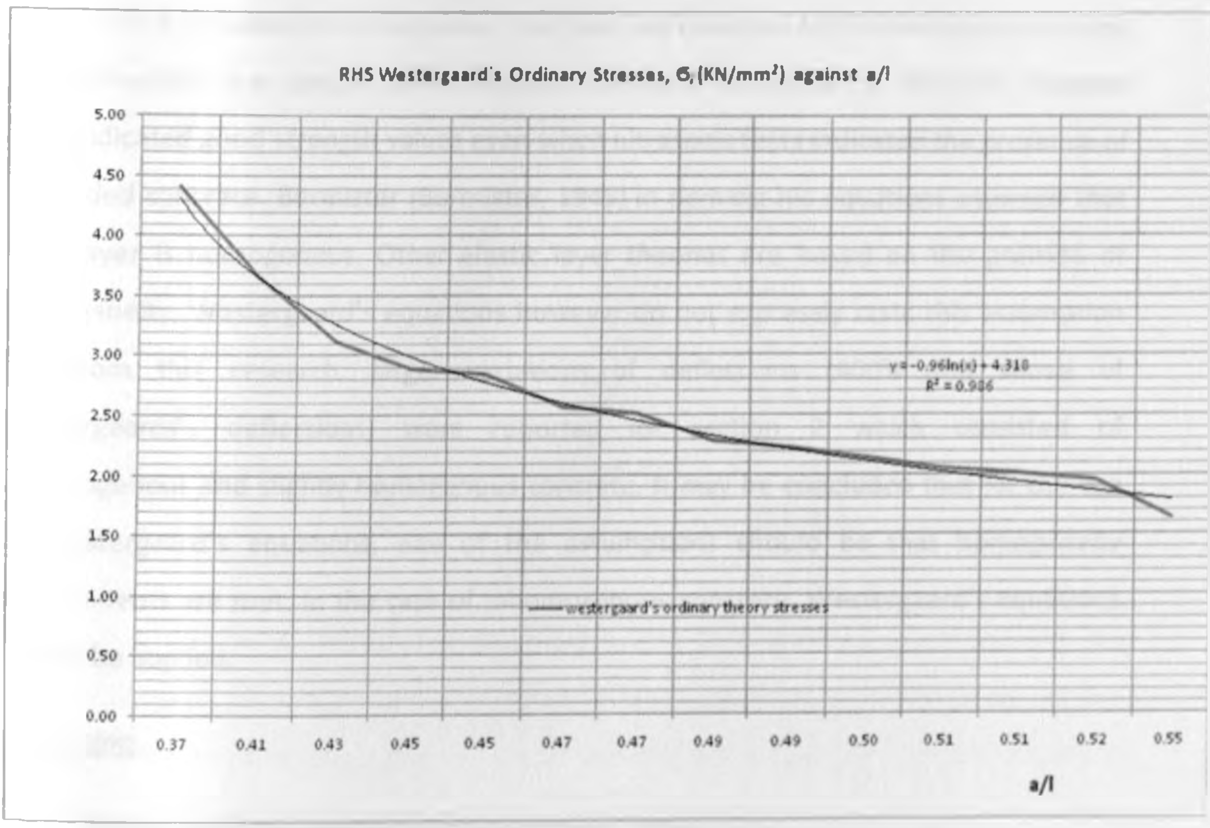


Fig. 5.2: RHS Westergaard internal stresses against a/l.

From this research, only interior stresses and deflections have been investigated.

Conclusion

Mbagathi road is weaker than the ideal Westergaard assumption since a/l is greater than 0.1. The values of a/l ranged between 0.37 and 0.55.

Stress is inversely proportional to a/l and for a/l between 0.37 and 0.55 the Equation 13 can be used to estimate Westergaard's internal stresses.

$$6i = 0.96 \ln\left(\frac{a}{l}\right) + 4.318$$
....Equation 13

For; P= 707 KPa.; μ = 0.5; h = 205; a = 150mm; E =27 KN/mm² and

τ = Euler's Constant (τ = 0.577 215 664 90)

5.3. Concrete strength testing

Sections that recorded in-homogenous concrete also recorded high deflections indicating that deflections are directly proportional to concrete homogeneity. Rebound hammer tests indicated good strength values even when ultrasonic tests indicated the presence of unbonded concrete. Burmister (Burmister, 1945) in deriving his equations assumed that each layer is homogenous. Other elastic layer theories are based on the premise of homogeneity. Westergaard's equations however do not expressly state this assumption but from this research, larger variations of deflections (400% and above of Westergaards's deflections) were reported for section 2 which consisted of inhomogenous and slightly homogenous concrete. It may be concluded that for the use of Westergaard's equations, one of the assumptions should be that homogeneity requirements are met. In the case of inhomogenous concrete, Westergaard's equations cannot be applied.

Conclusion

Homogeneity of concrete affects pavement deflections.

5.4. Joint performance

Mehta found that transverse joints are most important due to high frequency and intensive traffic loading. In his research, Mehta found that the only damages observed on concrete roads relate to joints and non-functional joints resulted in high noise levels. The high noise levels observed on Mbagathi Road can be attributed to high macro texture observed and joint widening.

Joint sealing compounds were observed sagging and protruding out of the concrete indicating joint failure. It is worth noting that higher deflections were recorded in joints that indicated joint failure. Other indicators of joint failure include spalling, faulting and pumping. Pumping was closely related to cracking and joint failure indicating water intrusion into the concrete pavement through cracks and joints. In concurrence with Mehta, damage to transverse joints were more prevalent indicating that transverse joints are under intensive traffic loading as compared to longitudinal joints.

Ghauch (Ghauch, 2011) in researching the effect of concrete degradation on dowel load transfer capability found that damage was mostly confined to the concrete in the vicinity of the face of the joint. With increase in the level of the pavement structure (due to degradation of concrete matrix for example joint faulting, spalling and widening), dowels lose their load transfer capacity.

Conclusion

The performance of joints is a clear indicator of the performance of concrete pavements. Dysfunctional joints result in rapid deterioration of the pavement and non-functional joints result in high noise levels.

5.5. Riding quality

In his research, Mehta found that the main factors that affected riding comfort are friction, longitudinal unevenness and noise. This closely relates to this study where higher degrees of riding quality resulted from sections of the road where there was slight longitudinal unevenness with comfortable riding. Abrupt changes in road finished levels resulted in reduction in the PSI for the section. However due to the occurrence of high noise levels in the entire road, the PSI value was low even when smooth comfortable rides were observed.

Conclusion

Riding quality is influenced by friction, longitudinal unevenness and noise levels. High noise levels were observed on Mbagathi Road.

CHAPTER 6

RECOMMENDATIONS

Based on this research, the following recommendations have been made

1) The installation of kerbs on concrete pavements should be made at the edges of the pavement and not on top of hardened concrete. The kerbs may be installed on as foundation structure to improve on their strength against traffic impact loading.

2) Further study on the time series of deflections will provide clearer results on the propagation of stresses on concrete pavements. This research should be extended to include edge and corner loading conditions both dry and wet seasons for extensive analysis of the ensuing stresses. Further, investigations on the effects of thermal curling due to differential temperature, warping stresses due to moisture gradient and support of adjacent slab need to be investigated.

3) Further research into the effects of different gear configurations and tied outer lane considerations on stresses and deflections of concrete rigid pavements needs to be carried out in order to depict the actual pavement field conditions.

4) Regular inspection of cracked areas in order to allow timely interventions in the form of sealing of cracks in order to prevent ingress of water into the pavement. This will control mud pumping

5) Special attention need to be paid to pavement drainage analysis during design, construction and rehabilitation of concrete pavements. The use of kerbs to channel water out of the pavement and regular maintenance of drainage channels are mandatory to ensure water does not seep into the pavement. In addition, the subbase must be free draining with a separation membrane between the subbase and concrete slab to prevent water entering the pavement. The subbase must continue through to the road shoulder.

REFERENCES

ASTM Standard D6433 (2003); *Standard practice for roads and parking lots pavement condition index surveys,* ASTM International, West Conshohocken, PA, 2003, DOI: 10.1520/D6433-03, www.astm.org .

ASTM Standard D6433 (2007); *Standard practice for roads and parking lots pavement condition index surveys,* ASTM International, West Conshohocken, PA, 2003, DOI: 10.1520/D6433-07, www.astm.org.

Bagus H. Setiadji (2009); *Closed-form backcalculation algorithms for pavement analysis;* National University of Singapore.

Berenberg E.J and Ioannides A.M, (1989); *Structural evaluation of concrete slabs using falling weight deflectometer results;* Advanced Construction Technology Centre, Newmark Civil Engineering Laboratory University Of Illinois At Urbana-Champaign 205 North Mathews Avenue Urbana, Illinois.

Bulman J.N and Smith H.R (1977); Pavement performance and deflection studies on Malaysian roads: Department of the Environment Department of Transport, TRRL Laboratory Report 795: Crowthorne, Transport and Road Research Laboratory.

