THE ORAPA EMULSION-TREATED KALAHARI SAND EXPERIMENT: PERFORMANCE OVER 30 YEARS AND DERIVED MATERIAL AND PAVEMENT DESIGNS

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ABSTRACT

The purpose of this experiment on the Serowe-Orapa road in Botswana constructed in 1989 was to evaluate the performance of both grey and red fine Kalahari sands treated with SS60 emulsion both in the upper half only and the full 150 mm of the base. After 19 years of regular performance monitoring and 0,3 MESA, ten test and three control sections were still in a good to very good condition and all were still in a satisfactory condition after 30 years and a projected 0,5 MESA. The red sand sections performed better than the grey and only the 2,5% emulsion half-depth grey sand section failed. Maintenance applied over the first 20 years was a fog spray, two reseals and patching of edge breaks, mole tunnel depressions and, on two grey sand sections, base course shear failures. CBR and UCS empirical laboratory design guidelines for SS60 ETBs for both grey and red sands with 2,5 – 6,5% emulsion as well as the requirements for the raw sand and the whole pavement, are presented. The most economical designs are red sands with 2,5% emulsion in the upper base only for up to a projected 0,8 MESA and 2,5% in the whole base for up to 1,0 MESA for a Botswana Category II or a South African Category C road.

1. INTRODUCTION

Kalahari (Setswana: *Kgalagadi*) Sands are the most widespread road construction materials in Botswana, and together with calcretes, are practically the only materials over the western three-quarters of the country but are normally considered to require stabilization with cement or bitumen for use as base course. In 1989 the Orapa long-term pavement performance (LTPP) Experiment was therefore constructed on the Serowe-Orapa road in order to evaluate the performance of Kalahari sand treated with small percentages of bituminous emulsion.

This is apparently the first LTPP experiment anywhere in southern Africa involving emulsion-treated Kalahari sand bases (ETB) to have been regularly closely monitored and reported on for almost 20 years – i.e. the traditional design life of a major rural road − and followed up thereafter to cover the normal analysis period of 30 years. The only others known were either unsuccessful (Mainwaring, 1968), only monitored for 8 years, 2 years of which were under a sand seal and 6 years of which were under 30 mm of asphalt (Marais & Freeme, 2017) and one which was only followed up after 55 years (Netterberg, 2017).

A secondary objective was to use as far as possible simple construction and control methods such as would be available for normal granular pavement construction for low-volume roads.

Monitoring was also to be carried out simply by visual assessments and manual measurement of rut depths and strength using a dynamic cone penetrometer (DCP) according to the National Institute for Transport and Road Research (NITRR) TM6:1984 and analysed using the 5.1 version of the CSIR (2012) computer program.

It is the purpose of this paper briefly to review the history of the experiment, to report on the results of the final pavement evaluation, and to derive empirical base material and pavement specifications for similar emulsion-treated Kalahari sand bases. The untreated sand section is dealt with in more detail in the companion paper by Netterberg *et al.* (This conf.).

2. LOCATION, LAYOUT AND CLIMATE

The Orapa Experiment (Table 1) is located about 20 km on the Serowe side of the village of Letlhakane with the Francistown-Orapa road; log km 41 post = SV 41+027 km and section "chainage" 77 m on Section 5; GPS coordinates start Section 1 : Lat. (º S) 21,56455; Long. (º E) 25,68143; end Section 13: 21,56903; 25,69978.

Two types of nonplastic (NP) fine sand with a grading modulus (GM) of about 1,1 were evaluated, with five sections of white sand treated with 2,5 and 5,0% undiluted SS 60 anionic emulsion (i.e. 1,5 and 3,0% residual bitumen, respectively) and five of red sand treated with 2,5 – 6,0% of emulsion (1,5 – 4,0% residual bitumen) using one untreated red sand and two ferricrete gravel bases as control sections. In Sections 4 – 7, respectively only the upper half of the 150 mm-thick base was treated whilst in Sections 2, 8 and 9 the amount of binder in the lower half was halved. In Sections 3, 10 and 11 the 2,5% emulsion was mixed into the full thickness of the base.

As the Orapa-bound lane (RHS) was constructed with the shoulder stabilized as per the base there are actually a total of 24 test sections. Moreover, the Orapa lane has carried over four times the ESAs of the Serowe-bound lane. These factors have had to be taken into account in the evaluation.

The area has a semiarid warm climate with a moisture deficiency in all seasons, a Thornthwaite moisture index (Im) of about minus 35 cm (Emery, 1992), a Weinert (1980) N-value of about 6, and lies within the Botswana Road Design Manual (BRDM) (1982) and the Committee of Land Transport Officials (COLTO) TRH 4:1996 dry macroclimatic region for pavement design purposes. The mean annual rainfall of about 400 mm (BRDM, 1982 map) falls mostly between November and March.

Table 1: Layout and as-built test results of Orapa emulsion-treated Kalahari sand base experiment [1]

SECTION No. [2]		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
	Units	**Gravel**	**←GREY / WHITE SAND →**				**←**				**RED SAND**		**→**	**Gravel**
Binder (net bit.)	%	0	3,0	1,5	1,5	3,0	3,0	1,5	4,0	3,0	1,5	1,5	0	0
BASE [3]			1,5		0	0	0	0	2,0	1,5				
CBR (lab.) [4]	%	102	52	48	48	39	39	53	29	29	42	42	103	104
Compaction [4]	%	102	103	103	102	101	102	101	104	103	99	99	99	99
MDD [5]	kg/m^2	2072	1876	1878	1875	1868	1887	1889	1887	1893	1884	1888	1829	2102
OFC/OMC [6]	%	8,8	6,2	6,1	6,1	6,1	6,7	7,8	6,6	8,6	7,7	8,0	7,4	7,7
FFC / FMC [7]	%	6,1	4,4	4,8	4,2	4,3	5,9	6,0	6,2	5,2	3,6	4,7	4,3	6,1
S (in-situ) [8]	kPa	-	365	600	480	420	290	530	595	435	280	565	440	-
S @ 40 °C [9]	kPa	-	275	300	405	400	230	360	475	295	230	475	-	-
CBR (in-situ) [10]	%	-	55	72	67	67	59	67	107	74	48	83	86	-
Temp. (surf.) [11]	°C	32	35	28	37	39	29	19	29	20	30	31	30	34
FFC / FMC [12]	%	3,5	3,5	1,6	2,1	2,3	4,0	3,1	3,6	3,4	5,6	2,8	3,4	3,2
SUBBASE [13]														
CBR (lab.)	%	42	42	47	47	48	39	39	45	45	36	37	39	39
Compaction	%	101	←					99				→	98	98
UPPER SEL. [14]														
CBR (lab.)	%	28	28	48	48	44	49	49	36	36	23	36	26	49
Compaction	%	←				95			→	←	93	→	95	95

