PROJECT ID: CEET/HEM/2011-12/595

COLLEGE OF SCIENCE AND TECHNOLOGY

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SCHOOL OF ENGINEERING

(Nyarugenge Campus)

DEPARTMENT OF CIVIL ENGINEERING AND ENVIRONMENTAL TECHNOLOGY

A THESIS REPORTON

"IMPROVEMENT OF COBBLESTONE ROAD CONDITIONS VERSUS RIDING QUALITY IN THE CITY OF KIGALI"

Submitted by:

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Under the Guidance of:

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Submitted in partial fulfillment of the requirements for the award of

MASTERS OF SCIENCE DEGREE IN

HIGHWAY ENGINEERING AND MANAGEMENT

JULY 2014

COLLEGE OF SCIENCE AND TECHNOLOGY

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C E R T I F I C A T E

This is to certify that the Thesis Work entitled "Improvement of cobblestone road conditions versus riding quality in the City of Kigali" is a record of the original bonafide work done by NYANDWI Emmanuel (REG.NO: PG2011595) in partial fulfillment of the requirement for the award of Masters of Science Degree in Highway Engineering and Management of College of Science and Technology, during the Academic Year 2011-2012.

……… …………..   …………………….

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Submitted for the final defense of thesis held at College of Science and Technology on ………………………………….

DECLARATION

I hereby declare that the thesis entitled "Improvement of cobblestone road conditions versus riding quality in the City of Kigali" submitted for the Degree of Master of Science is my original work and the thesis has not formed the basis for the award of any Degree, Diploma, Associateship, Fellowship of similar other titles. It has not been submitted to any other University or Institution for the award of any Degree or Diploma.

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BONAFIDE CERTIFICATE

Certified that this thesis titled "Improvement of cobblestone road conditions versus riding quality in the City of Kigali"is the bonafide work of NYANDWI Emmanuel (REG.NO: PG2011595) who carried out the research under my supervision. Certified further that to the best of my knowledge the work reported herein does not form part of any other thesis or dissertation on the basis of which a degree or award was conferred on an earlier occasion for this or any other candidate.

ELIAS MATHANIYA TWAGIRA Ph.D

ACKNOWLEDGEMENTS

Praise and glory to the Almighty Father for his gracious help throughout all my studies, with God, every challenge has a solution.

I am grateful and express my sincere appreciation to Dr Elias MATHANIYA TWAGIRA who supervised my research, provided assistance and advice throughout the research.

Special thanks to all Lecturers involved in my studies, Prof. Kim Jenkins, Frank Montgomery, Prof. J B Odoki for their precious experience and knowledge they shared with us during the studies.

My thanks to my colleagues in Highway Engineering and Management at Kigali Institute of Science and Technology for their support and teamwork during studies and research.

Special thanks to my colleague UTABAZI Pierre Claver, working in Rwanda Transport Development Agency for his support in data collection.

I would like to express my gratitude to my Mother KANZAYIRE Domitille and my Father NTAGARA Felicien for their encouragement endowed with love and for their prayers.

Finally, I would like to thank my wife UWIMPUHWE Mariam and my sons Gwiza and Manzi for their love, encouragement and patience.

ABSTRACT

The use of stones for paving roads is not new idea; it is dating from ancient times when people used horses as a mean of transport. When vehicles started to replace horses as a mean of transport, cobblestone roads started to be declined due to their uncomfortable riding quality. The poor riding quality is mainly caused by the unevenness of the surface finishing of these roads made with irregular and bumpy stones.

In the City of Kigali, the surfacing using cobblestone have been adopted as alternative cheaper solution compared to surfacing using asphalt concrete or surface seal, because row materials are sufficiently available in quality and quantity. However, road users are not only suffering from poor riding quality of existing cobblestone roads but also from early degradation of these roads. The visual inspection conducted on existing cobblestone roads showed that these degradations are including displacement of cobbles, erosion of the surface joints, edge break, undulations and depression of the carriageway surface.

The objectives of this study was to carryout the assessment of existing conditions of cobblestone roads towards riding quality and road durability, to analyse the cause of earlier degradation of the existing cobblestone roads and to propose the improvement for the construction technique of cobblestone roads that prevents the displacement of cobblestones and that reduce the stressful conditions of roughness.

The assessment of the riding quality of existing roads has been conducted by using the bump integrator classified as a Response Type Road Roughness Measuring System (RTRRS) calibrated by MERLIN device; as a rapid, cheaper and accurate method. The riding quality was assessed in terms of roughness converted into International Roughness Index (IRI) and measurements were done at a speed of 32km/h.

The study found that the level of roughness of existing cobblestones roads is greater than 11.76 IRI, which is beyond acceptable limits of 4IRI for paved roads and 8IRI for unpaved roads as set by Rwanda Transport Development Agency (RTDA) for roads constructed in Rwanda. It was also found that the displacement of cobblestones was caused by irregularities in shape and dimensions of manually shaped stones used as surface finishing of cobblestone roads. These irregularities reduce the confinement between cobblestones and the movement of vehicle tyres displace them easily.

The improvement of the surface finishing of cobblestone roads requires the use of stones with regular shape and dimensions. It was found that manual production cannot satisfy this requirement and the research recommended the use of mechanically cut stones on the surface finishing of the road. A regular *Large paving block* of 14cm of width, 20cm of length and 14cm height was recommended for use due to its advantages in production, since more quantities of *Large paving blocks* is produced in shorter period compared to blocs of smaller dimensions. Furthermore, *Large paving blocks* have another advantage in stone laying because they can be accommodated to any laying pattern. A kerbstone was recommended to have 20cm of width, 80cm of length and 20cm of height by merging local practice with the dimensions proposed in literature surveys.

The research recommended using an arch layout as a stable laying pattern against stone displacement. Paving stones are laid on a bed course of sand of thickness 4cm after its compaction. The joints between the two adjacent laid stones must be less or equal to 2cm and must be filled with sand. During the construction of the pavement, it is required to control the alignment of laid stones and inequalities beyond ±5mm must be eliminated. The compaction of paved stones is required to increase the confinement between paved stones and this is done by using a vibrating plate of 200 to 600 kg of weight and of centrifugal force equivalent to 30KN. The use of the technique provided for in this research will benefit road users in reduction stressful conditions of driving and in reduction of vehicle operating cost.

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LIST OF SYMBOLES AND ABREVIATONS

ARRB	Australian Road Research Board
ARS	Average Rectified Slope
ASTM	American Society for Testing and Materials
B.C	Before Christ
BI	Bump Integrator
CoK	City of Kigali
COTO	Committee of Transport Officials
CPAF	Common Performance Assessment Framework
EAGI	East African Granite Industries
giz	Gesellschaftfür Internationale Zusammenarbeit
GPS	Global Positioning System
ILO	International Labour Organization
IRI	International Roughness Index
IRRE	International Road Roughness Experiment
MERLIN	Machine for Evaluating Roughness using Low-cost instrumentation
MINAGRI	Ministry of Agriculture and Animal Resources
NAASRA	National Association of Australian State Road Authorities
NCHRP	National Cooperative Highway Research Program
NCHRP	National Cooperative Highway Research Program
NZTA	Zealand Transport Agency
PI	Profile Index
PI	Profilograph Index
PIARC	Permanent International Association of Road Congresses
PV	Profile Variance
QCS	Quarter-car simulation
RMSVA	Root Mean Square Vertical Acceleration
RN	Riding Number
RTDA	Rwanda Transport Development Agency
RTRRMS	Response-type road roughness measuring systems
TRL	Transportation Research Laboratory
UK	United Kingdom

ULGDP	Urban Local Government Development Project
VOC	Vehicle Operating Cost

CHAPTER 1 INTRODUCTION

1.1. BACKGROUND

Cobblestones have been used to pave roads since ancient times. For many centuries, cobblestones were an effective means of creating a durable road that would not be washed away in harsh weather but also a mean of protecting road users against mud or dust. The first paved roads were built by the ancient Romans by creating a network of cobblestone roads to link all parts of the empire. The first ancient paved road is called *Clivus Publicus* which is ancient Roman street, built with irregularly shaped cobblestones beginning in 238 B.C (Staccioli, 2003). Romans roads were usually made of layers of sand and stone, held together with a mixture of lime (Staccioli, 2003). Roads were extremely sturdy, and some are still existing to date.

In the middle Ages, the paving of streets was important enough that in the 1350s, King Edward of UK ordered and levied tolls for the paving of the high road from Temple Bar to Westminster (Rose, 1952).

In the beginning of 19th century, cobblestones sizes were made smaller because it was found that horses that were the principal means of transport, could not step easily when there were larger spaces between the stones. By 1900, the standard size was a 10cm width to enable a horse to get a toe-hold on the spaces between the cobblestones (Gillmore, 1876). By this time, usage of cobblestones was likely coming to an end.

Throughout the 19th century, when cars began to replace horses for transportation, many roads were paved with asphalt for a variety of reasons including the desire of having a smoother, drier, cleaner, less noisy and more pleasing to the eye road (Gillmore, 1876).

The construction of cobblestone roads in the City of Kigali started in 2005 and currently covers a total length of 86 km in 2014. In recent time, the surfacing using cobblestone have been adopted as alternative cheaper solution compared to surfacing using asphalt concrete or surface seal, because row materials are sufficiently available in quality and quantity.

Cobblestone roads are constructed at low speed roads especially in residential areas where speed is restricted to 30km/h.

1.1.1. Problem statement

In recent time, the City of Kigali has adopted the use of cobblestones for paving urban roads with main objectives of reducing earth roads, minimising dust within residential areas, managing the surface storm water, avoiding soil erosion by rain water, minimise the maintenance costs and so forth. However, the riding quality of existing cobblestone roads constructed in the City of Kigali has been criticized by road users due intensive vibrations of vehicles on riding, which progressively cause damage to vehicles. This uncomfortable riding increase the vehicle operating cost due to time spent and vehicle repairs required from time to time.

Even if cobblestones are designed for low speed areas, vehicles tend to slow their speed as much as vibrations are tolerated by vehicle operators. This increases the travel time resulting increase in fuel consumption, business delays associated with a slow operating speed. Some vehicles prefer to use existing nearest asphalt roads instead of cobblestone roads and are merged into main collectors which contribute to traffic congestion, and subsequent travel delays and environmental pollution.

Existing cobblestone roads suffer from degradation at the surfacing area due to displacement of paving blocs which, in most cases, occurred at the earlier stage of the their design life. The visual inspection conducted on the Kigali cobblestone roads shows that these displacements are caused by the lack of appropriate technique for laying cobbles. Furthermore, it has been observed irregularities in shape and dimension of cobbles because they are manually made. These irregularities in shape and dimension contribute to poor interlocking of cobbles, uneven surface that resulting to their displacement due to tyres abrasion. When displacement of cobbles is not replaced on time, the confinement between cobbles reduces instantly and big sections around the point of displacement become widely deteriorated.

This research is conducted to provide new construction technique which will reduce stressful conditions exerted by the current conditions of existing cobblestone roads towards riding quality, road stability and vehicle operating cost. The technical measures to improve riding quality and to reduce costs incurred by road users in form of Vehicle Operating Cost (VOC) will focus on constructability and surface finishing as presented in the subsequent chapters.

1.2. OBJECTIVES OF THE DISSERTATION

1.2.1. General objectives

Following the need for upgrading of the urban earth roads located in residential areas of the City of Kigali by using cobblestone, the main objective of the research is to carryout technical assessment in all aspects of existing cobblestone roads (i.e. type of surfacing materials, extractions and cutting process, construction methods and finishing). The identified challenges will be addressed and technical proposal for improvements of these roads towards riding quality, road stability and reduction of VOC will be presented and discussed.

1.2.2. Specific objectives

1. To carryout technical assessment of the existing conditions of cobblestone roads of the City of Kigali towards riding quality and road durability. This includes the visual inspection, measurement and rating of the riding quality in terms of road roughness. The road roughness is measured in reference to the International Roughness Index (IRI);

2. To analyse the cause of earlier degradation of the existing cobblestone roads of the City of Kigali. This analysis is essential to provide a more stable road structure;

3. To propose the improvement for the construction technique of cobblestone roads that prevents the displacement of cobblestones and that reduce the stressful conditions of roughness.

CHAPTER 2 LITERATURE SURVEY ON CONSTRUCTION OF COBBLESTONE ROADS

2.1. INTRODUCTION

2.1.1. What is cobblestone?

In general, cobblestone refers to a rounded water-worn stone used for paving streets (Treskon, 2006). However, the term often refers to any type of paving stone bloc that can be used in road surfacing. Cobblestone road refers to the road with surface finishing made with blocks of shaped stones.

2.1.2. History of cobblestone, progress and modernity

Using stones for paving streets is not a new idea. At the beginning, the concept of the road was central to Roman cultures the saying goes, “All roads led to Rome”. The continuing existence of many Roman roads points to the care taken in constructing them. These roads were made up of multiple layers: stone chips at the bottom, topped by smaller rocks set with lime or lava dust, topped with sand or crushed stone, and finally topped with stone slabs placed in a bed of sand as shown in Figure 2.1 (Treskon, 2006).

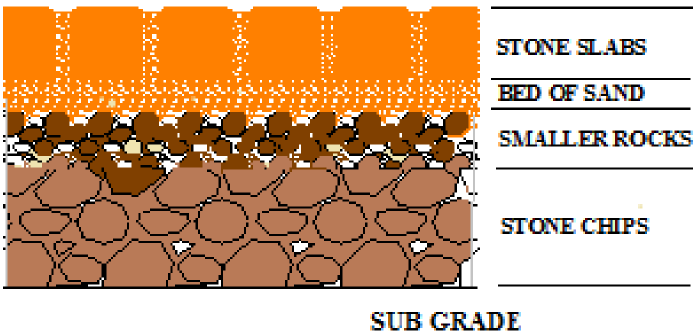


Figure 2-1: Roman paved roads (Treskon, 2006)

By the time of the Industrial Revolution, the improvement of roads was linked closely with progress in development. In 1848, the conditions of roads were considered as signs of civilization and road construction was one of the first indications of the emergence of a people from the savage state (Gillespie, 1848). Gillespie further provided a ranking of road surfaces according to their perfection:

1. Earth
2. Gravel
3. Broken Stone or Macadam Roads/Telford Roads
4. Paved Roads
5. Roads of Wood
6. Roads of Other Materials
7. Roads with Trackways (railroads)

As of 1848, traditional cobblestone streets were quite prevalent in some countries especially in the United States and Europe and some of them still exist because of their aesthetic value and linkage to the past (Williams, 1975). However not all cobblestone roads are from the days of old. Many municipalities, especially those in Europe, actively build new roads in *Belgian Block*, in order to achieve an atmosphere of old world charm.


Figure 2-2: *Evere* District road (Belgium) Figure 2-3:Paved roads at Darmstadt (German)

Throughout the 19th century, the horse played an integral role on how stone blocks evolved and on how they converged to have a specific width by1900 (Durham, 1913). The10cm width that developed was sized to enable a horse to get a toe- hold on the spaces between the stones. This was especially important in warehouse and industrial districts where horses, weighed down with heavy loads, needed especially dependable traction (Durham, 1913). A larger stone surface, while it would have been better for humans, would have been too wide for horses. This is part of the reason why stone blocks were laid out perpendicular to the street edge – the stones had to be oriented to the direction of horse movement (Treskon, 2006).

Currently, after the development of vehicles in replacement of horses as a mean of transport, the worst disadvantage of cobblestone roads is their uncomfortable riding quality (IBGE, 2011). The comfort of road users depends on shape of cobbles (surface unevenness, dimensions), to the technique of laying cobbles (joints, laying style) and to the degradation of the pavement (Areaurbanisme, 2011). Cobblestones present bumpy surface finishing because they are traditionally manually made, which makes them uncomfortable for driving as shown in Figure 2.4.

Figure 2-4: Human production of cobblestones in Ethiopia (Giz/Ethiopia, 2008)

Areaurbanisme (2011) proposed the dimensions to be adopted for the improvement of road users' comfort which are the cubical shape ranging from 4 to 6 cm of sides for the smallest dimensions, 14 to 20 cm for the largest and joints less than 2cm, but after then uncomfortable riding still persisted.

These dimensions are function of:

1. Local tradition;
2. Nature of the rock to be used;
3. Purpose of the paved area (road, sidewalks, …).

Some styles of laying cobblestones proposed by ILO (1992) such as mosaic and arch layout styles contributed only to the stability and aesthetic of cobblestone roads but not to its comfort.

Figure 2-5 : Mosaic layout (ILO, 1992)

Figure 2-6: Arch layout (ILO, 1992)

In Rwanda the unevenness of cobblestones is not the only source of uncomfortable riding. One of the causes of poor riding quality is the early degradation of the surfacing materials characterised by the displacement of cobblestones as shown in Figure 2.5 below.

Figure 2-7: Degradation at Gisimenti & Kacyiru roads

2.1.2.1.Material type for cobblestone

The material of stones was not arbitrarily chosen. Granite blocks were used because their natural cleavage points meant that they could be broken into blocks relatively easily (Bateman, 1913). In addition, Granite blocks also would not wear completely smooth over time with use as shown by Gregory (1938). In contrast, Samer (2001) recommended the good quality basalt rock due to its fine grain, glassy texture, hardness and density. However, in Rwanda, Gneiss and quartz sandstones are the most used cobblestones (STUDI, 2009).

2.1.2.2.Patented stone

Even though the development of the stone block was a gradual, generally anonymous process, occasionally an individual could be linked to some allied improvement. In 1876, Gillmore (1876) noted that a specific pavement type was especially well adapted to heavy street traffic in New York, and had been placed on Broadway south of 14th Street. This one type was referred to as the "*Guidet Pavement*" after Charles Guidet, its inventor and patent-holder.

According to the patent documents (original patent in 1869; repatent in 1870), Guidet's pavement was a large improvement on the existing Belgian or Russ pavements in use at the time. The close jointing of those pavements meant that they gave no footholds for draught animals. Guidet claimed that his pavement offered a firm foothold for animals, provided a relatively smooth surface for the wheels of vehicles, and was constructed in such a manner that the blocks would remain firmly in place (Guidet, 1870).

The 1870 patent re- issue for Guidet states that a pavement is composed of stone blocks made in the form of parallelepipeds, having their narrow edges or ends cut smooth, and their broad sides purposely cut rugged or uneven, when the blocks are arranged with their rugged surfaces transversely to the street (Guidet, 1870).

By the time of issuing the patent to Guidet's pavement, the riding quality was not an issue since the pavement was fitting the draught animal. However, after the arrival of cars in replacement of draught animals, pavements in ancient cobblestones were rejected and some of them were covered by bituminous pavement materials because they were uncomfortable for vehicles and cyclists (Areaurbanisme, 2011).

Figure 2-8: Covering ancient cobblestone road with bituminous materials (Areaurbanisme, 2011)

2.1.2.3.Historic Dimensions and names of stone blocks

By the beginning of the 20th century, the size of stone paving blocs had generally converged in important aspects, but calling all paving stones 'cobblestones' hides differences that did exist (Treskon, 2006). Some of this definitional looseness is likely attributable to the wide variety of names over time for these stones, resulting to inability of any one name to stick. The various names given to these stones did reflect real distinctions, but the slow evolution of size also precluded any one name from taking hold over time. As presented in Table 2.1, and Table 2.2 both sizing and naming for paving stones changed significantly over time.

