A case investigation into causes of premature rutting failures in rehabilitated asphalt pavements in Tanzania

Joseph K. Anochie-Boateng[1], and John T. Malisa[2]

ABSTRACT

Tanzania was faced with high incidences of premature rutting failures on their asphalt pavements. Some pavements experienced failures within one to two years after construction/rehabilitation. The objective of this investigation was to identify the factors which contributed to the observed failures on five rehabilitated road sections on a national highway in Tanzania. Pavement temperature data collection, traffic surveys, visual inspection, rut depth measurements, and Falling Weight Deflectometer tests constituted the main activities of the field investigation reported in this paper. Laboratory study included a visual assessment of cores extracted from the studied road sections to determine both physical and engineering properties including density, stiffness, strength, aggregate shape properties, grading and physio-chemical tests on the recovered binders. The results of the study indicated that the degree and extent of rutting on the investigated road sections was rated as severe., i.e., rutting ranged from 38 to 138 mm on the five sections when compared to the acceptable threshold value of 15 mm for high volume roads in Tanzania. The elastic deflection results indicated that the underlying layers of the pavement system were generally in a sound condition, which validated the suggestion that the rutting observed was mostly

[1]Corresponding Author, Civil Engineering Department, University of Pretoria, Private Bag X20 Hatfield 0028, South Africa, ORCID: 0000-0002-2632-7904, joseph.anochieboateng@up.ac.za
[2]Civil Engineering Department, University of Dar es Salaam, P. O. Box 35091, Tanzania; and Research and Development Unit, Tanzania National Roads Agency, P. O. Box 9452, Dar es salaam, Tanzania, john.malisa@tanroads.go.tz

confined to the asphalt concrete layers. Factors such as relatively high axle loads, poor asphalt mixes and possibly inadequate quality control during construction and rehabilitation were suspected to contribute to the rutting on the sections. Practical measures recommended to the roads agency to avert future occurrences are provided in this paper.

Keywords: *Premature failures, Asphalt pavements, Rutting, Asphalt mix design, Wide-base tyres.*

Introduction

Rutting in asphalt concrete (AC) layers is one of the most frequent and more serious distresses associated with asphalt surfaced pavements. Recent studies have revealed that premature rutting failures are not uncommon in some African countries including Ethiopia, Ghana, Tanzania, Malawi, and South Africa.[1, 2, 3, 4,] The major contributing factor to premature rutting in asphalt layers is often associated with relatively heavy traffic volume and high axle loads, which are immediately imposed onto an inadequately designed and/or compacted AC layer, as well as overloading due to an inadequate or lack of traffic law enforcement. A substantial amount of rutting in the asphalt layer is attributed to excessive bitumen binder content, use of excessive mineral fillers, use of too many rounded aggregate particles, use of wrong grade of bitumen binder, and insufficient field compaction effort. Other factors are pavement surface temperatures (> 40°C), lower vehicle speeds, viscosity of the mastic, and voids filled with binder. One of the causes of accelerated rut development, especially when the asphalt mat is still fresh, is insufficient compaction at the time of construction, which not only would result in higher levels of densification under traffic, but also could render the asphalt mix more susceptible to shear deformation in the early life of the asphalt layer. Verhaeghe, Myburgh, and Denneman[5] found that for every one per cent decrease in density below the minimum required density, the life of the asphalt layer could be reduced by as much as 10 percent.

High incidences of premature rutting failures in asphalt concrete layers of roads have been reported in Tanzania for several years. This has been mainly attributed to the increasing traffic volumes and loading on roads in urban areas and highways. Although overloading is a major concern, recent study by the Central Materials Laboratory of Tanzania National Roads Agency (TANROADS) on selected highways in Tanzania attributed premature failures of roads to the advent of “wide-base” (or super single) tyres. Previous studies conducted on urban roads in Dar es Salaam along the Tanzam highway revealed that the failures were mainly plastic deformation in the form of rutting or shoving. The causes of the failures were attributed to the use of inappropriate materials and a poor-quality control during construction.

In 2014, TANROADS commissioned a project to identify the factors that contributed to the premature failures of the asphalt concrete layers, identify an asphalt mix design methodology that would be suitable for the prevailing environmental (temperature) and traffic loading conditions currently experienced on the roads and highways in the country, and to develop viable solutions that would mitigate the occurrence of premature failure in the future. The overall investigation was done from 2014 to 2016 on 12 road sections (seven pavement sections in good conditions and five rehabilitated pavement sections – in poor conditions) on the Tanzam highway. The Tanzam highway is a single carriageway with one lane (3.7 m wide) in each direction and a total length of about 900 km with a surfaced shoulder along a large portion of the highway.

This paper focuses on the five rehabilitated road sections that formed part of the investigation – four asphalt overlay sections (i.e., Nelson Mandela, Mlandizi-Chalinze, Mikumi-Iyovi and Makambako-Mbeya) and one reconstructed/rehabilitated section (Chalinze-Morogoro).

All five road sections experienced rutting failures in the outer and inner wheel tracks. The objective is to present and discuss detailed field and laboratory results on the five sections. To solve the problem and to bridge the gap between theory and practice, findings and the likely causes of the premature failures as well as proposed remedial actions are also presented in this paper.

Methodology

The Tanzam highway (T1) was selected for the study. T1 is historically known to experience the highest volume of heavy truck traffic in Tanzania (i.e., the average daily traffic for very heavy goods vehicles are approximately 1,000 vehicles per day). The Tanzam highway is 900 km long, and links Tanzania to Zambia, hence providing vital services for the importation and exportation of strategic goods to and from the country. The road is thus, critical to the socio-economic development of Tanzania

A detailed field and laboratory testing formed the core of this study. The project team conducted a field investigation of 12 road sections on the Tanzam highway. These sections were selected from the Nelson Mandela Road in Dar es Salaam to the Mbeya region of the country. Pavement temperature data collection, traffic surveys, visual inspection, rut depth measurements, test pit profiling, Falling Weight Deflectometer (FWD) and Dynamic Cone Penetrometer (DCP) tests constituted the main activities of the field investigation. It should be mentioned that no comprehensive data were accrued to discuss DCP and test pit results in this paper. Also, limited field study was conducted to assess cracking, mechanical failure, bleeding, and other obvious pavement structural and functional failures on each road section.

The laboratory study included a visual assessment of cores extracted from the 12 investigated road sections including the five rehabilitated sections discussed in this paper to determine both physical and engineering properties including density, stiffness, strength, aggregate shape properties and grading. The conditions of the bituminous binder recovered from the cores were to be assessed by means of various physio-chemical tests. It was expected that the laboratory test data would be correlated with design and as-built information to make logical conclusions.

Field study and results

TRAFFIC VOLUME AND LOADING

In Tanzania, the permissible legal axle load is fixed at 100 kN, irrespective of the type of axle or number of tyres on a particular axle. The tyre load for an axle fitted with a wide-base tyre is 50 kN, whereas that of dual is 25 kN on each tyre. Two independent studies indicated that traffic volume of very heavy vehicles on the Tanzam highway is about 5,000 equivalent axle loads (ESALs) /day. As part of the field study, a survey of trucks with wide-base and dual tyres was carried out for seven days over 24 hours period at a weighbridge station (located at Wenda in Iringa region) to compare the proportion of wide-base and dual tyres used on the Tanzam highway. The perception is that these tyres are the main source of premature AC failure on the highway. The survey was conducted for traffic in both directions. In summary, results of the survey are presented in table 1. For both directions, it was found that the total number of heavy trucks that use wide-base tyres constitutes 50 percent of the total traffic counted at the station.

TYRE CONTACT STRESS (WIDE-BASE AND DUAL TYRES)

For this study, the TANROADS team visited 10 selected fuel stations along the Tanzam highway to obtain basic tyre information (tyre type, TiP, and ply width) that can be used to calculate tyre contact stresses applied on the road surface by the wide-base and dual tyres. For semi-trailers and full trailers (all heavy vehicles), the maximum and minimum TiPs for a truck with wide-base tyres were found to be 896 and 689 kPa, respectively. For dual wheel tyres, the maximum TiP was 896 kPa (full trailers) and the minimum was 758 kPa (semi-trailers). Consequently, three TiPs (i.e., 689, 758 and 896 kPa) were analysed to compare contact stresses applied on the Tanzam highway by wide-base and dual tyres. The analysis was done by using CSIR *TyreStress* Software (*In-house*). Table 1 provides the analysis results, which indicate that the Normalised Contact Stress (NCP) ratios of the wide-base tyres are generally high compared to the dual tyres.

