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RESEARCH ARTICLE
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A Comparison of the Structural and Functional Performance of a Flexible Pavement Constructed in a Swampy and Non-Swampy Area

Kigaiga Ibrahim*; Chris Bic Byaruhanga, Ph.D.

Department of Civil and Environmental Engineering, Faculty of Engineering, Kyambogo University, Uganda.
Corresponding Author's Email: kigaigaibrahim@gmail.com

Abstract

Pavement condition evaluation is a key component of a pavement management system (PMS) that facilitates decision-making in asset management. Whereas traffic loads and other factors may contribute to pavement deterioration, it appears that subgrade condition and its treatment contribute significantly to early deterioration. Generally, it appears there are few or limited studies that have explored the effectiveness of pavements built in swampy areas. Therefore, this paper attempts to examine the performance of a pavement built in different types of soil or subgrade strength. Structural and functional data that were collected using a Falling Weight Deflectometer (FWD) and Road Measurement Data Acquisition System (ROMDAS) are used in this study. A structural number (SN) for the different road sections is computed using FWD pavement deflections. Rutting and Roughness data measured by ROMDAS are used to assess the functional condition of the pavement. The results show that the functional performance of both sections (swampy and non–swampy) is satisfactory. However, the structural condition of the non–swampy section is better than the swampy section. This study contributes to the existing knowledge regarding the performance of flexible pavement sections built in swampy areas in comparison to other soil types. In conclusion, pavements constructed in swampy areas may achieve the required performance provided effective foundation and subgrade treatment is provided during design and construction.

Key words: Functional condition; Pavement; Roughness; Rutting; Structural condition; Swampy.

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INTRODUCTION

Pavement condition evaluation is a key component of a pavement management system (PMS) that facilitates decision-making in asset management regarding maintenance and rehabilitation needs at network level planning. At project level, pavement evaluation is a key input to road infrastructure design but may also be used to inform policy and practice to improve design and construction methods.

The performance of a pavement depends on a number of factors such as materials used, construction method and quality, environment, destructive effect of heavy traffic loads and subgrade strength (Alaswadko & Hassan 2016, Bhandari, Luo & Wang 2023). Despite knowing and taking care of these factors during the design and construction stages, some pavements still develop defects and may not perform as expected as soon as they are opened to traffic. Whereas traffic loads may contribute significantly to pavement deterioration and eventual failure, it appears that the subgrade condition and its treatment are another key contributing factor that may greatly initiate and contribute to early deterioration.

To understand the extent to which this may affect pavement performance requires an assessment of different uniform sections of the pavement that were given appropriate design and treatment during construction. There is a need to examine climate and subgrade-related factors to understand pavement deterioration and distress manifestation. As an example, it appears there are limited studies that have examined the performance of pavements built in swampy/wetland and non-swampy areas.

Road sections in wetlands often receive more special and appropriate foundation treatment due to the existing problems compared to non-swampy sections. However, evidence for the effectiveness of such treatments in swampy areas is still limited in the scholarly literature. Pavements built in non-swampy areas may also be susceptible to excessive water that may accelerate rutting, fatigue cracking, and roughness. Thus, this study emphasises the need to evaluate the performance of pavements built in these different climatic areas to inform design and practice.

The life span and operational performance of a flexible pavement largely depend on drainage of both surface and ground water. Therefore, based on the design and construction improvements made to pavements built in swampy areas, they may perform better than those in non-swampy areas, more specifically with ground water and capillary rise effect.

Considering economics, provision of capillary cutoffs to prevent capillary rise of water may be expensive for the entire pavement and thus justified in exceptional circumstances. The ingress of water from the bituminous surfacing and the migration of water over time by capillarity may progressively deform the subgrade of the pavement built in a non – swampy due to insufficient drainage mechanisms during design and construction. This eventually triggers the deterioration mechanisms that lead to some of the pavement defects such as rutting and roughness. Generally, it appears there are few or limited studies that have explored the effectiveness of pavements built in swampy area. The evidence for this is limited, and this paper attempts to examine the performance of the pavement built in different types of soil or subgrade strength.