Table 2-1: Dimensions and names of Stone Blocks, (Gillmore, 1876)

Name	Length (cm)	Width (cm)	Depth (cm)
Guidet	25.4-38.1	8.9-11.4	20.3-22.9
Russ	25.4-45.7	12.7-30.5	25.4
Belgian	12.7-17.8	12.7-15.2	12.7-17.8

Table 2-2: Dimensions and names of Stone Blocks, (Bateman, 1939)

Name of stone block	Length (cm)	Width (cm)	Depth (cm)
Durax	7.6-10.2	7.6-10.2	7.6-10.2
Standard	20.3-30.5	8.8-11.4	9.5-13.3
4 inch	17.8-27.9	10-11.4	10.2-11.4
Hassam	15.2-30.5	7.5-11.4	10.2-11.4

From the Table 2.1, Gillmore noticed that the Guidet stone was the best at fulfilling its stated goals – the *Russ stone*, at12-30cm wide, was too wide for effective spacing for draught animals, as was, to a lesser extent, the *Belgian block*.

There are two especially notable differences in the Table 2.2.The first is the decreased depth of the stones. The second is that variation in width has almost disappeared – a process that had already been in place across the United States and Europe by the turn of the century, as the dimensions of these stones came to be standardized to fit horses (Durham, 1913).

In both tables, the cubical stones (earlier the *Belgian*, later the *Durax*) are noticeably different. In North America, neither form is particular prevalent. This makes the current use of the term "*Belgian Block*" as a general descriptive term for stone blocks (Treskon, 2006).

A later stone type, the *Durax Block*, apparently first used in the Brooklyn Navy Yard in 1913, was a 10cm-cube. This mean any side could serve as the surface and the importance of perpendicular layout was irrelevant given its square-ness (Bateman, 1939). The relative lateness in its development is presumably because the added technical skill needed to properly quarry and create these stones.

The other named pavement, the *Hassam Block*, was named after the Hassam Paving company, of Worcester, Massachusetts. While the Hassam Company did have a patent (dated

August 6, 1918); it did not concern the stone block itself, but rather what lie underneath (Treskon, 2006). Specifically, the patent called for a process in which wood (placed vertically, so the strength of the wood grain was fully utilized) was used in place of finely broken stone as filling for both strength and cost-effectiveness, given that wood was cheaper than stone (Hassam, 1918). Although Table 2.2 shows the *Hassam Block* as consisting of a certain size of stone, the importance of the stone itself was not what was important to the company (Hassam, 1918).

2.1.2.4.Current dimensions of stone blocs

Currently, the most often used blocks for road-surfacing works are given in the Table 2.3 and represented on Figure 2.9, 2.10, 2.11 and 2.12.

Table 2-3: Currently used blocks for road surfacing, (ILO, 1992)

Description	**Dimensions in cm**		
	Width(w) in cm ± 1cm	Length (I) in cm	Height (h) in cm ± 1cm
Mosaic paving-blocks	7 to 10	7 to 10	8 to 10
Large paving-blocks	14	20	14
Bondstone	14	30	14
Edging curbstone	16	80	20

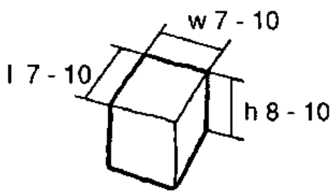


Figure 2-9: Mosaic paving blocks

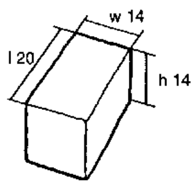


Figure 2-10 Large paving blocks

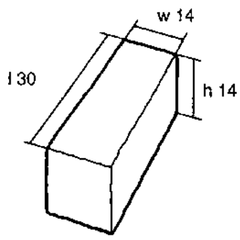


Figure 2-11: Bondstone

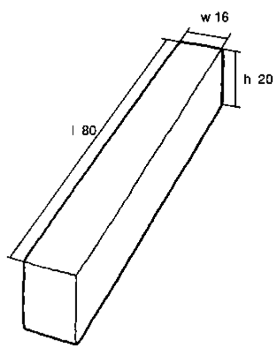


Figure 2-12: Edging kerbstone

Furthermore, Antonio (2001) proposed different morphological characteristics of stone blocks to be used in surfacing of roads and streets as presented in Table 2.4 and schematically represented in Figure 2.13. For Antonio (2001) commercial dimensions of side A ranging from 4 to 20 cm and depth C ranging from 4 to 20 cm in reference to the Figure 2.13.

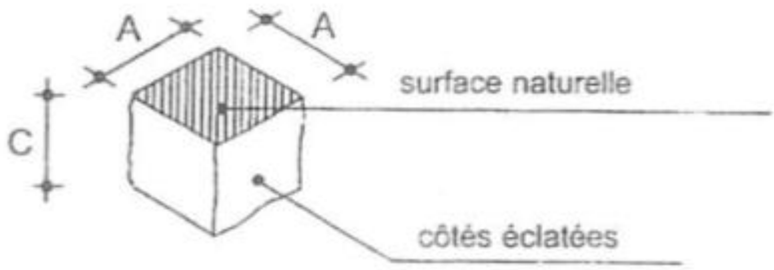


Figure 2-13: Geometry of stone blocks (Antonio, 2001)

Table 2-4: Morphological characteristics of stone blocks (Antonio, 2001)

Type of block	**Side (A)**	**Depth (C)**	**Weight Kg/m^2**	**Pieces per m^2**	**Recommended use**
4/6	4 to 7 cm	4 to 6cm	100	290-300	Only sidewalks
4/6 “slim”	4 to 7 cm	2 to 4cm	75	290-300	Only sidewalks
6/8	6 to 9 cm	5.5 to 8cm	135	155-160	Sidewalks and light vehicles
8/10	8 to12 cm	7.5 to 11cm	190	95-100	All type of vehicles
10/12	10 to 14cm	10 to 13cm	220	65-70	All types of vehicles
12/15	12 to 16cm	12 to 15cm	300	44-47	All types of vehicles
14/18	14 to 20cm	14 to 20cm	350	27-31	All types of vehicles

However, in Rwanda the commonly used paving stone has 14cmx14cmx14cm of dimensions that is almost similar to the dimensions of the *Large paving stone* except on the length.

2.1.3. Current practices

2.1.3.1.Quarrying and stone preparation

Quarrying, channelling and cutting are the steps needed to prepare the blocks (Samer, 2001). Ordinarily hand tools used for quarrying; breaking and shaping are sledgehammers, club hammers, crowbars and chisels are used by labourer. For larger stones, wedge holes are prepared along the channelled line at intervals of 150-200mm. A club hammer and grooving chisel are used to make wedge holes, 70mmlong and 40mm wide. Once this is completed, the worker can crack and break the boulder with a sledgehammer along the channelled line.

Figure 2-14: Laboaur based quarrying using crowbars   Figure 2-15:Breaking the stones with a sledgehammer (Samer, 2001)

Locally, continuous big rocks are intensively heated by using firewood before breaking them into smaller blocks with a sledgehammer. The heat applied to the rock surface reduces the cohesion of rocks particles which facilitate the rock workers to break it with minimum efforts.

Figure 2-16: Heating the rock with firewood at Mont Kigali quarry

2.1.3.2.Stone shaping

Normally, stone blocks are roughly shaped at the quarry and other shaping is carried out nearby the road site. A club hammer, template and sledgehammer are used to shape the blocks. The work norm for reshaping the blocks are usually set at 100 blocks per person per day (Samer, 2001). Once reshaping is completed, the top face is marked. This helps masons to lay the stones with the best face upwards.

Figure 2-17: Stone shaping (Giz/Ethiopia, 2008)

2.1.3.3.Stone dressing

In stone dressing, the stone blocks must be roughly smoothed on all sides. A club hammer and a chisel are used for this. Each worker can produce approximately 50 dressed blocks each day (Samer, 2001). Stone shaping and dressing may be done concurrently.

2.1.3.4.Laying stones

Before laying the stones, edge restraints or kerbstones are constructed to prevent the paved stones from moving horizontally and also restrain the sand and road base as shown in Figure 2.17. CERIB (2010) recommended a kerbstone of 200mm thick for the dressed cobblestone

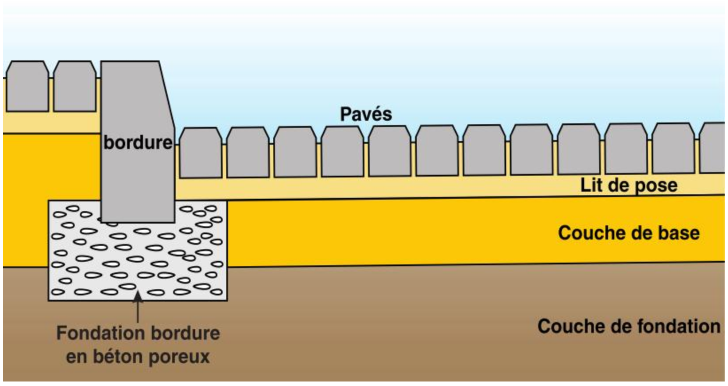


Figure 2-18 : Edge restraint for stone blocs (CERIB, 2010)

Stone blocks are laid on the bed of sand of grading 0-6mm and without contamination with soils. As the thickness of the bed sand is decreased to approximately 2cm due to stone laying operations (compaction and water spraying), Antonio (2001) recommended laying stone blocks on bed sand of thickness ranging from 6 to 8cm. Table 2.5 presents the optimum thickness of bed sand after compaction in relation to the dimensions of stone blocks.

Table 2-4: Optimum thickness of sand bed (Antonio, 2001)

Type of block	Sand bed thickness	Total thickness of the pavement
4/6 cm	4 cm approximately	10 cm
6/8 cm	5 cm approximately	12 cm
8/10 cm	6 cm approximately	15 cm
10/12 cm	6 cm approximately	18 cm
12/14 cm	6 cm approximately	20 cm
14/18 cm	6 cm approximately	24 cm

After the construction of kerbstones, stones are placed from the edges of the road to the centerline. Stones are laid so that each block settled on the sand cushion without any support from the blocks nearby and with a desired average space of 10-15 mm between blocks. This spacing is difficult to achieve due to the irregular shapes of the stones. The voids greater than 50mm between the stones are filled with broken stones packed in with a hammer. Experience showed that a skilled mason can lay stones to an acceptable standard at $6.5m^2$ per day (Samer, 2001).

2.1.3.5. Filling the joints

Once the stone blocks are laid, dry fine graded sand is swept over the paved area ensuring that all joints are full (Boral, 2007). Areaurbanisme (2011) recommend a joint of dimension less or equal to 2cm between stone blocks.

Figure 2-19: Filling the joints during the construction of Gitega road

Boral (2007) recommends to compact paved stones by using a mechanical plate compactor with a piece of carpet or rubber mat under the compactor to prevent the cobblestones from being scratched or damaged. For small areas, the compaction may be done by using a hammer and a hardwood plank as shown in Figure 2.19.

Figure 2-20: Compaction of paved stones (Boral, 2007)

2.2. DECLINE OF COBBLESTONE AND RISE OF ASPHALT

Cobblestones played a central role in the urban environment at the turn of the 20th century. The size, layout, and even spacing between these stones all had developed so as to increase their general utility (Treskon, 2006). However, with the development of the automobile cobblestones lost their utility (Bateman, 1939) , but this is not the only explanatory factor because even before the ascendance of the automobile, cobblestone streets were already being paved over by asphalt and other similar pavements throughout cities(Treskon, 2006).

Gillmore, a Lieutenant Colonel in the Army Corps of Engineers, writing a dissertation on paving and roads in 1876, extolled a number of the virtues of asphalt paving: there was no mud or dust such as associated with dirt roads, it was comparatively noiseless (stone was notoriously loud), and by reducing the force of traction also reduced wear-and-tear. While not being as good as stone for animals gaining toeholds, asphalt did not become slippery with wear, either (Gillmore, 1876).

2.2.1. Decline of cobblestone associated to non-technical reasons

There were other, non-technical reasons for declining cobblestone as well. Gillmore (1876) cited the example of the City of Paris, which justified repaving roads with asphalt on four grounds:

1. The want of connection and homogeneity in the elements of which the stone paving is composed,
2. The incessant noise produced by them,
3. The imperfect surface drainage which they secure by reason of which the foul waters are not carried off but filter into the joints,
4. The ease with which they can be displaced, and used for the construction of barricades, breastworks and rifle pits in time of civil war.

Reasons 2 and 3 relate to the basic civil engineering technocratic concerns, and were two weaknesses that even a highly evolved form of cobblestone could not overcome (Treskon, 2006). However, reasons1 and 4 are different: 1 is an aesthetic argument, and 4 is a civil-control one, since Gillmore's book was written in 1876, only a few years after the events of the Paris Commune. Figure 2.20 below shows the use of cobblestone as barricade during the events of the Paris Commune.

Figure 2-21: Barricade in Paris (Treskon, 2006)

The aesthetic argument, taken as the most important argument listed in the Parisian context (it was number ‘1’ on the list), was also central to the growing popularity of asphalt. Streets with paving stones were paved that way for useful reasons in mind. Visual continuity, and to a lesser extent, noise, were not central concerns in an industrial context (Treskon, 2006). However, in a residential setting, the advantages to other paving methods became more important. As an 1874 London report stated: “*asphalt is the smoothest, driest, cleanest, most pleasing to the eye, and most agreeable for general purposes, but wood is the most quiet* (Gillmore, 1876).”

In line with these aesthetic and noise issues, it is not surprising that cities were paving over streets even before the rise of automobile culture. With development and refinement of these new paving techniques, the use of stone paving blocks was an anachronism (Treskon, 2006).

Still, many stone streets remained: in alleys, in occasional industrial streets, or even hidden beneath layers of asphalt. Even though the stones themselves may have been obsolete surfacing, they still made good foundations. This happened to be the same chance that had befallen the original, rounded, cobblestones as more “perfect” stone blocks were introduced throughout the 19th century (Gillmore, 1876).

2.2.2. Decline of cobblestone associated to vehicle speed

After the introduction of asphalt pavement, it was found another unintended consequence of asphalts. It was possibly too effective at encouraging automobile movement and speed (McCluskey, 1979). The growing centrality of automobiles in city life led to a reassessment of the value of the small scale and bumpy texture of paving stones. Their very small scale and bumpiness had advantages. Small scale creates a psychological deterrent to high speeds, and the physical bumpiness also slows down traffic. Cobblestones found new utility as traffic-calming instruments (McCluskey, 1979).

2.2.3. Drawback of cobblestone associated to construction cost

Cobblestones are characterized by a remarkable long-term durability. For McCluskey (1979), this durability means a couple of things: one, they are difficult to get rid of and two, they can be reused and refit a number of times and into a number of places. The drawback of this durability is their expense. In developed countries of Europe and America, stone paving blocks had always been expensive due to labour cost, even when common in the 19th century; they were the highest cost surfacing material, even if their maintenance costs were lower than wood or asphalt. This has attracted the advancement in asphalt technology and asphalt plant.

However, in developing countries of Africa, some cities have adopted to do cobblestone road construction rather than build roads made of asphalt for the following benefits (ULGDP, 2012):

1. Generation of employment for the local population targeting the disadvantaged group. Employment focuses largely on unemployed youth and women, and includes the disabled;
2. Activation of the local economy as all resources are locally available and produced. All the projects expenditures circulate within the city. It does not depend on imported oil as asphalt does;
3. Creation of small enterprise that will grow and diversify in the future, helping increase capacity at grass root level;
4. Creation of a work culture, particularly among the unemployed;

5. Ease of maintenance and lifespan (cobblestone roads have a longer lifespan than asphalt roads).

2.2.4. Reinterpretation of cobblestone

As the 20th Century progressed, stone blocks became more and more associated with a past (McCluskey, 1979). This historical linkage, by way of Williams, plays a central role in the reinterpretation of the aesthetic value of stone pavement vis-à-vis asphalt (Williams,1975). The aesthetic value attributed to the paving stone changed because its role had changed. In the end of the 19th century, it was one of the most prevalent forms of street paving, and especially so in urban industrial districts. Asphalt did not have these associations, but did have associations with progress and cleanliness, which reflected back upon how people perceived the pavement aesthetically (McCluskey, 1979).

By the 1970s, these associations with paving stones had been weakened, and they could be aesthetically re-interpreted within a new cultural context. What is notable is that while the aesthetic valuation of asphalt in the 19th century was based on progress and the future, the aesthetic reevaluation of paving stones in the 20th century is based on historicity and the past (McCluskey, 1979).

2.2.5. Current meanings of cobblestone

Because of their durability, granite paving stones never completely disappeared from the urban landscape (Treskon, 2006). Often as not, they were simply covered up by asphalt, to be used as just one more foundational layer for the road. Stone roads often remained uncovered in industrial districts, where residents would not complain about the bumpy roads, and where asphalt pavement would get torn up by trucks too quickly to make it worth the municipality's expense and time. Cobblestone streets still exist in places that have not been reinterpreted (Treskon, 2006).

There is also a trend of extending the aesthetic reinterpretation of cobblestones outside of historic neighborhoods. In New York, numerous sidewalk and park paving projects have used these stone blocks as landscaping features. As shown in Figure 2.21, it can be seen that cobblestone are not used as actual paths but as edging. People go on the stone surface to sit down and to stop moving, not to get somewhere else (Treskon, 2006).

Figure 2-22: Stone Paving in Battery Park City, Manhattan (Treskon, 2006)

2.3. ROAD ROUGHNESS

2.3.1. Riding quality

The riding quality is publicly known as road smoothness with adequate skid resistance as any other single quality of a modern pavement. The driver often thinks of a smooth riding pavement as a good pavement and a rough riding pavement as a poor pavement. From the time when human being first began to travel from one place to another "road roughness" has been a factor in the safety and comfort of the traveler (Holloway, 1956).

Since safety and comfort depend to a great extent upon a smooth riding surface, highway engineers have for many years made a concerted effort to construct and to maintain pavements that are as smooth riding as possible. Considerable progress has been made in this direction with the development of the automobile from the early uneven models to the present day high speed, low clearance model. Road equipment manufacturers have also spent large amounts of time and money in the development of road building equipments to eliminate some of the irregularities inherent with hand construction methods (Holloway, 1956).

The American Society of Testing and Materials standard E867 defines roughness as the deviations of a pavement surface from a true planer surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads and drainage (Brown et al., 2010). Road roughness can also be defined as the distortion of the road surface which imparts undesirable vertical accelerations in the vehicle that contribute to an undesirable or uncomfortable ride.

A "rough" pavement not only gives rise to effects unpleasant to the passengers but also is detrimental to the vehicle. Smooth riding pavements mean greater mileage with less fatigue, less damage to car-goes, and lower operating costs for the vehicle. The "road roughness" produces also impact to surfacing pavement and this contributes to the early deterioration of any type of pavement. Thus, the subject of road roughness is a major economic factor to every country.

2.3.2. Pavement roughness characteristics

Longitudinal characteristics of the road roughness are measured long the wheel paths of the road surface. The PIARC Technical Committee on surface characteristics has specified frequency domains for various longitudinal characteristics as given in Table 2.4.

Table 2-4:PIARC specification of frequency ranges for road surface characteristics (Discornet, 1990)

Surface characteristics	**Frequency range**	
	Wave length	**Wave number (cycle/m)**
Microtexture	<0.5mm	> 2,000
Macrotexture	0.5 – 50 mm	20 – 2,000
Megatexture	50 – 500 mm	2 – 20
Roughness	0.5 – 50 mm	0.02 – 2

In Table 2.4, *Microtexture* is defined as irregularities with wave length less than 0.5mm and is associated with asperities on the surface of individual pieces of aggregate which makes up the road surface (Discornet, 1990). While instruments are becoming available for measuring microtexture in the field (Yandell and Sawyer, 1994), such measurements are not usually made on a routine basis.

Discornet (1990) defines *Macrotexture* as irregularities with wave lengths between 0.5 and 50mm and is related to the size, spacing and arrangement of aggregate particles at the surface. It is typically specified and measured as a texture depth. Historically, texture depth was measured using the sand patch method. This was a time consuming procedure which limited its application to special investigations. Developments in laser measurement technology over the last decade have resulted in vehicle mounted measuring systems which measure texture depth at highway speeds so that macrotexture can be routinely collected at network level.