SV km 40+350 ←To Letlhakane & Orapa Serowe → SV km 42+150

Notes:

[1] Bases constructed April 1989, primed 22 July, surfaced 30-31 August 1989, opened to traffic early Sept. 1989. [2] All sections 150 m in length with a prime and double seal; single seal on shoulders: LHS shoulder (towards Serowe): untreated sand base, RHS (towards Orapa) treated as per base. Surfacing mostly 13 on 9 mm seal except for 9 on 19 on three 100 m sections across the joints of Sections 2/3, 9/10 and 11/12. [3] Gravel ferricrete ex BP 49+200 ; white sand overburden ex BP 42+000 R; red sand ex BP 39+500 L; all NP. [4] At 98 %. MAASHO; standard soaked CBR procedure; Mean, *n* usually 1 for CBR, 8 for compaction (% MAASHO MDD). [5] MAASHO. [6] MAASHO optimum fluid (OFC) or moisture (OMC) content at 105 – 110°C. [7] Field (base) fluid or moisture (FMC) content at 105 – 110°C from field density tests after compaction in April 1989, mean of *n* = 9. [8] Vane shear strength (TMH6:1984) at road surface temp. just before first seal spray on 30 Aug 1989; vane in middle of treatment; mean of 2 sites on centreline, 5 positions each, i.e. *n* = 10. [9] S corrected to design 40°C using separate laboratory-derived relationships for white and red sands and surface temps. [10] Clegg Hammer-derived CBR using Clegg. (1999) CBR = $(0{,}24CIV+1)^2$; mean of 2 sites on centreline close to vane tests, 5 positions each, i.e. *n* = 10. [11] Mean of 5 sites in each lane for ball penetration tests, *n* = 10. [12] On centreline for vane tests, mean of 3. [13] All materials NP red sand ex BP 38+500. [14] Sections 1 & 2 in-situ; 3 - 8 ex BP 41+000; 9-11 ex BP 42+000; 12 -13 ex BP 42+100; all NP sand

3. TRAFFIC HISTORY

This is a minor BRDM:1982 Category II (equivalent TRH 4:1996 Category C) rural road which carried about 400 vpd in 2014 of which about 15% were heavy vehicles (Table 2). By the end of 2007 the left (Serowe-bound) lane had carried about 0,06 MESA and the right (Orapa-bound) lane about 0,27 MESA with a respective projected 0,15 and 0,50 MESA to 2019.

The Orapa-bound lane had also been subjected to a significant number of very heavy vehicles with an average 80 kN single-axle load equivalency factor of 7,0 from the start and 7,7 E80/vehicle since 2001. In contrast, these equivalency factors in the Serowe lane were only 0,67 and 1,2, respectively. The legal axle loads were increased in 1996, e.g. for single dual wheel axles from 8 200 to 9 000 kg. In 1999 30 and 13% of axles exceeded 8 200 kg and 10 000 kg respectively in the Orapa lane, but only 2 and 0,5% in the Serowe lane.

Table 2: Traffic history [1]

YEAR	AADT	AADT-H	LHS (Serowe)		RHS (Orapa)	
	v/d	hv/d	Year	Cum.	Year	Cum.
			MESA x 10^{-3}		MESA x 10^{-3}	
1990	134	19	1	1	9	9
1994	134	18	1	9	7	55
1999	170	23	2	17	13	112
2004	190	39	6	41	25	204
2007	262	48	8	60	30	269
2009	(280)	(51)	-	(70)	-	(300)
2014	(400)	(60)	-	(100)	-	(400)
2019	-	-	-	(150)	-	(500)

Notes:

[1] Summarised from mostly annual counts and several axle load surveys to 2013 and calculations by Mr C Overby assuming a relative damage exponent of 4,0. Opened to traffic early Sept. 1989.

[2] Figures in brackets are interpolations or projections

4. SOILS, ALIGNMENT AND DRAINAGE

The roadbed consists of a loose, NP, reddish Kalahari sand to a depth of at least 1,0 m.

With a fall of about 5 m towards Orapa, i.e. 0,25%, the vertical alignment is practically level.

The horizontal alignment is straight from just before the start of Section 1 until the start of Section 12 at SV 42+000, at which a gentle, slightly superelevated curve to the right begins and continues on through and past Section 13.

Both the riding surface and side drainage were assessed as adequate on all sections and side drains were not provided on the self-draining Kalahari sand roadbed. No culverts were present on any section.

5. CROSS-SECTION

The road is a Type 3A BRDM:1982 design with a 6,70 m-wide carriageway centrelined in white and edge-lined in yellow with 1,2 m-wide sealed shoulders, with a 2,5% camber on the carriageway and 3,5% on the shoulders. The bases were constructed to the full width of the shoulders except that the left-hand (Serowe-bound) shoulder was untreated.

The unclad sand fill side slopes were initially at about 1 : 4 but were later flattened to 1 : 6 to minimise erosion. The edge of the seal is about 0,3 – 0,5 m above the natural ground level.

6. PAVEMENT DESIGN

6.1 Test Methods

Only TMH1:1986 and TMH6:1984 test methods (National Institute for Transport and Road Research − NITRR) were followed on the experiment, including MAASHO MDD and OMC and only 2,54 mm, 4 day-soaked CBRs. The standard TMH 1 test methods for CBR and UCS were also used for the emulsion-treated sands. The UCS specimens were left for up to 24 hours in their moulds before extrusion, cured for various periods and soaked for 4–6 hours before testing. Compaction control was by the sand replacement method except on the ferricrete Sections 1 and 13, where a nuclear gauge was used and on the neat sand Section 12 where both methods were used. All compactions are as percentages of MAASHO MDD. The term ‘MAASHO’ alone means 100% MAASHO.

6.2 Pavement

The pavement design was mostly based on the Transport and Road Research Laboratory (TRRL) Overseas Road Note (ORN) 31:1977 for 0,5 MESA over 18 years and the seal design on TRRL ORN 3:1985 and consisted of:

Surfacing: 19 + 9,5 mm Silcrete; Prime: MC-30

Base: 150 mm Untreated natural gravel; min. soaked CBR 80. max. PI 6, etc., compacted to 98% MAASHO MDD (NP ferricrete ex BP 49 + 200R) on either side of test sections used as controls (Sections 1 and 13): essentially a COLTO:1998 G4 material, although a Zimbabwe Texas Triaxial Class of only 3,6 due to gap grading.

Subbase: 100 mm Selected NP yellow-brown or reddish Kalahari sand complying with the following developed on site compacted to 95%; CBR soaked): min. 35 at 95%; PI (075): 5-20; P075: max. 20%; FI075: 30–200 = PI (075) x P075: essentially a COLTO: 1998 G7, marginal G6, material. Always NP on P425 fraction, but PIs over 30 found on P075 fraction of some. However, two orange-coloured sands said to be good subbase contained 1,8 and 1,3% Fe_2O_3, respectively and one of these from BP 200+500 had a P425 of 98%, P075 of 21%, was NP on the P425, but had a LL of 60, PI of 37 and LS of 13 on the P075, and a TMH FI075 of 777 (i.e. P075 x PI of P075).