TABLE 1. Traffic data at weigh bridge station and maximum tyre contact stresses[a] (*in italics*) and NCP[b] results for a wide-base and dual tyre set

Traffic and Tire Information	MGV	HGV	VHGV	Buses	MGV	HGV	VHGV	Buses
Average daily traffic (ADT)	219	180	923	395	259	151	854	309
Seven-day total (heavy category)	12,019				11,011			
ADT (All)	1,717				1,573			
Total traffic with wide-base tire	6,063				5,461			
ADT (wide-base tire)	866				780			
Proportion of wide-base, %	50.4				49.6			
	West Bound				East Bound			
	MGV	HGV	VHGV	Buses	MGV	HGV	VHGV	Buses
ADT	219	180	923	395	259	151	854	309
VEF	2.36	2.51	5.40	1.68	2.36	2.51	5.40	1.68
E80 per day	516	452	4,988	664	610	379	4,615	520
Heavy vehicle traffic growth rate, %	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
E80 for 20 years	6,930,655	6,068,618	66,971,133	8,920,592	8,196,528	5,090,896	61,964,624	6,978,387
Total E80 for 20 years				88,890,999			82,230,436	

Tire/Ply Width, mm	Tire Loading, kN	TiP, kPa 689 (100, psi)	758 (110, psi)	896 (130, psi)
Maximum tire contact stress (385 mm wide-base tire)	50	1,125	1,201	1,406
Normalized contact pressure (385 mm wide-base tires)		1.63	1.58	1.57
Maximum tire contact stress (295 mm dual tire)	26.8[c]	1,050	1,114	1,170
Normalized contact pressure (295 mm dual tires)		1.52	1.47	1.31
Maximum tire contact stress (315 mm dual tire)	25	936	995	1,096
Normalized contact pressure (315 mm dual tires)		1.36	1.31	1.22

Note: MGV = medium goods vehicle; HGV = heavy goods vehicle; VHGV = very heavy goods vehicle; [a] From TireStress Software; [b] Normalized Contact Pressure (NCP) = Maximum vertical Contact Stress) / (TiP); [c] Minimum tire load for this group of tires (width = 295 mm) in the TireStress software.

ASPHALT CORING AND RUT DEPTH MEASUREMENT

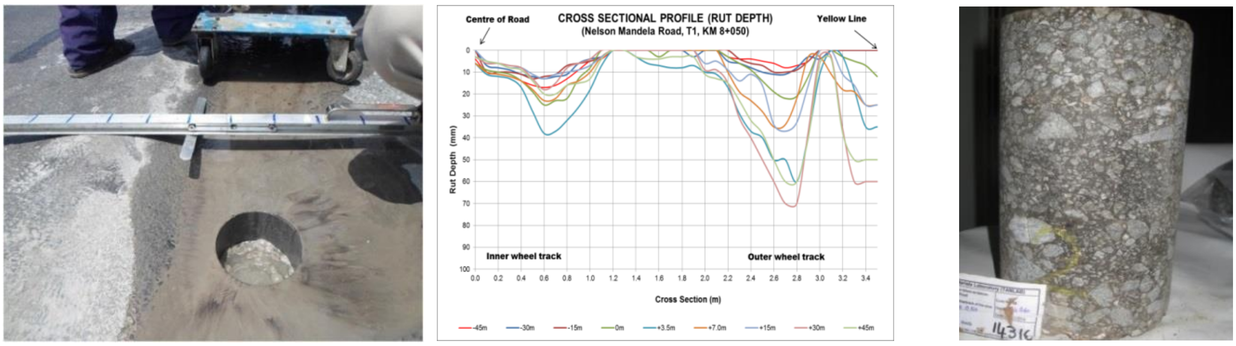
Core samples from the AC layer have traditionally been used to determine layer thickness and tested in the laboratory to determine the physio-chemical and engineering properties of the component materials, and the samples. Both 100, and 150-mm diameter cores were extracted from the road sections for detailed visual condition assessment and laboratory evaluation of the binder, aggregates and asphalt mix properties. The 150-mm diameter cores were used purposely for bitumen binder evaluation and characterisation tests whereas the 100-mm cores were used to determine the engineering properties of the asphalt mixes.

Coring results at the five rehabilitated sections showed that during rehabilitation, the old asphalt layers were not milled out before new AC overlays were placed. Rutting was believed to worsen after the overlay rehabilitation sections were opened to heavy truck traffic loading on the highway. A total of 24 cores (a set of eight cores for outer, between and inner wheel tracks) were extracted in the areas exhibiting moderate rutting on each road section.

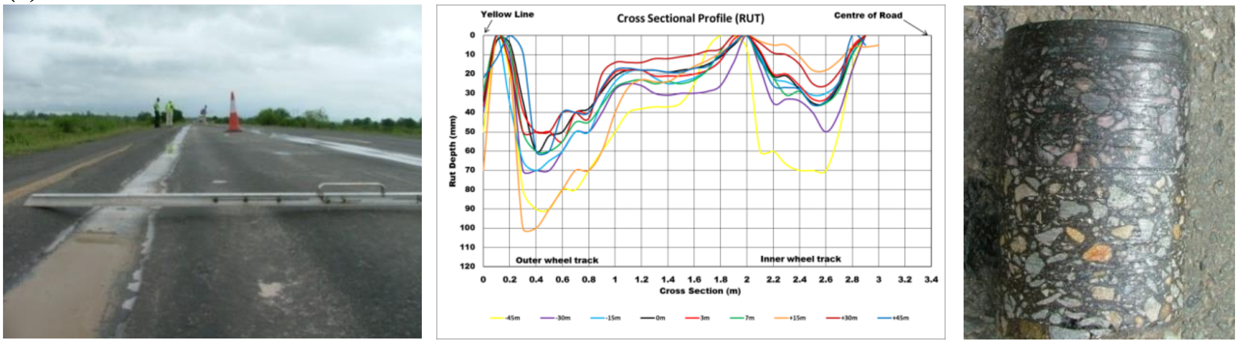
A two-metre-long straight edge and a wedge were used to measure rut depths of the road sections in accordance with procedures set in TMH9.[6] Rut depth is defined as the maximum permanent deformation measured under the two-meter straight edge. The cross-sectional profile was measured from the shoulder towards the centre of the pavement. In most cases, the cross-sectional profile was measured by placing the straight edge on top of the shoved asphalt so that a measurement of zero (0) mm could be obtained on the shoulder. The 90th percentile values of the rut depth as well as the average maximum and minimum pavement temperatures are summarised in table 2 for the five road sections.

Figure 1 shows rut depth measurements for the five rehabilitated road sections (Nelson Mandela, Mlandizi-Chalinze, Chalinze-Morogoro, Mikumi-Iyovi, and Makambako-Mbeya). The

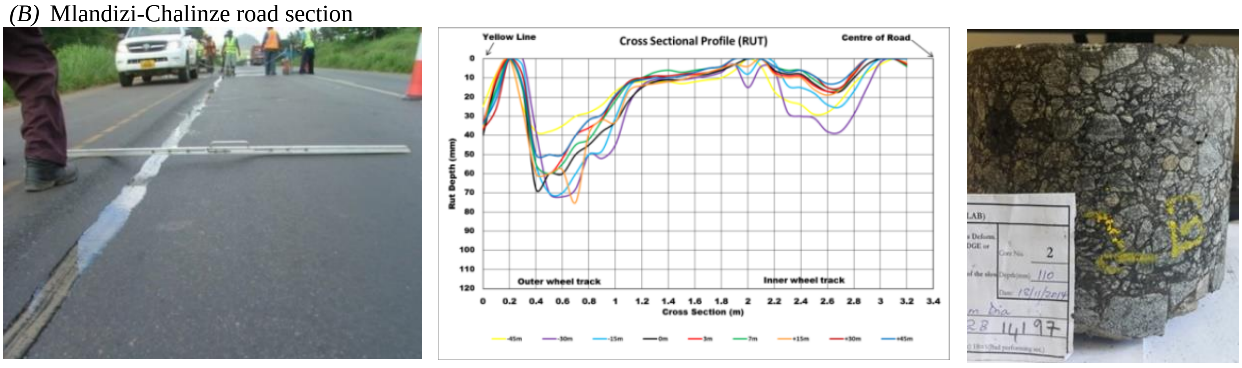
FIGURE 1
Road conditions, rut depths and representative field cores