Megatexture is defined by Discornet (1990) as surface irregularities with wave lengths in the range 50 to 500mm. Because megatexture wave lengths are of the same order as tyre contact patch lengths, it can induce undesirable tyre-surface interaction mechanisms. Historically, megatexcture data have not been collected on a routine basis, but this is now feasible using laser measuring technology.

Discornet (1990) defines *Roughness* as surface irregularities in the 0.5 to 50m wave length range. This corresponds to the frequency range which induces relative motion in road vehicle suspension systems over a reasonable range of operating speeds. Road roughness provides a good, overall measure of pavement and correlates well with subjective assessments.

2.3.2.1. Measure of the pavement roughness

In the early years of highway building, the roughness of a pavement was estimated by eye or with as traight-edge (Holloway, 1956). These visual measurements could not be recorded and were always subject to the variation of opinions of observers. Straight-edge measurements were satisfactory for short sections of road, but were slow and not adapted to use in measuring considerable mileage of pavement. With the rapidly increasing mileage in the highway system, it soon became apparent to highway engineers that there was a need for a more accurate and rapid method for measuring and recording road roughness.

Because of this need, engineers concerned with highway construction and maintenance sought to develop equipment with which to measure and compare pavement smoothness or roughness. As a result many methods and devices were developed and used.

A variety of equipments has evolved over the years to measure pavement roughness. This equipment varies among the highway agencies and has a range of design characteristics which are dependent on intended use. Perera and Kohn (2002) found that devices could be divided into the following five categories:

- Response-type road roughness measuring systems(RTRRMS);

- High-speed inertial profilers/profilometers;
- Profilographs;
- Light-weight profilers;
- Manual devices.

2.3.2.2. Review on roughness equipments

Most highway agencies, until the mid-1980s, used the response-type road *roughness measuring system* (RTRRMS) to measure road roughness (Brown *et* al., 2010). These devices measure the response of the vehicle to the road profile, using transducers to accumulate the vertical movement of the axle of the survey vehicle with respect to the vehicle body as shown in Figure 2.22. The measurement directly reflects the user's feeling of ride quality.

A variety of RTRRMSs have been developed over the years, but all are disadvantaged by the fact that the results are influenced by the suspension characteristics of the vehicle and the measuring speed, and do not provide pavement longitudinal profile for spectral analysis (Brown et al., 2010). With the advent of inertial profilers, the use of the RTRRMS has diminished for roughness measurements and most types of pavements.

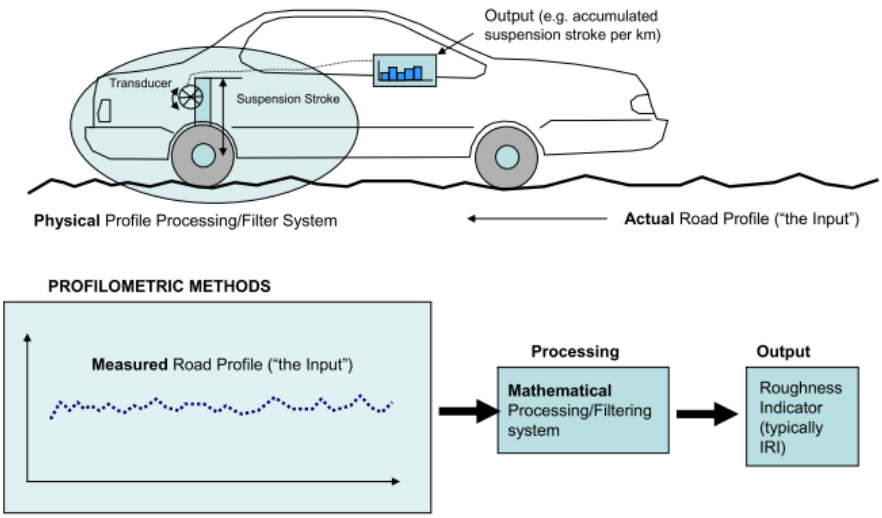


Figure 2-23 Response Type Road Roughness Measuring System (COTO, 2007)

Inertial road profiling is a technology that began in the 1960s at the General Motors Research Laboratory (Spangler *et* al., 1964). The number of countries that have adopted high-speed inertial profilers to collect roughness data on their highway networks has shown a remarkable increase in the last two decades. High-speed profilers collect pavement condition data at highway speeds and record sufficient data to monitor pavement profile.

The principal components of a *high-speed profiler* are laser-based height sensors, accelerometers and an accurate distance measuring system (Brown *et* al., 2010).The height sensors record the distance to the pavement surface from the vehicle. The accelerometers, located on top of the height sensors, record the vertical acceleration of the sensor. Double integration of the vertical acceleration gives the vertical displacement of the vehicle. The longitudinal profile is then derived from these two height measurements. The distance measuring system ties the measurements to a reference starting point. The non-contact height sensors currently used in profilers are either laser or ultrasonic waves. Figure 2.23 shows a typical high-speed profiler with 13 laser sensors.

Figure 2-24 : Laser profiler (Brown, 2010)

In contrast with the high-speed laser profiler, a *profilograph* consists of a rigid beam or frame with a system of support wheels at either end and a central wheel. This wheel is linked to a strip chart recorder or a computer that records the movement of the wheel from the established datum of the support wheels .The major difference between the high-speed profiler and the profilograph is that they use different reference planes and different filtering to record the surface profile. The profiler is a network survey device while the profilographs are widely used to evaluate the as-constructed smoothness of new pavements and overlays (Brown *et* al., 2010). Figure 2.24 shows the California profilograph.

Figure 2-25 Truss-type California profilograph (Brown, 2010)

Light-weight profilers (Figure 2.26) are increasingly used to evaluate new construction. The term lightweight profiler refers to devices in which a profiling system has been installed on a light vehicle, such as a golf cart or an all-terrain vehicle. The profiling system in the light-weight profilers is similar to ones used in high-speed profilers. The profile data is commonly used to simulate a profilograph over the pavement section, generate a profile index (PI) and identify bump locations. The profile data can also be used to compute other roughness indices, such as the IRI or ride number (RN).

Figure 2-26 Lightweight profiler and non-contact sensor (Brown, 2010)

Manual devices such as the dipstick, ARRB walking profiler (Figure 2.27) and rod and level are generally used to collect profile data to verify or validate the data collected by high-speed road profilers (Gregory, 2006). The rod and level is perhaps the most accurate method of obtaining the true elevations along a pavement surface and its standard reference procedure is described in the ASTM E-1364. The dipstick and walking profilers usually use an inclinometer between two support feet or multiple wheels to compute the surface profile. The general procedure to verify the output from road profilers is to collect profile data at test sections using a manual reference device, then compute a roughness index such as the IRI from that data and compare the result with the output from the road profiler.

Figure 2-27: Walking profiler with cowl on and Laptop Mounted (Greggory, 2006)

In this category of manual devices, a MARLIN shown on Figure 2.27 is widely used as a simple roughness measuring machine that has been designed for use in developing countries.*Merlin* stands for a Machine for evaluating roughness using Low-cost Instrumentation (Cundill, 1999). It can be used to calculate roughness directly, or for calibrating other more automated roughness collection devices, such as vehicle mounted response meters. The device consists of a metal frame 1.8m in length, a bicycle tyre at the front, a foot at the rear, and a moving foot mid-way to record the mid-chord deflection (Gregory, 2006).

Figure 2-28 Merlin machine for evaluating roughness (Greggory, 2006)

Rod and level illustrated in Figure 2.28 is a high precision manual device for measuring the road profile. The operational principal of precision rod and level is very similar to thatof a normal rod and level operation, as used for surveing. It should be noted that the test methodrequires at leasttwo persons and is time consuming and labourintensive (COTO, 2007). A typical profile measurement willinvolve around 260 readings, and an experiencedteam can profile approximately 600 m per day.The method is therefore only suited formeasuringprofiles on calibration sections or forresearch or construction control purposes (COTO, 2007).

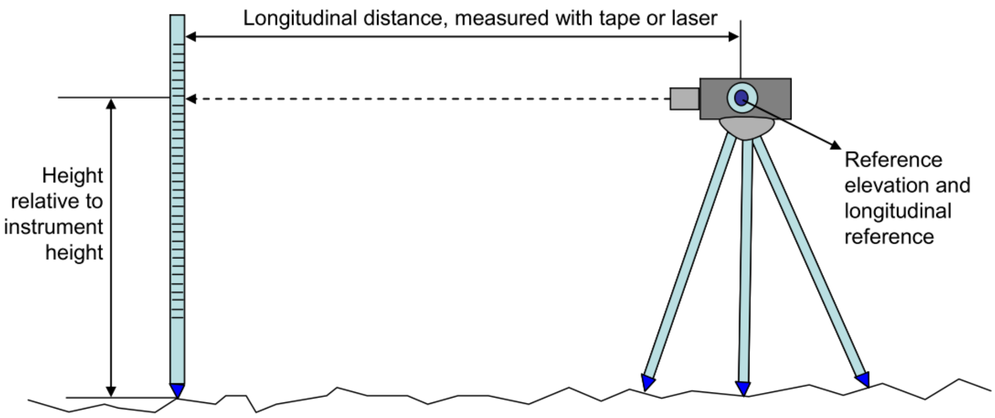


Figure 2-29: Operation of the precision rod and level (Sayers and Karamihas, 1998)

Among the above mentioned road roughness measuring equipment, the Response Type Road Roughness Measuring System (RTRRMS) was used in this research due to the following reasons;

1) Its availability in Rwanda for this research;

2) It can survey larger networks in short time;

3) It is cheaper for academic research;

2.3.2.3.Classification of roughness measuring devices

The World Bank sponsored International Road Roughness Experiments (IRRE) conducted in Brazil in 1982, categorised the related equipment into four classes, namely Class I, II, III, and IV as shown in Table 2.5(Kumar, 2010).

Table 2-5: Classification of roughness measuring devices (Kumar, 2010)

Class	**Description**	**Equipment**
Class I	This class gives higher standard accuracy which enables measurement of pavement surface profile	Rod and Level, TRRL beam, Dipstick, Merlin and Walking Profiler
Class II	Profile is measured as the basis of direct computation of International Roughness Index (IRI), very less accuracy compared to Class I measurement.	APJ Trailer, Profiling devices not capable of Class 1 accuracy
Class III	Response Type Road Roughness Measuring System (RTRRMS)	Automatic road unevenness Recorder/ Bump integrator/ Vehicle mounted Bump Integrator
Class IV	Method used in situation where higher accuracy is not essential	Ride experience, Visual inspection

It can be seen in Table 2-5 that the bump integrator used as road roughness measuring device in this research is of Class III. The bump integrator is less accurate compared to Class I and Class II measuring devices but it is more practical in surveying larger network in short time. However, prior calibration of the bump integrator using Class I measuring device such Merlin, is required before usage.

2.3.2.4. Factors influencing road roughness measurement

Although technology has been available for measuring road roughness for decades, gaps still prevail. A prevailing sense exists in the road community that if every agency measured the same road with their device, they would obtain a variety of different results. Brown (2010) argued that errors in profile and discrepancies between measurements arise from variations in equipment, inappropriate operating procedures, and aspects of the pavement surface and the surrounding environment. In a good number of cases, these factors interact to reduce their repeatability and accuracy.

Karamihas *et* al (1999), found 34 individual factors that affect longitudinal profile measurement studied in a National Cooperative Highway Research Program (NCHRP) as given in Table 2.6.

These factors fall into five broad categories:

- profiler design;
- surface shape;
- measurement environment;
- profiler operation;
- driver and operator proficiency

Table 2-6 : Factors influencing roughness measurement (Karamihas *et* al 1999)

Factor	Accuracy	Agreement	Repeatability	Interpretation	Factor	Accuracy	Agreement	Repeatability	Interpretation
Profiler Design	×	×		×	Measurement Environment	×			
Sample Interval	×				Wind	×			
Computation Algorithm	×				Temperature	×			
Automated Error Checking	×				Humidity	×			
Height Sensors	×	×			Surface Moisture	×			
Accelerometers	×				Surface Contaminants	×			
Longitudinal Dist. Meas.	×				Pavement Markings	×			
Number of Sensors				×	Pavement Color	×			
Lateral Sensor Spacing		×			Ambient Light	×			
Surface Shape	×		×		Profiler Operation	×		×	×
Transverse Variations			×		Operating Speed	×			
Daily Variations			×		Speed Changes	×			
Seasonal Variations			×		Lateral Positioning			×	
Surface Texture	×				Triggering			×	
Pavement Distress	×		×		Longitudinal Positioning			×	
Curves	×				Segment Length				×
Hills and Grades	×				Freq. of Data Collection				×
					Profiler Sanity Checks	×			
					Profiler Driver and Operator	×		×	

Even though errors may result from roughness measurement due to several factors indicated in Table 2-6, in this research however, measures for anticipating errors that may occur during road roughness surveys were taken by using a properly calibrated bump integrator, sampling of road sections that comply with the method of roughness measurement and by using an experienced survey vehicle and driver on the local network.

2.3.3. Characterising road roughness

Commonly used roughness indices include the International Roughness Index (IRI), Profile Index/Profilograph Index (PI), Ride Number (RN), root mean square vertical acceleration (RMSVA), National Association of Australian State Road Authorities (NAASRA) count and Profile Variance (PV).

2.3.3.1. International Roughness Index (IRI)

The IRI is a widely accepted measure of roughness developed by the World Bank in the 1980s and adopted by the World Road Association (Permanent International Association of Road Congresses: PIARC) (Brown et al., 2010). The IRI is a numerical representation of a road profile, designed to replicate the traditional roughness measures obtained from response-type road roughness measuring systems.

The computation of the IRI is based on a mathematical model called the quarter-car model. This mathematical model calculates the suspension deflection of a simulated mechanical system with a response similar to a passenger car. The simulated suspension motion is accumulated and then divided by the distance travelled to give an index with units of slope (m/km). The mathematical simulation carried out by the computer program is shown schematically in Figure 2.29.

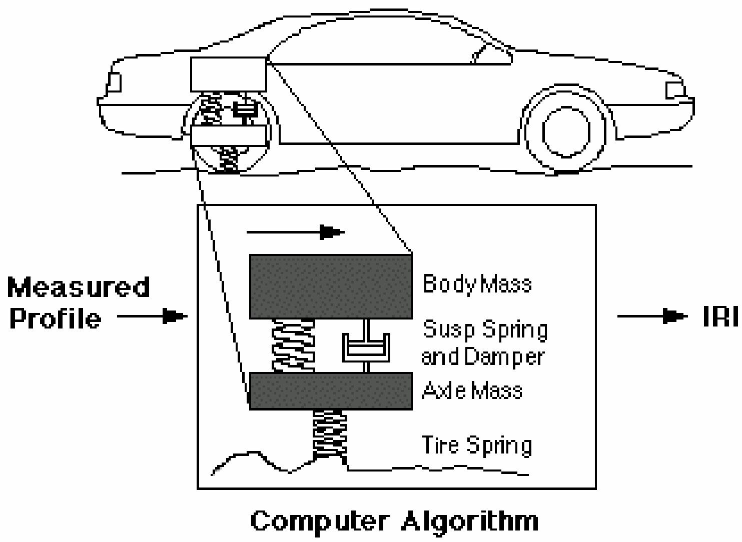


Figure 2-30 : Graphical presentation of algorithm used to compute IRI (Sayers and Karamihas 1997)

The IRI is so-named because it was a product of the International Road Roughness Experiment (IRRE), conducted by research teams from Brazil, England, France, the United States, and Belgium for the purpose of identifying such an index. The IRRE was held in Brasilia, Brazil in 1982 and involved the controlled measurement of road roughness for a number of roads under a variety of conditions and by a variety of instruments and methods (Sayers et al., 1986).

The roughness scale selected as the IRI is the one that best satisfies the following criteria, while also being readily measurable by all practitioners (Sayers et al., 1986):

- Stable with time;

- Transportable (measurable with equipment available in most countries, including developing countries with less technical support);
- Valid (reproducible with various types of equipment from all over the world, on all types of road surfaces without bias);
- Relevant (indicative of road condition as it affects user cost, ride quality, and safety)

The IRI is a standardized roughness measurement related to those obtained by response-type road roughness measurement systems (RTRRMs), with recommended units: meters per kilometer (m/km) = millimeters per meter (mm/m) = slope x 1000. The measure obtained from a RTRRMS is called either by its technical name of Average Rectified Slope (ARS), or more commonly, by the units used (mm/km, in/mi, etc.). The ARS measure is a ratio of the accumulated suspension motion of a vehicle (in, mm, etc.), divided by the distance travelled by the vehicle during the test (mi, km, etc.).

The reference RTRRMs used for the IRI is a mathematical model, rather than a mechanical system, and exists as a computation procedure applied to a measured profile. The computation procedure is called a quarter-car simulation (QCS), because the mathematical model represents a RTRRMs having a single wheel, such as the BI Trailer and BPR Roughometer (Michael et al., 1986). When obtained from the reference simulation, the measure is called reference ARS (RARS). This type of measure varies with the speed of the vehicle, and therefore, a standard speed of 80km/h is specified in the definition of the IRI. Thus, the more technical name for the IRI is RARS80, indicating a measure of average rectified slope (ARS) from a reference (R) instrument at a speed of 80km/h (Michael et al., 1986).

Sayers (1995) proposed assumptions for calculation of IRI:

1. IRI is computed from a single longitudinal profile. The sample interval should be not larger than 300 mm for accurate calculations. The required resolution depends on the roughness level, with finer resolution being needed for smooth roads. A resolution of 0.5mm is suitable for all conditions;
2. The Profile is assumed to have a constant slope between sampled elevation points;
3. The profile is smoothed with a moving average whose base length is 250mm;

4. The smoothed profile is filtered using a quarter car simulation, with specific parameter values (Golden Car), at a simulated speed of 80km/hr (49.7 mi/hr);
5. The simulated suspension motion is linearly accumulated and divided by the length of the profile to yield IRI. Thus, IRI has units of slope, such as in/mi or m/km.

The underlying IRI algorithm is a series of differential equations, which relate the motion of a simulated quarter-car to the road profile. The IRI is the accumulation of the motion between the sprung and unsprung masses in the quarter-car model, normalized by the length of the profile. Greggory (2006) express it mathematically as follows:

$$IRI=\frac{1}{L}\int_{0}^{\frac{L}{s}}|z_s - z_u|dt \qquad \text{Equation 2.1}$$

Where, IRI = the roughness in IRI m/km;

L = the length of the profile in km;

S = the simulated speed (80 km/h);

Z_s= the time derivative of the height of the sprung mass and;

Z_u= the time derivative of the height of the unsprung mass.

The International Roughness Index (IRI) is used as the reference unit of measurement, due to its wide use throughout the world. For this reason, the World Bank established roughness threshold shown on Figure 2.31 (OECD, 2001). As some countries use other tools such as longitudinal profilometers (Belgium), pavement rating by wave bands (Portugal) or Maintenance Control Index (Japan), these results had to be converted to the IRI.