Selected subgrade: Min. soaked CBR 15 (upper) and 10 (lower). Similar sand to that used for subbase compacted to at least 93% mostly used, but a PI (075) of down to SP found to be usable.

Fill: Kalahari sand compacted to at least 90% of MAASHO MDD.

7. MATERIALS DESIGN

7.1 Emulsion Treated Bases

The initial laboratory design work using the 2 x 30 blow modified Marshall test criteria (Marais & Tait, 1989) of a minimum stability at 40ºC of 1,0 kN and stiffness of 1,5 kN/mm with 5-15% air voids in the dry mix indicated that 5% residual bitumen in a 125 mm-thick red sand base would be required for 0,6 MESA and that only the red sand met these criteria. This binder content was regarded as too high and the vane shear strength method (Marais, 1966) was then used for the design. This work also generated laboratory temperature-correction graphs to correct shear strength to the standard 40ºC for both sands. The graph for the white sand yielding, for example, a factor of 0,30 from 20 to 40ºC was almost identical to that in TMH6:1984, but with 0,70 the red sand was far less temperature-sensitive. The specification adopted was a minimum MAASHO shear strength at 40ºC of 200 kPa as for a BT3 material (BRDM:1982; TRH 14:1985) − as later confirmed by the Jwaneng experiment (at only 93% in-situ) for up to 0,5 MESA (Netterberg and Pinard, 2019) or even lower strengths for less traffic. CBR or UCS criteria were also regarded as suitable, but would have to be developed as part of the experiment. A minimum of 98% in-situ compaction was specified. These tests were done by the site laboratory after various periods of shelf-curing at laboratory temperature after compaction as an alternative to the then standard 20 hours at 40ºC, which was believed to simulate six months in a road in a dry climate in southern Africa, after which the emulsion was expected to be in a fully cured state. A curing period of about 28 days of shelf-curing was taken as a reference period. No fines or cement were added to the sands.

7.2 Untreated Sand Base

This base (Section 12), considered both as a test and a control section, was not designed as such but was to be an untreated, good, red sand complying with the sand subbase specification and compacted to at least 100%, with both shoulders similarly compacted and sealed.

7.3 Untreated Ferricrete Gravel Bases

These two NP ferricrete control Sections 1 and 13 with a GM of 2,4 were simply the 150 m lengths of normal construction at each end of the test sections, with as-built 98% laboratory CBRs of 102 and 104, respectively.

7.4 Surfacing

The protection provided by the surfacing and its ability to prevent punching are critical to the performance of an inferior base such as sand – whether or not it is treated with bitumen or cement – and therefore, two conventional and two inverted seals were tried, all without a fog

A 13,2 on 9,5 (9+13) mm inverted seal applied on August 30-31, 1989, was used over most of the experiment, together with 100 m lengths of conventional 19+9, 10 m of inverted crusher dust +13, and 10 m of a 19 mm single seal (intended to be slurried as a Cape seal) on some sections. Both shoulders were sealed with 13 mm chippings as a single seal, initially without a fog.

The grey silcrete chippings from a quarry at SV 60+600 R were rather variable, with some all-in samples yielding a dry TFV of 300 kN and soaked TFV of 240 kN (i.e. 80%) and a flakiness index (FI) of 12 - 21% (19 mm) and 14 - 18% (9,5 mm), but a water absorption of 4,6%. Even selected strong aggregate possessed a water absorption of 2,2% against 11,7% for selected soft aggregate. That actually used on the experiment complied with the specification of a dry TFV of >210 kN, soaked / dry ratio of > 75%, FI of < 25% and a P425 of <0,5% (dry sieved). The chippings were rolled with an 8 t tandem steel wheel roller (SWR) followed by a 10 t pneumatic tyred roller (PTR), which resulted in some breaking of the weak fraction.

8. MATERIAL AND AS-BUILT PROPERTIES

A summary of the as-built material test results for the base, subbase and upper selected subgrade is shown in Table 1 and a summary of site laboratory test results on the sands used in Table 3. Not all those actually used were of subbase quality. There was surprisingly little difference between the grey and red sands as far as their engineering properties are concerned, only the CBR penetration curves of the red sands were somewhat better, but they both peaked at about 3−4 mm and their measured or extrapolated 5,08 mm CBRs were all much lower than those at 2,54 mm.

Table 3: Site laboratory test results on neat sands

SAND / LAYER			SUBBASE	GREY FOR BASE				RED FOR BASE					
SOURCE /SECTION			ALL	STOCKPILE		2 ; 3	4 ; 5	TRIAL HOLES	STOCKPILE	6 ; 7	8 ; 9	10; 11	12
BP		UNITS	38+500	← 42 + 000R →				← 39 + 500R →					
Results		No.	9	5	1 [1]	1	1	3	6	1	1	1	1 [1]
PASSING	(mm)												
2,00		%	94-98	100	100	97	98	100	100	100	95	97	100
0,600		%	-	98-99	98	95	97	99	99	98	94	96	99
0,425		%	56-83	74-82	81	83	84	87 -88	85-88	87	83	85	86
0,250		%	-	-	58	-	-		-	-	-		60
0,150		%	-	-	23	-	-		-	-	-		24
0,075		%	6-9	3-5	5	6	6	6-7	4-6	5	6	6	6
LL / PI / LS	(P425)	%	NP/0	NP/0	NP/0	NP/0	NP/0	NP/0	NP/0	NP/0	NP/0	NP/0	NP/0
LL / PI LS	(P075)	%	-	NP-SP 0-0,7	24/6 2,0	23/4 1,7	26/4 1,7	24-31/5-10 2,0-4,3	NP-24/5 0-2,7	25/4 3,0	24/5 2,0	22/3 1,3	28/9 4,7
MAASHO	MDD	kg/m^3	1890-1933	1824-1932	1832 [6]	1933	1882	1870-1934	1836-1914	1851	1896	1913	1842[8]
	OMC	%	7,0-9,3	6,8-8,6	8,8	7,8	8,5	6,3-9,2	7,7-8,6	8,0	7,3	8,2	8,5
CBR [2] @	MAASHO												
Soaked	104	%	-		60	40	50	70-90					76
	102	%	-		54	37	44	65-70	44-53	34	41	34	65
	100	%	-		50	34	39	60	40-51	33	36	30	55
	98	%	-	34-37	46	31	34	48-58	37-49	32	33	27	48
	95	%	36-47	25-30	39	28	28	32-48	30-34	30	25	23	41
@ OMC	104	%	-	-	70	-	-	-	-	-	-	-	69
	102	%	-	-	58	-	-	-	-	-	-	-	63
	100	%	-	-	48	-	-	-	-	-	-	-	58
	98	%	-	-	39	-	-	-	-	-	-	-	53
	95	%	-	-	28	-	-	-	-	-	-	-	50
@ 0,5 OMC	104	%	-	-	160	-	-	-	-	-	-	-	120
	102	%	-	-	120	-	-	-	-	-	-	-	110
	100	%	-	-	85 [7]	-	-	-	-	-	-	-	100 [9]
	98	%	-	-	59	-	-	-	-	-	-	-	90
	95				32			-	-	-	-	-	80
DERIVED DATA													
GM		-	1,10-1,43	1,15-1,23	1,13	1,14	1,12	1,06	1,07-1,11	1,08	1,16	1,12	1,08
Dust ratio (DR)	[3]	-	0,10-0,13	0,04-0,06	0,06	0,07	0,07	0,07-0,08	0,05-0,06	0,06	0,07	0,07	0,07
TMH FI075	[4]	-		4-10	30	24	30	35-60	5-30	20	30	18	54
CLASSIFICATION		-											
AASHTO M-145		-	A-3(0)	A-3(0)	A-3(0)	A-3(0)	A-3(0)	A-3(0)	A-3(0)	A-3(0)	A-3(0)	A-3(0)	A-3(0)
COLTO : 1996, 1998		-	G7-G6	G6	G7	G7	G7	G7	G7	G7	G7	G6	G7
Compactability	[4]	-	-	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
Subbase	[5]	-	Yes?	No	Yes	No	No	No - Yes	No	No	No	No	Yes