METHODOLOGY

To examine the performance of the different sections of the pavement built in swampy/wetland and non-swampy areas, structural and functional data were required and used in the analysis. Road pavement performance is usually determined by its structural and functional condition. The functional condition of the pavement refers to its ability to provide the required level of service in terms of safety and comfort for road users, often measured by the International Roughness Index (IRI). Structural condition relates to the structural or carrying capacity of the pavement to carry imposed loads. A case study of the Kampala Northern Bypass Highway, Kampala, Uganda, often referred to as the Northern Bypass, is used in this study. The Northern Bypass Road (approximately 23 Km) forms a semi–ring around Uganda's capital and largest city, Kampala. The entire construction of this Highway started in 2004 and ended in 2022, although it was opened to traffic in 2009 when the first phase of the project was completed. It was constructed to relieve traffic congestion and is currently connected to the first Expressway (Kampala – Entebbe Expressway) in the country. Northern Bypass Road was divided and mapped into 2 sections using ArcGIS software; the wet/swampy area (12.3km) starting from the Kyebando Flyover to Busega Roundabout and the non-swampy area of approximately 8.6km from the Namboole Roundabout to Kyebando Flyover. Surrounding sections along the Northern Bypass Road that are wet year-round with swamp vegetation were mapped as swampy area using ArcGIS software and the rest of the other sections as non – swampy area.

The 2020 Falling Weight Deflectometer (FWD) data obtained from Uganda National Roads Authority (UNRA) was used to determine the pavement structural condition. The FWD simulates how a pavement responds under traffic loading by applying an impulse load and measuring the pavement deflection bowl. Through back-calculation, layer moduli were estimated using the deflection values measured by the FWD and the layer thickness during construction. The pavement thickness during construction was obtained from a report by Transport Research Laboratory (TRL). The FWD structural number method developed by Rhode (1994) was used for characterising pavement strength in this study to determine the AASHTO structural number. A structural index of the pavement (*SIP*) (µm) was computed using Eq. 1

$$SIP = D_O - D_{1.5HD} \tag{1}$$

D_O= Peak deflection measured under a standard load of 40 KN.

$D_{1.5HD}$= Surface deflection measured at an offset of 1.5 times HP under a standard load of 40 KN.

Hp = Total pavement thickness (mm)

Consequently, the structural number (SN) in inches was computed using Eq 2.

$$SN = k_1 SIP^{k2} Hp^{k3} \tag{2}$$

k_1, k_2 *and* k_3 are coefficients obtained in Table 1. These are empirical coefficients used in pavement performance equations adjusting for surface type characteristics such as roughness, rutting and structural condition.

Table 1: Coefficients for SN calculation (Austroads, 2017)

Surface Type	Coefficients		
	k_1	k_2	k_3
Surface seals	0.1165	-0.3248	0.8241
Asphalt concrete	0.4728	0.4728	0.75871

Functional condition data was obtained from UNRA based on a Road Measurement Data Acquisition System (ROMDAS) survey conducted in 2023. ROMDAS is a modular system used to collect asset and pavement condition data using a Transverse Profile Logger (TPL), Laser Profilometers, Global Positioning System (GPS) and a High-Resolution Odometer installed in a vehicle. Specifically, rutting and roughness data were used in this study. Figure 1 below shows the guidance in interpreting and analysing the values of IRI.