Burmister, D.M (1945a); *The General Theory of Stresses and Displacements in Layered Soil Systems. I,* Journal of Applied Physics, Vol. 16, pp. 89-94.

Cement and Concrete Association of Australia (2004); *Australia Concrete Roads Manual; Guide to residential streets and paths;* Cement and Concrete Association, 2004.

Cement and Concrete Association of Australia (2001); *Road Note 59; Concrete streets;* Cement and Concrete Association.

European Commission (1999); Directorate General Transport, COST 333: "Development of New Bituminous Pavement Design Method". Office for Official Publications of the European Communities, Luxembourg.

EUPAVE, European Concrete Paving Association (2009). *Concrete Roads A smart and sustainable choice;* Vorstlaan 68 boulevard du Souverain 1170 brussels; 2009

Fwa, T.F. and Chandrasegaran S. (2001); *"Regression Model for Backcalculation of Rigid Pavement Properties"*, Journal of Transportation Engineering, Vol. 127, ASCE, pp. 353-355.

Gichaga J. Francis & Parker A. Neville (1988); *Essentials of Highway Engineering,* Ansti Technology Series; Macmillan Publishers Ltd, 1988

Ghauch G. Ziad (undated); *Finite Element Investigation of the deterioration of doweled rigid pavements.* Cornel University; Available at: http://arxiv.org/abs/1111.1001

Goldbeck A.T (1919); *Thickness of concrete slabs*. Public Roads, Vol. 1, No. 12

Gunter W. Goede (2009); *Pervious concrete: Investigation into structural performance and evaluation of the applicability of existing thickness design methods,* Washington State University, Department of Civil and Environmental Engineering

Harichandran, R. S., Mahmood, T., Raab, A., and Baladi, G. Y. (1994). *Backcalculation of pavement layer moduli, thicknesses and bedrock depth using a modified Newton method.* Nondestructive Testing of Pavements and Backcalculation of Moduli (Second Volume), ASTM STP 1198, H. L. Von Quintas, A. J. Bush and G. Y. Baladi (eds.) American Society for Testing and Materials, Philadelphia.

Kenya National Assembly Official Record, Hansard (2007); *Incorporation of concrete roads in Government Roads Manual;* Kenya National Assembly; Available at: http://books.google.co.ke/books?id=Rk_cPvc4v1wC&pg=PT11&lpg=PT11&dq=RESEARCH+ON+CONCRETE+ROADS+IN+KENYA&source=bl&ots=AfaKEXnAwi&sig=SludXBglISUK293x_Pk4txUx38c&hl=en&ei=EaYFTtDCO8e2hQfq_6XdDQ&sa=X&oi=book_result&ct=result&resnum=1&ved=0CBoQ6AEwAA#v=onepage&q&f=false

Kenya Roads Board (2007); *Kenya Roads Act;* Government Printer, 2007.

Ioannides A.M, Thompson M.R and Berenberg E.J (1984); *Westergaard Slutions Reconsidered;* Transportation Research Record, 1043; Air Force Office for Scientific Research.

KURA-Kenya Urban Roads Authority (2011); *KURA Mission, Vision and Core Values;* Available at: http://www.kura.go.ke

Losberg Anders (1960); *Structurally reinforced concrete pavements;* Doktorsavhandlingar Vid Chalmers Tekniska Hogkola, Gotesborg, Sweden.

Lytton L. Robert (1975); *Pavement Evaluation: Phase I, pavement Evaluation Equipment;* Report No. FHWA-RD-75-8, Federal Highway Administration.

Mehta Jay (1990); *Rigid Pavement Condition using Dynaflect and Falling Weight Deflectometer Measurements,* College of Engineering and Technology, Ohio University.

Ministry of Nairobi Metropolitan Development (2008); *Nairobi Metro 2030; A world class African metropolis; Building a safe, secure and prosperous metropolitan;* Government Printer-Government of Kenya.

M.O.R & P.W-Ministry of Roads and Public Works (1988); *Road Design Manual Part V; Pavement rehabilitation and overlay design;* M.O.R. & P.W.

M.O.R & P.W -Ministry of Roads and Public Works (2006); *Contract for the Rehabilitation of Mbagathi Way;* Contract No. RD 0431; Progress Report No. 8, Ministry of Roads and Public Works.

NCDOT-North Carolina Department of Transportation (2008); *Pavement Condition Survey Manual;* NCDOT.

Perrie Bryan & Rossmann Dennis (2009); *Concrete road construction manual;* Road Pavement Forum; Cement and Concrete Institute.

Rao K .V. Krishna and Mathew V. Tom; *Introduction to Transportation Engineering- Rigid pavement design;* National Programme on Technology Enhanced Learning (NPTEL, 2007). Available at:

http://el.trc.gov.om:4000/htmlroot/ENGG/tcolon/civil_3/NPTEL/Transportation%20Engineering%20I/Notes/Chapter%2029.pdf

SANRA-South African National Roads Agency Limited (1998); *Visual Assessment Manual for Concrete Pavements;* Pretoria.

Scott F. Ronald (1981); *Foundation Analysis;* Prentice-Hall, Inc., Englewood Cliffs, N.J.

Smith H.R & Jones C.R (1980); *Measurement of pavement deflections in tropical and sub-tropical climates:* Department of the Environment Department of Transport, TRRL Laboratory Report 935: Crowthorne,Transport and Road Research Laboratory.

TRL – Transportation Research Laboratory (2004); *Overseas Road Note 40; A guide to Axle load surveys and and traffic counts for determining traffic loading on pavements,* Department For International Development, DFID and TRL, United Kingdom.

WTIC- Wisconsin Transportation Information Center (2002); *Paser Concrete Roads Manual; Pavement Surface Evaluation and Rating;* Wisconsin Transportation Information Center; University of Wisconsin-Madison.

Westergaard Harold Malcom (1926); *Stresses in concrete pavements computed by theoretical analysis;* Public Roads, Vol. 7, No. 2, pp 25-35.

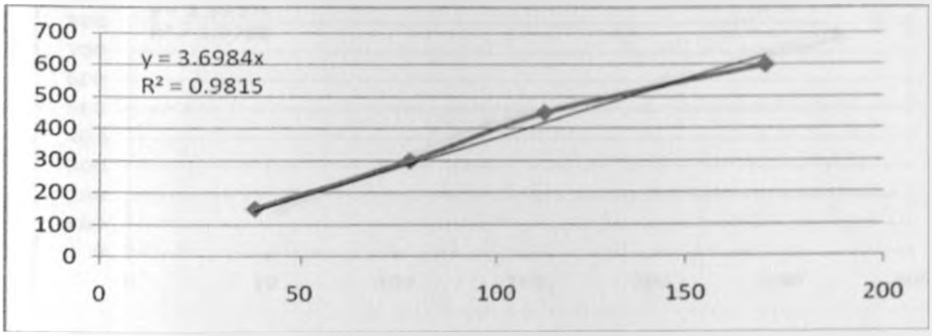
World Bank data bank (2012); *Gross Domestic Product, Kenya;* Available at: http://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG?page=6&order=wbapi_data_value_2010%20wbapi_data_value%20wbapi_data_value-last&sort=asc, retrieved 2nd April 2012.

APPENDIX I

HOMOGENEITY OF CONCRETE

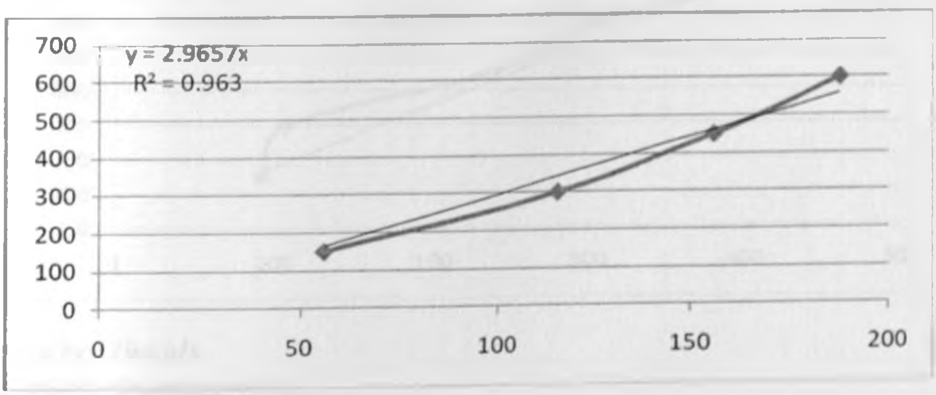
KM2+765

Time(μs)	Distance(mm)
38	150
78	300
113	450
170	600



velocity:3700m/s
Remark: homogenous

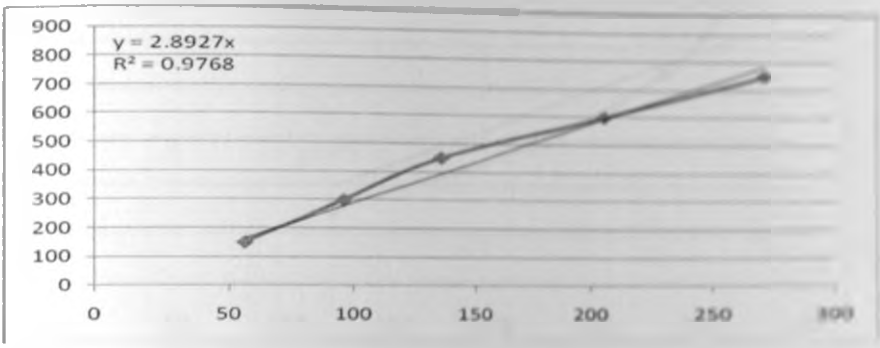
Time(μs)	Distance(mm)
56	150
116	300
156	450
188	600