Notes:

[1] Said to be typical. **[2]** All swells 0,0 %. **[3]** DR = P075 / P425 **[3]** FI(075) = PI(075) x P075. **[4]** Fineness index, modified from Mainwaring (1968) for TMH 1 (=ASTM) Cup PI = BS 1377:1990 Cup PI minus 4), i.e. for BS FI075 Good 0 - 200, equiv. TMH 1 FI075 = 200 – (4P075), e.g. 0 - 180 for P075 = 5 %. **[5]** Sand spec: P075 ≤ 20 %; CBR ≥ 35 @ 95 %; P075 = 5 - 20; TMH FI075 = 30 – 20. **[6]** BS 1377:1990 Vibrating Hammer MDD 1 906 kg/m^3, OMC 7,0 %. **[7]** 5,08 mm CBR 50, mean MC of top 25 mm 1,9 %, whole specimen 4,6 % (*n* = 3). **[8]** BS Vibrating hammer MDD 1 922 kg/m3, OMC 7,8 % **[9]** 5,08 mm CBR 200, but mean MC of top 25 mm 1,9 % , whole specimen 4,6 % (*n* = 3)

The unsaturated CBRs at OMC were probably too low because they were tested too soon after compaction, but those at about half OMC appear correct, but only the red sand at about half OMC yielded a (much) higher 5,08 mm CBR (of 200) than that at 2,54 mm (of 100). The only obvious difference between the two sands was their colour:

- The “red” sand was a yellowish red colour (Munsell 5 YR 4/6) dry and reddish-brown (2,5YR 4/4) moist, and
- the “grey” (also called white) sand was a greyish brown (10 YR 5/2) dry to brown (10 YR 5/3) and dark brown (10YR 3/3) moist.

Chemical, mineralogical and microscopic analyses confirmed that the red sands were composed of about 93-98% SiO_2, mostly as quartz, with 1,8 - 2,1% Al_2O_3 as 1 - 2% feldspar up to 2% smectite and up to 2% mica, and 1,8-3,0% Fe_2O_3 as haematite and/or goethite. The total Al_2O_3 + Fe_2O_3 contents of five samples were 3,6-4,9% and the CBD-extractable Fe and Al contents of them 0,3 – 0,4, and 0,03%, respectively.

The grey sands were not chemically and mineralogically analysed, but inspection under the microscope showed them to be almost identical to the red sands except for the almost complete absence of goethite and haematite coatings, but some fine organic matter. Under the microscope, both sands were composed mostly of clear quartz grains, spheroidal and subrounded in larger sizes, and more irregular and angular with decreasing particle size.

9. CONSTRUCTION

9.1 Roadbed

A 9,4 m width of the Kalahari sand roadbed (i.e. to just outside the sealed width of 9,1 m) was precollapsed using a combination of a 50 ton (t) PTR and a three-sided impact roller (Pinard & Ookeditse, 1988) to 90% MAASHO or 98% of proof density to a depth of 600 mm. The roadbed under the outer fill received either a 3-pass roller (one pass being two traverses) compaction or was compacted to 90%. This was best done during the rainy season in order to make use of the higher in-situ water content

9.2 Subbase

Only yellow-orange sands and selected reddish to light brown sands were used. White, blackish and dark brown sands were avoided. The specification used was derived largely on the basis of compactability and trafficability without rutting, ravelling or cracking during construction. Trafficability by construction vehicles was satisfactory provided that no turning of dump trucks was allowed. The subbase was not allowed to dry out and powder before dumping and spreading the base, and was spray-watered where necessary. Initial compaction was by a 9 or 11 t vibrating roller (VR) followed by a 14 t 9-wheel PTR. Compaction planes only occurred if the layer was allowed to dry out or if the vibrator was over-used. However, it could only be trafficked when relatively dry, heavy rains caused serious erosion, and use of the subbase by general construction traffic was therefore not permitted. Construction of such a subbase or base is, therefore, best done in winter.

Increasing the specified subbase compaction from 95% to 98% for A-2-4(0) and 100% for A-3 sands achieved 96-102% ($\bar{x}$ = 99,1, s = 1,85; n = 17) on Sections 2 - 12, 101% on Section 1, and 95% on Section 13, with 95% CBRs of 36 - 48. Compactions of 93,4 - 95,2% with 93% CBRs of 23 - 49 were achieved on the selected subgrade with 93 % specified.

9.3 Base Courses

9.3.1 Ferricrete Controls (02 May 1989)

The 98% CBRs achieved on the two untreated ferricrete Sections 1 and 13 were 102 and 104%, respectively.

9.3.2 Emulsion-Treated Sand Bases (03-11 April 1989)

The SS60 emulsion was not diluted, but all the sands were prewatered before application.

In the case of uniform 1,5% full-depth stabilization to 150 mm such as Section 3, all the emulsion was applied in two sprays of about 3,5 l/m^2 each on the surface with harrowing after each spray, followed by full-depth mixing by grader until a visually uniform mix was achieved.

In the case of the 1,5/0% Sections 4 and 7 (i.e. 1,5% only in the upper half of the base), the full amount of binder was applied as a single spray of about 3,5 l/m^2 followed by mixing to 75 mm with 10 passes of the harrow.