Paved Network IRI Limits

Distress	Attribute in Visuals perspective	*Data range describing each problem category – Paved roads*				
		Severe/ Very Poor	Warnin g /Poor	Moderate/ Fair	Isolated /Good	None/ Very Good
Roughness (measured)	Roughness Measured*	> 6.5 IRI	4.5 – 6.5 IRI	3 – 4.5 IRI	2 – 3 IRI	≤2 IRI

Unpaved Network IRI Limits

Distress	Attribute in Visuals perspective	*Data range describing each problem category – Unpaved roads*				
		Severe/ Very Poor	Warnin g /Poor	Moderate/ Fair	Isolated /Good	None/ Very Good
Roughness (measured)	Roughness Measured*	> 12 IRI	8.5 – 12 IRI	5.5 – 8.5 IRI	3.5 – 5.5 IRI	≤ 3.5 IRI

Figure 1: IRI interpretation guideline

For rutting, the rut severity classification in Table 2 by Fwa and Ong (2012) was used to interpret the rutting data.

Table 2: Rut Severity Classification by Highway Agencies

Highway Agency	Low	Medium	High
Pavement Condition Index (PCI) *(Shahin 1994)*	0.25-0.5 in. (6.3 – 12.7 mm)	0.5-1 in. (12.7-25.4mm)	>1 in. (>25.4 mm)
PASER Manual, Asphalt Roads *(Walker et al.2002)*	0-0.5 in. (0-12.7 mm)	>1 in. (>25.4 mm)	>2 in. (>50.8 mm)
Washington State DOT *(WsDOT 1999)*	0.25-0.5 in. (6.3-12.7 mm)	0.5-0.75 in. (12.7-19.1 mm)	>0.75 in. (>19.1 mm)

Advanced Journal of Science, Technology and Engineering
ISSN 2997-5972 • Volume 6, Issue 1, 2026 • pp. 144–153

Ohio DOT *(OhDOT 2006)*	0.125-0.375 in. (3.2-9.5 mm)	0.375-0.75 in. (9.5-19.1 mm)	>0.75 in (>19.1 mm)
Massachussetts Highway Dept. *(CMMPO 2006)*	0.25-0.5 in. (6.3-12.7 mm)	0.5-1.5 in. (12.7-38.1 mm)	>1.5 in. (>38.1 mm)
Ministry of Transportation and Infrastructure British Columbia *(MTI BC 2009)*	3-10 mm	10-20 mm	>20 mm
California DOT *(Caltrans 2006)*	Schedule corrections when rut depth >1 in. (>25.4 mm)		
Note: 1 in. = 25.4 mm			

RESULTS AND DISCUSSION

The results presented here are based on the data collected on the Northern Bypass Highway by UNRA using FWD and ROMDAS equipment. The accuracy of the measurements and the data used in this research is highly dependent on the calibration of the equipment used as well as the expertise and training provided to the data collection technicians. Validation of the different data sets obtained from UNRA was not conducted. In addition, the results below may change with time due to increased traffic loading and environmental-related factors. Nonetheless, the results provide evidence of the comparison of the functional and structural condition of a pavement opened to traffic built in a swampy and non–swampy area.

Structural Capacity

The results of the FWD data show relatively higher deflections for the swampy section compared to those in the non–swampy area, as seen in Figure 3 and Figure 4 below for both lanes. These results differ from earlier findings by an investigation conducted by TRL (2008) on the same road, where lower deflections were established in the swampy areas. The possible explanation for this might be associated with an increase in subgrade moisture content and floods along this highway in the swampy area that may have weakened the subgrade strength over the years since the TRL assessment was conducted in 2008.

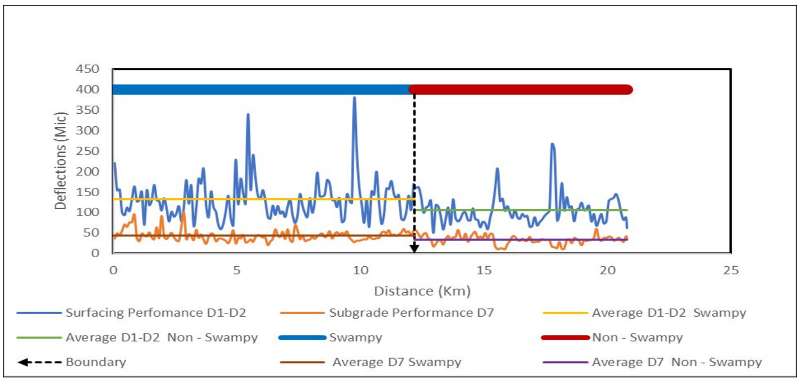

Figure 2: FWD deflections Eastbound (Busega – Bweyogerere Lane)