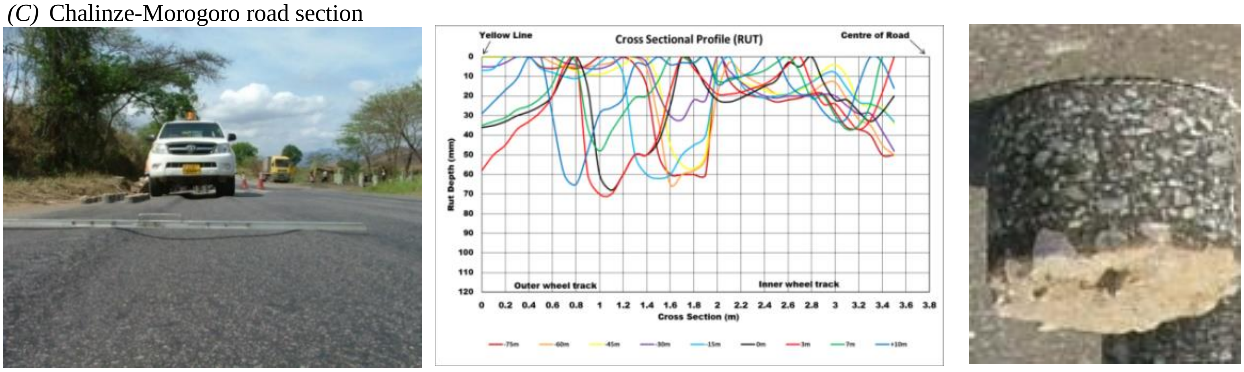
(A) Nelson Mandela road section



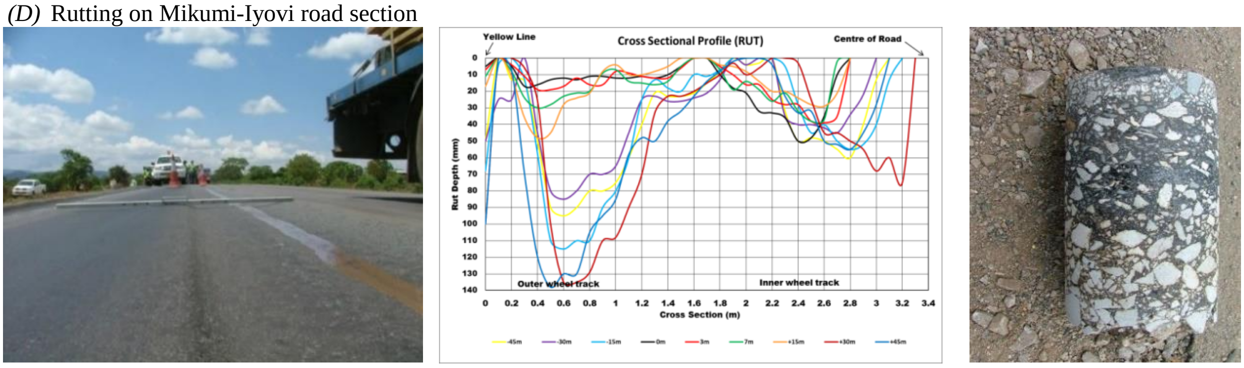
(B) Mlandizi-Chalinze road section



(C) Chalinze-Morogoro road section



(D) Rutting on Mikumi-Iyovi road section



(E) Makambako-Mbeya road section

outer wheel tracks of these sections have experienced a more severe rutting. A common feature for these sections was that after rain, water stays in the wheel tracks, resulting in ponding and hydroplaning. In addition, bitumen bleeding was accompanying rutting on some of these AC sections.

TABLE 2. Results of 90th percentile rut depths and average temperatures

Road Section	Outer wheel track, mm	Inner wheel track, mm	Max pavement temperature	Min pavement temperature
Nelson Mandela	70	38	56.3 °C	17.2 °C
Mlandizi-Chalinze	100	70	56.5 °C	18.6 °C
Chalinze-Morogoro	75	38	56.0 °C	18.7 °C
Mikumi-Iyovi	70	50	56.5 °C	14.9 °C
Makambako-Mbeya	138	75	53.5 °C	12.4 °C

TEMPERATURE MEASUREMENTS

A seven-day average maximum pavement design temperature (mean of the seven hottest consecutive days in a year) at 20 mm depth and a one-day minimum pavement temperature at the surface are related to the evaluation of rutting behaviour of asphalt pavements.[7] The lowest annual pavement temperature is the coldest day of the year. In the absence of detailed information on the daily air temperatures, a ten-year (2004 to 2014) average of monthly air temperatures for six cities in the vicinity of the Tanzam highway was analysed. The Superpave equations (1) and (2) could not be used directly to determine the pavement temperatures of T1 as only average values were available for the study.[7]

$$T_{20} = (T_{air} - 0.006181 \times Lat^2 + 0.2289 \times Lat + 42.2) \times (0.9545) - 17.78 \backslash \qquad (1)$$

T_{20} = pavement temperature at a depth of 20 mm in °C;

T_{air} = maximum average high air temperature during the hottest seven-day period in °C;

Lat = latitude in degrees.

The minimum temperature can also be obtained from the empirical formula presented below:

$$T_{min} = 0.859 \times T_{air} + 1.7 \qquad (2)$$

T_{min} = minimum pavement temperature in °C;

T_{air} = minimum air temperature in average year in °C.

Table 2 also provides summary results of a pseudo maximum and minimum pavement temperatures computed for the respective cities (locations). A major assumption made was that these temperatures would be calculated at a depth of 20 mm from the surface of the road.

FALLING WEIGHT DEFLECTOMETER (FWD) TESTING

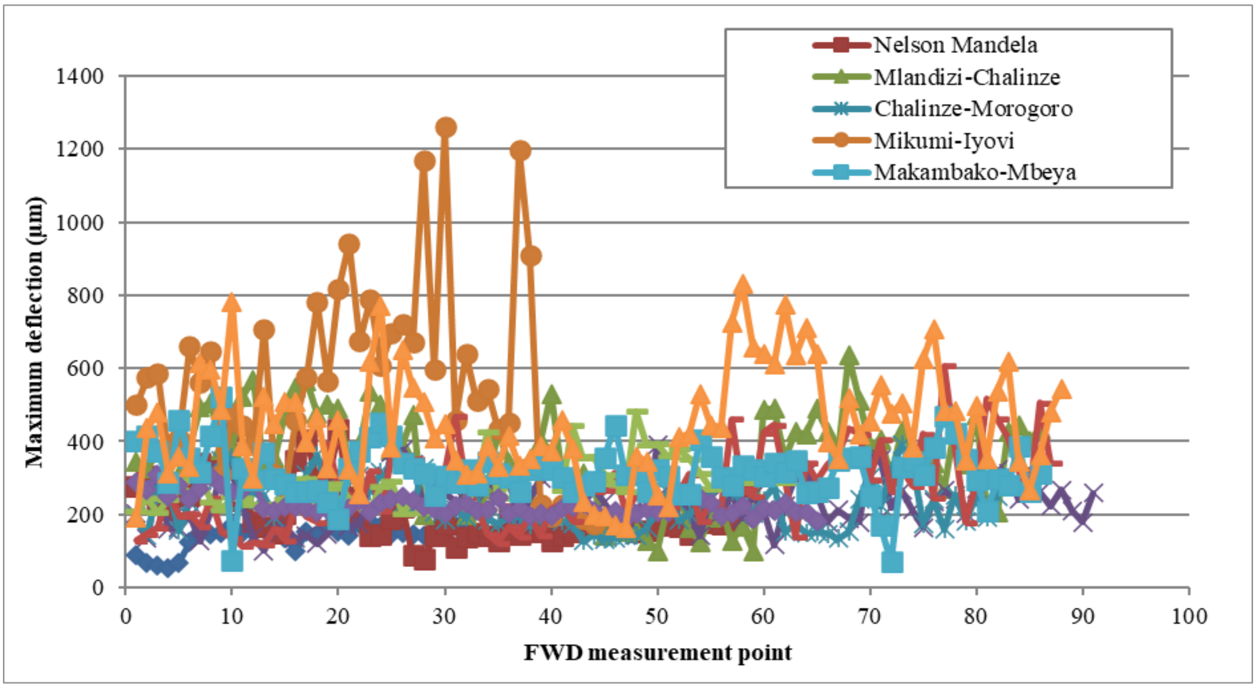
FWD is commonly used to measure elastic deflections, evaluate the in-situ strength and stiffness properties of the pavement structure, and to establish the condition of the underlying layers. The tests were carried out on the five road sections using an impact load of 40 kN from PRIMAX 1500 FWD equipment. Deflection bowl parameters – Maximum Deflection (D0), Radius of Curvature (RoC), Base Layer Index (BLI), Middle Layer Index (MLI) and Lower Layer Index (LLI) computed from FWD data can provide an indication of the strength of individual pavement layers.[8] The BLI, MLI and LLI have been found to correlate well with the structural condition of the base, subbase and subgrade layers, respectively. The tolerances of these parameters are included in TRH12.[9]The FWD results were analysed based on a proposed three-tiered color-coding rating criteria to express whether the underlying layer is in sound (green), warning (gold), and severe (red) conditions.[10].