In the case of the 3/0% Sections 5 and 6, two sprays of binder were applied at about 3,5 l/m^2 each, with harrowing between each spray to 75 mm (a total of 15 passes) and grader levelling after each five passes.

In the case of Sections 8 (4/2%) and 9 (3/1,5%), two sprays were given on the surface with three passes of the harrow after each spray, followed by full-depth mixing with the grader leveling and spreading. A further single spray of half the total of the first two was then applied and harrowed to 75 mm with about 12 passes, with surface leveling after eight passes.

Although mixing was always continued until it was visually uniform, some flecking and streaking was always noticed when cutting levels.

After aeration to their OFCs of mostly 6 - 8%, compaction to 101 - 104% was achieved with five or six passes of the 9 t VR and seven or eight passes of the 10 t PTR, with only Sections 10 and 11 at 99% (Table 1).

Most sections were badly damaged by cattle in spite of the employment of herd guards. Loose sand was removed by brushing and a compressor, and areas were brushed and reprimed by hand spraying. However, the surface was still uneven and too rich in places and all the sections were eventually skimmed and reprimed with MC-30 at 0,8 l/m^2 on July 22 before surfacing on August 30, i.e. about five months after compaction.

In-situ vane shear strengths just before surfacing at the test temperature ranged between 280 kPa on Section 10 and 600 kPa on Section 3, and between approximately 230 on Sections 6 and 10 and 475 kPa on Sections 8 and 11 when corrected to the design temperature of 40ºC, using the laboratory-derived relationships (attempts to derive in-situ relationships were mostly unsuccessful) and the surface temperature. All shear strengths when surfaced were thus in excess of the minimum of 200 kPa at 40ºC required. In-situ Clegg Hammer CBRs ranged between 48 on Section 10 and 107 on Section 8. Details of the strength development during curing are provided in Netterberg (This Conf.).

Except for Section 10 with 5,6%, the other ETB base course FMCs when surfaced of 1,6 – 4,0% were about half their OFCs of 6,1 - 8,0%. The subbase FMCs at that time were about twice those of the base, and close to their OMCs.

9.3.3 Untreated Red Sand Base (12 April 1989)

Details of the untreated sand base are provided in Netterberg *et al* (This Conf.).

9.3.4 Surfacing (30 -31 August 1989, Opened to Traffic Early September 1989)

TMH 6:1984 ball penetration tests carried out on the bases just before surfacing (Table 4) showed that substantial allowance has to be made for embedment on such bases.

Table 4: Results of ball penetration tests just before surfacing

SECTION	**BASE**		**PENETRATION [1]**	**SURFACE TEMP. [1]**	**FFC OR FMC [2]**
No.	**Type**	**Binder**			
		%	mm	º C	%
1	Ferricrete	0	3	32	3,5
2 - 5	White sand	1,5 - 3,0	7 - 9	28 - 39	1,6 - 3,5
6 - 9	Red sand	1,5 - 3,0	6 - 7	18 - 29	3,1 - 4,0
10	Red sand	1,5	9	30	5,6
11	Red sand	1,5	10	31	2,8
12	Red sand	0	6	30	3,4
13	Ferricrete	0	3	34	3,2

Notes:
[1] Means of 5 results in each lane on each section (*n*=10) uncorrected for seal design temperature
[2] Means of 3 results on centreline of each section

10. PERFORMANCE

In order to exclude construction effects monitoring was generally limited to the central 100 m (i.e. section "chainage" (CH.) 25 -125 m), with a "buffer zone" of 25 m at each end.

10.1 During Construction

As a guide to emulsion treatment, in general, is available (Sabita, 2020) only the most important problems encountered will be discussed.

It was apparent from the flecking and streaking noticed during the cutting of levels that mixing was poor and/or that some of the emulsion had broken prematurely. The red sand sections cured about twice as fast as the grey (Netterberg, this Conf.).

Surface preparation of the grey sand Sections 3 and 4 for priming was difficult. However, the greatest problem was the severe damage caused by cattle, and all of the sand sections were eventually skimmed and reprimed. Despite this – which reduced the thickness by about 20 mm – after 30 years all the sections were still there and carrying traffic.

10.2 Short-Term

In general, the seal suffered from significant ravelling of the 9,5 mm silcrete chippings, especially on the shoulders, which were not initially fogged. The reasons for this appeared to include poor adhesion, too low a binder application rate on the shoulders, absorption by the chippings, and some crushing of the weakest fraction. After one year, substantial loss of the 13,2 mm stone on the 9+13 seals had taken place on all the sections and slight punching of the 19+9 seal on Section 12.

A base course shear failure in the outer wheelpath of the Orapa lane on the grey sand Section 4 (1,5/0%) was investigated inconclusively in August 1990, practically identical with DCP results in both the failure and good area both in the strength of the upper base (DN of 8 mm/blow; approximate of CBR 30) and the DSN_{800} of 200. By 1991 over 8 m^2 of patching and more failures were evident.

Section 8 (4/2%) started bleeding within three months, and by six months, it was severe, and remained so until resealed after 8 years.

Severe edge breaking due to shoulder erosion, reaching to the yellow line in a few places took place on the shoulders of several sections, including Section 12 when the side slopes were still at 1 : 4 and a berm of chippings had been left along the edge. The necessity for a minimum side slope of 1 : 6 for unclad Kalahari sand fills was confirmed on this road.

A Benkelman beam deflection survey (62 kN axle load, 590 kPa tyre pressure) in June 1990 in the outer wheelpath of the Orapa lane yielded mean deflections of 0,25 – 0,30 mm on all sections, indicating a sound and uniform pavement for a Category C or II road.

10.3 Long-Term

The most important condition statements are those in 1995 (Table 5) before resealing in 1996 and after nearly 20 years in 2008 and a second reseal in about 2006 (Table 6).

Table 5 shows that both lanes of all the sections except Section 4 (1,5/0% grey sand) with Degree 3 Extent 3 (D3/E3) base course shear failures and D3/E4 longitudinal cracks and Section 8 (4/2% red sand) with D4/E5 bleeding were, according to TMH 9:1992 criteria (COLTO,1992), visually in a good to very good condition after about 0,06 MESA in the Orapa lane and 0,01 in the Serowe lane before resealing in 1996. D3/E4 block cracking was present on Section 2 (3/1,5% grey sand), but only D2/E2 transverse cracking on Section 5 (also with grey sand and 3% binder, but only in the upper base), and none on Section 6, with 3% in the upper base only of red sand.

A quick visual inspection in 1997 after the 7 mm precoated silcrete single reseal showed all sections to be in at least a good general condition with Degree 2 active stone loss on all sections, D2/E5 rutting and undulations on some, and edge breaking on most sections.