AB Journals
Advanced Journal of Science, Technology and Engineering
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Previous research by Cumberledge et al. (1974) showed that surface deflections increased with an increase in moisture content of the subgrade. These results are similar to the pavement evaluation findings by Keyser and Laforte (1984) conducted 10 years after construction for a pavement built in a swampy area.

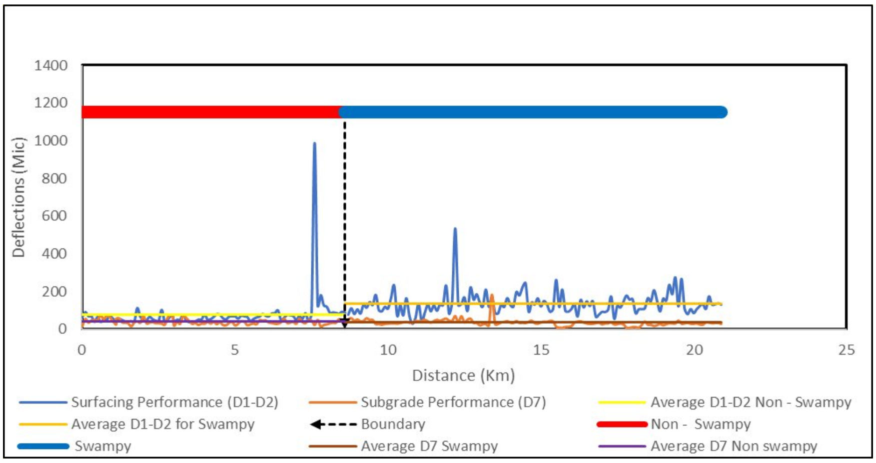

Figure 3: FWD deflections Westbound (Bweyogerere – Busega Lane)

Secondly, the study computed an SN based on the above using FWD deflection data. An average SN of 4.2 and 4.5 was obtained for the swampy and non–swampy areas, respectively, in the Westbound Lane (Figure 6). The SN computed for the swampy area is lower than the design SN of 4.4 according to the report by TRL (2008). Similarly, for the Eastbound Lane (Figure 5), average SN of 5.4 and 6.4 was obtained for the swampy and non–swampy areas respectively. In the design of pavements, the SN is an abstract number used to express the strength of the pavement required for a combination of soil support value (S), total traffic expressed in Equivalent Standard Axles (ESALs), terminal serviceability and environment.

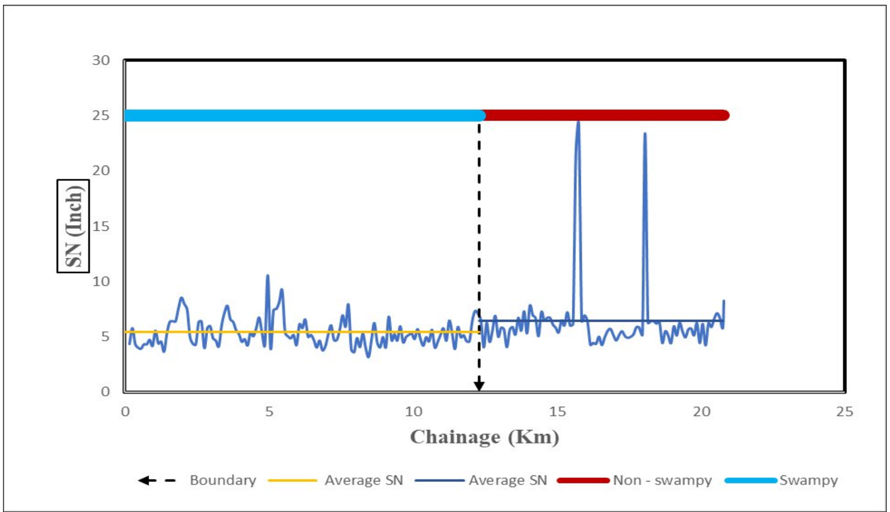

Figure 4: SN Eastbound (Busega – Bweyogerere Lane)