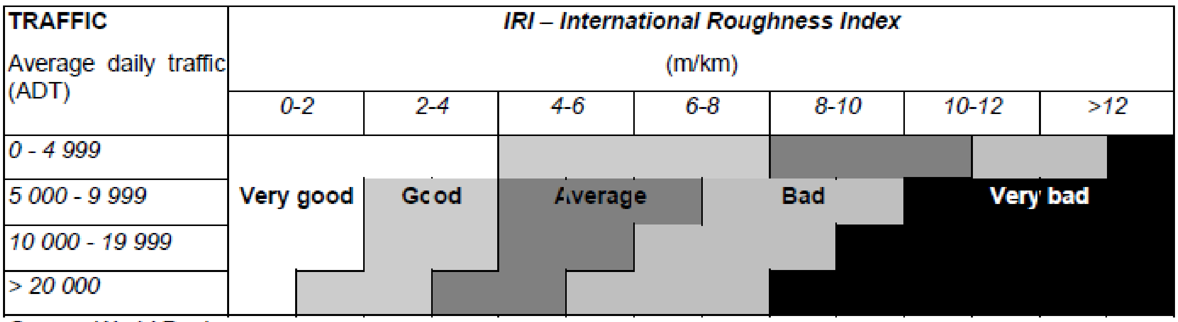
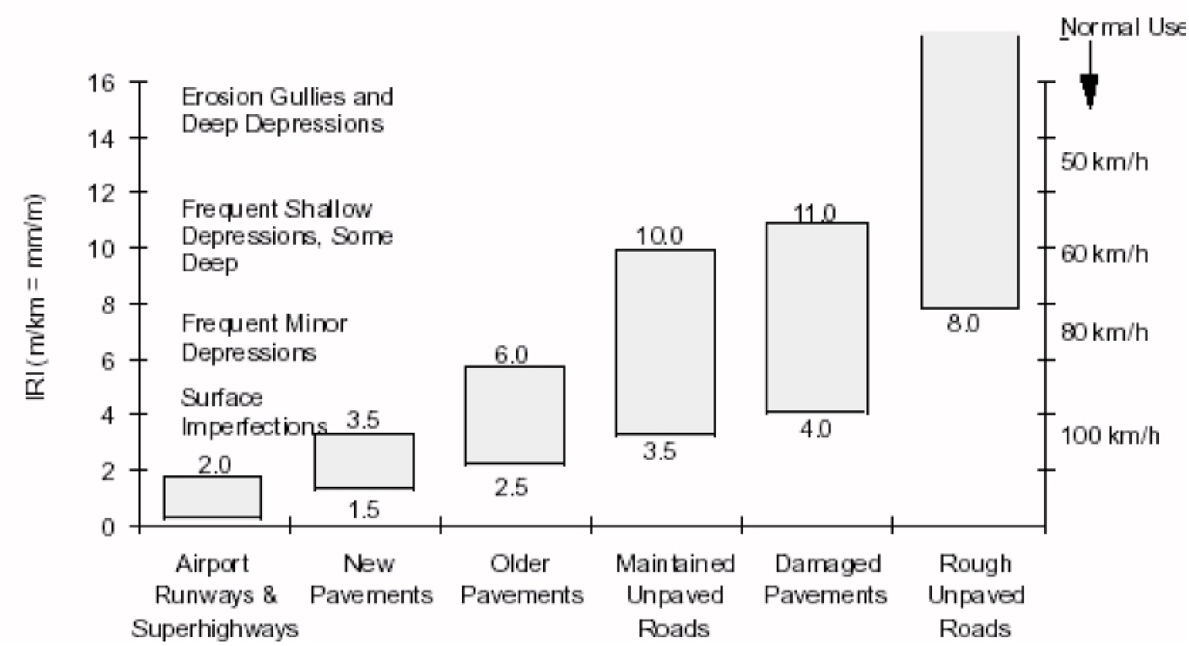


Figure 2-31 IRI threshold matrix (World Bank, OECD paper 2001)

In addition to the above IRI threshold matrix, the World Bank provided an open-ended IRI scale for different category of road pavement as shown on Table 2.7.

Table 2-7: IRI Roughness Scale (Sayers et al., 1986)



In Rwanda, the roughness less or equal to 4 IRI on paved roads is stated to be GOOD, whereas the roughness greater than 4 IRI is BAD in reference to Rwanda Transport Development Agency (RTDA) guidelines. For unpaved roads, the roughness less or equal to 8 IRI means a GOOD condition of roughness, whereas the roughness greater than 8 IRI is BAD (RTDA, 2013).

2.3.3.2. Profile Index/Profilograph Index (PI)

Profilers have been widely used to measure the smoothness of new pavements. The profilers provide a trace of the pavement profile, which is reduced to obtain the PI. This in turn is used to judge the roughness of the pavement. The first step in trace reduction is outlining the trace. This averages out spikes and minor deviations caused by rocks, texture, dirt or transverse grooving. The next process in trace reduction is to place the blanking band on the profile trace. A blanking band is typically 0.2 inches (5 mm) wide but some agencies have used 0.1 inch (2.5 mm) wide bands, while some use zero blanking bands (Brown et al., 2010). Excursions, which extend in height more than 0.03 inches (0.8 mm) above the blanking band for at least 0.08 inches (2 mm) in horizontal distance (i.e. 2ft on the pavement) will be recorded on the profile and rounded to the nearest0.05 inches(1.3 mm) (Ibid).

Perera and Kohn (2002) expressed the sum of the recorded heights within a given segment as the PI for that segment. This is expressed in terms of inches per mile or in meters per Kilometer.

The PI was not selected as appropriate index of expressing the road roughness in this research because the available roughness equipments were not able to express the measured roughness in terms of PI. The PI is only measured by using a profilograph or any other profiler device that can record the road profile; however, these devices are not locally available for use.

2.3.3.3.Ride Number (RN)

The RN is an index intended to indicate ride quality on a scale similar to the PI. The RN uses a scale from 0 to 5. This scale was selected, as it is familiar to the highway community. The RN is a nonlinear transform of the PI that is computed from profile data. The PI ranges from 0 (a perfectly smooth profile) to a positive value proportional to roughness. The PI is transformed to a scale that goes from 5 (perfectly smooth) to 0 (the maximum possible roughness) (Brown et al., 2010).

The RN was not selected as appropriate index of expressing the road roughness in this research because the available roughness equipments were not able to express the measured roughness in terms of RN, which has many similarities with PI.

2.3.3.4. Root Mean Square Vertical Acceleration (RMSVA)

Hudson (1983) defines a RMSVA as a statistic that measures the root-mean-square of the rate of change of the grade of a pavement longitudinal profile. The method was named RMSVA for two reasons. First, the computation is equivalent to the second derivative of the height with respect to the time of the object in contact with the profile moving at a constant horizontal speed. Such computation yields a vertical acceleration of the object. Second, a series of acceleration values result from the discrete elevation points; therefore, a root mean square of these values is computed to arrive at a single value.

The RMSVA can be computed for any base length. The capacity provides the technique with a strong ability to distinguish between the various components of the roughness that exists in a pavement longitudinal profile.

The measure of the road roughness in terms of RMSVA requires profilometer devices that were not available for use in this research; therefore, the surveyed road roughness was not expressed in terms of RMSVA.

2.3.3.5. National Association of Australian State Road Authorities (NAASRA)

Since the early 1970s, road pavement roughness has been measured in Australia and New Zealand using the NAASRA roughness meter. This is a standard mechanical device for measuring road roughness by recording the upward vertical movement of the rear axle of a standard station sedan relative to the vehicle’s body as the vehicle travels at a standard speed along the road being tested (Austroads, 2000).
The NAASRA meter is classified as a response-type road roughness measuring system (RTRRMS).

Austroads (2000) define NAASRA roughness that counts per kilometer as the cumulative total relative upward displacement between axle and body of a standard vehicle, registered in units of counts per kilometer of distance travelled at either of two principal standard speeds, 80km/h or 50km/h. One NAASRA roughness count corresponds to a measured axle-to-body separation of 15.2 mm. Although NAASRA roughness meters have been successfully used for many years, there are particular concerns about maintaining their calibration, and about repeatability and reproducibility of the results. Outputs are very dependent on vehicle suspension characteristics (eg, shock absorbers, springs, tyres) and the speed of travel.

Due to the drawback associated to calibration, repeatability and reproducibility in measuring road roughness in NAASRA, this roughness index was not used in this research. Instead, the response type device composed with the bump integrator calibrated with Merlin was used to express the road roughness in terms of IRI. When calibrated with a Class I measuring device, the BI provides the roughness index measurement in IRI with a proper repeatability and reproducibility.

2.3.3.6.Profile Variance (PV)

In the United Kingdom, ride quality is assessed by Profile Variance (PV), obtained by calculating the differences between the profile and its moving average over selected moving average lengths (Board, UK Roads, 2003). Three moving average base lengths (3m, 10m and 30m) are commonly used and accordingly, the road profile data is processed to compare the actual profile and the moving average of the profile over these three lengths. The results are presented in terms of the square of the difference between the moving average of the profile and the measured profile.

Profile variance is also used by some Commonwealth countries, for instance Singapore and New Zealand. In a research report prepared by Jamieson (2008) and published by the New Zealand Transport Agency (NZTA), developed a methodology based on road profile variance to identify and prioritize treatment of road sections that promote poor ride quality for heavy commercial vehicles. In his research, Jamieson (2008) found that high values of profile variance, particularly in the 10m and 30m wavelength data, generally corresponded to locations exhibiting poor truck ride quality in the measured on-road data. However, there were many sections with high-profile variance that did not show poor truck ride. If profile variance is to be used successfully to select and prioritize road section for remedial work the profile variance must first be modified or filtered according to geometry factors and/or vehicle speed (Jamieson, 2008).

Even if the PV is a widely used in UK and some Commonwealth countries, this research has not adopted to express the road roughness in terms of PV because it involves other maneuvers of modifying and filtering the profile variance according to road geometry factors and/or vehicle speed which are not required in the used research method. The research adopted to express the roughness in IRI which is directly measured by the BI calibrated by Merlin.

2.3.3.7.Summary of commonly used roughness indices

The table 2.8below shows a summary of the roughness indices mentioned above, together with their underlying principles and short descriptions.

Table 2-8 : Commonly used roughness summary indices (Doug et All, 2010)

Index	Principle	Description
IRI	Quarter-car simulation	A statistic that summarizes the roughness qualities impacting on vehicle response based on the quarter-car vehicle model at a standard simulation speed of 80km/h.
PI	Profilograph simulation	A smoothness index that is computed from a profilograph trace.
RN	Ride comfort estimation	A calculated roughness index, between 0 and 5, that approximates the mean panel rating for a pavement surface.
RMSVA	Vertical acceleration simulation	A statistic that measures the root mean square of the rate of change of the grade of a pavement longitudinal profile.
NAASRA count	Response accumulation	Cumulative recording of the upward vertical movement of the rear axle of a standard station sedan relative to the vehicle's body as the vehicle travels at a standard speed along the road being tested.
PV	Moving average filtering	A statistic presented in terms of the square of the difference between the moving average of the profile and the measured profile.

During this research, the roughness index used is IRI because of the following reasons:

1) It is commonly adopted in Rwanda for the road roughness measurements

2) It is related on the data computation for the selected measurement method of RTRRMS

3) It can easily be understood in comparison with the existing measurement

2.3.4. Calibration of a RTRRMS

Since response type devices do not measure the actual road profile, the IRI cannot be calculated directly. Instead, the output of these devices is calibrated or adjusted to enable a relatively accurate assessment of the IRI to be made. The reference device to calibrate a response type device should be able to match the criteria of a Class 1 device, as specified in ASTM E1365-95. This standard also defines the longitudinal sampling distance and vertical resolution of the device. The Precision Rod and Level, Merlin, Dipstick and ARRB Walking Profiler devices are capable of meeting these criteria (COTO, 2007). In this study the bump integrator used as response type device was calibrated by using the Merlin as a Class 1 profiling device.

2.3.4.1. Calibration equations MERLIN-Bump Integrator

The relationships between the Merlin scale and the BI and IRI scales were developed by Cundill (1991) as follows:

For all road surfaces *IRI =0.593+0.0471 D* Equation 2.2
42< D<312(2.4< IRI< 15.9)

Where IRI is the roughness in terms of the International Roughness Index measured in metres per kilometre and D is the roughness in terms of the Merlin scale measured in millimetres.

BI = -983 + 47.5 D (3.2)
42< D <312 (1,270< BI < 16,750)

Where BI is the roughness as measured by a bump integrator towed at 32 km/h and is expressed in millimetres per kilometre.

When measuring on the BI scale, greater accuracy can be achieved by using the following relationships for different surface types (Cundill, 1991):

Asphaltic concrete
BI = 574+ 29.9 D Equation 2.3
42< D <177 (1,270< BI < 5,370)

Surface treated
BI= 132+37.8DEquation2.4
57 < D <124 (2,250 < BI < 4,920)

Gravel
BI = -1,134 +44.0 D Equation 2.5
77< D <290 (2,010< BI < 12,230)

Earth
BI = -2,230+ 59.4 DEquation2.6
84 < D < 312 (2,940 < BI < 16,750)

These relationships are shown by Cundill (1991) in graphical form in Figures 2.31and 2.32. The equations were derived over the range of roughness shown and care should be used if extrapolating outside these ranges.

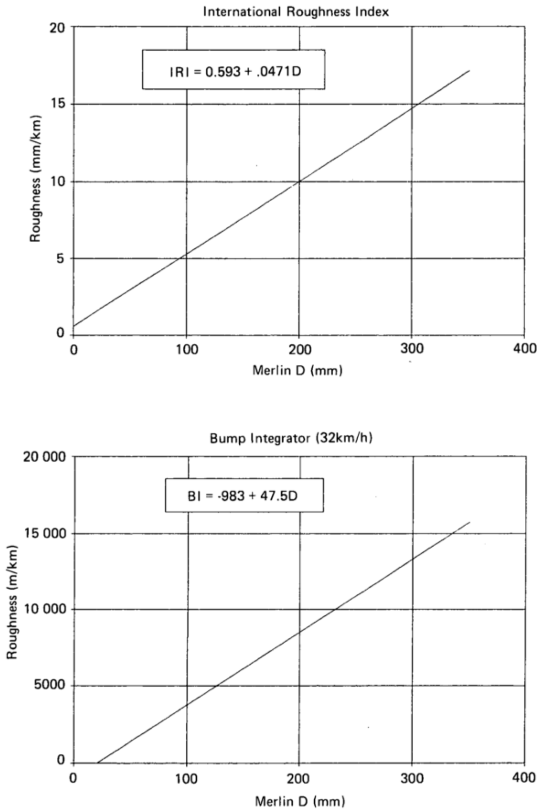


Figure 2-32Calibration relationships (Cundill, 1991)

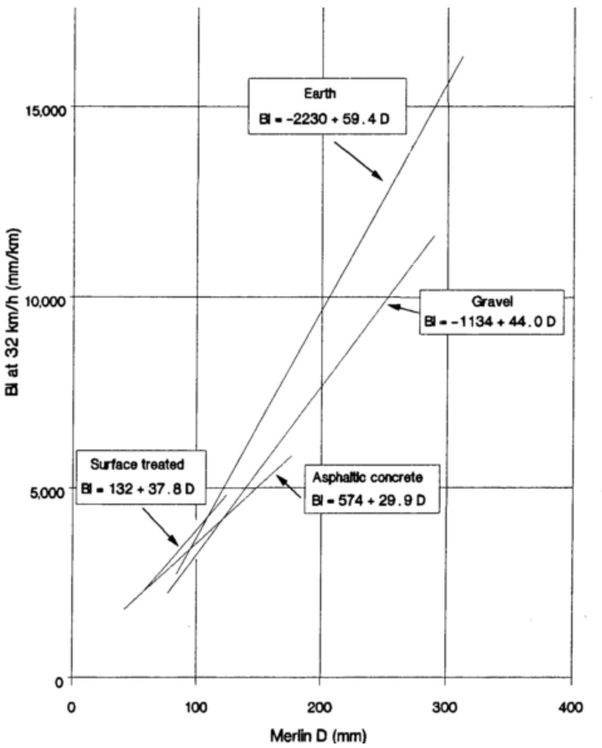


Figure 2-33Calibration relationships for the BI-different surface types (Cundill, 1991)

2.3.4.2.Calibration and control testing of the response type devices

The South African Committee of Transport Officials shows guidelines for setting requirements for the calibration procedure as presented in Tables 2.9 and 2.10.

Table 2-9 Guidelines for calibration acceptance criteria (COTO, 2007)

Parameter	Recommended Criteria for Application Type :	
	Lower Reliability	**Higher Reliability**
Scatter plot showing IRI (Y axis) versus measured parameter	Examine scatter plot and ensure that the relationship is linear, and that the data range covers the range of expected IRI values on the network.	
Coefficient of determination (R) for regression	Greater than 0,950	Greater than 0,975
Standard error for regression	0,45	0,35

In the above table 2-9, the regression refers to a simple regression analysis. For this regression, the dependent (Y) parameter is the reference IRI over each 100 m of the calibration section. The independent (X) parameter is the measured parameter over each 100 m segment, and for each repeat. Thus, there should be one data point for each repeat measurement on each 100 m segment of each calibration section.

Table 2-10 Calibration Requirements for Response Type Devices (COTO, 2007)

Parameter	Recommended requirements for application type	
	Lower Reliability	**Higher Reliability**
Number of sites for each relevant roughness range	2	3
Minimum site length	200m	200m
Repeat runs per site	4	5

Table 2.10 shows that, the calibration procedure requires a number of repeat measurements on each calibration section.

It is recommended that the criteria shown in Table 2.10 be used as a guideline for accepting or rejecting a calibration for a response type device. The surveyor should compile a calibration report in which the details of the calibration are clearly defined. The calibration report should show the following:

- Details of calibration sections used;

- Table showing average device count or measure for each run over each section, with the average and standard variation for of all runs over each section, versus the reference IRI;
- Evaluation summary sheet, showing compliance to the criterion shown in row 3 of Table 2.10 (repeatability per calibration section);
- Regression summary sheet showing compliance to regression criteria as shown in rows 4 and 5 of Table 2.9.

2.3.4.3.Validation of positioning equipment

The required fields surveys depend on the survey objectives but should include aspects such as section name, start km, end km, GPS coordinates, region, direction, survey date, IRI (for one or more wheel paths) and measurement speed.

The GPS should be validated by comparing coordinates at several benchmark locations set out and maintained by a surveying authority. It is recommended that this check be carried out at five to ten benchmark locations.

GPS benchmark locations should be roughly 1 km apart, and the dynamic accuracy of the GPS should be checked by completing several survey loops through the benchmark positions. These checks should preferably also be performed over more than one day, and at different times of the day.
The GPS coordinates should be within 5 m of the vertical and horizontal benchmark values, and for repeat dynamic measurements this accuracy should be achievable 90 per cent of the time (COTO, 2007).

2.3.4.4. Control testing

Control testing should be performed from time to time during the survey to ensure that the calibration is still relevant for the device. Control testing is specifically used to determine if there is a gradual shift in the measurements taken by the device, or if the repeatability of the device has changed.

Control testing can be performed on the calibration sections, or special control sections can be identified in different areas within the network. For the control tests, the reference IRI is not needed, since the control check is performed against the raw measurement of the response type device (typically counts per km or metre).

Control testing should be performed on a regular basis as part of the survey process. If calibration sections are not used for control testing, then control sections can be identified at various locations within the network, which will minimize the travel time to control sections. Control sections should be at least 400 m in length, and preferably more than 800 m.

The values measured for the control sections after calibration should be used as reference values for future testing. For each control section, the IRI values should be determined over each 100 m segment. These IRI values will then be used as control values.

Control testing performed during the survey should consist of a once-off remeasure of the IRI over each 100 m segment, and each 100 m IRI value should then be compared with the control IRI values. Each 100 m, IRI values should be within a specified percentage of the reference values on each control site. A maximum deviation of 5 to 10 per cent (using the reference values as a basis) can be considered as a guideline for control testing.

The frequency of testing is basically a compromise between the cost of control testing (which not only delays the survey, but requires additional time and travel), and the risk of remeasuring all data collected since the last control test. As a rough guideline, COTO (2007) recommends to perform the control testing at five stages (equally spaced in terms of length surveyed) during the survey process.