The results of a more detailed pavement evaluation in 2008 after about 0,30 MESA in 19 years in the Orapa and 0,07 M in the Serowe lane in Table 6 show that all the carriageways except the Orapa lane of Sections 4 and 5 were still in a good to very good condition, with practically all the 80 %ile rut depths still in the sound range. Cracking of any kind was absent except for short D2/E5 transverse shoulder edge cracks on Section 2. However, a 10 m-long D2/E3 shallow base failure was present in the right outer wheelpath (ROWP) of both Section 4 and Section 5 (25 m-long D1/E5).

Non-sampling-and mole-associated patching was absent except for a 50-m length (i.e. D1/E5) along the left edge of the stabilization on Section 3 (previously a narrow 10 m-long D4/E3 rut), and a 10-m length (D1/E3) in the right outer wheelpath of Section 4, as well as a 40-m length on the shoulder extending into the outer wheelpath (i.e. D1/E4), apparently representing both mole damage and shear failures.

A D3/E2 shear failure (10 m-long) was again present in the right (Orapa) outer wheelpath (ROWP) of Section 4 together with surfacing rippling, the 80 and 90% ile rut depths were at a warning level and the average DN of the base was only 5,0 (approximate CBR of 53).

Table 5: General condition in 1995 after 0.06 MESA in six years in the Orapa lane before resealing

SECT. NO.	**BASE**	**NET BITUMEN IN BASE (%)**		**MAIN SEALS [1] mm**	**SECTION CH. (m) GENERAL PAVEMENT CONDITION [2] Rating**	**REMARKS [3]**			**RUT DEG. / EXT. [2] Rating**
		UPPER 75 mm	**LOWER 75 mm**			**BLEEDING Rating**	**CRACKING & SHEARS [4] Rating [4]**	**PATCH-ING Rating**	
1	Ferri-crete	-	-	19+9; 9+13	25-74 Very good 74-125 Good	D2/E5 D3/E5	- -	- -	1/5
2	Grey sand	3,0	1,5	9+13 ; 19+9	Good	D2/E5 ; D0	B : D3/E4	-	1/5
3		1,5	1,5	19+9 ; 9+13	Good	D0 ; D2/E5	B : D2/E4	D1/E1	1/5
4		1,5	-	9+13	Fair	D2/E5	L : D3/E4 ; T : D2/E4 ; S : D3/E2	D1/E4 D1/E4	3/3
5		3,0	-	9+13; CD+13	Very good	D2/E5 D2/E5	T: D2/E2 T D2/E2	- -	1/5
6	Red sand	3,0	-	9+13	Very good	D2/E4	-	-	1/5
7		1,5	-	9+13	Good	D3/E5	B : D2/E3	-	2/5
8		4,0	2,0	9+13	Fair-good	D4/E5	B : D2/E5	-	1/5
9		3,0	1,5	9+13 19+9	25-100 Good 100-125 Very good	D2/5 D0	B : D2/E5 B : D1/E3	- -	1/5
10		1,5	1,5	19+9 ; 9+13	Very good	D0 ; D2/E5	T : D1/E3	-	1/5
11 [5]		1,5	1,5	9+13 ; 19+9	Very good	D0 ; D2/E5	B : D1/E4	-	1/5
12		-	-	19+9 ; 9+13; CD+13	Very good	D0 ; D2/E5 D2/E5	T : D1/E1	-	2/5
13	Ferri-crete	-	-	9+13 ; 19+9	Very good	D2/E5 ; D0	-	-	1/5

Notes: All according to TMH9:1992:

[1] Seals: 19+9 = 9,5 mm on 19 mm; 9+13 = 9,5 on 13,2 mm; (D+13 = 13 mm on crusher dust− the best). Single seal types: reasonable, but critical). Degree 1 -2 active stone loss on all even though fogged. All chips and crusher dust silcrete.

[2] General condition and rut rating on visual basis only. Section chainages, i.e. 0-150 m. Contrary to normal practice sealed shoulders excluded from general pavement condition rating, and described separately (not shown). Rut rating: 1 = < 5; 2 = 5 -10 ; 3 = 10 -15 mm; etc.

[3] Degree (D) and Extent (E) e.g. D3 = Warning; D5 = Severe; E3 = Scattered (10 – 25% of length); E5 = Extensive (> 50%) occurrence.

[4] B = Block ; L = Longitudinal ; T = Transverse cracking; S = base shear. {5] Repeat of Section 10 with new emulsion

Table 6: Summary of visual inspection, rut depths and DCP strengths of bases of carriageway after 19 years in 2008 [1]

SECTION NO.	BASE TYPE	BASE					LEFT (SEROWE-BOUND) LANE (0,07 MESA)							RIGHT (ORAPA-BOUND) LANE (0,30 MESA)								
		UPPER 75mm		LOWER 75 mm		MAIN SEALS (1995)	GENERAL PAVEMENT CONDITION	OUTER WHEELPATH					RIDING QUALITY	GENERAL PAVEMENT CONDITION	OUTER WHEELPATH					RIDING QUALITY	TOTAL CAPACITY PROJECTED TO (mm)	
								RUTTING			MEAN DCP [6]				RUTTING			MEAN DCP [6]			20 [7]	25 [7]
		NET BIT. %	LAB CBR [2] %	NET BIT. %	LAB CBR [2] %	[3] mm	[4] Rating	DEG. [4] Rating	80 %-ile [5] mm	90 %-ile [5] mm	DN mm/ blow	CBR %	[4] Rating	[4] Rating	DEG. [4] Rating	80 %-ile [5] mm	90 %-ile [5] mm	DN mm/ blow	CBR %	[4] Rating	80 %-ile (Cat. C) MESA	90 %-ile (Cat.II) MESA
1	Ferri-crete	-	123	-	123	19+9 ; 9+13	V. good	1	5	6	1,3	250	V. good	V. good	1	7	8	1,9	180	V. good	2,3	2,6
2	Grey sand	3,0	35	1,5	(36)	9+13 ; 19+9	V. good	1	4	4	3,4	90	Good	V. good	1	6	7	3,4	90	Good	2,4	3,2
3		1,5	36	1,5	36	19+9 ; 9+13	V. good [8]	1	8	9	3,6	80	Good	V. good [8]	1	9	10	4,2	66	Good	0,9	1,1
4		1,5	32	-	40	9+13	Good	2	5	6	3,5	84	Good	Fair [8, 10]	4	14	17	5,0	53	Good	0,5	0,5
5		3,0	22	-	40	9+13	V. good	2	6	7	2,9	105	Good	Fair [8]	4	9	11	2,9	105	Good	1,1	1,1
6	Red sand	3,0	50	-	33	9+13	V. good	1	7	8	2,3	145	Good	Good	2	8	9	2,4	135	Good	1,5	1,8
7		1,5	48	-	33	9+13	V. good	1	6	7	1,5	220	V. good	V. good	2	10	11	2,3	145	V. good	1,0	1,1
8		4,0	35	2,0	62	9+13	V. good	1	6	7	1,7	200	V. good	V. good	2	8	9	1,7	200	V. good	1,0	1,3
9		3,0	56	1,5	53	9+13 ; 19+9	V. good	1	6	7	2,5	128	Good	V. good	2	8	9	3,6	80	Good	1,2	1,6
10		1,5	26	1,5	26	19+9 ; 9+13	V. good	1	10	12	1,9	180	V. good	V. good	2	8	9	1,8	185	V. good	1,2	1,6
11		1,5	44	1,5	44	9+13 ; 19+9	V. good	1	6	7	3,4	90	V. good	V. good	2	8	9	3,0	100	V. good	1,2	1,5
12		-	55	-	55	19+9 ; 9+13	V. good [9]	2	9	10	1,8	185	Good [9]	Good [9,11]	3	12	13	2,1	160	Fair [9,11]	0,7	1,0
13	Ferri-crete	-	118	-	118	9+13 ; 19+9	V. good [9]	1	8	9	1,4	240	V. good [9]	V. good [9]	1	10	11	1,8	185	V. good [9]	1,3	1,7