Therefore, based on the above results, generally, the pavement in the swampy area has a lower SN compared to the non-swampy section. The pavement in the non–swampy area appears to have sufficient structural strength to sustain the design structural loadings. However, the swampy section (Westbound Lane) appears insufficient to carry the anticipated loading. It is possible that this swampy area may not have received adequate treatment to meet the required standard. This may have been exacerbated by the flooding since it is usually experienced along the Northern Bypass Highway. Flooding reduces the structural capacity and subgrade strength of highway pavements (Zhang et al. 2008, Sultana et al. 2015, 2016). Traffic loading is a key contributing factor to pavement damage and deterioration. A combination of heavy traffic loads and insufficient structural capacity of the pavement may facilitate premature failure manifested by surface defects of rutting and roughness.

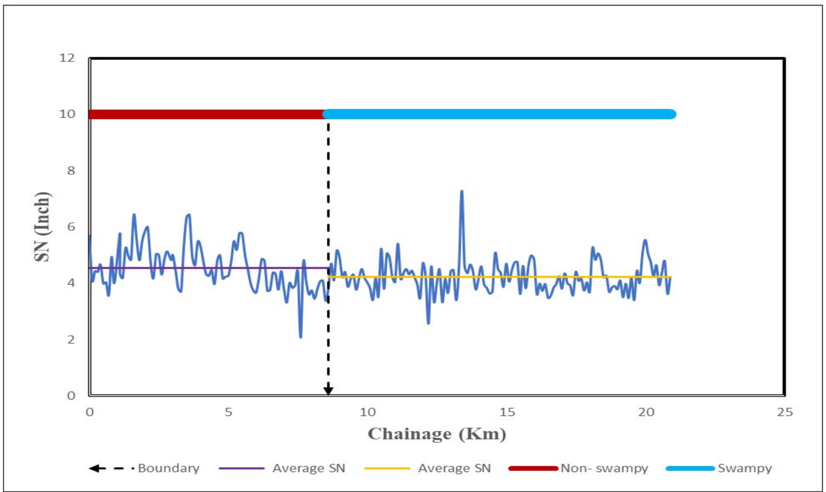

Figure 5: SN Westbound (Bweyogerere – Busega Lane)

Functional Capacity

Roughness

The roughness data measured using ROMDAS shows an average roughness of 1.9m/km and 1.8m/km in the swampy and non-swampy sections, respectively, for the entire road (Figure 7 and Figure 8). The two sections are performing equally in providing comfort to the road users. One possible explanation is that ROMDAS tests were conducted on recently completed works, thus the reason for this comparable functional condition. Thus, these results provide a foundation for future tests to be conducted before any intervention is done. Although the difference in roughness is minor, it is still comparable to a study conducted by Haider and Chatti (2009) where pavement sections in the wet-freeze zone exhibited a higher roughness increase. Similarly, a study by Keyser and Laforte (1984) that was conducted 10 years after opening the road to traffic established rough surfaces for sections built over peat deposits in comparison to other areas.