2.4. CONCLUSIONS

Cobblestones played a significant role in the urban environment before 20th century but with the development of the automobile, cobblestones started to lose their utility due to reasons associated to poor riding quality. For these reasons, asphalt roads started to replace cobblestone roads in many countries.

Furthermore, granite paving stones never completely disappeared from the urban road development because of their utility and durability and some still exist in industrial districts, where residents have no complain on their bumpy texture. From the time of the rise of asphalt, researchers were not interested in improvement of these types of roads, especially on the aspect relating to riding quality. This justifies the need for a study for the improvement of the riding quality of cobblestone roads in other countries where they are economically competitive.

The roughness measurements were conducted by using a Response Type Road Roughness Measuring System (RTRRMS) in this research as available, rapid, cheaper and accurate method. This method enabled to express the measured roughness in terms of IRI which is a standardised and widely used index of roughness.

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CHAPTER 3 RESEARCH METHODOLOGY

3.1. INTRODUCTION

The improvement of cobblestone roads towards riding quality requires the technical assessment in various aspects of existing cobblestones roads that are prone to stressful conditions of driving.

The visual inspection is the method used to describe the status of the surface distress and the physical characteristics of surfacing materials (cobblestones) of existing cobblestone roads by visual assessment. While there are wide varieties of possible technique of measuring road roughness as discussed is chapter two, in this study, the Response Type Road Roughness Measuring System (RTRRMS) has been adopted due to its availability in Rwanda for this research and to its capacity of surveying larger network in short time. Other advantages of the RTRRMS are discussed in this chapter.

In RTRRMS, a vehicle mounted Bump-Integrator was used to measure the cumulative vertical movements of the axle with respect to the chassis of the vehicle as it was travelling along the road. The response was converted to a standard roughness measure IRI by calibration.

3.2. VISUAL INSPECTION OFEXISTING COBBLESTONE ROADS

The visual inspection of the pavement of existing cobblestone roads was conducted to assess the physical aspects of the surfacing materials and to find out relationships between these aspects and the riding quality of the roads. Furthermore, the visual inspections enable to assess the existing status of cobblestone roads versus their early degradation, various systems used of laying and interlocking cobbles and other shortfall underling the construction of cobblestone roads.

The entire cobblestone road network of the City of Kigali was inspected in order to appreciate the actual status of cobblestone roads, since the network is small to be covered in a shorter period. Various surface defects were described and paired with their observed causes.

3.3. MEASURE OF THE ROAD ROUGHNESS BY USING A BUMP INTEGRATOR

3.3.1. Operational concept

A response type system consists of the following main components:

- The measurement vehicle;
- A transducer that detects the relative movement of the suspension;
- A recording system and display which is connected electronically to the transducer, and
- Automatic speed control and accurate distance measuring instruments.

The transducer, recording system and display are normally manufactured and sold as a single system (often called a Roadmeter), which measures the response of the vehicle to the road profile at the measurement speed. The transducer measures the movement of the suspension in "counts" or millimetres. When the counts or total mm are summed, a parameter is obtained which gives an indication of the total suspension stroke that occurred over the length of road travelled. According to COTO (2007), when the total count of summed mm of travel is divided by the length of the test section, the Average Rectified Slope (ARS) is obtained.

The Bump Integrator (BI) used during the survey is the property of the *Rwanda Transport Development Agency* (RTDA) equipped with the *Viziroad* equipment as a recording system and display unit. The *Viziroad* equipment is a counter unit that records the movements of the back axle of the survey vehicle as it is travelling along the road. These counts are recorded is discreet units of measure.

The BI was mounted inside the deck of the survey vehicle of type pick up, into both the centreline of the vehicle and the axle. Figure 3.1 shows the survey vehicle used during the study and Figure 3.2 shows the bump integrator used during the surveys.

Figure 3-1 Vehicle mounted Bump Integrator belong to RTDA

Figure 3-2: Bump Integrator fixed at the vehicle

The used Viziroad-Bump Integrator equipment consists in two components:

- The physical components which constitute the material assembled into the vehicle and comprise:
    i. The distance sensor connected to the vehicle gearbox;
    ii. Two Viziroad consoles comprising 48 keys as shown on Figure 3-3;
    iii. Bump integrator;
    iv. Two peripheral devices such as the camera and the GPS;
    v. A portable computer.
- The software components connected to the portable computer, which is the Viziroad software and its utility tools.

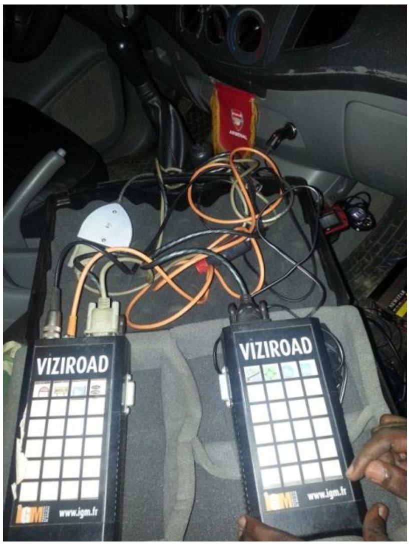

Figure 3-3: Two Viziroad consoles connected to the vehicle

3.3.1.1.Advantages of the BI

The following advantages are exhibited:

- Response type devices have been used in many parts of the world for many years. In Rwanda, many engineers of RTDA are therefore well acquainted with the operation and output of these devices. This facilitates the apprenticeship of RTRRMS.
- In general, response type device outputs are known to agree with engineers' assessment of roughness and pavement condition;
- Response type devices are relatively inexpensive. The cost of response type systems is generally less than1/10th of a high speed profiling device according to COTO (2007);
- Although response type devices require frequent maintenance and care of operation to ensure that the calibration remains valid, the maintenance and care of the equipment is relatively simple and inexpensive to perform;
- The calibration process for response type devices is relatively easy and inexpensive to perform once calibration set out and measured;
- In Rwanda, response type devices appear to be more successful on gravel roads than profiling devices;
- Response type devices can be used on gravel roads whilst Inertial Profilometers cannot.

3.3.1.2.Disadvantages of the BI

Even if there are many advantages associated to the use of response type devices, the following disadvantages are exhibited:

- The precision (and hence repeatability) of response type devices is significantly lower than that of a Class 1 profiling device. Furthermore, the annual deterioration of IRI on a typical road section is often smaller than the measurement error of response type devices (the measurement error occurs because of the lack of high precision, and also because of errors inherent in the calibration to correlate with IRI). This means that response type devices generally cannot track the deterioration of a road network on an annual basis (although it can perhaps do so over a 3 or 5 year period);

- In response type devices, the transformation of the road profile to an IRI value is completely dependent on the properties of the vehicle suspension system. These properties are known to change over time, and also from one response type vehicle to the next. The output of response type devices thus has a tend time (i.e. it is not stable). Because of this, response type devices require calibration at least on an annual basis;

- Response type roughness measurement devices only measure road roughness. By contrast, many modern high speed surveillance devices can measure the lateral and longitudinal profile, and obtain high resolution photographs or videos of the road surface at the same time.

3.3.2. Calibration and control testing for the BI

System calibration for response type devices was performed to ensure that the measurement device as well as the data acquisition system are working properly, and to adjust the device output so that it is adequately correlated to known values over a range of roughness values. This was done in accordance to the specifications recommended by COTO (2007), where the following aspects were covered:

- The number and type of calibration sites were specified. These sites were located and measured (using MERLIN as Class 1 profiling device) under the support of RTDA;
- The lengths of the calibration sections were specified;
- Details of the calibration procedure, such as demarcation of sections, measurements speeds, and data to be gathered were specified.

The BI was calibrated, using a MERLIN- model A1460 based upon the UK Transportation Research Laboratory (TRL) design procedure of measuring roughness. This machine was chosen to calibrate the BI because it is one of the Class 1 device which was available in RTDA, inexpensive, easy to use and easily maintained. MERLIN is an acronym for a Machine for Evaluating Roughness using Low-cost instrumentation.

3.3.2.1.Principal of operation of the MERLIN

MERLIN is a manually operated instrument which is wheeled along the road and measures surface undulations at regular intervals. Readings are easily taken and there is a graphical procedure for data analysis so that road roughness can be measured on a standard roughness scale without the need for complex calculation. It was designed on the basis of a computer simulation of its operation on road profiles measured in the International Road Roughness Experiment.

The device has two feet and a probe which rest on the road surface along the wheel-track whose roughness is to be measured. The feet are 1.8 metres apart and the probe lies mid-way between them as shown in Figure 3.4. The device measures the vertical displacement between the road surface under the probe and the centre point of an imaginary line joining the two points where the road surface is in contact with the two feet. This displacement is known as the “mid-chord deviation.

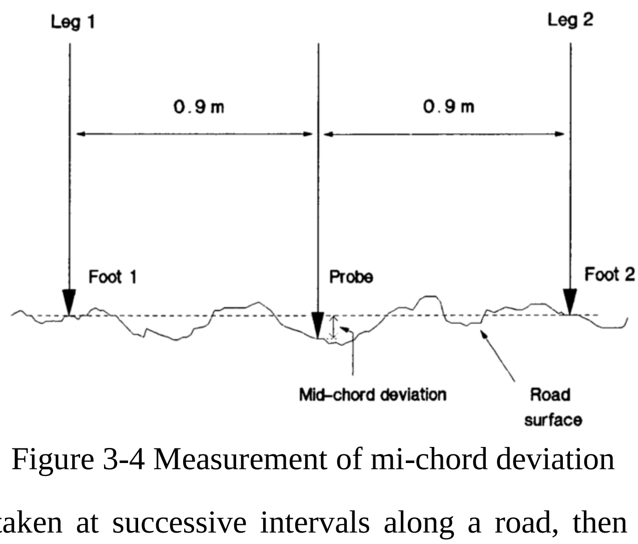

Figure 3-4 Measurement of mi-chord deviation

If measurements are taken at successive intervals along a road, then the rougher the road surface, the greater the variability of the displacements. By plotting the displacements as a histogram on a chart mounted on the instrument, it is possible to measure their spread and this has been found to correlate well with road roughness, as measured on standard roughness scales.

For ease of operation, a wheel is used as the front leg, while the rear leg is a rigid metal rod as shown in Figure 3.5 and schematically presented in Figure 3.6. On one side of the rear leg is a shorter stabilising leg which prevents the device from falling over when taking a reading. Projecting behind the main rear leg are two handles, so that the device looks in some ways like a very long and slender wheelbarrow.

Figure 3-5 The Merlin

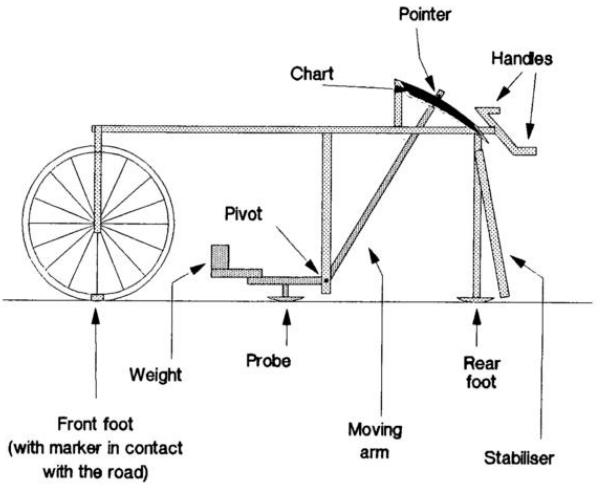

Figure 3-6 Sketch of the Merlin

The probe is attached to a moving arm which is weighted so that the probe moves downwards, either until it reaches the road surface or the arm reaches the limit of its traverse.

At the other end of the arm is attached a pointer which moves over the prepared data chart. The arm has a mechanical amplification of ten, so that a movement of the probe of one millimetre will produce a movement of the pointer of one centimetre. The chart consists of a series of columns, each 5 mm wide, and divided into boxes.

3.3.2.2.Method of using the MERLIN

The procedure undertaken to determine the roughness of a stretch of road is to take 200 measurements at regular intervals, say once every wheel revolution. At each measuring point, the machine is rested on the road with the wheel in its normal position and the rear foot, probe, and stabiliser in contact with the road surface. The operator then records the position of the pointer on the chart with a cross in the appropriate column and, to keep a record of the total number of observations makes a cross in the ‘tally box’ on the chart as shown on Figure 3.7.

The handles of the MERLIN are then raised so that only the wheel remains in contact with the road and the machine is moved forward to the next measuring point where the process is repeated. The spacing between the measuring points does not matter, as long as the readings are always taken with the wheel in the normal position. This has been done according to the recommendations of Cundill (1991), who recommends taking measurements at regular intervals because it should both produce a good average sample over the whole length of the section and reduce the risk of bias due to the operator tending to avoid particularly bad sections of road.

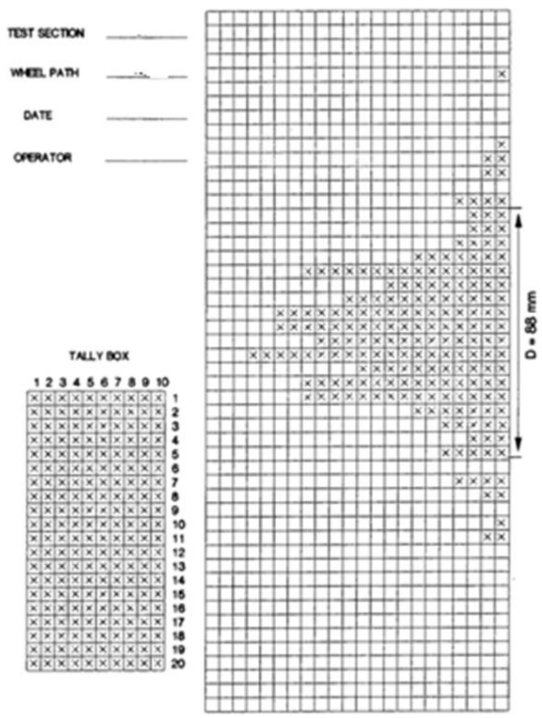

Figure 3-7 : Typical completed chart

When the 200 observations have been made, the chart is removed from the Merlin. The positions mid-way between the tenth and the eleventh crosses, counting in from each end of the distribution, are marked on the chart below the columns. It may be necessary to interpolate between column boundaries, as shown by the lower mark of the Figure 3.7. The spacing between the two marks, D, is then measured in millimetres and this is the roughness on the MERLIN scale. Road roughness, in terms of the international Roughness Index or as measured by a bump integrator, can then be determined using equation 2.2.

3.3.2.3.Calibration sections requirements

The identification and selection of calibration sections is required before starting any roughness survey. This has been done in accordance to COTO (2007) who recommends selecting and profiling calibration sections upon the guidance of the network agency, or by a contractor other than the one responsible for the actual survey. Therefore, calibration sections have been selected and profiled by RTDA engineers who are familiar with the road network and with the use of roughness equipment.

Calibration section was done as follows:

- The calibration sections was selected so that there is at least one section in each of the roughness ranges shown in Table 3.1;
- The sites were selected so that there are approximately an even proportion of sections in each roughness range;
- Each calibration section had a relatively uniform roughness over its length as well as over the 50 m preceding the start of the section;
- The sections were selected preferably on straight (tangent) sections of road. The sections did not need to be on level, but they were selected so that no significant change in grade within or before the section;
- The calibration sections had different surfacing types, representing the types of surfacing frequently found on the network.

Table 3-1 : Roughness ranges for calibration section selections

No	**IRI range**
1	1.0 to 3.0
2	3.0 to 4.5
3	4.5 to 6.0
4	6.0 to 8.0
5	8.0 to 16.0

3.3.2.4. Profiling calibration sections and determining the reference IRI

The following procedure was conducted for the measurement of reference profiles and IRI values on calibration sections:

- Each wheel path of each calibration section was profiled four times, consisting of two runs in which the device returns along the same wheel path to form a closed return loop;
- The IRI was calculated for every 100m segment of each measurement run over each wheel path;
- The reference IRI for each wheel path of the calibration section was calculated as the mean of the four runs.

3.3.2.5. Selection of calibration sections

In respect of calibration sections requirements, five sections located on five different National Roads (NR) have been identified for calibration. Each calibration section had 600m. These sections represent various grade of roughness of paved road network in Rwanda since they represent different IRI ranges found along the whole paved roads.These sections were identified on the following National Roads given Table 3.2.

Table 3-2: Roads selected for calibration sections (RTDA, 2013)

S/N	Road Name	Location	Length (km)
1	NR 2	Kigali- Musanze-Rubavu	90.670
2	NR 5	Kicukiro - Nyamata-Nemba	21.100
3	NR 24	Kayonza - Kiramuruzi-Kabarore-Gabiro - Kagitumba	116.261
4	NR 17	Cyakabili - Nyabikenke - Musanze-Cyanika	103.670
5	NR 4	Kigali-Rwamagana-Kayonza-Rusumo	79.300

Each section was selected on the straight alignment of 600m length without sharp curves in order to respect the required calibration speed of 32km for the BI.

3.3.2.6. Marking calibration sections

After the identification of calibration sections, the usual traces of vehicle wheels on test sections are materialized by painting them from start to end as shown on Figure 3.8. The traces for the two wheels must be marked out. The start, the end and sub-sectionof the calibration section must bear the cumulative distances measured from the starting point.

Figure 3-8 : Materialization of calibration sections (RTDA, 2013)

3.3.3. Procedure for calibrating the BI on site

The calibration of BI has been carried out in four steps:

- The *VIZIROAD* distance calibration;
- The IRI measurement with *MERLIN* along the testing sections;
- The acquisition of BI on the testing sections;
- The determination of coefficient A and B of the flatness formula of the BI

3.3.3.1.Viziroad distance calibration

The Viziroad distance calibration has been carried out on the paved section road of Muhanga - Nyabikenke - Musanze - Cyanika (RN 17) along a section of 1,000m in a straight alignment which has been manually measured using a tape measure of 50m.The calibration was done by driving a survey vehicle of type car *Pick Up TOYOTA HILUX*, at a speed of 32km/h required for measuring the IRI using *Bump Integrator*.

This operation enabled to master the synchronization of the speed of measure recorded by *Viziroad* (called absolute speed of measure) together with that indicated by the car's dashboard, which is a reference speed of the driver, as shown on Table 3.3.

Table 3-3: Synchronization of *Viziroad* speed and dashboard car's speed (RTDA, 2013)

Speed recorded by VIZIROAD (Average speed of measure)	Speed indicated by the car's dashboard (Reference speed of the driver)
32,4 km/h	40 km/h
33,4 km/h	41 km/h
31 km/h	39 km/h
30,6 km/h	38 km/h

3.3.3.2. Measure of IRI by Merlin along calibration sections.

Measuring is carried out along 400m on the two traces of the car's wheel. The first trace was found located at 80 cm of the roadway bank while the second is shifted from 1,40m which is equal to the distance between axes of two wheels connected by the axle. Each wheel trace has been marked out by painting in order to survey the appropriate roughness of the section. The first measurement is recorded when the mark fixed on the Merlin wheel is in contact with the road surface, other measurements are recorded at each revolution of the wheel mark when the it is in contact with the surveyed road surface. The Table 3.4 presents the roughness values obtained per section on calibration sections.

Table 3-4: IRI values obtained per section (RTDA, 2013)

Name of road section	**IRI axis**	**IRI Bank**	**Average**
RN 2 (Kigali-Musanze-Rubavu)	1.695	1.846	1.77
RN 5 (Kicukiro-Nyamata-Nemba)	1.493	1.580	1.54
RN 24 (Kayonza-Kagitumba)	4.156	4.060	4.11
RN 17(Section Ruhengeri-Cyanika)	3.650	4.243	3.95
RN 4 (Kigali-Kayonza-Rusumo)	4.416	4.187	4.30

3.3.3.3.Determination of coefficients A&B of the calibration equation

After determination of the IRI by Merlin on calibration sections, a vehicle mounted bump integrator was used to determine coefficients A&B of the calibration equation, also called *flatness formula of the BI*. While driving on calibration section of 600m, the first covered distance of 200m along enabled the driver to be prepared to keep the constant measuring speed, before passing to the second zone of length 400m, and enabled the two wheels circulate on the painting marks at the same speed.