Table 3 provides representative deflection bowl parameter results for five sections and the criteria for BLI, MLI and LLI. Similar to the Chalinze-Morogoro section, the results from the Nelson Mandela section showed that the underlying layers were all in sound conditions (i.e.,

TABLE 3. FWD deflection bowl parameters for the five rehabilitated road sections

CH, m	Load, kN	D_0, µm	RoC, mm	BLI, µm	MLI, µm	LLI, µm	CH, m	Load, kN	D_0, µm	RoC, m	BLI, µm	MLI, µm	LLI, µm
Mlandizi-Chalinze							Chalinze-Morogoro						
1,501	40.1	340	282	121	101	62	2,341	43.5	215	476	75	60	36
1,554	40.8	201	455	70	56	38	2,356	43.6	191	526	70	49	29
1,603	39.6	260	488	69	74	57	2,369	44.2	240	444	82	68	40
1,650	40.4	270	303	95	73	54	2,386	44.3	186	526	70	50	27
1,699	40.7	433	177	169	126	76	2,399	44.3	176	488	74	46	22
1,748	39.7	343	286	101	95	70	2,416	44.3	191	476	73	48	25
1,805	39.5	307	351	90	86	63	2,432	44.2	196	556	63	47	28
1,854	39.8	351	211	128	94	64	2,445	43.4	170	588	60	38	24
1,900	39.7	401	222	144	125	71	2,461	44.6	187	571	64	51	29
1,948	41.1	531	144	215	168	88	2,465	43.9	200	513	70	53	32
2,002	39.6	317	385	87	91	65	2,470	44.7	182	588	64	47	28
Mikumi -Iyovi							Makambako-Mbeya						
1,500	41	574	192	181	180	98	1,498	39.9	263	317	113	75	33
1,565	39.2	780	125	248	257	135	1,549	40.4	268	339	104	80	38
1,600	40.9	564	217	165	176	107	1,604	41	236	417	92	66	31
1,653	39.3	817	121	280	264	153	1,650	39.5	190	476	78	48	25
1,702	40.2	943	156	297	375	133	1,701	41.1	326	308	121	97	45
1,751	39.7	675	192	194	231	130	1,751	39.9	375	244	150	108	49
1,799	40	790	127	268	247	137	1,800	41.1	412	270	150	136	60
1,850	39.8	608	241	155	188	121	1,850	41.3	453	198	176	138	66
1,898	40.1	697	206	177	199	136	1,900	42.2	416	357	123	149	88
1,949	38.6	721	172	230	225	119	1,951	41.3	343	274	135	99	49
2,002	38.9	670	144	249	215	102	2,002	41.5	326	357	108	99	50
Nelson Mandela													
4	39.8	89	690	44	2	14							
15	40.4	67	1,053	21	4	15							
29	40.2	62	1,053	20	6	12							
46	40	52	1,176	17	7	11							
62	41.1	69	909	29	4	10							
76	39.9	124	667	42	8	16							
98	41.1	149	392	71	10	16							
119	41.3	145	645	45	12	19							
131	39.8	150	667	42	16	20							
147	40.4	171	513	58	19	20							
159	40.1	151	800	39	15	21							
Granular base	Sound	<500	>100	<200	<100	<50	Granular base	Sound	<500	>100	<200	<100	<50
	Warning	500-750	50-100	200-400	100-200	50-100		Warning	500-750	50-100	200-400	100-200	50-100
	Severe	>750	<50	>400	>200	>100		Severe	>750	<50	>400	>200	>100
Bituminous base	Sound	<400	>100	<200	<100	<50	Bituminous base	Sound	<400	>100	<200	<100	<50
	Warning	400-600	250-250	200-400	100-150	50-80		Warning	400-600	250-250	200-400	100-150	50-80
	Severe	>600	<100	>400	>150	>80		Severe	>600	<100	>400	>150	>80

FIGURE 2
Maximum FWD deflections on the road sections



"green"). Figure 2 presents the maximum deflections for the road sections plotted on the same graph for comparison. The deflections are plotted against FWD test points instead of chainage since the tested sections are at different locations. High deflection values were generally reported for the Mikumi-Iyovi and Mlandizi-Chalinze roads sections. This agrees with the deflection bowl parameter results presented in table 3, and akin to low stiffness, and consequently indicating that these two sections had excessive rutting in both outer and inner wheel tracks of the asphalt layer. However, this assertion could only be a speculation based on the empirical data presented in this paper as there is no direct relationship between rutting and FWD deflection bowl parameters. It is worth mentioning that rutting is due to plastic deformation and FWD only measures elastic response, and the two are not linearly related.

Laboratory study and results

VISUAL CONDITION ASSESSMENT

All asphalt cores extracted from the road sections were visually assessed in the laboratory to determine the extent of damage to the asphalt layers. The aim of the condition assessment was to identify any distinct distresses or abnormalities in these cores, and to log any other observations. The assessment included details such as bleeding, binder condition (dry, wet or lively appearance/not aged), origin of cracking (top or bottom), crack length and width (across the face of the core), presence of rolled-in-chips and size of the chip, types of binders (modified or virgin), type of modifiers, porosity (subjective evaluation only) of the core, and segregation of the mix.

Cores were generally assessed based on a ranking criterion ranging from 1 (low extent) to 5 (high extent) for the identified distresses and condition of the core (*in-house protocol, CSIR*). It was found that the thickness of surfacing asphalt layers for the rehabilitated road sections ranged between 40 mm and 60 mm, whereas the underlying asphalt layers were in some cases 200 mm thick. In the absence of mix design and as-built data, the major challenge was how to identify the number of different layers that constitute these relatively thick underlying asphalt layers.

RECOVERED BINDER TESTING AND RESULTS

The bitumen binder properties were determined for all binder types recovered from the asphalt cores. Both empirical and the advanced (i.e., dynamic shear rheometer) tests were conducted to determine the binder properties. The binder was firstly recovered from the asphalt cores before the properties were determined. The original binders for the road sections were unmodified 40/50 and 50/70 penetration grades. TMH1[11] methods for the determination of the binder contents of compacted mixes were used to determine binder contents for the cores. Table 4 presents the detailed test results.

It was difficult to draw a clear conclusion from the results, as the investigators did not have retained binders, mix design sheets or as-built data against which to evaluate the results. However, trends for G*/Sinδ failure temperatures, bitumen non-recoverable compliance parameter (*Jnr*), penetration and softening point results of the recovered binders follow logic. The asphalt mixes volumetric (binder volume) could not be determined for the sections due to the extent of damage the samples had already suffered prior to retrieval. Overall, the rheology of the recovered bitumen binders indicated that the binders had sufficient stiffness to resist rutting.

TABLE 4. Recovered binder properties

Road Section	Binder content, %	Softening point, °C	Penetration @ 25°C	G*/sinδ failure temperature, °C	*Jnr* @3.2kPa, 64°C, kPa^{-1}
Nelson Mandela	3.7	56.2	30	68.1	2.48
Mlandizi-Chalinze	4.9	54.6	43	65.5	3.79
Chalinze-Morogoro	4.6	58.4	35	71.4	1.56
Mikumi-Iyovi	5.2	54.8	36	65.2	3.82
Makambako-Mbeya	3.9	65.0	24	77.6	0.51

RECOVERED AGGREGATE TESTING AND RESULTS

The grading results of the recovered aggregates are illustrated graphically in (figs. 3*A* and 3*B*) to compare with the Tanzania specifications. The road sections investigated were constructed with AC-14 (dense-graded asphalt mix with nominal maximum aggregate size 14 mm) and AC-20 (dense-graded asphalt mix with nominal maximum aggregate size 20 mm), with AC-20 being the predominant asphalt mix type used on the road. Most gradings did not conform to both AC-14 and AC-20 specifications as illustrated in these figures.