Notes:

[1] Visuals in April 2008, rut depths and DCPs in July-Sept 2008

[2] 7 Days air drying and 4 days soaking, at 100 % MAASHO on emulsion-treated sands. Standard 4-day soak at 100 % on untreated sand; Sections 1 and 13 at 98 %,. (36) Inferred from Section 3.

[3] Current seal 13 mm precoated granite single seal**.** Original silcrete seals as shown with fog, 6,7 m-wide

[4] Carriageways rated on best average, (i.e. ≈ Extent 5) fivefold basis : Very good, Good, Fair, Poor, or Very Poor but shoulders on threefold basis (Good, Fair or Poor) according to TMH 9:1992. All **shoulders** Good on both sides except for Sections 3-5 (Fair), mostly due to mole damage. More mole damage on Orapa side than Serowe. Narrow patch 50 m-long on left shoulder of Section 3 due to previous D4 rut. Mole damage, depressions and potholes due to poor sample reinstatement excluded from riding quality ratings. Visual rutting also on five-fold basis

[5] Rut depths by 2,0 m straight edge & 25 mm wide wedge, $n = 21$; 80 % iles all practically same as July 1990 except Section 4 ROWP (was only 8 mm). TRH 12 : Cat. C 1997 criteria: < 10 mm Sound; 10 -19 Warning; > 20 Severe (80 %-ile). BRD (2000) Cat. II criteria: < 15 mm Sound; 15-25 Warning; >25 Severe (90%-ile)

[6] DCP analysis by BRD using CSIR WinDCP 5.1 program, granular model, optimum moisture condition. DN and CBR are weighted means for top 0-160 mm of pavement, **including surfacing**. Means of six results in each wheelpath. Mid-base temps 24 – 28 º C on 20 – 22 Aug. 2008. DSN_{800} all >290, i.e. estimated residual structural capacities all > 12 MISA, but unreliable above this. Mid-base temperatures on Section 8 mostly 24 - 29 °C, rarely 39 °C. Relative damage exponents all ≤ 1. Practically all averagely balanced inverted (ABI) pavements

[7] Based solely upon rut depth

[8] Mole damage (transverse depressions due to collapsed tunnels)

[9] Depressions and/or potholes due to poor reinstatement at previous sampling sites

[10] One 5-m long shallow Deg. 3 base shear failure and extensive rippling in ROWP and whole right shoulder patched

[11] Corrugations due to shifting of seal

Although some of the rutting was in or near a warning level they were practically unchanged from 1990 and those for the neat sand Section 12 were practically the same as the adjacent ferricrete control Section 13.

The in-situ DCP strengths of all the bases were all very good, with only those in the Orapa lane of Sections 3 and 4 (grey sand with 1,5% net bitumen) at a DN of 4,2 (CBR 66) and 5,0 (CBR 53), respectively on the low side. In spite of this, both lanes of Section 3 were still in a very good overall condition.

Both sealed shoulders of all sections were in good condition except those of Section 3 and 4 and the Orapa shoulder of Section 5, which were all in a fair condition. Edge breaking was present on all sections except the controls and the left side of Sections 4 to 12 and was generally worst and most extensive on the right side of the grey sand sections.

The greatest problem was undulations ranging up to D4/E5 caused by the collapse of dune mole tunnels, some of which extended into the mid lane on Sections 3 to 5. The mole damage was generally worse and more extensive on the grey sand sections than on the red, and mostly in the Orapa-bound shoulder and lane, but all sections except the red sand Sections 6 and 8 and the ferricrete controls were affected.

Although no pavement evaluation or even visual inspection on foot was carried out since 2008, the excellent Google Earth photographic road survey in May 2012 after 23 years and about 0,36 MESA in the Orapa lane showed little change, all sections to be still in at least a visually satisfactory condition except for the mole damage and patching on Section 4 in particular, no new patches except along some edges, and the section markings on the seal and the rows of sample patches to be still visible. Only the lines had been repainted, all in white. One of us (KJR M) subsequently drove over the experiment at least twice yearly and reported all sections to still be in good condition at least up to 2018, i.e. after 30 years.

11. MAINTENANCE

The only maintenance applied to the sections over the first 20 years was a fog spray due to initial ravelling, precoated reseals in 1996 and about 2006, patching of the shear failures in the Orapa lane of Sections 4 and 5 and a rut on the Serowe shoulder of Section 3, mole damage and edge breaks due to shoulder erosion, and flattening of the unclad Kgalagadi sand side slopes from 1 : 4 to 1 : 6 or flatter. No attention to the seal was recommended in 2008 and the Google Earth road survey showed that the road had not been resealed by 2012. The whole experiment was overlaid with 30 mm of asphalt in early 2020.

12. DISCUSSION AND DERIVED SPECIFICATIONS

12.1 Performance Criteria

The criteria used for the performance and structural capacity analyses were those of TRH4:1996, TRH12:1997 and the BRD:2000. The chief modes of distress were shallow base shear failures on the grey sand Sections 3, 4 and 5 only, and rutting, for which the terminal criteria are an 80%-ile limit of 20 mm for a South African Category C and a 90%-ile limit of 25 mm for a Botswana Category II road.

The projected capacities in Table 6 – see Note 7 − should probably be regarded only as indicative upper bounds because they were derived from only three sets of rut depth measurements and a few visual estimates and also do not take other modes of distress and future maintenance levels into consideration. However, they serve also to indicate the differences in capacity prediction depending upon the limit adopted, those for a Category II road being mostly slightly higher than for a Category C road. These capacities would be greater if the 90 %-ile limit of 30 mm of Gourley and Greening (1999) or the mean of 30 mm of Otto *et al* (2019) is accepted. Nevertheless, (because of only a 2 mm increase in rut depth since construction), only those for Section 2 appear unrealistically high.