velocity:2970m/s

KM2+720

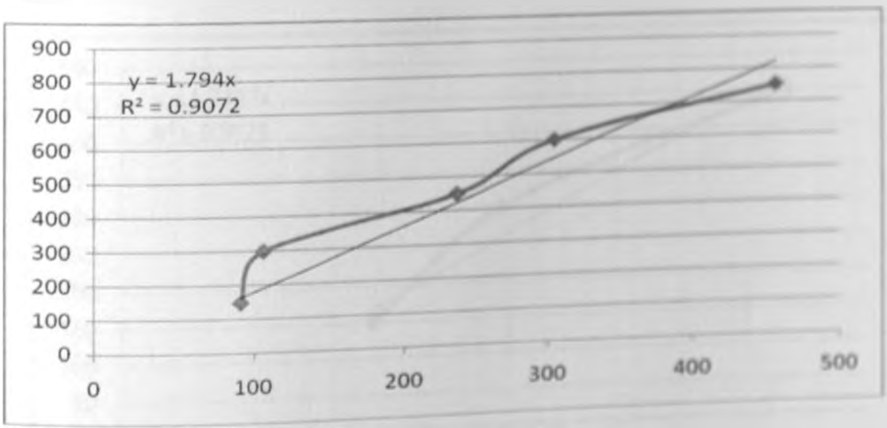
Time(μs)	Distance(mm)
56	150
96	300
136	450
206	600
272	750



velocity:2893m/s
Remark : Homogenous

KM2+660

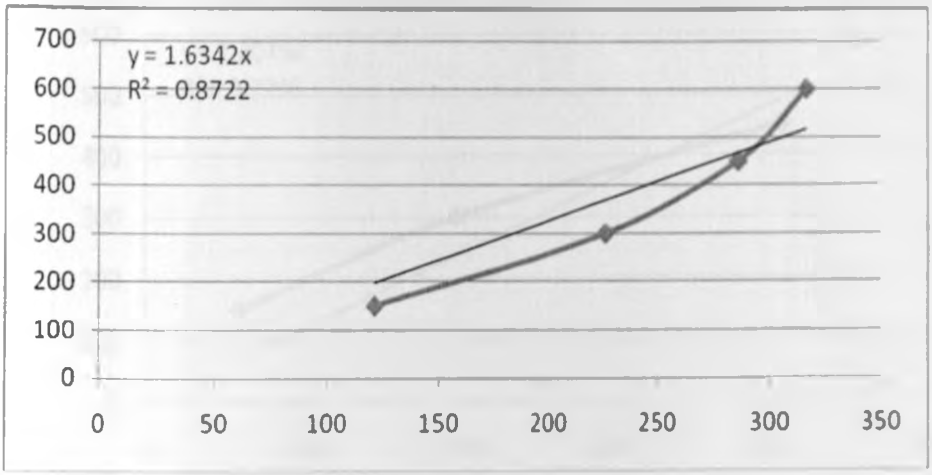
Time(μs)	Distance(mm)
91	150
106	300
236	450
305	600



velocity:1794m/s
Remark: inhomogeneous

KM2+380

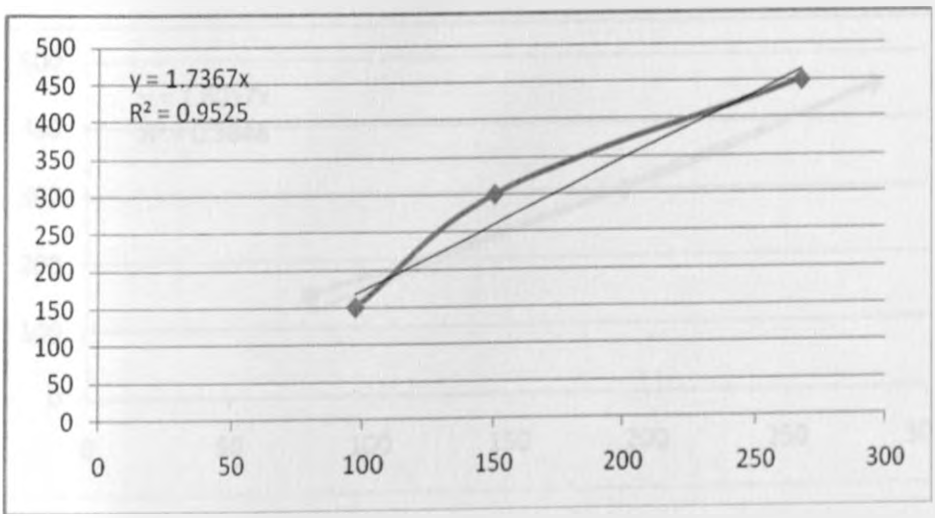
Time(µs)	Distance(mm)
121	150
226	300
286	450
316	600



velocity:1634m/s

Remark: homogenous

Time(µs)	Distance(mm)
97	150
150	300
268	450

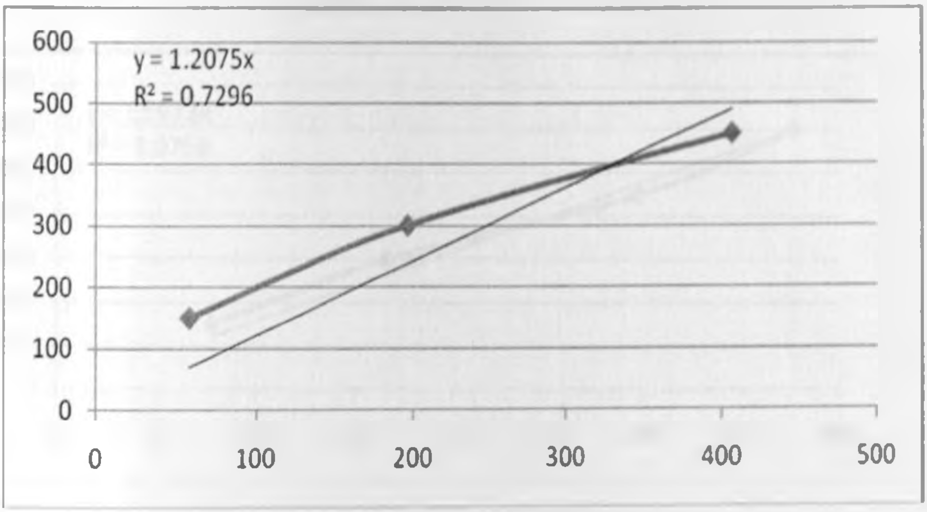


velocity:1737m/s

Remark: homogenous

KM2+300

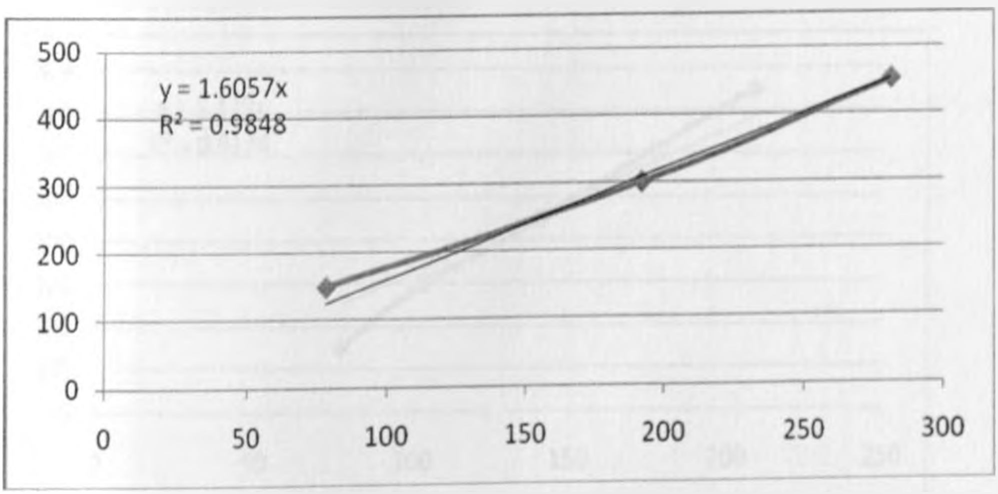
Time(μs)	Distance(mm)
57	150
197	300
407	450