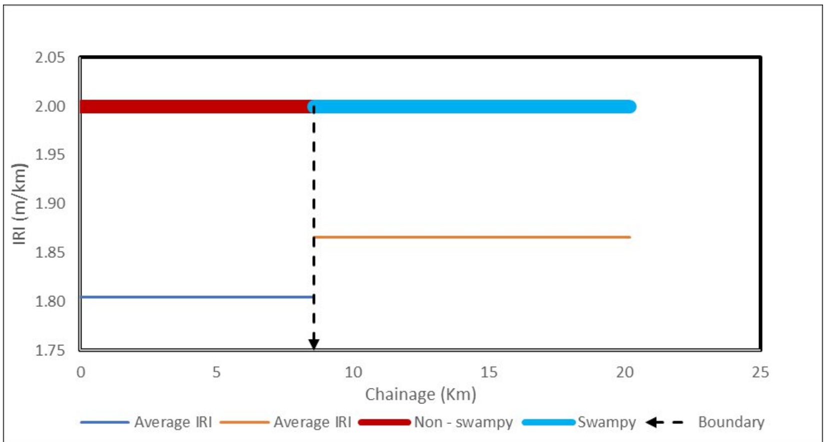

Figure 6: Average Roughness Westbound (Bweyogerere – Busega Lane)

Generally, the results show that the entire Northern Bypass Highway is very good in terms of providing comfort to the drivers since the measured roughness is below 2m/km. A study by Tarefder et al. (2008) found that roughness is sensitive to subgrade strength and that effective subgrade treatment results in substantial sustainability against IRI degradation. Therefore, as long as the proposed design treatments are well implemented during construction, sections of the road in a swampy area may perform well or even better than those in non-swampy areas.

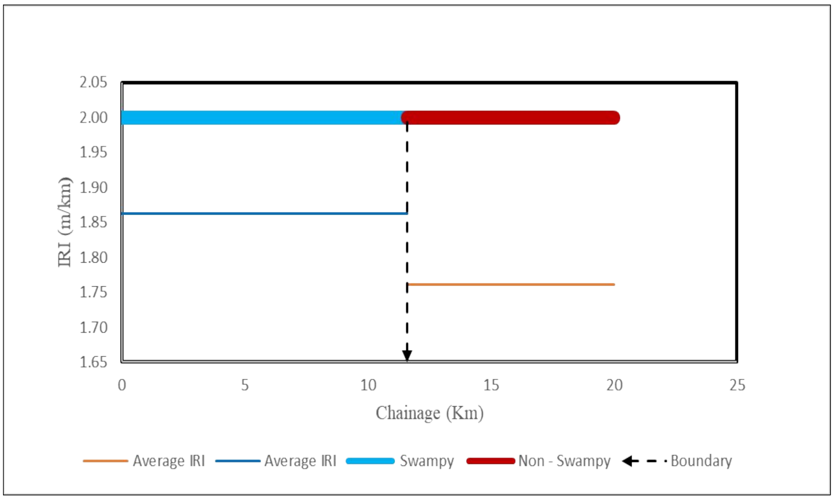

Figure 7: Average Roughness Eastbound (Busega – Bweyogerere Lane)

Rutting

The results for rutting show an average of 3.8 and 2.8 in the swampy and non-swampy sections, respectively, of the highway for the Bweyogerere – Busega Lane (Figure 9).

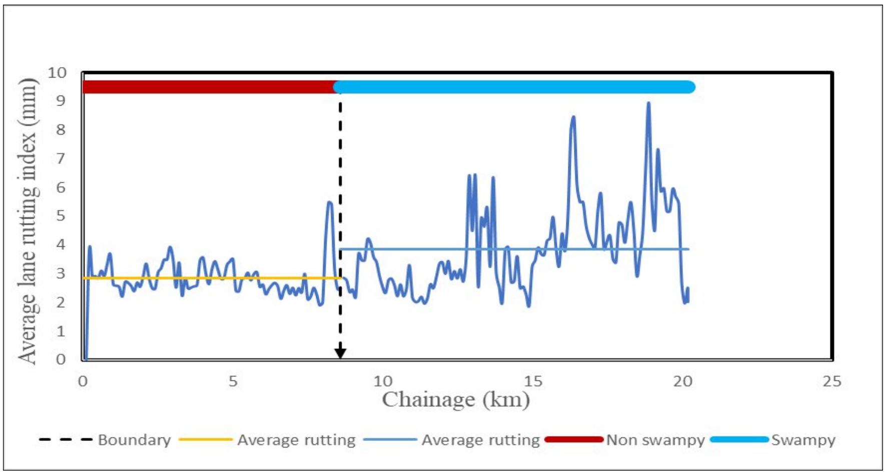

Figure 8: Average rutting Westbound (Bweyogerere – Busega Lane)