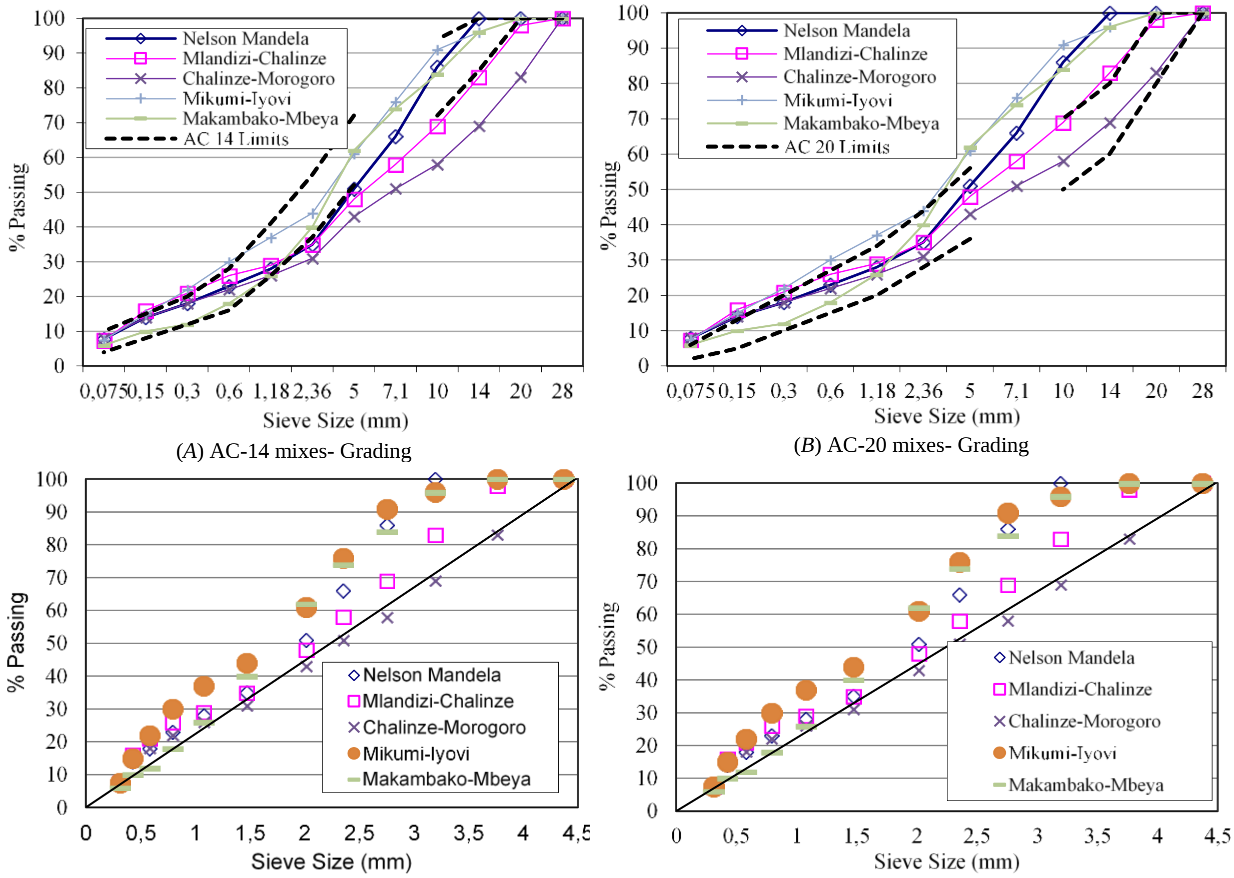
Generally, the fines content for all road sections met the specifications. The gradings are also plotted on the 0.45 power graph in (figs. 3*C* and 3*D*), where the sieve size values are raised to the power of 0.45 before being plotted. The straight line in these figures represents the grading of theoretical maximum density, i.e., 0 percent voids and 0percent VMA. Generally, there was no consistency in the grading data on the 0.45 power graphs. In many cases, the results for the lower sieves plot too close to the maximum density line, whereas the results of the upper sieves plot too wide from the density line, which could be a marker for rutting failure in these AC mixes used on the road.

VOLUMETRIC PROPERTIES OF CORES

The bulk relative density (BRD) and the maximum theoretical relative density (MTRD) values were determined for all cores extracted from the five road sections in accordance with Technical Methods for Highways (THM 1, 1986)[11], and the results were used to calculate the percentage of voids in the cores. These densities are subsequently used to calculate the volumetric parameters of the asphalt mix.

FIGURE 3

Grading analysis results of AC cores compared with specification limits



(*A*) AC-14 mixes- Grading

(*B*) AC-20 mixes- Grading

(*C*) AC-14 mixes – 0.45 power chart

(*D*) AC-20 mixes – 0.45 power chart

The voids content in the mix (VIM) is the difference between the MTRD and BRD, expressed as a percentage of the MTRD. Depending on the mix type, the mix design voids are expected to be within the range of 3 to 6 %.

The values of voids in mineral aggregate (VMA) calculated are the inter-granular void space between aggregate particles in a compacted paving mixture that includes the air voids and effective binder, expressed as a percentage of the total volume. The VMA is calculated based on the relative density of the aggregate and expressed as a percentage of the bulk volume of the compacted paving mixture.

The voids filled with binder (VFB) are the percentage of the inter-granular void space between aggregate particles (VMA) that are filled with binder. VMA includes binder and air; hence VFB is calculated by subtracting the air voids from the VMA and dividing it by the VMA (expressed as a percentage). The measurement of volumetric quantities also requires the percentage binder content to be known. This quantity is normally determined during the mix design process. In the absence of mix as-built data, bitumen contents were determined from the recovered binders.

Table 5 presents the summary of volumetric results and percentage fines and the binder contents to calculate filler-binder ratios for the cores on which binder tests were conducted. The voids content for all cores ranges from very low (1.4 %) to very high (10.4 %). This range of voids was too wide for the cores tested. However, this is somewhat expected as cores from these road sections are damaged (rutting) before testing for volumetric properties.

Tanzania specifications generally require that filler/binder ratio of the continuously graded wearing course mixes should meet the criterion of 1.0 to 1.5. Only Chalinze-Morogoro and Mikumi-Iyovi sections met this criterion (see table 5). Generally, small increases in the amount of filler in grading can literally absorb much of the binder, resulting in a dry unstable mix, whereas small decreases (i.e., too little filler) will result in too rich (or wet) mixes. A wet mix is susceptible to rutting as was observed on the investigated road sections.

ENGINEERING PROPERTY TESTS AND RESULTS

The indirect tensile strength (ITS) and resilient modulus were the two engineering properties determined for the cores from the various road sections. The ITS test is commonly used to evaluate the cohesive strength of asphalt mixes. This property can be used to evaluate tensile strength (related to toughness and durability) and is also an important component of rutting resistance in the medium temperature range (i.e., 10 to 30°C). The stiffness of asphalt determines its ability to carry and spread traffic loads to the underlying layers. Stiffer mixes are typically expected to have the ability to resist permanent deformation under the high traffic and elevated temperatures as experienced on the investigated road sections. Thus, relatively lower resilient modulus values are indicative of a potential rutting problem. The engineering properties determined for the cores from the five road sections are also presented in table 5.

The ITS test was conducted on all cores at a temperature of 25°C in accordance with ASTM D6931.[12] For each road section, three duplicate cores were tested to represent samples from the outer wheel tracks and between wheel tracks. The formula for calculation of the ITS (in kPa) is as follows:

$$ITS = \frac{2P_{ult}}{\pi t D} \tag{3}$$

where, *Pult* is the ultimate applied load, in kN, t is the thickness of the specimen, in mm; and D is the diameter of the specimen, in mm, The resilient modulus test was conducted on the cores in accordance with BS EN 12697-26.[13] A relatively lower resilient modulus values are indicative of a potential rutting problem. Testing was conducted at the test temperature of 25°C. Like the ITS tests, the resilient modulus test was conducted on three duplicate cores extracted from the outer wheel tracks and from between wheel tracks. The principle of the indirect tension test is that the asphalt sample is exposed to repeated compressive loads through the vertical diameter plane, which develops a relatively uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametral plane. The resulting horizontal deformation of the specimen is measured, and an assumed Poisson's ratio is used to calculate the tensile strain at the centre of the specimen. The resilient modulus is defined after 100 repetitive loading cycles. The reported value for M_R is the average of the last five cycles.