velocity:1208m/s

Remark: slightly homogenous

Time(μs)	Distance(mm)
78	150
192	300
281	450

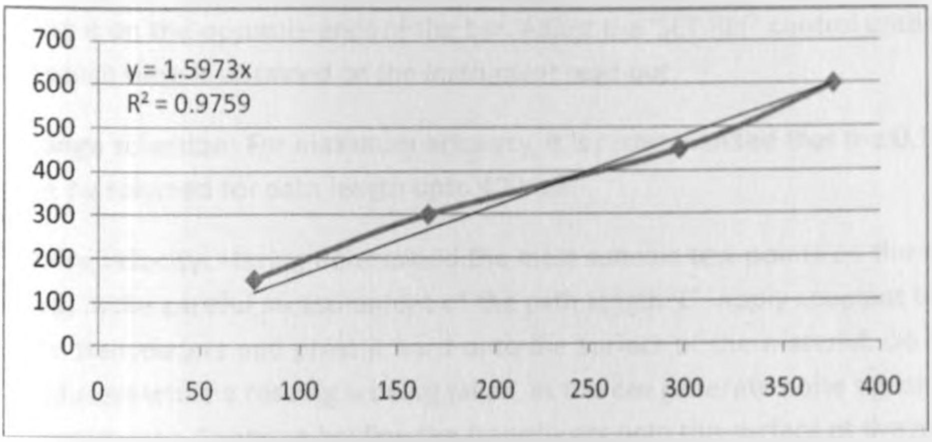


velocity:1606m/s

Remark: homogenous

KM2+290

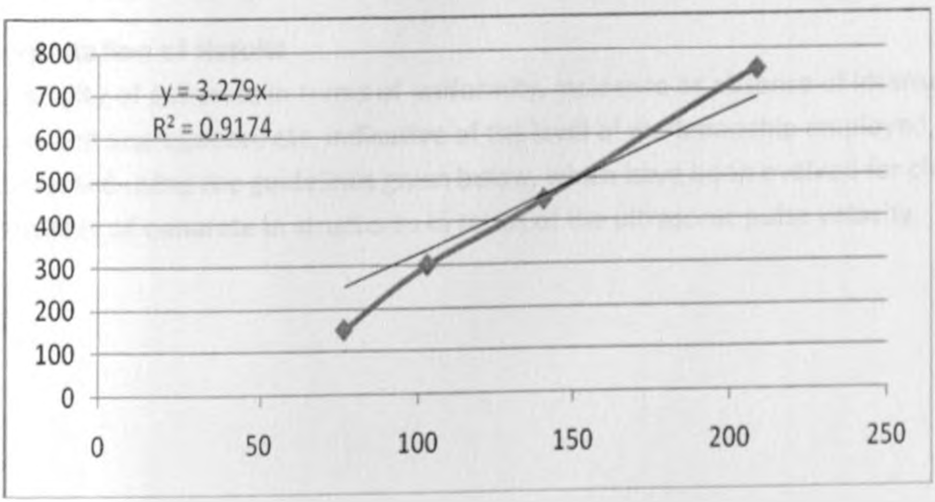
Time(μs)	Distance(mm)
76	150
166	300
298	450
376	600



velocity:1597m/s
Remark: homogenous

KM1+950

Time(μs)	Distance(mm)
77	150
103	300
141	450
209	750



velocity:3279m/s
Remark: inhomogeneous

METHODOLOGY FOR ULTRASONIC PULSE VELOCITY TESTING.

i) Preparing for use: Before switching on the 'V' meter, the transducers should be connected to the sockets marked "TRAN" and " REC".

ii) Set reference: A reference bar is provided to check the instrument zero. The pulse time for the bar is engraved on it. Apply a smear of grease to the transducer faces before placing it on the opposite ends of the bar. Adjust the 'SET REF' control until the reference bar transit time is obtained on the instrument read-out.

iii) Range selection: For maximum accuracy, it is recommended that the 0.1 microsecond range be selected for path length upto 400mm.

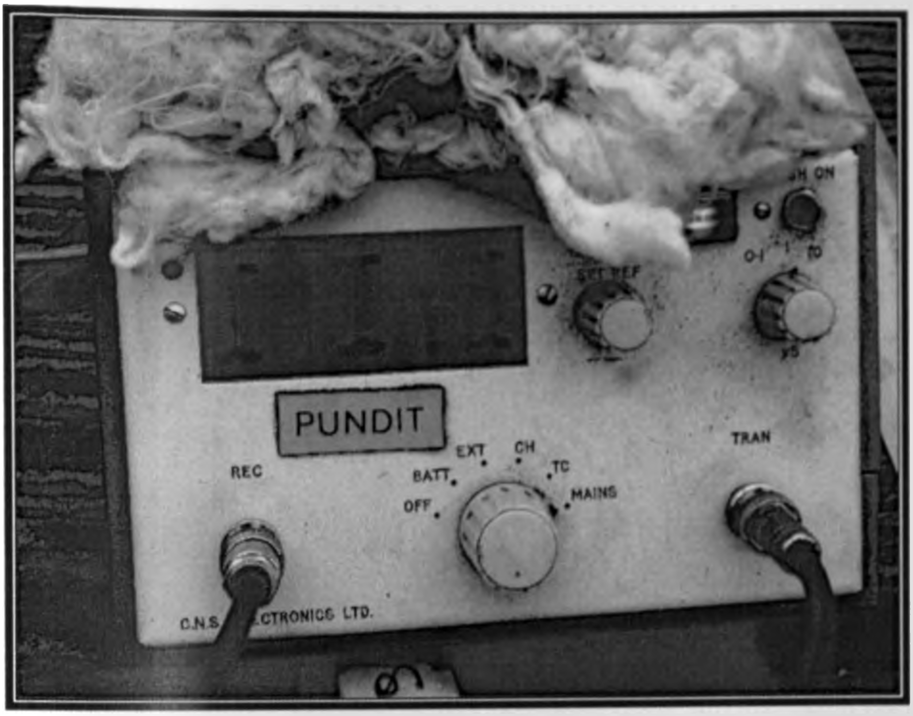
iv) Pulse velocity: Having determined the most suitable test points on the material to be tested, make careful measurement of the path length 'L'. Apply couplant to the surfaces of the transducers and press it hard onto the surface of the material. Do not move the transducers while a reading is being taken, as this can generate noise signals and errors in measurements. Continue holding the transducers onto the surface of the material until a consistent reading appears on the display, which is the time in microsecond for the ultrasonic pulse to travel the distance 'L'. The mean value of the display readings should be taken when the units digit hunts between two values.

Pulse velocity= (Path length/Travel time)

v) Separation of transducer leads: It is advisable to prevent the two transducer leads from coming into close contact with each other when the transit time measurements are being taken. If this is not done, the receiver lead might pick-up unwanted signals from the transmitter lead and this would result in an incorrect display of the transit time.

Interpretation of Results

The quality of concrete in terms of uniformity, incidence or absence of internal flaws, cracks and segregation, etc, indicative of the level of workmanship employed, can thus be assessed using the guidelines given below, which have been evolved for characterizing the quality of concrete in structures in terms of the ultrasonic pulse velocity.



Showing a display of transit time on an ultrasound equipment

APPENDIX II

PROCEDURE FOR DETERMINING PRESENT SERVICEABILITY RATINGS

II. A. Selection of the Rating Panel

The rating panel should be composed of 5 persons, who fully understand the purpose of the pavement ratings and rating method

If possible, the panel of five should be compared for rating ability against a larger group of 10 to 15 engineers. The comparisons can be made by means of a small experiment.

In this preliminary experiment, about 10 sections of pavement, each approximately 500 m long and of fairly uniform appearance, should be selected, so located that all sections can be rated during a few hours of driving. The beginning and end of each section should be clearly marked on the road surface. The condition of these sections should range from "very poor" to "very good".

Each member of the larger group and the panel of five should rate each section, using the standard rating form (see page A.3). All ratings should be tabulated and the mean ratings and probabilities of acceptance calculated for both the small panel and the larger group.

The mean ratings of the panel of five should be compared with those of the larger group. If the mean ratings consistently differ by less than about 0.3 and the probability of acceptance curves are reasonably close, then the panel is satisfactory.

The panel ratings should then be examined for consistency. The experiment should be repeated by the five members to check their ability to reproduce results. They should not be permitted to see their original ratings nor any of the results of the first experiment. In the second rating, each member should match his original results within about 0.3. There should be even less difference between the who1e panel's mean values for each section.

If the panel is not consistent or if its mean ratings are not in agreement with those of the larger group, other engineers should be substituted for at least one or two members of the panel.