Therefore, the number of impulsions provided by the *Bump,* during the passage of the first zone of 200m was not taken into consideration for the calibration of the *Bump.*

For each measuring pass, the *Viziroad* is configured to record the number of impulsions of the Bump and the speed of measure within a section surveyed. Measurements have been carried out at a constant speed of 32km/h with a tolerance of 5% (meaning that the minimum speed was 30,6km/h and a maximum speed 33,4km/h)**.** Below and beyond this limited range of speeds, the recorded numbers of impulsions were not considered for the calibration process.

During the survey, the vehicle mounted BI had to realize ten (10) passes (ten measures) on each calibration section in order to get at least five (5) valid measures of impulsions, then, the average value of recorded impulsions was calculated. The Table3.5 summarizes the recorded values of impulsions on various calibration sections of length 400m.

Table 3-5: Number of impulsions by the BI on calibration sections

	Distance	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5	Pass 6	Pass 7	Pass 8	Pass 9	Pass 10	AVERAGE200m	AVERAGE400m
RN 2	200-400	7	5	6	6	7	5	7	6	5	5	5.9	5.6
	400-600	7	5	5	6	5	5	5	6	4	5	5.3	
RN 5	200-400	5	6	4	5	4	4	5	5	5	5	4.8	4.65
	400-600	5	5	4	5	5	4	5	4	4	4	4.5	
RN 24	200-400	29	28	29	28	29	29	28	30	30	29	28.9	28.1
	400-600	26	27	27	27	28	27	27	28	27	29	27.3	
RN17	200-400	22	21	22	22	22	22	23	24	24	24	22.6	
	400-600	20	21	21	21	22	22	21	21	21	21	21.1	21.85
RN4	200-400	28	29	31	31	31	30	30	31		29	30	
	400-600	29	29	31	30	32	30	32	33	32	32	31	30.5

The value colored in green cell was not considered due to its high deviation compared to other values on the same section.

By matching the IRI values calculated from the Merlin measurements and the corresponding number of impulsions recorded on similar sections by using Viziroad- bump integrator, the Table 3.6 summarizes the results of calibration.

Table 3-6Results of calibration (RTDA 2013)

Road section	Number of impulsions on 400m	IRI (MERLIN on 400m)
RN 2	28.08	4.317668
RN 5	5.54	1.55855
RN 24	26.05	4.07369
RN 17	22.60	3.64979
RN 4	6.60	1.655105

The output of the calibration exercise of the Bump Integrator is the determination of the "*Bump Integratorflatness formula*". The calibration operations lead to a formula which enables to convert the number of impulsions in IRI. This formula is a linear equation of the following form:

Y= A+ BX Equation 3.1

Where, **Y=** the calculated IRI;
X = the number of impulsions provided by the BI;
A&B are coefficients which determine the correlation between the calculated values of IRI and the number of impulsions provided by the BI for a given distance.

The coefficient A&B of the calibration equation of the BI are obtained by plotting a graph of linear tendency from the scatter of points presented along the ordinate, the IRI values obtained from the Merlin measure of each calibration section of 400m and on the abscise, the corresponding number of impulsion in form of equation (3.2). Excel software was used to plot the linear graph representing this relationship as shown on Figure 3.9.

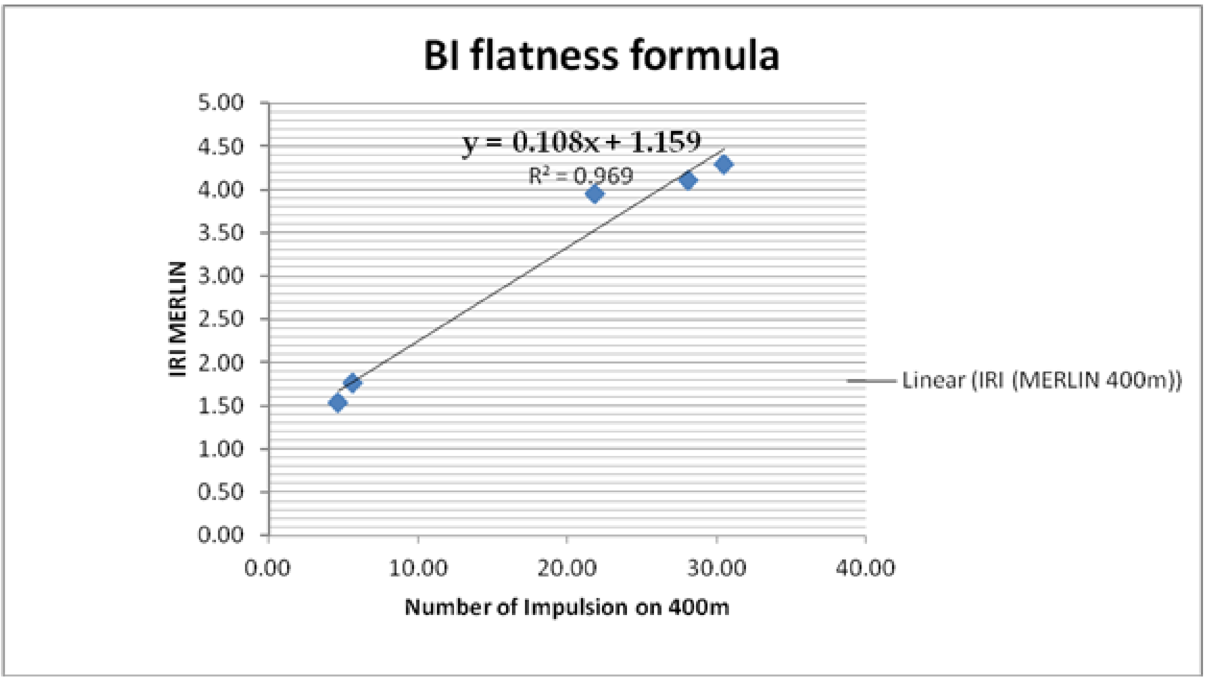

Figure 3-9: Correlation IRI (MERLIN)- Impulsions

From the graph plotted with Excel software, the relationship IRI (MERLIN)- Impulsions (Bump Integrator) is interpreted by the equation 3.2, which is the BI flatness equation:

IRI= 1.159+0.108 x   Equation 3.2

Where, **x** = the number of impulsions;

The coefficient A= 1.159;

The coefficient B= 0.108.

The calculated IRI is the indicator that enables to make a decision on the riding quality of roads and on the required road improvement, when the roughness is beyond acceptable standards.

3.3.3.4. Direct measure of International Roughness Index

The coefficients A & B were incorporated in *Viziroad* device and enabled the software to convert the impulsions to IRI during roughness measurement with the Bump Integrator. The interface of the software displayed these coefficients as shown on Figure3.10.Thisenabled to read directly the IRI value of the surveyed section as displayed by *Viziroad.*

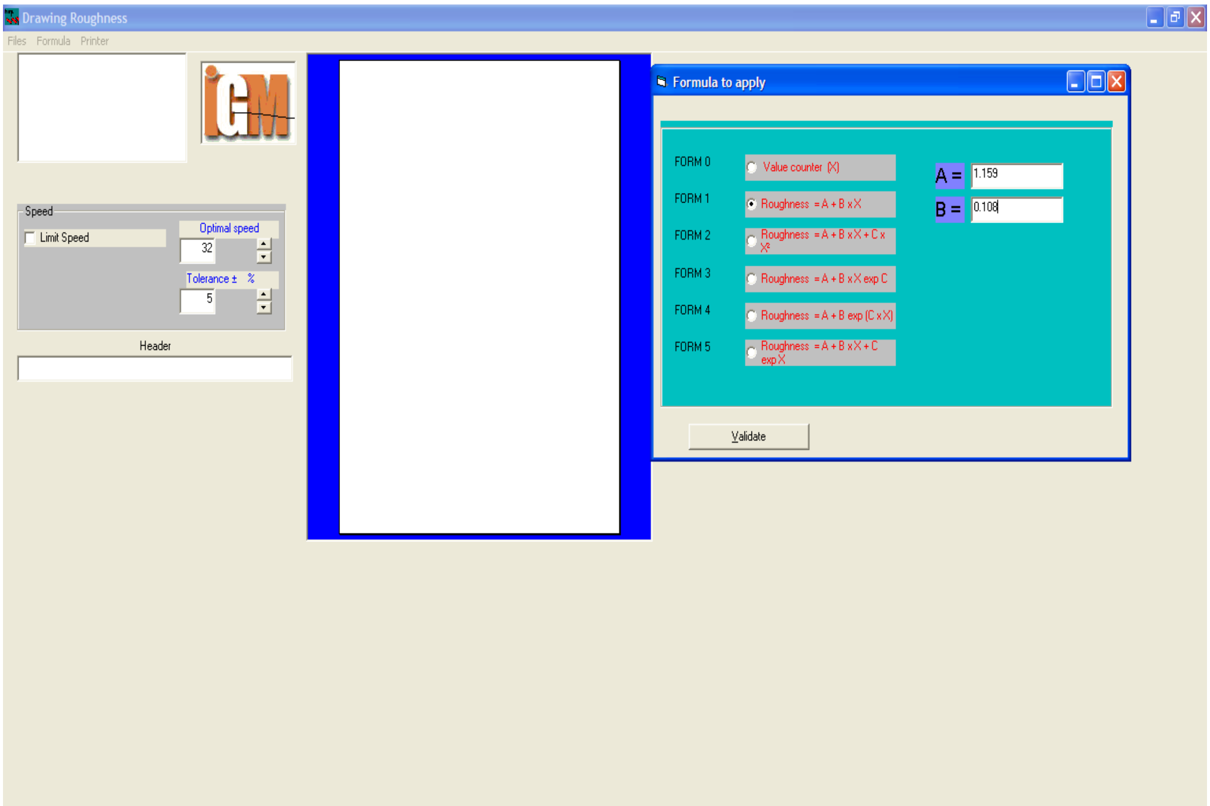

Figure 3-10: Incorporation of coefficients A&B in *Viziroad* software

3.4. CONCLUSION

The visual inspection of existing cobblestone roads is one of the methods that enabled to assess physical aspects of the road networks andto relate these aspects with the riding quality of the roads. This visual inspection covered the whole cobblestone road network since it is still small to be covered in shorter period. During the inspection, various surface defects were described accompanied by their observed causes.

The measure of the road roughness required accurate measuring devices calibrated to local conditions using recognized standards. The Bump Integrator classified as Response Type road roughness measuring device has been selected to be used in the study, due to its availability in Rwanda and readily calibrated for this research and to its capacity of surveying larger network in short time. However, the following concepts were taken into account while using the BI in measuring road roughness in IRI:

- The output of the BI needs to be correlated to the known IRI values on several sections by calibration. The correlation was used to determine a calibration equation which was used to convert the device outputs to IRI estimates;
- Calibration sections were profiled before calibration starts and using Merlin as a Class 1 measurement device.
- During control testing, the measured outputs of the BI were compared to benchmark outputs determined during calibration. Control tests were used to determine if there was a gradual shift in the device output or if the repeatability of the device had changed.

3.5. REFERENCE

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CHAPTER 4 ASSESSMENT OF EXISTING COBBLESTONE ROAD CONDITIONS

4.1. INTRODUCTION

In this chapter, the existing status of cobblestone roads is analysed using:

1) The visual assessment;

And

2) Using BI to determine its conditions on aspects related to riding quality, road roughness and surface distress.

Different types of degradation of surfacing materials have been identified and described. The visual inspection of existing cobblestone roads enabled to find out the origin of the observed degradation. The assessment of the riding quality of existing roads has been conducted by using the bump integrator calibrated by the MERLIN device. This assessment enabled to estimate the roughness of existing cobblestones in form of IRI.

4.2. VISUAL ASSESSMENT ON THE SURFACE DISTRESSES OF EXISTING COBBLESTONE ROADS

4.2.1. Displacement of cobblestones

Visual assessments were done on the cobblestone road networks within CoK including Kimisagara, Gitega, Nyakabanda, Biryogo, Muhima, Commercial City Centre, Mumena, Kagarama, Nyanza, Kanombe, Gikondo, Gisimenti, Kabuga, Kimihurura, Kacyiru and Nyarutarama. The visual assessment shows the surface distress on cobblestone roads characterised by a displacement of cobblestones of the pavement area. The major source of this displacement is a poor interlocking of cobblestones that enable them to move due to the abrasion movement of vehicle tyres. At the beginning of the service life of the road, the movement of vehicle tyres stimulate a slight movement of poorly interlocked cobblestones. This movement keep on increasing with the time and this situation becomes highly critical when the first stone is pulled out of the road pavement.

After the displacement of the first stone, other stones follow in the direction imposed by the slop of the road as shown on Figure 4.1. The displacement is significantly influenced by an increase in slope of the road.

Figure 4-1 Start of rock displacement MINAGRI-KACYIRU road

4.2.2. Pattern stability

Two laying patterns of cobblestones have been identified on existing cobblestone roads; longitudinal and arch patterns. The visual inspection has shown that the arch laying pattern of cobblestones is more stable against the displacement of cobblestones. Existing cobblestone roads in arch layout have less displacement of cobblestones as indicated in Figure 4-2 and Figure 4-3.

Figure 4-2: Kimihurura road with a stable arch layout

Figure 4-3: Ryanyuma road with a longitudinal laying pattern

4.2.3. Irregularities in shape and dimension

Existing cobblestones are manually produced by using ordinary manual hummer. They are shaped in cubic dimensions of 14cm of side. It is practically not possible to respect these dimensions due to limited accuracy of shaping equipment in use.

Irregularities in shapes and dimensions of produced cobblestones reduce the confinement of laid cobblestones because they are not properly interlocked. Under repeated abrasion movement of vehicle tyres, slight movements of cobblestones starts and become very important with time. The irregular shaped stones used for the road construction resulted into early displacement are indicated in Figure 4-4 and Figure 4-5.

Figure 4-4: Irregularities in shape and dimensions of stones at Mumena road

Figure 4-5: Displacement of paved stones at Ntaraga road

4.2.4. Erosion of the surface joints

The joints between cobblestone roads are filled with sand. Surface rain water has eroded some areas of the carriageways, especially on the sections located on high slopes. This erosion reduces the confinement between cobblestones and incites their movement, when the sand is not timely replaced during road maintenance. The wider the joint the worse the road is eroded. Joints have various dimensions ranging from 2cm to 10cm because the shapes of cobblestones are not regular. The non-uniformity of the joints between stones is indicated in Figure 4-6 and 4-7.

Figure 4-6: Erosion of joints at Mumena road

Figure 4-7: Repaired joints at Mumena Road

4.2.5. Undulations of the carriageway surface

The surface area of the pavement has some undulations due to bumpy surface finishing of cobblestones. During construction, it is not possible for operators to respect a perfect alignment of the road surface due to unevenness of cobblestones. This has a negative impact on driving quality of the road because this unevenness of cobblestones creates intensive vibrations of vehicles during riding.

Due to the critical roughness of existing cobblestone roads, road users prefer to use longer asphalt sealed routes in order to avoid vibrations and damages of their vehicles, whereas one of the reasons for construction of these roads is to reduce traffic volume on main sealed roads.

4.2.6. Depression of the carriageway surface

The cobblestones roads characterised by the local depression of the carriageway surface is a defect most of the time caused by failure of the road structure, when the foundation and/or the subgrade have no required bearing capacity to resist the traffic loads. This kind of defect is rare on existing roads. However, it has been observed little depression at some areas due rain water that stagnated and penetrated into the road structure through surface joints. The road structure loses its bearing capacity due to variations in moisture content created by seepaged water.

The poor maintenance of drainage structures is another source of depression of the carriageway surface when rain water is diverted to the road surface due to the obstruction of drainage structures. When water stagnates to the road surface for long time, the bearing capacity of layers underneath cobblestones decreases and depressions are created at the road surface. Figure 4-8 present the common drainage blockage resulting to damaging the bearing capacity of the subgrade

Figure 4-8 Depression at the road surface at Kamuhoza road due to poor maintenance of drainage structures

4.2.7. Edge break

Edge break is not a common defect on existing cobblestone roads. This defect occurred on some roads where kerbstones were not properly constructed. A proper construction of kerbstones can prevent this defect, but a bad choice and fixing of kerbstones stimulate large displacement of cobblestones. Figure 4-9 and 4-10 present the displacement of cobblestones due poor construction of kerbstones resulting in edge break.

Figure 4-9: Edge break at Kabusunzu road   Figure 4-10: Edge break at Kimisagara road

4.2.8. Lessons learnt from visual inspection

From visual inspection, it has been observed that the irregularities in shape and dimensions of surfacing stones is the main cause of early degradation of cobblestone roads and also the source of the above mentioned surface distress. This can be described into three aspects:
Firstly, these irregular shaped stones are not properly interlocked during pavement construction which incites their slight movement in contact with the abrasion forces of vehicle tyres. With time, slight movements of surfacing cobblestones became very important and the displacement of cobblestones starts to be observed.

Secondly, the dimensions of the surface joints between laid cobblestones and filled with sand become irregular due to the shape of cobblestones. In many places, the dimensions of these joints become wider enough to be eroded by rain water, where they exceed 2cm. This erosion of joints reduces the confinement between cobblestones due to voids created between them. The risk of displacement of cobblestones associated to poor confinement between cobblestones starts at this occasion.

Thirdly, the bumpy texture of the surface finishing of irregularly shaped cobblestones results in unevenness of the road surface. This impact on riding quality where road users feel uncomfortable due to intensive vibrations of their vehicles. The bumpy texture of the surface finishing of cobblestones not only impacts of road roughness, but also on vehicle repair. This is the reason why most road users prefer to use longer sealed routes instead of shorter constructed cobblestone roads.

The improvement of existing conditions of cobblestones requires the use of regularly shaped cobblestones as surface finishing and a proper construction of the cobblestones that ensures durability, long-term performance and acceptable riding quality, as presented in the following chapters of this study.

4.3. ASSESSMENT OF THE RIDING QUALITY OF EXISTING COBBLESTONE ROADS

The assessment of the riding quality of existing cobblestone roads was conducted by using the bump integrator calibrated by MERLIN. The procedure and parameters of calibration are presented in Chapter 3.The International Roughness Index found on cobblestone roads will be compared to other roughness indexes measured on other types of road pavement.

4.3.1. Sampling of cobblestone roads for roughness measurement

For sampling purpose, a tour on all constructed cobblestone roads of the City of Kigali was done for selection of roads that complies with the guidelines for roughness measurements as presented in chapter 3. The selection of samples was challenging because most of cobblestone roads are constructed in residential areas where it is difficult to find a straight road section of more than 600m. Furthermore, many cobblestone roads are in bad condition and other roads present sharp corners which may prevent the survey car to achieve a required measuring speed of 32km/h. At the end of the tour, two roads presented in Table 4.1, were found to comply with the requirements of roughness measurements using a BI. The locations of the two sampled roads are presented in Appendix A and B.

Table 4-1: Samples of cobblestone roads

S/N	Road name	Location	Total road length (m)	Surveyed length (m)
1	KG 14Ave (1st Direction)	Kimihurura - CADILAC	1,300	1,262
2	KG 14Ave (2nd Direction)	CADILAC - Kimihurura	1,300	1,200
3	KN112st	Mutwe -Kimisagara Maison des Jeunes	2,500	2,469

4.3.2. Results of roughness measurements

The row results of roughness measurements by the BI-Viziroad are presented by Tables 4.2 to 4.4 and graphically represented by Figure 4.11 to 4.13.