The resilient modulus (M_R)is calculated as follows:

$$M_R = \frac{P}{\delta_h . t.} \ (0.27 + v) \tag{4}$$

where: M_R = Resilient modulus (MPa)

P = Applied load (N)

δ_h = Horizontal elastic deformation (mm)

t = Thickness of specimen (mm)

v = Poisson's ratio

Poisson's ratio can be calculated from the vertical and horizontal deformation, where v (Poisson's Ratio):

and where δv is the vertical elastic deformation measured along the axis of loading.

$$\upsilon = 3.59 \times \frac{\delta_h}{\delta_\upsilon} - 0.27 \qquad (5)$$

TABLE 5. Volumetric properties and engineering properties of asphalt cores

Road section	BC, percent	VIM, percent	VMA, percent	VFB, percent	Percent fines	F/B ratio
Nelson Mandela	3.7	3.8	12.4	69.0	7.8	2.11
Mlandizi-Chalinze	4.9	4.6	16.3	71.6	7.4	1.51
Chalinze-Morogoro	4.6	4.7	15.6	70.0	6.1	1.32
Mikumi-Iyovi	5.2	1.4	14.1	90.4	7.5	1.44
Makambako-Mbeya	3.9	10.4	18.3	43.0	6.0	1.54

Road section	Indirect tensile strength, MPa		Resilient modulus, (M_R), MPa	
	Outer wheel	Between wheel	Outer wheel	Between wheel
Nelson Mandela	1,657	1,281	1,854	4,511
Mlandizi - Chalinze	951	793	2,794	3,064
Chalinze - Morogoro	812	789	2,715	1,879
Mikumi - lyovi	700	808	1,595	1,766
Makambako - Mbeya	810	623	1,407	1,368

Findings and discussion of results

DISCUSSION ON RESULTS FROM THE FIELD

Rut Depth, Temperature and DCP Measurements

In Tanzania, the 90th percentile rut depth is the criterion used in road design. The criterion is based on the standardized traffic loading in Tanzania, i.e., rut depth of equivalent single axle loads (ESALs) of 1 million should not exceed 20 mm, and 3 million ESALs should not exceed 15 mm.[14]

The 90th percentile rut depths ranged between 70, and 138 mm for the measurements taken in the outer wheel tracks, and between 38, and 75 mm for the inner wheel track measurements. Consequently, rutting on the Tanzam highway (> 40 million ESALs) could be considered excessive. The maximum rut depths occurred in the rehabilitated sections with asphalt overlays (i.e., Nelson Mandela, Mlandizi-Chalinze, Mikumi-Iyovi and Makambako-Mbeya) in comparison with the reconstructed section (i.e., Chalinze-Morogoro). Asphalt overlays are the most common rehabilitation strategy to restore both functional and structural capacity of a pavement. However, it is not uncommon for an asphalt overlay to perform poorly due to continued rutting of the previous old asphalt layer underneath the new asphalt layer. It was found that during the overlay rehabilitation of the four road sections, there had been no milling of the existing older rutted surfacing before the new asphalt overlay was placed.

Temperature plays a key role in the durability and the rut resistance of asphalt mixes. Results from heavy vehicle simulator tests have indicated that the rate of rutting of a mix evaluated under a standard axle load at a pavement surface temperature of 60ºC can be 20 times higher than at 40ºC[15].

As presented in table 2, the average maximum temperature of the investigated road sections for a period of 10 years (2004-2014) ranged between 51 and 57°C. It is believed that in reality these temperatures could have been approximately +5°C higher than reported. Such temperatures are relatively high under high traffic loading conditions, and if not considered, could lead to a poor asphalt mix design and performance, and subsequently to severe rutting if the incorrect types of bitumen binder and aggregate skeleton are specified.

The DCP data indicated sufficient in-situ structural strength in the underlying pavement layers on the majority of the road sections, which implies that rutting in the road sections investigated was mostly confined to the asphalt layers. In most cases the DCP probe could not penetrate more than approximately 40 mm into the underlying layers. As indicated in table 2, the underlying layers of the Mlandizi-Chalinze, Chalinze-Morogoro and Makambako-Mbeya sections gave sound to warning conditions, implying that rutting on these sections was mainly confined to the AC layer. However, to some extent, the underlying layers of the Mikumi-Iyovi section contributed to the total rutting of the pavement.

Traffic and Axle Loads

The load applied to a pavement by a vehicle generally consists of elements such as the axle load, tyre pressure, axle configuration, number of applications, load distribution, frequency of load and type of load, i.e., static, dynamic and/or acceleration or braking. Among other factors, premature rutting in asphalt layers is often associated with heavy traffic volume and high axle loads (which are immediately imposed onto an inadequately designed and/or compacted layer), as well as overloading due to inadequate or a lack of law enforcement.

The results of the survey that was carried out for this study were presented in table 1. The total traffic counted for both directions was comparable. For both directions, it was found that the total number of heavy trucks that use super single tyres constitutes 50 % of the total traffic counted at the station. The data also indicated that the proportion of trucks with super singles in the very heavy goods vehicle category with semi and full trailers was about 70 %, and on all commercial vehicles other than buses above 55 %.

Traffic characteristics are generally determined in terms of the number of repetitions of standard 80 kN single axle load (E80) applied to the pavement on two sets of dual tyres with the damage caused by the different vehicle types were presented in table 1. Based on the normal traffic (not considering suppressed, generated or diverted traffic) and assumed annual traffic growth rate of 6% and design period of 20 years, the traffic load was found to be 88.9 million E80 for west bound direction and 82.2 million E80 for east bound (see table 1). The projected design traffic loading of 88.9 exceeded the maximum range (20 to 50 million E80) specified for highways in Tanzania, suggesting that the Tanzam highway was overloaded in excess of 50 million E80.

The permissible legal axle load in Tanzania is fixed at 10 tonnes, irrespective of the type of axle or number of tyres on a particular axle. The relatively high axle load and overloading, coupled with high tyre inflation pressures of the wide-base and dual tyres that are used on the Tanzam highway cause concern as damage (premature rutting failure) is inevitable under such conditions. To assess whether or not the asphalt sections failed prematurely from an expected traffic point of view, available traffic and pavement structural information have to be used for damage analysis based on the traffic estimate used for the pavement design. Moreover, as 50 percent of heavy/very heavy vehicles on the Tanzam highway use wide-base tyres, which were found to potentially cause more relative damage because of the potentially high normalised contact pressure, severe rutting was likely to occur on the Tanzam highway.

Effect of Tyre Contact Stress on Rutting

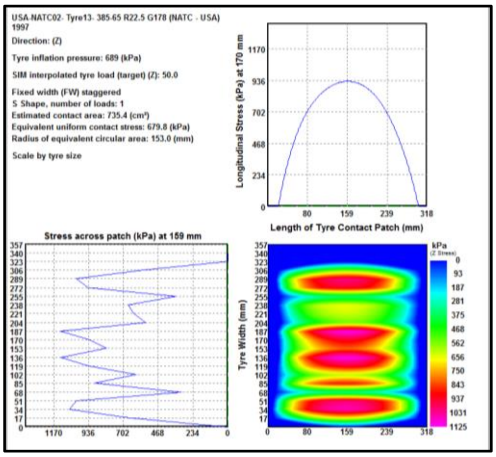
The effect of Tyre inflation Pressure (TiP), axle load and traffic volume on permanent deformation/rutting of asphalt mixes is well known. In Tanzania, the legally permissible axle load limit for a single axle fitted with super single tyres and dual (twin) tyres is 10 tonnes (i.e., 100 kN). Thus, the tyre load for a super single will be 50 kN, whereas the tyre load for a dual will be 25 kN. Table 1 showed the detailed results for both super single and dual tyres with three different tyre ply widths. The vehicle classes are semi-trailers and full trailers (all heavy vehicles). The maximum and minimum tyre inflation pressures for a truck with super single tyres were found to be 896, and 689 kPa respectively. Three tyre inflation pressures – 689, 758, and 896 kPa (shaded green cells) – were used for the analysis. These tyre pressures cover the range of the results presented in table 1.

From table 1, the NCP ratios of the wide-base tyres are generally high compared to the dual tyres, meaning that the asphalt layer of the investigated rehabilitated road sections experiences higher stresses under wide-base tyres than under dual tyres. This could also imply that the wide-base tyres used for this analysis can potentially cause more damage (i.e., rutting) than the dual tyres. The contact stress shapes for the wide-base and dual tyres are illustrated in figure 4 using the TiP of 689 kPa for the three different tyres. Usually, the maximum stresses for dual tyres, depending on the tyre loading, are 1 to 2 times higher than the actual tyre inflation pressures as indicated by a study conducted by De Beer et al. [16] For a rut depth of 12.5 mm, the study found that a wide-base tyre could cause a damage of more than 10 times that of a dual tyre. Ponniah et al.[17] reported that wide-base tyres produce 20 percent higher stress than the dual tyres under the same axle loading and noted a wide-base tyre causing 2 to 3.5 times damage than dual tyres.