II. B. Rating Rules

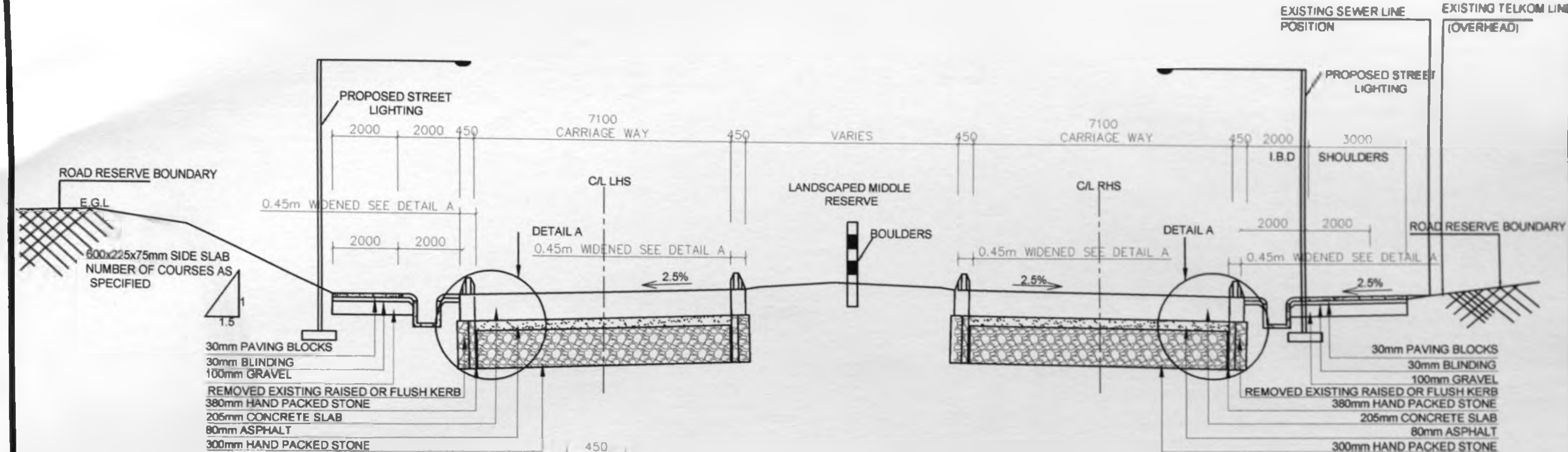
The following general rules should be observed:—

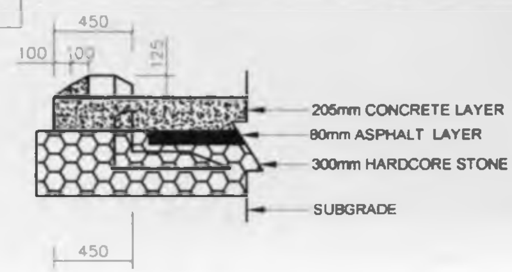
(i) The rater should consider only the present condition of the surface and consequently may rate a pavement good even if he strongly suspects it will fail in the near future.

(ii) The rating should be based on the fact that the pavement has to carry mix traffic (high-speed cars and low-speed trucks) under all types of weather conditions.

APPENDIX III

EXISTING PAVEMENT STRUCTURE IN MBAGATHI ROAD





NOTE:

1. ALL MEASUREMENT IN MM UNLESS OTHERWISE STATED
2. PLEASE NOTE THAT ACCELERATION AND DECELERATION LANES ARE NOT SHOWN
3. DRAIN WIDTH AND DEPTH VARIES
4. SEE DRAIN PROFILE FOR LOCATION WITH DRAIN AT MIDDLE OF THE RESERVE

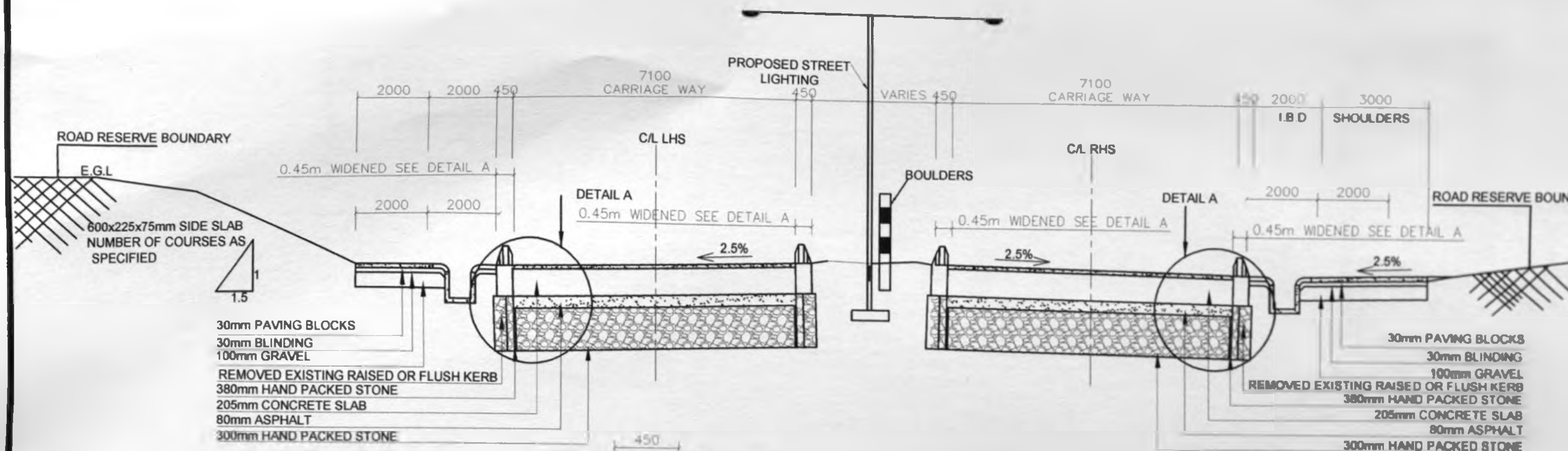
WIDENING DETAIL A

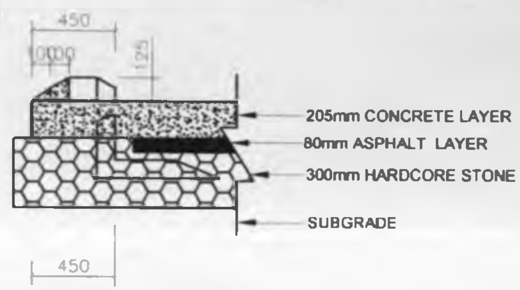
SCALE:

HORIZONTAL SCALE 1:100

VERTICAL SCALE 1:25

TYPICAL CROSS SECTION OF MBAGATHI ROAD AT CHAINAGE 750m TO 1500m





WIDENING DETAIL A

NOTE:

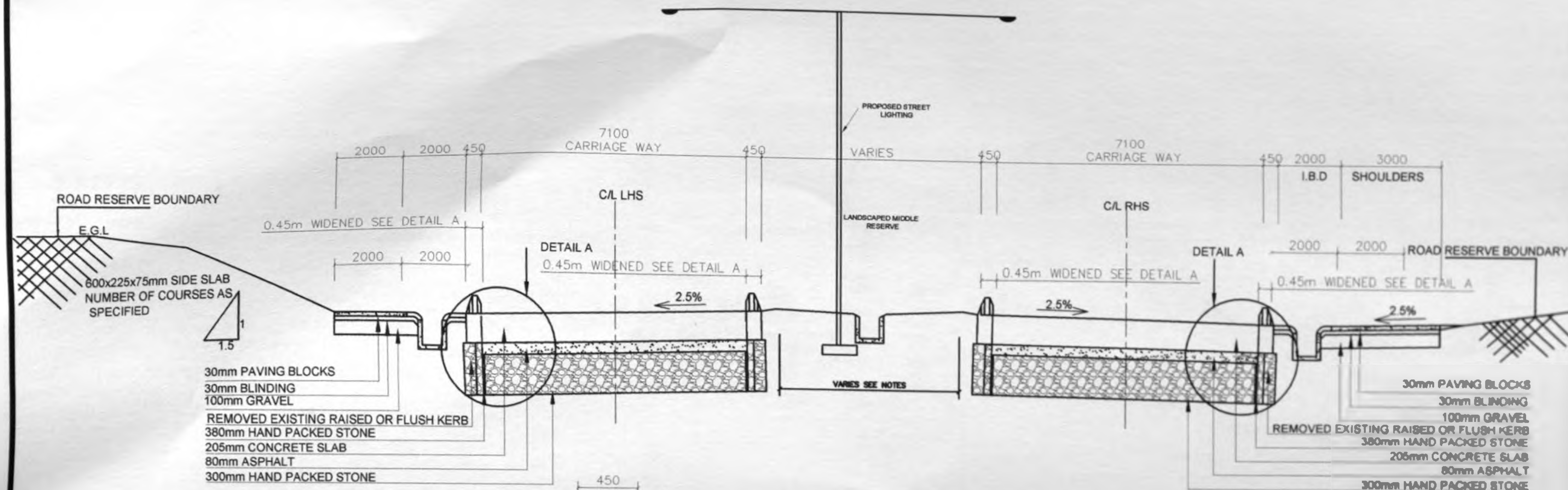
1. ALL MEASUREMENT IN MM UNLESS OTHERWISE STATED
2. PLEASE NOTE THAT ACCELERATION AND DECELERATION LANES ARE NOT SHOWN
3. DRAIN WIDTH AND DEPTH VARIES
4. SEE DRAIN PROFILE FOR LOCATION WITH DRAIN AT MIDDLE OF THE RESERVE