For the Busega – Bweyogerere Lane, the results show an average of 3.2 and 2.9 in the swampy and non-swampy sections, respectively (Figure 10). Generally, there is more rutting in the swampy area compared to the non–swampy area, an indication that rutting is sensitive to subgrade strength and stiffness as previously identified by Tarefder et al. (2008). Generally, these results indicate low rutting of the entire Northern Bypass Highway at completion of construction works. Again, the difference is minimal when comparing the two sections, implying a comparable functional performance. Therefore, pavements built in swampy areas may provide a comparable or better functional performance to non–swampy areas provided adequate design and treatment is achieved.

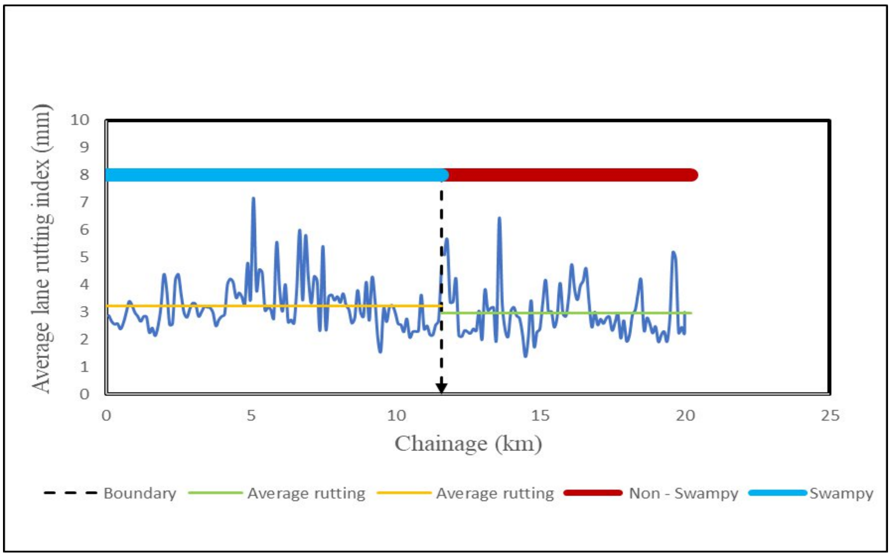

Figure 9: Average rutting Eastbound (Busega – Bweyogerere Lane)

CONCLUSION

In this study, the aim was to assess the performance of the pavement section built in a swampy and non–swampy area. Generally, the functional performance of both sections (swampy and non–swampy) is satisfactory. The results show that rutting is low, and based on the IRI values, the Northern Bypass Highway is in a very good condition. Nonetheless, the structural condition of the swampy section along the Westbound Lane appears insufficient to handle the anticipated loads. Flooding, inadequate design, and construction may explain the low structural capacity of this swampy section of the Northern Bypass Highway. It is recommended that future assessments are conducted to ascertain the performance of these sections over time. The study contributes to our understanding that pavements constructed in swampy areas may achieve the required performance at completion provided effective foundation and subgrade treatment is provided during design and construction. It also further reiterates the understanding that rutting and roughness are responsive to subgrade strength. This study contributes to the existing knowledge regarding the performance of flexible pavement sections built in swampy areas in comparison to other soil types. Prior to this study, it was difficult to make predictions about the performance of pavement sections built over different soil or subgrade types. The ROMDAS results provide a good foundation for future assessments of the same road before any interventions are carried out.

CRediT Author Statement

Kigaiga Ibrahim: Methodology, Formal analysis, Investigation, Writing – Original Draft, Visualization, and funding acquisition. **Chris Bic Byaruhanga**: Conceptualization, Writing - Review & Editing, Supervision, and Project administration.

Declaration of Competing Interests: none .

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