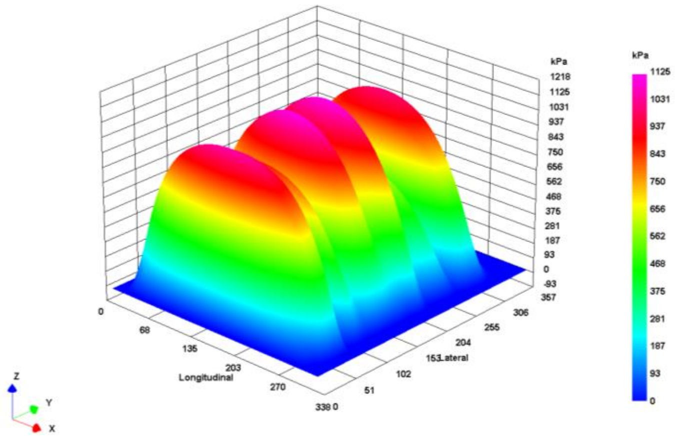
A study found that the first-generation super single tyres were shown to decrease the tyre contact area and therefore increase the pavement contact stresses.[18] The first-generation super single tyres are defined as those having ply width of 385 mm and 425 mm designated as 385/65R22.5 and 425/65R22.5 respectively. The increase in the vertical and lateral stresses induced by the super singles significantly increased the likelihood of top-down cracking and near-surface rutting of asphalt pavements. For a rut depth of 12.5 mm, the study indicated that a super single tyre (type: *Goodyear* G286 A SS, 425/65R22.5) could cause a damage of more than 10 times of a dual tyre (type: *Goodyear* Unisteel G149 RSA, 11R22.5). It may also be noted that the super single tyre used in the above study had a relatively larger ply width (425 mm) as compared to 385 mm ply width of super single tyres mostly used in Tanzania.

FUGURE 4

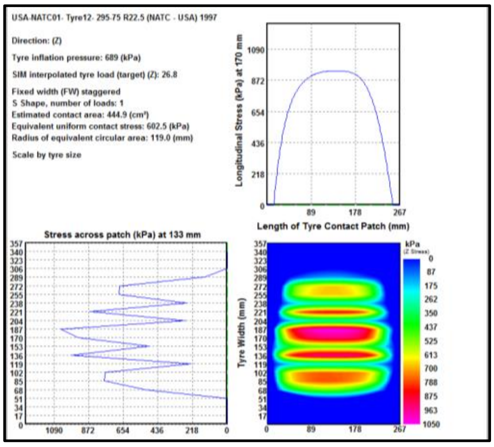
Contact stress pattern for wide-base and dual tyres



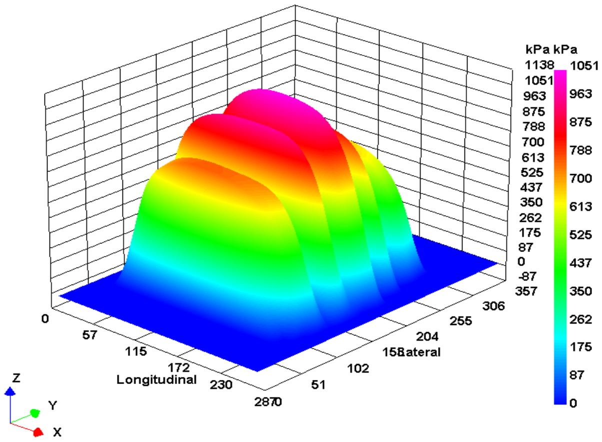
(A) 2D Tyre stress contact pattern -385 wide-base tyre



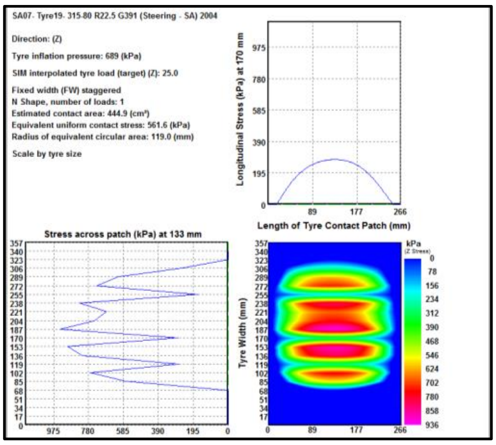
(B) 3D Tyre stress contact pattern -385 wide-base tyre



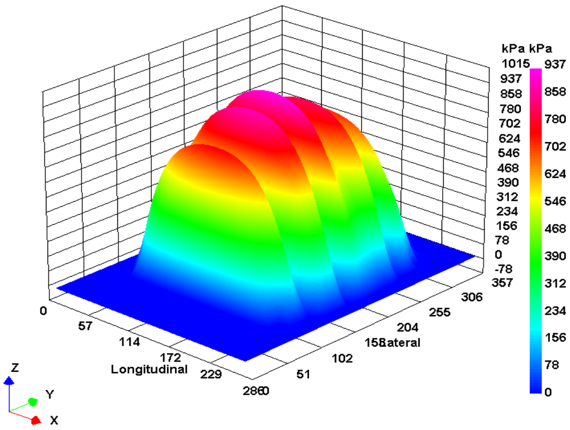
(C) 2D Tyre stress contact pattern- dual tyre 295



(D) 3D Tyre stress contact pattern- dual tyre 295



(E) 2D Tyre stress contact pattern - dual tyre 315



(F) 3D Tyre stress contact pattern- dual tyre 315

The main difference between the two super single tyres is that the 385/65 R22.5 is narrower than the 425/65R22.5. Hence it further increases the contact stress at the pavement surface under the same nominal tyre pressure, which implies that the potential damage could be significant. However, in the above study there are considerable differences in terms of the type and ply width of super single tyres used, as well as the pavement structure, pavement materials, asphalt mix design methodology and the loading conditions when compared with the prevailing traffic loading conditions and the existing pavement structure of the Tanzam highway.

The National Cooperative Highway Research Programme (NCHRP) of the Transportation Research Board (TRB) in the USA conducted a study to determine damage caused by super-single and single-out dual truck tyres in a pavement.[19] The pavement responses and performance caused by a super single tyre (425/65R22.5) were compared with those observed under the dual tyre (11R22.5) based on similar load ratings. The findings indicated that the super singles generated 25% to 50% more rutting damage than the dual tyre.

A study conducted locally in South Africa compared the effect of contact stresses of a standard axle (40 kN on dual tyres; tyre inflation pressure of 620 kPa) and 60 kN axle with tyre pressure of 800 kPa on permanent deformation of a standard dense-graded asphalt mix used in South Africa *(CSIR Internal Report*). These investigators found that a 60 kN axle with 800 kPa tyre pressure developed higher permanent deformation (rutting) in the asphalt layer than the 40 kN, 620 kPa pressure loading system as expected. Also, the study by De Beer et al.[16]found that *n-shape* stresses (see figure 4) could contribute to accelerated rates of rutting like those observed on the investigated road.

DISCUSSION ON RESULTS FROM LABORATORY STUDY

Visual Assessment of Cores

Cores from between wheel tracks were more porous (based on subjective visual assessment) than cores from outer wheel tracks, implying that voids are expected to be higher between wheel tracks. Depending on the extent of rutting, the volumetric results could be affected by the shear flow, which can in turn lead to diminishing or creation of voids. Also, cores between wheel tracks appeared to bleed more than cores from the outer wheel tracks. Spillage of oils from vehicle engines is a possibility at the sites where these cores were extracted. Fine cracks were observed more on the outer wheel tracks than between wheel tracks (Mlandizi-Chalinze sites). Weak sublayer materials are the possible cause of these cracks. Comparisons of some cores taken from the same vicinity indicated that materials moved laterally between the wheel tracks. Some sites that experienced this problem had large differences between the heights of cores extracted from the wheel tracks (thinner cores) and between wheel tracks (thicker cores). This phenomenon is as a result of shear displacement of materials, which is an indication of an unstable mix. In addition, a notable increase in binder content at the bottom of this section indicates that excess binder migrating upwards from the layer below could be the chief contributory cause of the rutting observed in this section.

Influence of Binder Properties

Overall, the rheology of the recovered bitumen binders indicated that the binders had sufficient stiffness to resist rutting. All recovered binder samples had low *Jnr* values, an indication of sufficient rut resistance by the binders) as well as low *Jnr* differences (<75percent) at both 58°C and 64°C, indicating stress resilient behaviour at these two temperatures. The Superpave

Performance Grade (PG) failure temperatures agree with the trends shown by the *Jnr* values (see table 4). Nonetheless, the correlation proofed that the bitumen binder rheology has an influence on the rate of rutting once it was initiated. Therefore, implementing stricter binder selection criteria in terms of temperature and traffic requirements could possibly reduce the severity and extent of rutting in this region, but will not prevent it. Furthermore, the lack of trend in binder behaviour of the road sections located in areas further inland (e.g., Mikumi-Iyovi, Iyovi-Iringa, Iringa-Mafinga, Makambako-Mbeya), of which most had been designed with Superpave, confirmed that the binder type was not the cause of rutting.