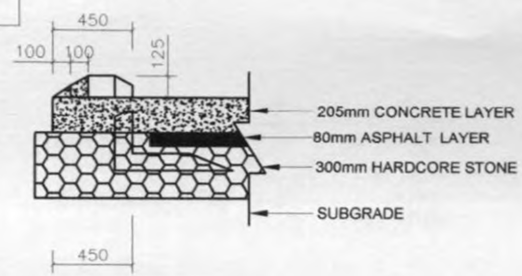
SCALE:

HORIZONTAL SCALE 1:100

VERTICAL SCALE 1:25

TYPICAL CROSS SECTION OF MBAGATHI ROAD AT CHAINAGE 1700m TO 2000m





NOTE:

1. ALL MEASUREMENT IN MM UNLESS OTHERWISE STATED
2. PLEASE NOTE THAT ACCELERATION AND DECELERATION LANES ARE NOT SHOWN
3. DRAIN WIDTH AND DEPTH VARIES
4. SEE DRAIN PROFILE FOR LOCATION WITH DRAIN AT MIDDLE OF THE RESERVE

WIDENING DETAIL A

SCALE:

HORIZONTAL SCALE 1 100

VERTICAL SCALE: 1 25

TYPICAL CROSS SECTION OF MBAGATHI ROAD AT CHAINAGE 0m TO 750m AND 2000M-3000M

APPENDIX IV

FALLING WEIGHT DEFLECTOMETER RESULTS

Falling Weight Deflectometer set up used during the research

(Includes traffic control truck at the back, the FWD equipment at centre and a tow truck in front)

MBAGATHI RD

(c) ROAD SYSTEM 2000

$1
Filename:.............. mbagathi rd.fwd
Client code:...........
Road number:...........
Name of client:........
Districtnumber:........
Road reference:........
Start reference:....... LHS-INNER LANE
Date [dd/mm/yy]:....... 31/01/12
FWD number:............ SN 214
Load plate radius [mm]. 150

	R(1)	R(2)	R(3)	R(4)	R(5)	R(6)	R(7)	R(8)	R(9)
Radial offset [cm].....	0	20	30	60	90	120	150	180	210
Tolerance [%]..........	5.00	5.00	5.00	5.00	5.00	5.00	10.00	10.00	10.00
Correction [%].........	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Filter ON:............. Cut Off Frequency = 60 Hz

$2
Chainage[m]............ 100
Lane................... LEFT
Pavement description... CONCRETE
Remarks................ START OF INNER LANE

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 105 Time: 08:34

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	D(9)	kPa	kN	Air	Sur.	Man.	Pulse time
1	87	74	68	51	38	27	19	11	8	713	50.41	22.1	19.6	20.8	24.06
2	82	70	65	49	36	26	18	11	8	673	47.57	22.1	19.6	20.8	23.84

$2
Chainage[m]............ 151
Lane................... LEFT
Pavement description... CONCRETE
Remarks................ NONE

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 105 Time: 08:39

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	D(9)	kPa	kN	Air	Sur.	Man.	Pulse time
1	198	167	152	105	71	49	37	28	23	665	46.98	17.3	20.2	20.8	23.93

2	203	171	156	108	73	51	38	30	24
682	48.20	17.6	20.2	20.8	23.81				

$2
Chainage[m]............ 253
Lane................... LEFT
Pavement description... CONCRETE
Remarks................ SLAB

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 105 Time: 08:41

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	84	79	76	67	59	51	40	30	22
684	48.37	20.9	20.3	20.8	23.68				
2	88	82	79	70	62	53	42	31	23
711	50.29	21.0	20.3	20.8	23.69				

$2
Chainage[m]............ 354
Lane................... LEFT
Pavement description... CONCRETE
Remarks................ J

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 105 Time: 08:43

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	263	217	198	137	90	57	36	22	15
667	47.12	22.5	20.5	20.8	23.66				
2	267	220	200	139	91	58	36	23	15
677	47.84	22.6	20.5	20.8	23.65				

$2
Chainage[m]............ 447
Lane................... LEFT
Pavement description... CONCRETE
Remarks................ SLAB

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 105 Time: 08:44

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	110	102	98	84	71	60	49	42	35
685	48.43	23.0	20.6	20.8	24.18				
2	107	100	96	83	70	59	50	43	35
689	48.71	23.0	20.6	20.8	23.88				

$2

MBAGATHI RD

Chainage[m]............ 554
Lane................... LEFT
Pavement description... CONCRETE
Remarks................ JNT

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 105 Time: 08:45

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	359	327	303	227	167	121	89	64	48
696	49.18	23.2	20.7	20.8	24.82				
2	350	319	295	221	164	119	89	64	48
670	47.33	23.3	20.7	20.8	24.28				

$2
Chainage[m]............ 660
Lane................... LEFT
Pavement description... CONCRETE
Remarks................ SLAB

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 105 Time: 08:46

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	149	142	138	125	113	101	95	77	62
660	46.66	23.4	20.8	20.8	24.33				
2	151	144	140	128	116	105	100	81	65
679	48.01	23.5	20.8	20.8	24.02				

$2
Chainage[m]............ 745
Lane................... LEFT
Pavement description... CONCRETE
Remarks................ J

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 105 Time: 08:47

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	282	244	228	179	140	109	86	66	53
685	48.40	23.5	20.8	20.8	24.48				
2	272	236	221	173	137	107	85	67	53
658	46.55	23.6	20.8	20.8	24.08				

$2
Chainage[m]............ 846
Lane................... LEFT
Pavement description... CONCRETE
Remarks................ SLAB

$3

MBAGATHI RD

Sequence: 1/1   No. of drops: 2 Fallheight: 105 Time: 08:49

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	118	111	107	96	84	72	63	55	46
690	48.79	23.6	20.9	20.8	24.23				
2	113	106	103	92	81	69	61	53	45
674	47.65	23.7	20.9	20.8	23.97				

$2
Chainage[m]........... 956
Lane.................. LEFT
Pavement description... CONCRETE
Remarks............... J

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 105 Time: 08:50

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	160	135	123	89	61	39	24	13	6
658	46.53	23.8	20.9	20.8	24.25				
2	160	135	123	89	60	39	24	12	6
680	48.09	23.8	20.9	20.8	23.72				

$2
Chainage[m]........... 1057
Lane.................. LEFT
Pavement description... CONCRETE
Remarks............... SLAB

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 105 Time: 08:51

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	71	64	60	47	35	23	16	12	10
659	46.59	24.2	21.0	20.8	23.91				
2	72	65	61	47	35	24	16	12	9
677	47.87	24.2	21.0	20.8	23.83				

$2
Chainage[m]........... 1155
Lane.................. LEFT
Pavement description... CONCRETE
Remarks............... SLAB

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 110 Time: 08:54

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	129	123	120	106	93	79	71	64	55
670	47.35	24.9	21.3	20.8	24.03				
2	129	123	119	106	93	79	71	64	56

667	47.15	24.9	21.3	20.8	24.04

$2
Chainage[m]............ 1217
Lane................... LEFT
Pavement description... CONCRETE
Remarks................ ALLIGATOR CRACKS

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 110 Time: 08:55

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	178	154	143	111	84	63	48	36	28
693	48.96	25.0	21.3	20.8	24.20				
2	174	151	141	109	83	62	48	36	29
680	48.06	25.0	21.3	20.8	23.95				

$2
Chainage[m]............ 1355
Lane................... LEFT
Pavement description... CONCRETE
Remarks................ SLAB AFTER BRIDGE

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 110 Time: 08:57

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	95	87	83	69	57	45	37	30	24
704	49.74	25.1	21.2	20.8	23.97				
2	94	86	82	68	57	46	38	31	25
711	50.26	25.2	21.2	20.8	23.70				

$2
Chainage[m]............ 1453
Lane................... LEFT
Pavement description... CONCRETE
Remarks................ J

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 110 Time: 08:58

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	340	301	278	199	132	78	43	23	14
690	48.74	25.5	21.1	20.8	23.93				
2	336	297	275	197	131	78	44	24	14
675	47.70	25.5	21.1	20.8	24.23				

$2
Chainage[m]............ 1555

Lane.................... LEFT
Pavement description... CONCRETE
Remarks................ SLAB

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 08:59

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	85	78	73	58	45	32	22	14	7
695	49.12	26.0	21.1	20.8	24.00				
2	85	78	74	59	46	32	22	13	7
703	49.70	26.0	21.1	20.8	24.02				