Table 4-2: Recorded roughness for KIMIHURURA-CADILAC road (KG 14Ave), 1st Direction

```
15/04/2014
CHAINAGE
FROM          TO         IRI_m/km   Speed-km/h

0000.000    0000.200    0010.02       030
0000.200    0000.400    0011.53       033
0000.400    0000.600    0011.64       031
0000.600    0000.800    0011.31       032
0000.800    0001.000    0012.72       032
0001.000    0001.200    0013.36       032
0001.200    0001.262    0005.16       028
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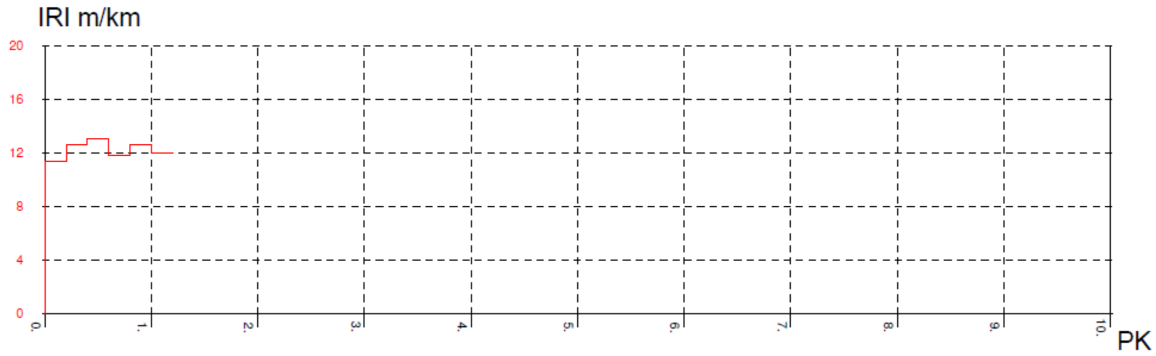

Figure 4-11 Graphical representation of the roughness profile for KIMIHURURA-CADILAC road (KG 14Ave), 1st Direction

The Table 4-2 represents the recorded row data of roughness of the first surveyed direction of the road KIMIHURURA –CADILAC at each road segment of 200m from the starting point of the road. Graphically, the relationship between the profiled road sections at every 200m of length is represented by the Figure 4-11. From that table, the recorded roughness at end of the road and highlighted in yellow was not taken into account because the surveying speed was beyond the acceptable limits of the calibration speed of 32km with a tolerance of 5%.

Table 4-3Recorded roughness for CADILAC – KIMIHURURA road (KG 14Ave), 2nd Direction

15/04/2014

CHAINAGE FROM	TO	IRI_m/km	Speed km/h
0000.000	0000.200	0011.42	023
0000.200	0000.400	0012.61	031
0000.400	0000.600	0013.04	031
0000.600	0000.800	0011.85	032
0000.800	0001.000	0012.61	031
0001.000	0001.200	0011.96	031

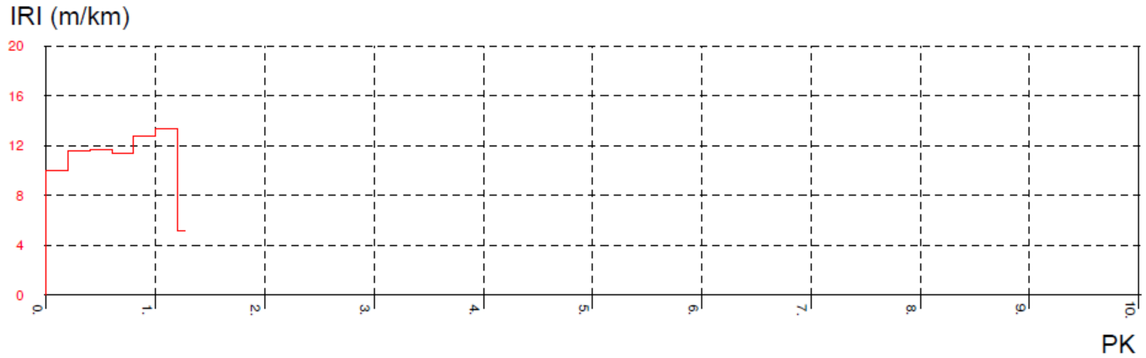

Figure 4-12Graphical representation of the roughness profile for CADILAC - KIMIHURURA road (KG 14Ave), 2nd Direction

The second direction of the road KIMIHURURA-CADILAC is graphically profiled on Figure 4.12, whereas the Table 4.3 presents the row data of the road roughness at each segment of 200m starting from the end of the road. The first recorded roughness of this table is ignored, considered as outlier because it was measured at the surveying speed below the acceptable limits of the calibration speed of 32km with a tolerance of 5%.

Table 4-4: Recorded roughness for MUTWE-Kimisagara Maison des Jeunes road (KN 112 st)

18/06/2014

FROM	TO	IRI_m/km	Speed km/h
0000.000	0000.200	0013.47	019
0000.200	0000.400	0014.55	015
0000.400	0000.600	0014.66	022
0000.600	0000.800	0013.36	031
0000.800	0001.000	0013.47	032
0001.000	0001.200	0012.82	033
0001.200	0001.400	0014.66	018
0001.400	0001.600	0013.58	031
0001.600	0001.800	0013.47	031
0001.800	0002.000	0012.28	033
0002.000	0002.200	0013.69	032
0002.200	0002.400	0012.61	031
0002.400	0002.469	0005.26	018

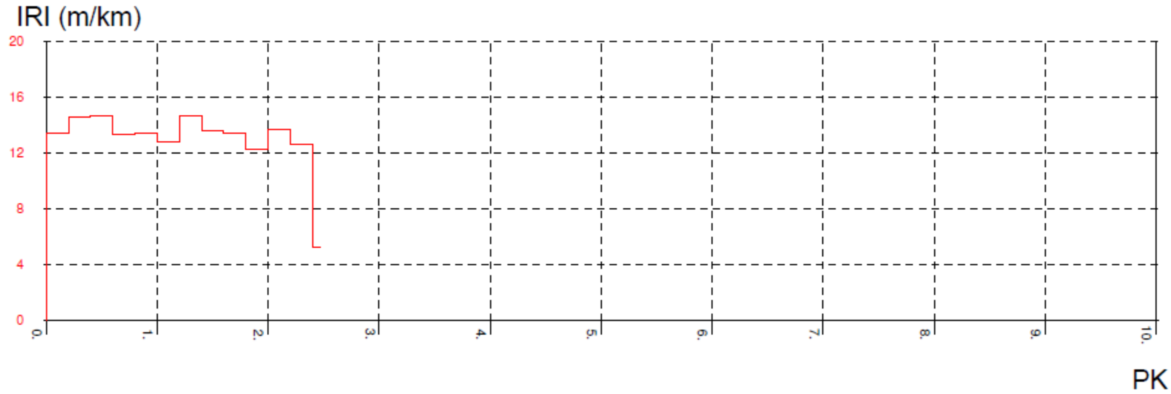

Figure 4-13 : Graphical representation of the roughness profile for MUTWE-Kimisagara road (KN 112 st)

From the Table 4.4 representing the recorded row data of roughness of the road MUTWE-Kimisagara Maison des Jeunes, the recorded roughness for the first three segments of total length 600m, were not considered because they were surveyed at a surveying speed below 32km with a tolerance of 5%. For the same reason, the recorded roughness between chainage 1+200 and 1+400 and the roughness recorded at the end of the road were ignored, considered as outlier.

After excluding unacceptable roughness data, Tables 4.5 to 4.7 present the recorded roughness taken into consideration.

Table 4-5: Average roughness for KIMIHURURA-CADILAC road, (1st Direction)

From km	To km	IRI_m/km	Speed km/h
0	0.2	10.02	30
0.2	0.4	11.53	33
0.4	0.6	11.64	31
0.6	0.8	11.31	32
0.8	1	12.72	32
1	1.2	13.36	32
Average		**11.76**	

Table 4-6: Average roughness for CADILAC -KIMIHURURA road, (2nd Direction)

From km	To km	IRI_m/km	Speed km/h
0.2	0.4	12.61	31
0.4	0.6	13.04	31
0.6	0.8	11.85	32
0.8	1	12.61	31
1	1.2	11.96	31
Average		**12.41**	

From Tables 4-5 and 4-7, the average of the roughness surveys profiled from the first and second direction of the road KIMIHURURA-CADILLAC is$\frac{11.76+12.41}{2} = 12.085$ m/km.

This roughness of 12 IRI, is far beyond acceptable standards for a GOOD paved road in accordance to Rwanda Transport Agency (RTDA) that stipulates a roughness less than 4IRI.

Table 4-7: Average roughness for MUTWE-Kimisagara Maison des Jeunes road

From km	To km	IRI_m/km	Speed km/h
0.6	0.8	13.36	31
0.8	1	13.47	32
1	1.2	12.82	33
1.2	1.4	14.66	18
1.4	1.6	13.58	31
1.6	1.8	13.47	31
1.8	2	12.28	33
2	2.2	13.69	32
2.2	2.4	12.61	31
Average		**13.33**	

Similarly, the average roughness of the road MUTWE-Kimisagara, which is 13 IRI, is far beyond the limits of acceptable GOOD roughness for a paved road, set at 4 IRI by RTDA.

4.3.3. Interpretation of results of roughness measurements

From Tables 4-5 to 4-7, it was found that of the roughness cobblestone roads is ranging from 11.76 to 13.33 IRI. This range of roughness is very far beyond the acceptable limits of roughness for a good paved road set at 4 IRI by RTDA. This range of roughness is even beyond the acceptable limits of roughness for a good unpaved road set at 8 IRI as discussed in Chapter 2. This means that the riding quality of existing cobblestone roads is worse than the riding quality of a normal unpaved road. This comparison demonstrate a need for improving the technique for construction of cobblestone roads vis-à-vis their riding quality.

The sample of the two roads “KIMIHURURA-CADILLAC” and “MUTWE-KIMISAGARA Maison des Jeunes”, both totalling 3.8 km represent the roughness status of the whole cobblestone road network of Kigali City, since all existing roads were constructed with the same technique using manually made cobblestones of cubic dimensions 14cmx14cmx14cm. Furthermore, all cobblestones were laid using labour based method by locally trained people.

4.4. CONCLUSION

The visual inspection conducted on existing cobblestone roads has shown various surface distresses of cobblestone roads constructed in the City of Kigali. These distresses are among the cause of their poor riding quality and are including displacement of cobbles, irregularities in shape and dimension, erosion of the surface joints, Edge break, undulations and depression of the carriageway surface.

The assessment of the riding quality of existing cobblestone roads by using Bump Integrator-Viziroad came out with a roughness ranging from 11.76 to 13.33 IRI, which is the worst roughness in reference to acceptable limits of roughness for paved and unpaved roads. These worst conditions of roughness require an improved technique for construction of cobblestone roads that increases the riding quality.

CHAPTER 5 PROPOSALS FOR TECHNICAL IMPROVEMENTS OF CONSTRUCTION OF COBBLESTONE ROADS

5.1. INTRODUCTION

The improvement of cobblestone roads discussed in this chapter concerns the constructability and surface finish of cobblestone roads with emphasis on elements responsible of poor riding quality and degradation of these roads. These elements include the shapes of cobblestones, the system of laying and locking cobblestones and the joints between cobblestones.

5.2. IMPROVEMENT OF COBBESTONE ROAD ROUGHNESS

5.2.1. Shape and dimensions of cobblestones

As presented in Chapter 2 and Chapter 4, existing cobblestones used for the construction of road are not regular in shape because they are manually manufactured. From a quarried rock, a manual hammer is used to shape the stones into smaller stones of cubic dimensions 14cmx14cmx14cm as locally used in the City of Kigali. The prescribed dimensions are used as guidance because it is not practically possible to respect them while using a manual hammer.

On construction sites, stones are further smoothed into approximate dimensions of 14 cm with a high dispersion of dimensions and shapes, some of them becoming semi-spherical and others are used without regular shape as shown on Figure 5.1.

Figure 5-1: Irregularities in shape and dimensions of cobblestone used at Mumena road, Kigali

The surface profile of the road constructed with these irregular cobblestones must become uneven, and drivers feel enormous vibrations of their vehicles while riding on cobblestone roads. These vibrations vehicles are converted into road roughness with an International Roughness Index greater than 11 as presented in Chapter 4.

As manual methods of stone shaping have not given satisfactory results, mechanical techniques are recommended for use in preparation of stones for road pavement. There are a big variety of machines that use different technologies of cutting the rock on the market. The Figure 5.2 shows the example of the rock cutting machine fabricated by the Italian factory “MEC”.

Figure 5-2 Rock cutting machine made by MEC factory

By using rock cutting machines, it becomes possible to realize stones with regular shape and dimensions to be used as surface finishing of roads. However, the cost of mechanisation bring the cost of the road construction to be relatively higher .The Figure 5.3 shows the samples of mechanically cut stones produced from waste stones by a local granite processing factory in Rwanda, the *East African Granite Industries* (EAGI).

Figure 5-3: Locally produced mechanically cut stones by EAGI Nyagatare,

In reference to the currently used dimensions presented in chapter 2 in ILO (1992), it is preferable to use in construction the *Large paving blocks* of dimensions 14cm of width, 20cm of length and 14cm of height because their production and construction are likely to be faster than other smaller dimensions. Furthermore, the dimensions of a *large paving block* can be accommodated to all types of laying systems of stone blocks.

In contrast with the higher cost of road construction resulting from mechanisation, the shape and dimension of cobblestone can be improved by using a labour technology with the support of the small scale cutting machine. There are various types of small rock cutting machine on the market, equipped with a rock cutting saw that enable to reshape in regular dimensions a stone block roughly shaped manually as shown in Figure 5-4.

Figure 5-4: Small scale rock cutting machine

The combination of labour technology and small scale rock cutting machine is recommended for use because it cheaper than the cost of heavy mechanisation. In this combination, surfacing stones are initially roughly shaped manually and the final regular shape is achieved by using the rock cutting machine.

5.2.1.1.Advantages of mechanically cut rocks

1. Due to their regular shapes, mechanically cut stones are laid very easily and by respecting a proper alignment. A proper and continuous alignment of mechanically cut stones can reduce considerably the roughness of the road compared to usual manually shaped stones with bumpy surfaces;
2. The interconnection of mechanically cut stones is properly executed during road construction which increases the confinement between stones. This prevents the displacement of stones upon the movement vehicle tyres, which is a dangerous degradation of the pavement of a cobblestone road;
3. Production of mechanically cut stones is faster than manual production which increases the speed of construction works on site. As example, the project that was aiming at the construction of 9km of cobblestone roads at Nyarutarama (one of the residential area of the City of Kigali) failed in terms of time management in 2009 due to deficiency in cobblestones that were manually prepared. At the failure of the project, only 4km out of 9km were constructed, after then, the City of Kigali decided to construct the remaining 5km in double surface dressing.
4. On construction site, the speed of laying stones is likely to increase due to easier workability of mechanically cut stones.

5.2.1.2.Disadvantages of mechanically cut rocks

1. The skid resistance of mechanically cut stones may decrease and become more slippery compared to manually shaped stone. To overcome this problem the top surfaces of stones used by vehicle tyres are not polished. While other sides of the stone may become polished during the cutting with a sow of the machine, the top surface of the stone is obtained by only splitting the stone into the pre-set dimensions.
2. By using mechanical cutting machines, there is a cost implication one construction works compared to manual procedure. The cost implication is discussed in Table 5.1 and 5.2, where the costs for supply and laying of $1m^2$ of manually and mechanically cut stones are compared in reference to the report of the study on cobblestone roads conducted by STUDI International in 2009.

3. Stone cutting required significant amount of water supply, which could be major hindrance for the massive construction on the urban roads.

Table 5-1: Costs for supply and construction of 1m^2 of manually cut stones (STUDI, 2009)

No	Year of reference	Cost for supply and construction of 1m^2 of manually cut stones (Frw/m^2)
1	2006	6,000
2	2007	12,000
3	2008	6,800
4	2010 (Projection)	11,500

From the Table 5.1, STUDI (2009) recommended to use a unit price of 12,650 Frw/m^2 from the year 2010 obtained by raising 10% on the cost of 2010, as a margin of security for budget prevision in road construction.

With reference made to the current contracts for construction of roads in the City of Kigali using mechanically cut stones, Table 5.2 presents the costs for supply and construction of 1m^2 of these type stones. These contracts have started in 2014 and the unit prices shall remain unchanged for the next four years coming.

Table 5-2 Costs for supply and construction of 1m^2 of mechanically cut stones

No	Contract	Cost for supply and construction of 1m^2 of mechanically cut stones (Frw/m^2)	Average cost (Frw/m^2)
1	Contract for construction of 70.268km	14,000	14,017
2	Contract for construction of 35 km	14,033	

Comparing the average unit cost of 14,017 Frw/m^2 for mechanically cut stones in 2014 with 12,560Frw/m^2 relating to manually cut stones, the cost implication incurred in using mechanically cut stones is 10%, which is a slight increase compared to the benefits expected in using mechanically cut stones for the improvement of the riding quality.

5.2.2. System of laying stones and joints

The visual inspections on existing cobblestone roads has demonstrated that roads with surfacing stone in arch layout are stable towards the displacement of stone and present less degradation compared to other system of laying stones. For example *Mutwe road* (KN 18 Ave) and *Kimihurura road* (KN 14 Ave) located respectively in Nyarugenge and Gasabo District are still in good conditions after more than 8 year of construction, because the surfacing stones were laid in arch layout. Therefore, the system of laying stones in arch layout as shown on Figure 5.5 is recommended for use.

Figure 5-5 Recommended system of laying surfacing stone blocks

It is recommended that the joints between paved stone blocks to have a dimension less or equal to 2cm, to prevent erosion of the joints.

Before laying the stone blocks, it is necessary to assure a good alignment and flatness of the foundation with adequate bearing capacity, because defects at foundation level are transferred sooner or later to the road surface.

5.2.3. Edge restraints and strut blocks

CERIB (2010) recommended an edge restraint or kerbstone of 20cm of thickness, while ILO (1992) recommended 16cm of thickness, 80cm of length and 20cm of height. For a purpose of harmonizing with the local practice where kerbstones in use have 20cm of thickness, it is recommended a kerbstone of 20cm of width, 80cm of length and 20cm of height in comparison with the dimensions of the kerbstone recommended by ILO (1992).

In reference to the study conducted by STUDI International (2009) on construction of 65km priority roads in the City of Kigali, strut blocks are recommended to be constructed at each 10 to 25m interval along the longitudinal profile of the road and depending on the slop of the road. These blocks are constructed across the road width and restraint the possible horizontal movement of paved stones due to traffic.

In Rwanda, the edge restraints and strut blocks are made in concrete of grade 350kg/m^3. Usually, struts blocks are recommended to have 20x30$cm^2$of rectangular section. The figure 5.6 shows the example where the strut has been constructed at Gitega road.

Figure 5-6: Strut block in concrete constructed at Gitega road, Kigali

5.2.4. Recommendations on construction materials

5.2.4.1.Recommendations on mechanical properties of surfacing stones

The surfacing stones of the road must have an abrasion coefficient (Los Angeles) less than thirty five (< 35).In reference to STUDI (2009), Table 5.3 presents some characteristics of potential quarries usually used in construction of paved roads.

Table 5-3 Characteristics of potential stone quarries used in the City of Kigali (STUDI, 2009)

Quarry name	Nature of rock	Cell/ Sector	District	Province	Route	PK side	Access road	Observations	Geotechnical characteristics