Significant contamination was detected via the gas chromatography test (an indicative test) which showed that bitumen binder from the second/lower layer of the Makambako-Mbeya route (rut depth on outer wheel tracks ≥ 70 mm) contained paraffinic-type low boiling point compounds. The contamination may have contributed to the rutting observed. However, there was also a notable increase in binder content towards the bottom of these sections, indicating that excess binder migrating upwards from the layer below could be a contributory cause of the rutting observed in the upper AC layers on these road sections.

The migration of the binder from the lower layer could not be substantiated, since binder contents were not checked at various depths of the asphalt layer during rehabilitation. Moreover, given that retained binders of the original bitumen used at the time of construction were not provided for analysis, it is not possible to conclude whether the contaminant was originally part of the bitumen or whether it got into the binder after some time. Another possible cause of contamination could be fuel spillage on the road sections. In addition, the presence of extra volatiles to that required to bring the binder into specification could possibly have had a softening effect on the binder. However, even if this was the case, it should not be regarded as the only contributor to the bleeding observed in some cores.

Mix Volumetric Properties and Grading

A total of 80 asphalt cores were investigated for their air voids content of the five road sections. The cores from the road sections had an average air voids content of between 1.4 percent and 10.4 percent. Such a wide range of voids could potentially lead to erroneous interpretations of the effect of voids content on the observed rutting. Moreover, majority of the cores for the study were extracted from failed road sections, and hence could introduce significant variability into the data. It is believed that the continued application of traffic or compaction energy tends to reduce the void content to a refusal density limit that may be as low as 1.4 percent. Mixes for which the air voids content decreases to below 3 percent during the densification period are more prone to rutting than those mixes that stabilise at air voids levels of approximately 4 percent.

Based on the grading results obtained from the recovery aggregates, the Nelson Mandela, Mlandizi-Chalinze and Chalinze-Morogoro sections for instance did not meet the minimum voids in the mineral aggregate (VMA) criteria for AC-14 and AC-20. The VMA of the second layer of the Chalinze-Morogoro section was very low (i.e., 9.6 %, voids content of 0.6 %) when compared to the top layer of the same section that has a VMA value of 15.6 per cent. Contrary to the general belief that very low air voids contribute to rutting, the results show that the Mikumi-Iyovi section (maximum rutting of 70 mm) had relatively low air voids of only 1.4 per cent. Also, apart from the Chalinze-Morogoro samples, they were generally too close to the density line on the 0.45 power graph at the lower sieve sizes. Grading for the Chalinze-Morogoro section for instance, plotted too close to the line of maximum density allowing for insufficient VMA, and consequently, rutting and bleeding were found to be excessive on this section. The Mlandizi-Chalinze section also plots too close to the maximum density line although this behaviour is found on only the lower sieves.

Engineering Properties

The ability of asphalt mixes to resist rutting depends on factors such as the tensile strength resulting from the bonding ability of the binder in the mix. Thus, asphalt mixes with low indirect tensile strength (ITS) values are more prone to rutting than mixes with high ITS values. Also, the stiffness of asphalt concrete determines its ability to carry and spread traffic loads to the underlying layers. Stiffer mixes are typically expected to have the ability to resist permanent deformation under the high traffic and elevated temperatures as experienced on the the Tanzam highway. Thus, relatively lower stiffness values are indicative of a potential rutting problem.

. The average ITS values measured for cores from between wheel tracks ranged from 623 to 1 281 kPa, whereas the minimum and maximum values for the cores from the outer wheel track were 810 and 1 657 kPa, respectively. The Makambako-Mbeya Road section (rut depth of 138 mm) had the lowest ITS value for the cores extracted from between wheel tracks. Field studies in South Africa suggest that typical rutting potential tends to increase for ITS values below approximately 1 000 kPa. At the same time, ITS values in excess of 1 700 kPa may indicate a tendency to brittleness and low flexibility. Based on this evidence, the general impression is that the minimum values as commonly reported for the five road sections for this study vindicate the excessive rutting observed on those sections.

Similar to the ITS results, cores from Makambako-Mbeya and Mikumi-Iyovi had low resilient modulus values. No general trend was observed in the results for the outer and between wheel tracks for the five sections.

REHABILITATION DESIGN AND REMEDIAL ACTIONS

The impression is that relatively thin overlay blanket solutions (less than 30 mm) are being used too widely without proper investigation of alternatives and consequences. It should be mentioned that using a 40 to 50 mm overlay (for instance) has only limited benefit in reducing the shear stresses that cause rutting, and that proper rehabilitation design procedures should be followed at all times to determine the thickness of the overlay asphalt. The performance of an asphalt overlay depends primarily on the thickness of the overlay, the asphalt mix design, and good overlay rehabilitation practices (e.g., pre-overlay repair, surface preparation). A typical solution is to mill out the rutted layer and replace it with a new high stable asphalt mix, especially where the sub-structure is sound.

The perceived likely causes of rutting on the five road sections investigated are common to the Tanzam highway. These can be attributed to possibly unstable asphalt mix under relatively high axle loads (from heavy trucks) causing densification, or shear failure (plastic flow) in the asphalt layers. The applicable rehabilitation options identified for remedial action are; (1) overlay on sections with stable asphalt mixes and (2) mill out and replace the unstable mix with a high stability mix (> 100 mm asphalt base course, 40 to 50 mm AC wearing course) on the sections with unstable asphalt mix.

Asphalt surfacing on Tanzam highway is generally subjected to relatively high traffic volume and elevated temperatures, under which the binder softens significantly. For such conditions, especially where resistance to rutting is the key consideration, asphalt mixes with appropriate binder types and strong aggregate skeletons should be specified. The use of stone skeleton mixes (e.g., coarse dense-graded mixes, gap-graded mixes) with or without modified binders for wearing course, and a high stiffness asphalt mix for base course can potentially arrest the rampant rutting occurring on the Tanzam highway.

Conclusions

The excessive rutting on the investigated road sections was initiated partly because of inadequate asphalt mix design that cannot cater for the combined climate/traffic loading conditions. Factors such as overloading, the high proportion of trucks with first-generation wide-base tyres, poor construction and rehabilitation practices, and a lack of quality management may also have contributed to the rutting observed on the road sections. However, these factors were not necessarily the main causes of the problem. Based on the data set that was gathered from the investigation, the following conclusions can be made:

- The two primary causes of the severe rutting are inappropriate asphalt mix design and overloading. While overloading (about 50 to 60% based on 8 tonnes legal limit, and 10% based on a legal limit of 10 tonnes) may have accelerated the rutting, it is believed that controlling it could be a daunting task. However, developing an appropriate mix design that caters for high volume traffic and overloading for instance, can possibly be achieved. The seemingly high legal permissible axle load (10 tonnes for both dual and super single tyres on a single axle) allowed on Tanzania roads is a concern, as this obviously contributed to rutting observed on the road sections.

- It was established that the observed rutting was mainly restricted to the asphalt layers , implying that the total permanent deformation was mainly due to the poor AC mix design and the unstable old AC surfacing layer that had not been removed during the rehabilitation.
- Using relatively thin overlays to fill existing ruts as was done on these sections might be a viable option, but only if the rate of rutting under traffic of the underlying layers is known, so that a proper prediction of the remaining life can be made. In the current situation it can be concluded that the existing older asphalt layers underneath the new AC overlay on the investigated road sections were the weakest link in the pavement structure, and the question should be raised as to whether the existing asphalt layer should not have been removed in its entirety instead of only stripping off the top few millimetres.
- The types of super singles used in Tanzania are of the first generation with narrow ply width of 380, and 385 mm, whereas the new generation super singles that cause less damage have a ply width of 425 mm. As indicated previously, trucks with 425 mm ply width super single tyres would cause more rutting damage than trucks with 279 mm dual tyres. Since the 380, and 385 mm tyres are narrower than the 425 mm tyre, the implication is that they apply higher contact stresses on the surface of pavement under the same nominal tyre pressure and thus increase the potential for damage.
- On the basis of the field study, it was concluded that the majority of the road sections on the Tanzam highway was in dire need of rehabilitation (asphalt overlay after milling) in order to be responsive to safety, traffic loading requirement, environmental concerns, socio-economic impacts, and especially transportation needs.

- The elastic deflection and in-situ strength results indicate that the underlying layers of the pavement were generally in a sound condition. This validated the suggestion that rutting was mostly confined to the asphalt concrete layers.
- The perception of road designers and the industry that the Superpave mix design methodology will prolong the life of the asphalt mix could not be proven conclusively in this investigation, as excessive rutting (up to 75 mm) was observed on the Chalinze-Morogoro road section that is reported to have been designed in accordance with the Superpave system.

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