$2
Chainage[m]............ 1657
Lane.................... LEFT
Pavement description... CONCRETE
Remarks................ J

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:00

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	257	220	202	146	103	69	46	30	22
730	51.57	26.2	21.1	20.8	24.45				
2	252	217	199	143	101	68	45	31	22
699	49.42	26.2	21.1	20.8	24.01				

$2
Chainage[m]............ 1756
Lane.................... LEFT
Pavement description... CONCRETE
Remarks................ SLAB

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:02

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	155	132	121	84	57	35	20	10	2
702	49.65	26.8	21.2	20.8	23.79				
2	154	131	120	84	56	35	20	9	2
695	49.13	26.9	21.2	20.8	23.89				

$2
Chainage[m]............ 1852
Lane.................... LEFT
Pavement description... CONCRETE
Remarks................ J

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:03

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	213	187	175	134	100	72	51	34	22
715	50.51	26.9	21.2	20.8	24.32				
2	205	181	169	130	98	71	50	34	23
707	49.95	27.0	21.2	20.8	24.10				

$2
Chainage[m]............ 1958
Lane................... LEFT
Pavement description... CONCRETE
Remarks................ SLAB

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:05

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	130	124	121	105	89	69	51	37	26
713	50.37	27.3	21.2	20.8	23.71				
2	130	125	121	105	89	69	51	37	26
713	50.40	27.4	21.2	20.8	23.61				

$2
Chainage[m]............ 2059
Lane................... LEFT
Pavement description... CONCRETE
Remarks................ J

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:06

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	271	236	220	165	123	88	63	43	29
697	49.30	27.5	21.3	20.8	24.48				
2	257	224	209	157	117	85	61	42	29
675	47.68	27.6	21.3	20.8	24.20				

$2
Chainage[m]............ 2161
Lane................... LEFT
Pavement description... CONCRETE
Remarks................ SLAB

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:07

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	138	126	120	99	81	64	49	42	40
717	50.65	27.7	21.3	20.8	24.04				
2	133	122	116	97	80	63	49	42	39
714	50.44	27.8	21.3	20.8	23.76				

$2
Chainage[m]............ 2258
Lane.................... LEFT
Pavement description... CONCRETE
Remarks................. J

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:08

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	264	287	286	220	165	117	84	59	43
699	49.44	27.8	21.3	20.8	24.59				
2	257	280	279	215	161	115	84	58	43
690	48.77	27.9	21.3	20.8	24.29				

$2
Chainage[m]............ 2354
Lane.................... LEFT
Pavement description... CONCRETE
Remarks................. SLAB

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:09

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	252	282	258	186	125	75	40	20	12
712	50.31	28.0	21.3	20.8	23.98				
2	248	278	254	183	123	74	39	20	12
713	50.43	28.1	21.3	20.8	23.85				

$2
Chainage[m]............ 2461
Lane.................... LEFT
Pavement description... CONCRETE
Remarks................. J

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:10

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	308	263	238	159	97	55	29	14	7
709	50.10	28.2	21.4	20.8	24.18				
2	303	258	234	155	95	53	28	14	8
716	50.61	28.3	21.4	20.8	23.94				

$2
Chainage[m]............ 2566
Lane.................... LEFT

MBAGATHI RD

Pavement description... CONCRETE
Remarks................ SLAB

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:11

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time		
1	90	81	76	64	53	42	33	25	18
773	54.66	28.4	21.4	20.8	24.33			
2	87	78	74	63	52	41	32	24	18
717	50.66	28.5	21.4	20.8	24.01			

$2
Chainage[m]............ 2656
Lane................... LEFT
Pavement description... CONCRETE
Remarks................ J

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:12

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	231	191	174	122	83	52	31	19	12
700	49.48	28.6	21.5	20.8	24.09				
2	227	188	171	120	81	51	32	20	13
705	49.83	28.7	21.5	20.8	23.79				

$2
Chainage[m]............ 2751
Lane................... LEFT
Pavement description... CONCRETE
Remarks................ SLAB

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:14

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	88	79	74	61	49	37	29	21	19
745	52.64	28.8	21.7	20.8	24.36				
2	85	77	73	59	48	37	29	22	19
712	50.30	28.9	21.7	20.8	23.97				

$2
Chainage[m]............ 2822
Lane................... LEFT
Pavement description... CONCRETE
Remarks................ END OF LHS-INNER LANE (SLAB)

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:16

MBAGATHI RD

Drop D(1) D(2) D(3) D(4) D(5) D(6) D(7) D(8)
D(9) kPa kN Air Sur. Man. Pulse time
1 98 88 83 68 54 43 34 27 22
714 50.45 29.2 21.8 20.8 23.84
2 96 87 82 67 54 41 33 25 21
707 49.98 29.3 21.8 20.8 23.82

(c) ROAD SYSTEM 2000

$1
Filename:.............. mbagathi rd.fwd
Client code:...........
Road number:...........
Name of client:........ MATERIALS DEPT-RESEARCH
Districtnumber:........
Road reference:........
Start reference:....... RHS-INNER LANE MORTUARY ROUNDABOUT
Date [dd/mm/yy]:....... 31/01/12
FWD number:............ SN 214
Load plate radius [mm]. 150
R(1) R(2) R(3) R(4) R(5) R(6)
R(7) R(8) R(9)
Radial offset [cm]..... 0 20 30 60 90 120 150
180 210
Tolerance [%].......... 5.00 5.00 5.00 5.00 5.00 5.00
10.00 10.00 10.00
Correction [%]......... 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00
Filter ON:............. Cut Off Frequency = 60 Hz

$2
Chainage[m]............ 3034
Lane................... LEFT
Pavement description... CONCRETE
Remarks................ J

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:19

Drop D(1) D(2) D(3) D(4) D(5) D(6) D(7) D(8)
D(9) kPa kN Air Sur. Man. Pulse time
1 293 257 239 182 134 94 67 45 31
694 49.09 28.9 21.5 20.8 24.43
2 287 252 235 178 131 92 65 44 32
695 49.15 29.0 21.5 20.8 24.13

$2
Chainage[m]............ 2822
Lane................... RIGHT
Pavement description... CONCRETE
Remarks................ JOINT

$3

Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:21

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	291	255	238	181	134	94	67	46	32
697	49.26	29.1	21.3	20.8	24.54				
2	288	252	236	179	132	93	66	45	32
698	49.32	29.2	21.3	20.8	24.07				

$2
Chainage[m]............ 2703
Lane................... RIGHT
Pavement description... CONCRETE
Remarks................ SLAB

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:22

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	333	290	266	193	136	92	63	41	28
691	48.84	28.9	21.1	20.8	24.31				
2	327	284	261	189	133	91	62	40	28
701	49.58	29.1	21.1	20.8	24.03				

$2
Chainage[m]............ 2600
Lane................... RIGHT
Pavement description... CONCRETE
Remarks................ J

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:23

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	371	356	330	247	183	133	99	73	54
685	48.41	29.0	21.1	20.8	24.47				
2	361	349	324	243	181	132	98	72	55
692	48.92	29.1	21.0	20.8	24.03				

$2
Chainage[m]............ 2502
Lane................... RIGHT
Pavement description... CONCRETE
Remarks................ SLAB

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:25

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	90	80	75	58	46	33	25	17	10
692	48.95	29.3	21.1	20.8	23.99				
2	89	79	74	58	45	33	25	17	10

687	48.54	29.4	21.1	20.8	24.07				

$2
Chainage[m]............ 2403
Lane................... RIGHT
Pavement description... CONCRETE
Remarks................ J

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:26

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	410	362	332	235	157	90	51	29	17
688	48.60	29.1	21.1	20.8	24.32				
2	404	358	328	231	154	89	52	29	18
702	49.63	29.3	21.1	20.8	23.79				

$2
Chainage[m]............ 2293
Lane................... RIGHT
Pavement description... CONCRETE
Remarks................ SLAB

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:27

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	140	128	122	103	85	66	51	37	26
762	53.90	29.2	21.2	20.8	24.82				
2	136	125	119	99	82	64	49	36	26
702	49.60	29.3	21.2	20.8	24.13				

$2
Chainage[m]............ 2194
Lane................... RIGHT
Pavement description... CONCRETE
Remarks................ J

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:28

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	268	237	217	157	112	76	54	38	28
697	49.28	29.3	21.3	20.8	24.36				
2	258	228	209	151	108	75	54	39	30
696	49.21	29.4	21.3	20.8	23.97				

$2
Chainage[m]............ 2099

Lane.................... RIGHT
Pavement description... CONCRETE
Remarks................ SLAB

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:29

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	232	243	247	223	171	123	89	63	48
700	49.45	29.4	21.3	20.8	24.38				
2	225	235	239	217	167	121	89	65	50
703	49.69	29.5	21.3	20.8	23.92				

$2
Chainage[m]............ 1994
Lane................... RIGHT
Pavement description... CONCRETE
Remarks................ J