Gakombe 1	Grèsquartzique	Gakombe Gahanga	Kicukiro	City of Kigali	Kicukiro-Nyamata-Nemba	15+500 Left side	200m	Volume=25,000 m^3	LA=37.2% MDH=34.6% Adhesivite1=2 Adhesivite2=2 %enrobage1=40% % enrobage 2=40%
Gakombe2	Grèsquartzique	Gakombe Gahanga	Kicukiro	City of Kigali	Kicukiro-Nyamata-Nemba	15+500Left side	200m	Volume=20,000 m^3	LA=37.2% MDH=34.6% Adhesivite1=2 Adhesivite2=2 %enrobage1=40% % enrobage 2=40%
Nyamarondo	Gneiss quartzique	Nyamarondo Nyamirambo	Nyarugenge	City of Kigali	Kicukiro-Nyamata-Nemba	18+000 Right side	5Km	Volume=75,000 m^3	LA=37.2% MDH=34.6% Adhesivite1=2 Adhesivite2=2 %enrobage1=40% % enrobage 2=40%
Bicumbi	Grèsquartzique	Bicumbi Bicumbi	Est	Est	Kigali-Kayonza	53+000 Right side	5Km	Volume=200,000m^3	LA=37.2% MDH=34.6% Adhesivite1=2 Adhesivite2=2 %enrobage1=40% % enrobage 2=40%

5.2.4.2.Recommendations on bed course of sand

Surfacing stones are laid on the sand bed course after levelling and finalization of the foundation. The bed course serves on one hand to compensate for small irregularities in the foundation and any differences in thickness of the pavement, and on the other hand, to properly clamp the paved stone by vibration and hold them in place. The recommended thickness of the bed course should not exceed 3cm after its compaction.

For a smooth implementation of the bed course it is recommended to consider its workability when choosing materials. Natural sand and crushed gravel are recommended for use and must respond to the following characteristics:

- Sand equivalent greater than or equal to 80%;
- Passing the sieve (0.080 mm) lower than 2%;
- Passing the sieve (0.42 mm) greater than 51%;
- Passing the sieve (20 mm): 100%.

STUDI (2009) presented the potential quarries of quality sand that can be used in road construction as given in Table 5.6.

Table 5-4 Identified sand quarries (STUDI, 2009)

No	Quarry name	Location from the City centre	Grading			Sand equivalent
		km	0.08	2	20	
1	Kayumbu	39	0.4	50.6	100	91.5
2	Rusine 1	26	0.9	92.6	100	87.7
3	Rusine 2	23	0.1	80.6	100	48.7
4	Marenge	25	3.2	91.5	100	88.3

The sand Kayumbu is widely used in road construction because it is the best in fulfilling required geotechnical characteristics and has demonstrated good results in road structures where it was used. Therefore, the sand Kayumbu is recommended for use in construction of the bed course.

5.2.5. The New Construction Technic and procedure for laying paving stones

- The bed course must be distributed evenly over the entire surface of the road, which effectively means that the tolerance for thickness should be as small as possible. It is recommended a tolerance not exceeding 5 mm. A constant thickness contributes to the reduction of risk of early onset damages of a cobblestone road;
- The thickness of the bed course must not exceed 40 mm after compaction. This is realized by spreading evenly a bed layer of 6cm at first instance, followed by a compaction of the stone blocks laid on bed sand, where 2cm are reduced from the original thickness of 6cm. A bed course too thick can lead to rutting and settling caused by the movement or rotation of the stones of the road pavement. Unequal thicknesses of the bed course are at the origin of deformations of the road surface;
- The method "click-and-drop" is recommended for laying pavement stones. This method consists in laying the stone in vertical sliding position. To realize this, each stone is placed slightly against stones already laid and the stone is then allowed to slide downwards so that it takes its final position. The goal is to prevent stones from colliding violently, which could damage them. This method has the following advantages:
  1. A joint of 2 cm appears automatically;
  2. The chosen pattern of stone laying is more easily respected;
  3. No material from the sand bed is interjected between the stones;
  4. The previous row is not affected, which helps keeping joints perfectly aligned;
  5. Small differences in length and width of stones are better compensated.
- Once the entire pavement surface (including the edges) is laid, joints are filled with sand for the first time by brushing. After this step, there cannot be a significant amount of sand or gravel on the surface of the pavement. Stones are then consolidated by means of a vibrating plate, which also provides the compaction of the underlaying bed of sand. While compacting, passes are overlapped half the width of a vibration plate.
- The vibrating plate must be covered with rubber or plastic to avoid damaging the stone pavement. The vibrating plate approaches as much as possible the edge restraints (kerbstones) of the pavement and the strut blocks but must keep a distance of at least 1m at the surface areas where stones have yet to be implemented.

- Compaction of the bed course is done only after the laying of the pavement stones. A pre-compaction of the bed course leads to differences in height at the surface level of the road pavement. It is recommends a vibrating plate of 200 to 600 kg of weight and of centrifugal force equivalent to 30KN;

- The jointing and vibration are repeated until the stones are completely fixed/clamped and can therefore absorb the horizontal movements from vehicle wheels. After these steps, a thin layer of sand is spread on the pavement joints. Few weeks after the execution of the pavement, any badly filled joints must be refilled again;

- During vibration, broken stones are replaced and any other unevenness of the longitudinal and lateral profiles, especially the difference in height between adjacent laid stones, is corrected. In regard to the respect of a proper alignment, it is recommended the following:
    i. The flatness must be measured by a straight edge of 3m of length and inequalities beyond 5mm must be eliminated;
    ii. The difference in height between the two adjacent paved stones must be less than 2mm;

- The control of the execution of the pavement consists in its final stage in verifying the final alignment of the constructed pavement in comparison to the projected longitudinal and lateral profiles, general pattern of laying stones, specific finishing around the critical points such us shoulders and drainage structures, and filling of joints after compaction.

5.2.6. Control measures after execution of the pavement

- It is necessary to control the joints shortly after the opening of the road to traffic. Joints may become empty due to various reasons including:
    i. Heavy rainfall;
    ii. Violent wind;
    iii. Inappropriate cleaning of the road;
    iv. Effects of bumping inside the voids of vehicle tires.

  In these cases joints must be refilled with sand swept on the pavement surface;

- If any settlement of the pavement occurs, the paved stones are removed, the bed-sand is repaired and stones are laid again and stabilized by vibrating compaction. This repair has a sense if settlement occurred in the sand bed layer; otherwise it is required to repair the foundation of the road;

- Locally, the problem that was observed on cobblestone roads is the removal of the stones during the installation of utility equipment such as water and electricity. These stone are not carefully replaced which result into degradation around the repaired pavement area. For the removal and replacement of stones, it is recommended the following:
    i. The use of a specific fastener that facilitate, after the removal of the sand joints, to extract safely the stone without damages;
    ii. If it is not possible to extract the specific stone without damage, it is required to demolish a certain number of stones surrounding the concerned area where there is a possibility of removing the stones without damages;
    iii. In case of excavating a trench that crosses the paved road, it is recommended to remove at least two supplementary lines of paved stones on both sides of the trench. The removed stones must be cleaned and stored in a secured area;
    iv. During rainy season, the pavement area where stones are removed must be protected against the accumulation of rain water between the foundation and sand bed layer;
    v. After excavation of the trench and laying of the utility equipment, the foundation is reconstructed with new materials of the same nature, quality and standard as the foundation in place. The use of stabilized sand is also recommended for used in reconstruction of the excavated trench;
    vi. The sand bed is removed from the whole area where paved stones are extracted and laid again after finalization of the reconstruction of the foundation. A slight thickness of sand is added to the normal level of the sand bed in order to recover the settlement induced by vibrating compaction of the paved stones;
    vii. Stored stones are re-laid and joints filled with sand. The paved stones are then compacted with vibrating plate and joints fully refilled like in normal procedure.

5.3. CONCLUSION

The improvement of the surface finishing of stone paved road is the key parameter for the improvement of the riding quality of the cobblestone road. This improvement requires the use of stones properly cut in regular shapes and dimensions. This report recommended the use of mechanically cut stones or combination of labour and small scale mechanical in road construction as cobblestone roads constructed because manually cut stones alone have poor riding quality.

The *Large paving blocks* of dimensions 14cm of width, 20cm of length and 14cm of height was recommended for use in stone paved roads due to its advantages in production and construction. This block is faster in production and can be accommodated to any type of laying pattern of the pavement stones. The arch layout is the laying pattern recommended for construction since it has demonstrated a good stability of existing cobblestone roads versus stone displacement. The dimensions of the kerbstone were recommended to be 20cm of width, 80cm of length and 20cm of height.

Technical measures of stone laying are recommended for use during the construction of the pavement like the method “click-and-drop” adopted to minimize damages of stone blocks during construction and to respect the chosen laying pattern of stones. Compaction of laid stones after filling the joints between adjacent stones was found very essential in improving the confinement of the pavement stones, whereas it was not done during the construction of existing cobblestone roads of the City of Kigali. The compaction is done by using a vibrating plate of 200 to 600 kg of weight and of centrifugal force equivalent to 30KN.

Control measures after construction of the stone paved road including inspection of joints inspection of possible local settlement after the opening of the road to traffic, are recommended to enable a timely fixing of the required repairs. A timely repair of defects enables the road to be used for long time without critical degradation.

5.4. REFERENCE

ILO. Special Public Works Programmes-Stone paving blocks-Quarrying, cutting and dressing. Booklet no.8.UNDP, 1992.

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CHAPTER 6 CONCLUSION AND RECOMMENDATIONS

This research contributed to the improvement of construction of cobblestone roads versus riding quality. Even if the literature survey showed the existence of cobblestone roads from ancient times, construction of these types of roads has not improved so much towards their roughness, which is one of the reason for declining them. In the City of Kigali, uncomfortable riding on cobblestone roads is the most critical aspect for declining them.

This chapter summarizes the findings of the research by assessing the conditions of riding in terms of IRI and by describing typical surface distress of existing cobblestone roads of the City of Kigali. From this assessment, the research recommended some improvements on surface finishing and constructability of cobblestone roads and the results increase the riding quality of cobblestone roads.

6.1. COMFORT OF COBBLESTONE ROAD USERS

It was found that the comfort of road users depends on the surface finishing of the road. The surface finishing of existing cobblestone roads was found uneven due to bumpy surface of paved stones that were manually produced. The level of comfort was estimated by estimating the roughness of existing cobblestone roads using the Bump Integrator. The roughness was found greater than 11.76 IRI, which is beyond acceptable limits of 4IRI for paved roads and 8IRI for unpaved roads as set by RTDA for roads constructed in Rwanda.

The riding quality is worsened by various degradations of the pavement of existing cobblestone roads including displacement of cobblestones, erosion of the joints, edge break undulations and depression of the carriageway surface. It was found that the displacement of cobblestones was caused by irregularities in shape and dimensions of manually cut stones used in construction. These irregularities reduce the confinement between cobblestones and the movement of vehicle tyres displace them easily.

6.2. SURFACE FINISHING AND CONSTRUCTABILITY

The improvement of the surface finishing of a cobblestone road requires at first instance, the use of stones with regular shape and dimensions. It was found that manual production cannot satisfy this requirement and the research recommended the use of mechanically cut stones on the surface finishing of the road.

The regular mechanically cut stones were recommended to be of dimensions of a *Large paving bloc* where the width is 14cm, length is 20cm and height is 14cm. The *Large paving bloc* has many advantages in its production and construction. In production a bigger quantity of *large paving stones* is produced in shorter period compared to blocs of smaller dimensions. In construction, it has an advantage of being accommodated to any type of laying pattern. The dimensions of the kerbstone were recommended to be 20cm of width, 80cm of length and 20cm of height by merging local practice with the dimensions proposed by ILO (1992) and by Antonio (2001).

The research recommended using an arch layout as a stable laying pattern against stone displacement based on visual inspection conduced on various existing cobblestone roads. Paving stones are laid on a bed course of sand of thickness 4cm after its compaction. The joints between the two adjacent laid stones must be less or equal to 2cm and must be filled with sand.

6.3. TECHNICAL MEASURES DURING AND AFTER CONSTRUCTION

During the construction of the pavement of cobblestone road, it is required to control the alignment of laid stones and inequalities beyond 5mm must be eliminated. The control is done by using a straight edge of 3m and the difference in height between the two adjacent paved stones must be less than 2mm.

The compaction of paved stones is required to increase the confinement between paved stones. This is done by using a vibrating plate of 200 to 600 kg of weight and of centrifugal force equivalent to 30KN. The vibrating plate must be covered with rubber or plastic to avoid damaging the paved stones.

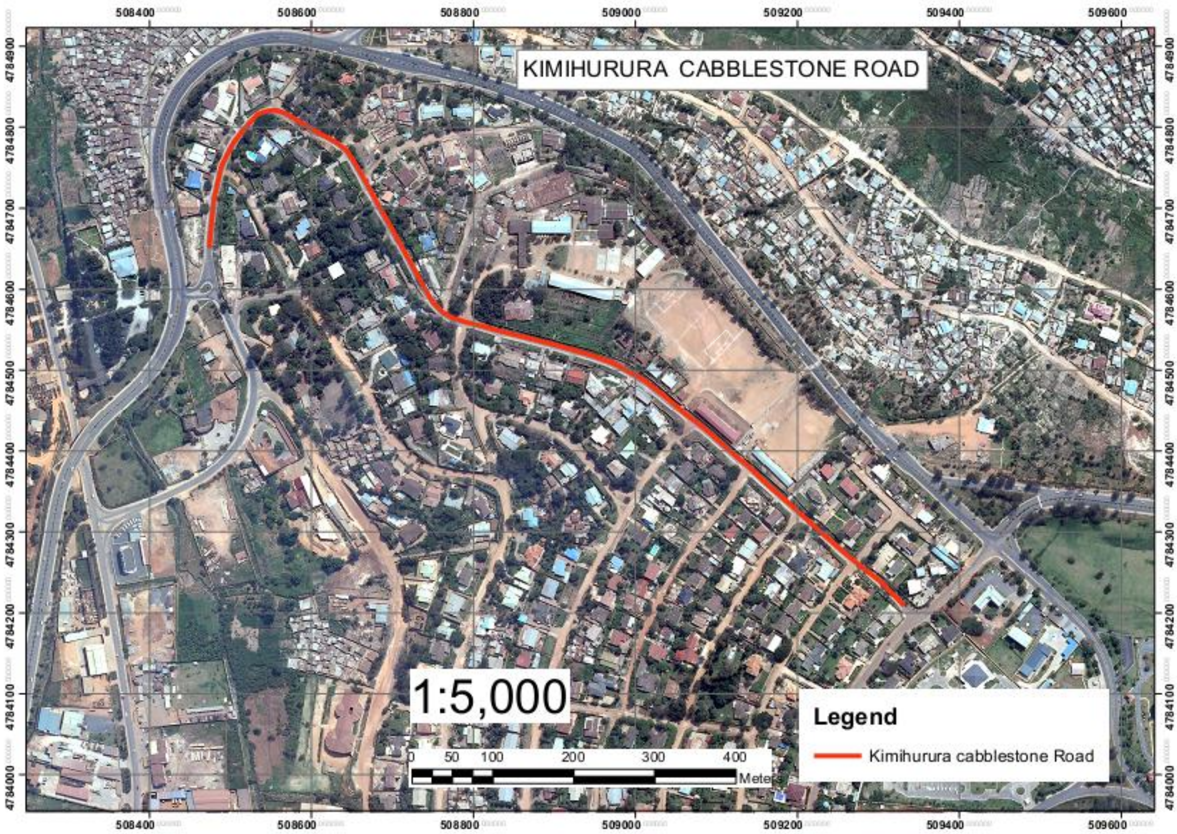
After opening the cobblestone road to traffic, it is required to control the joints and any other defect that may arise from using the road. Unfilled joints must be refilled again followed by fixing the observed defect if any. The refilling of joints and fixing of required repairs are done in the same technique as in previous work done.

6.4. RECOMMENDATIONS FOR FUTURE WORK

- This study concerned the improvement of cobblestone road towards riding quality and reducing the operating cost. Technical improvements of construction of cobblestone roads have been discussed and recommendations on constructability and surface finishing have been provided for in this research. The roughness of existing cobblestone roads was estimated greater than 11.76 IRI which is a worse roughness compared to unpaved road which has a limit of acceptability of 8IRI in Rwanda. For a more understanding of costs incurred by road users during the riding on existing cobblestone roads, there is a need to conduct a study on Vehicle Operating Cost through it components: fuel consumption, tire wear, maintenance and repair, oil consumption, capital depreciation, license and insurance, and operator labour and wages;

- Future studies require the understanding of the sustainability of the cobblestone technology against the strict environmental regulation for the opening of the new borrow pits;
- The comparison of the use of the paved clay or cement block versus cobblestone in terms of constructability, addressing the dust and mud's palliative.

APPENDIX A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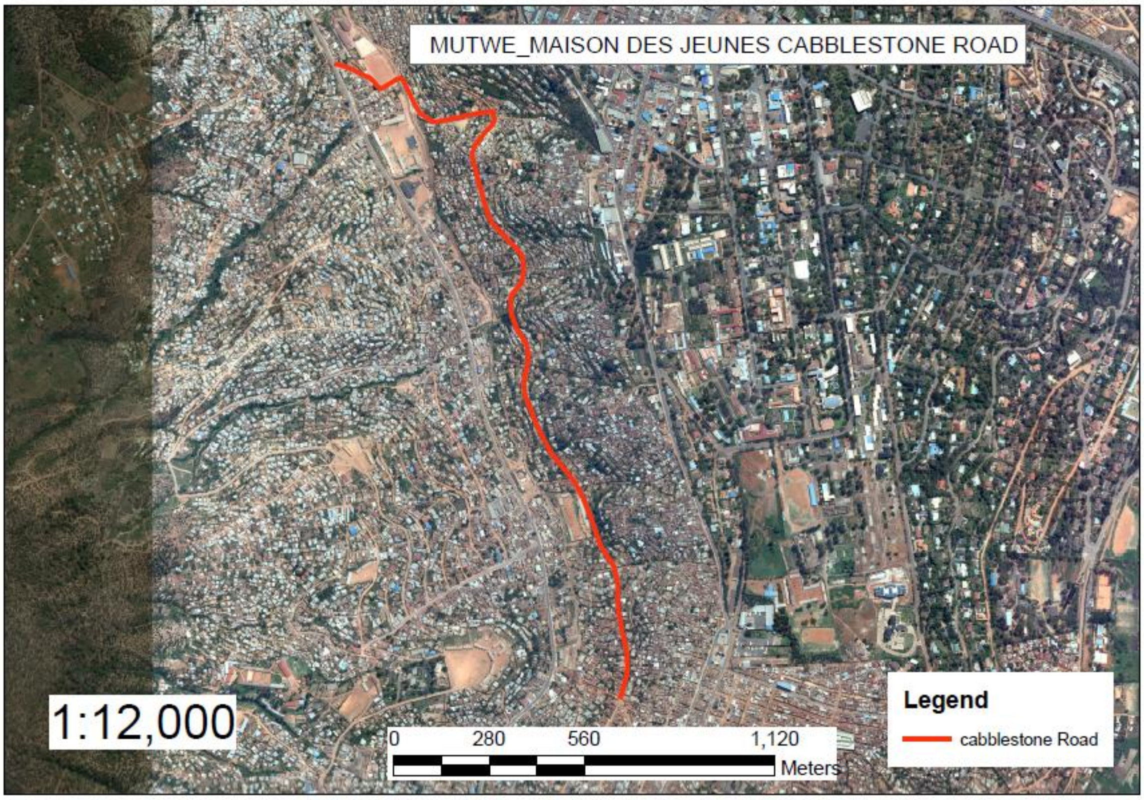
APPENDIX B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