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:30

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	270	227	208	153	110	75	52	36	27
709	50.14	29.5	21.4	20.8	24.67				
2	261	219	201	148	107	74	52	37	27
692	48.91	29.6	21.4	20.8	24.21				

$2
Chainage[m]............ 1890
Lane................... RIGHT
Pavement description... CONCRETE
Remarks................ SLAB

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:31

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	184	188	189	191	156	117	85	60	43
707	49.95	29.6	21.5	20.8	24.39				
2	179	183	184	186	153	114	84	59	42
710	50.18	29.7	21.5	20.8	23.84				

$2
Chainage[m]............ 1797
Lane................... RIGHT
Pavement description... CONCRETE
Remarks................ J

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:32

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	121	100	90	64	44	29	20	14	11
755	53.40	29.7	21.5	20.8	24.01				
2	118	98	88	62	44	29	20	14	10
718	50.78	29.8	21.5	20.8	23.66				

$2
Chainage[m]............ 1697
Lane................... RIGHT
Pavement description... CONCRETE
Remarks................ SLAB

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 110 Time: 09:33

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	137	128	122	105	89	70	55	41	32
704	49.75	29.9	21.6	20.8	24.35				
2	133	123	118	102	87	69	55	42	35
709	50.11	30.0	21.6	20.8	24.05				

$2
Chainage[m]............ 1587
Lane................... RIGHT
Pavement description... CONCRETE
Remarks................ J

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 110 Time: 09:34

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	292	241	219	151	99	61	38	24	17
708	50.06	30.0	21.7	20.8	24.29				
2	295	243	221	151	100	62	40	26	18
710	50.17	30.1	21.7	20.8	23.92				

$2
Chainage[m]............ 1485
Lane................... RIGHT
Pavement description... CONCRETE
Remarks................ SLAB

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 110 Time: 09:35

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	73	65	60	45	33	22	13	8	7
727	51.36	30.3	21.9	20.8	23.84				
2	72	64	59	44	32	21	13	8	7
714	50.50	30.4	22.0	20.8	23.79				

$2
Chainage[m]............ 1398
Lane................... RIGHT
Pavement description... CONCRETE
Remarks................ J

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:37

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	119	108	97	68	47	30	17	9	5
722	51.01	30.5	22.1	20.8	23.90				
2	119	107	97	68	46	29	17	9	4
720	50.91	30.6	22.1	20.8	23.91				

$2
Chainage[m]............ 1267
Lane................... RIGHT
Pavement description... CONCRETE
Remarks................ RAIL BRIDGE

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:38

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	171	147	136	103	80	62	51	44	37
722	51.01	30.4	22.1	20.8	24.40				
2	166	144	133	102	79	62	51	42	35
716	50.58	30.5	22.1	20.8	23.98				

$2
Chainage[m]............ 1200
Lane................... RIGHT
Pavement description... CONCRETE
Remarks................ J

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:39

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	176	172	157	116	84	57	40	29	23
739	52.24	30.5	22.1	20.8	24.37				
2	170	166	152	111	81	55	39	29	24
722	51.06	30.7	22.1	20.8	24.02				

$2
Chainage[m]............ 1098
Lane................... RIGHT

MBAGATHI RD

t description... CONCRETE
.... SLAB

e: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:40

D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
kPa	kN	Air	Sur.	Man.	Pulse time			
117	105	99	83	70	56	43	33	26
52.44	30.6	22.1	20.8	24.26				
112	102	97	82	68	54	42	33	26
50.62	30.8	22.1	20.8	23.87				

ge[m]............ 991
.... RIGHT
nt description... CONCRETE
s................ J

ce: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:41

D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
kPa	kN	Air	Sur.	Man.	Pulse time			
209	173	158	115	83	57	38	25	18
50.36	30.9	22.1	20.8	24.19				
214	177	161	117	84	58	39	26	18
50.40	31.0	22.1	20.8	24.24				

ge[m]............ 901
.... RIGHT
nt description... CONCRETE
s................ SLAB

nce: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:42

D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
kPa	kN	Air	Sur.	Man.	Pulse time			
105	97	91	75	61	46	34	23	14
50.87	31.3	22.2	20.8	24.02				
105	96	91	75	61	46	34	23	14
50.55	31.4	22.2	20.8	23.97				

age[m]............ 798
.... RIGHT
ent description... CONCRETE
ks................ J

nce: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:44

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse	time		
1	204	170	155	114	83	58	43	32	27
720	50.89	31.5	22.3	20.8	24.02				
2	204	170	155	114	84	58	43	33	28
721	50.96	31.6	22.3	20.8	24.01				

$2
Chainage[m]............ 699
Lane................... RIGHT
Pavement description... CONCRETE
Remarks................ SLAB

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 110 Time: 09:46

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse	time		
1	167	163	159	147	132	103	82	63	51
711	50.22	31.2	22.6	20.8	24.41				
2	161	156	153	142	127	100	80	62	50
710	50.18	31.4	22.6	20.8	24.01				

$2
Chainage[m]............ 596
Lane................... RIGHT
Pavement description... CONCRETE
Remarks................ J

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 110 Time: 09:47

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse	time		
1	198	177	167	135	110	87	70	55	44
699	49.44	31.6	22.9	20.8	24.38				
2	193	174	164	133	109	86	69	55	45
710	50.16	31.7	22.9	20.8	24.05				

$2
Chainage[m]............ 498
Lane................... RIGHT
Pavement description... CONCRETE
Remarks................ SLAB

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 110 Time: 09:52

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse	time		
1	95	82	76	58	42	29	20	15	14
688	48.60	31.9	23.4	27.1	24.05				
2	94	81	74	56	41	29	20	15	13
681	48.13	32.0	23.4	27.1	24.05				

$2
Chainage[m]............ 396
Lane.................... RIGHT
Pavement description... CONCRETE
Remarks................ J

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 110 Time: 09:54

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	130	116	109	87	68	51	39	29	22
720	50.89	19.1	24.4	27.1	24.17				
2	125	112	105	84	67	50	39	29	22
698	49.37	19.0	24.4	27.1	24.09				

$2
Chainage[m]............ 305
Lane.................... RIGHT
Pavement description... CONCRETE
Remarks................ SLAB

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 110 Time: 09:56

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	94	88	84	73	53	37	26	18	14
704	49.73	19.5	24.8	27.1	23.80				
2	96	90	86	74	55	38	27	19	14
713	50.40	19.5	24.8	27.1	23.77				

$2
Chainage[m]............ 196
Lane.................... RIGHT
Pavement description... CONCRETE
Remarks................ J

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 110 Time: 09:57

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	122	105	96	68	48	32	21	13	9
706	49.94	28.2	25.1	27.1	24.04				
2	123	106	97	69	49	32	21	13	9
716	50.62	28.7	25.1	27.1	23.96				

$2
Chainage[m]............ 98
Lane.................... RIGHT
Pavement description... CONCRETE

Remarks................ SLAB

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 09:58

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	116	114	112	104	98	80	63	47	36
717	50.68	31.8	25.3	27.1	23.75				
2	115	113	111	103	98	80	63	47	36
710	50.19	32.1	25.3	27.1	23.77				

$2
Chainage[m]............ 49
Lane................... RIGHT
Pavement description... CONCRETE
Remarks................ J

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 10:00

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	170	149	139	111	88	67	52	41	31
709	50.12	33.3	25.4	27.1	23.98				
2	169	149	139	110	88	67	52	40	32
707	49.99	33.5	25.4	27.1	24.02				

$2
Chainage[m]............ 30
Lane................... RIGHT
Pavement description... ASPHALT
Remarks................ END OF SECTION-LANGATA JN

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 10:01

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	351	296	261	154	90	56	39	29	24
710	50.17	34.1	25.5	27.1	23.96				
2	354	298	263	156	91	57	40	30	25
717	50.71	34.2	25.5	27.1	24.01				

$2
Chainage[m]............ -41
Lane................... RIGHT
Pavement description... ASPHALT
Remarks................ ROUNDABOUT

$3
Sequence: 1/1 No. of drops: 2 Fallheight: 110 Time: 10:03

Drop D(1) D(2) D(3) D(4) D(5) D(6) D(7) D(8)

MBAGATHI RD

D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	612	496	418	215	121	70	44	29	23
701	49.57	34.2	25.6	27.1	24.66				
2	608	494	417	215	121	70	44	29	23
695	49.15	34.3	25.6	27.1	24.72				

$2
Chainage[m]............ -154
Lane................... LEFT
Pavement description... ASPHALT
Remarks................ LHS ASPHALT

$3
Sequence: 1/1   No. of drops: 2 Fallheight: 110 Time: 10:04

Drop	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)	D(7)	D(8)	
D(9)	kPa	kN	Air	Sur.	Man.	Pulse time			
1	245	207	190	138	97	65	45	31	23
692	48.93	34.2	25.6	27.1	24.36				
2	244	207	191	139	98	65	45	31	23
701	49.52	34.3	25.6	27.1	24.12				