All of the DCP tests which achieved full penetration to 800 mm recorded a DSN_{800} of at least 290 blows, more than satisfying the BRD:2000 minimum of 155 for a sound Botswana Category II road (the TRH12:1997 limit for a moisture condition dry of MAASHO OMC) and the TRH12:1997 minimum of 190 for a sound Category C road at optimum moisture content.

The suggested capacities to follow are based upon consideration of other distress criteria in addition to rut depth over the whole analysis period as well as construction problems and are necessarily conservative and less than those predicted from rut depth alone. Although, unless limited by another form of distress, a Category II road should have a capacity of 0,1 – 0,2 MESA greater than a Category C, the capacities suggested are intended to apply to both categories unless otherwise indicated.

12.2 Pavement Required

The following requirements and specifications have been deliberately and empirically derived largely from the results of this experiment with limited consideration of other work. A pavement and environment similar to that of the experiment and as constructed is therefore assumed, with all base courses 150 mm (absolute minimum 125 mm) in thickness, i.e:

Roadbed: Kalahari sand, precollapsed to a depth of 600 mm if potentially collapsing.

Fill: Kalahari sand, compacted to 95 % if A-2-4(0) and 100 % if A-3(0).

Subgrade: Kalahari sand, compacted to 95 % if A-2-4(0) and 100 % if A-3(0).

Subbase: Reddish Kalahari sand as specified in Section 6.1 compacted to 100%, whether A-2-4(0) or A-3(0), and at least 100 mm in thickness.

Shoulders: Shoulders of grey or white sand treated as per the base course if more than about 0,05 MESA is anticipated. The good performance of the untreated shoulders of both lanes of **Section 12** (Netterberg *et al*, This conf) showed that shoulders of red sand complying with their untreated base specification and compacted to 100% need not be treated. In either case, the shoulders should be sealed with at least a fogged single seal.

Surfacing: Prime at about 0,8 l/m, followed by either crusher dust + 13 mm (the best), a 19+9 mm double seal or a Cape seal. Provision must be made for embedment and also precoating and/or absorption if calcrete or silcrete chippings are used.

12.3 Emulsion Treated Sand Base

12.3.1 Raw Sand

The raw sands should comply roughly with the specification in Table 7 derived from both the grey and red sands used (Table 3) and would classify as a COLTO:1996, 1998 G7.

Table 7: Recommended specification for raw Kalahari sand for emulsion-treated base

PROPERTY	REQUIREMENT
AASHTO M-145 classification	A-3(0)
GM	1,05 - 1,20
P075	3 - 6
PI (P425)	NP
PI (P075)	NP - 6
TMH FI075 (= TMH 1 PI on P075 x P075)	4 - 30
Min. soaked CBR @ 95% MAASHO	20

12.3.2 Emulsion Treated Material

A grey or white sand with 1,5% residual bitumen in the upper base only (as in Section 4) is not recommended due to finishing problems, shear failures, rippling, longitudinal cracking and rutting. Although still in a fair condition and in service in 2008 and at least until 2012, the Orapa lane of the grey sand Section 4 is regarded as having “failed”, i.e. in a terminal condition for a Category C road due to a total length of more than 20 m (20% of the section) of patching and shear failures in the outer wheelpath after about 0,05 MESA. Although it was initially thought that 1,5% binder was too little, the Serowe lane of Section 4 was still in good condition after at least 19 years and 0,07 MESA and the 1,5% full-depth Section 3 was still in very good condition after 0,3 MESA, the failures were probably therefore due to poor mixing. This Section 4 design could – with better mixing and greater care in surface preparation – probably therefore be used for up to about 0,10 MESA.

The carriageways of the full-depth 1,5% grey sand Section 3 performed well apart from the finishing problems and incipient early block cracking (not present in 2008) and should be adequate for 0,5 MESA. However, the presence of a 50 m-long, 0,5 m-wide patch on what was previously a narrow D4/E2 rut along the inside edge of the Serowe shoulder (the edge of the stabilization) illustrates the necessity of also treating the shoulder if grey sand is used.

In short, the use of only 1,5% binder in this grey sand is risky.

Section 2 (3/1,5%) was the best of the grey sand sections and both lanes were still in very good condition in 2008. The capacity estimates based on rut depth alone are probably unrealistic and it should probably be restricted to 1,0 MESA for a Category C and 1,2 for a Category II road.

The grey sand Section 5 (3 % only in the upper base) initially performed better than Section 2 (3/1,5%), which exhibited extensive D3 block cracking in 1995 (not present in 2008) before resealing. However, the presence of a D4/E4 rut in the Orapa lane resulted in it only receiving a Fair rating in 2008 (Table 7) and it should probably be restricted to 0,5 MESA.

As well as being more difficult to work and finish, the grey sand sections exhibited more mole damage, edge breaks and shoulder edge erosion than the red sand sections.

In general the red sand sections performed better than the grey sections. All of them performed well and, on the basis of their condition, their 80%-ile rut depths of only 8 -10 mm in comparison with the 10 mm of Section 13 and their high strengths in the Orapa lane should all be adequate for 0,8 MESA for a Category C and 1,0 for a Category II road.

Although the best of all the sections up to at least 2008 and marginally the best red sand section, a Section 8 design (4/2%) is not recommended on the grounds of cost, severe (D4/E5) early bleeding and also because its performance – up to 0,3 MESA at least – had not been any better than the others. However, too much should probably not be made of this bleeding and the Degree 2-3 bleeding on Section 7 as at 1995, as Degree 3 bleeding of the identical seal also took place on the ferricrete control Section 1. Assuming adequate pavement balance, it could be considered for heavier traffic where the cost is justified, as with an average DN of 1,7 (CBR 200) in both lanes it had the strongest base of all in the Orapa lane, comparable with that of the ferricrete control sections. The edges of the shoulders were also the most erosion-resistant of all the sand sections. Nevertheless, due to its rehabilitation, apparently due to excessive bleeding in 2020, it should possibly be restricted to about 0,5 MESA. Four percent binder is probably too much for this sand and the optimum design is probably that of Section 9 (3/1,5%), which should be adequate for 1,0 MESA for a Category C and 1,2 for a Category II road.

The most economic design is that of Section 7 (1,5% in the upper base only) which, apart from the early D3 bleeding and only a few minor (D2/E3) block cracks in 1995 (not present in 2008) had performed well and in 2008 had a good average base course strength (DN 2,3; CBR 145) and 80 and 90-%ile rut depths of only 10 and 11 mm, respectively. This design should be adequate for at least 0,5 MESA for a Category C and 0,8 for a Category II road.

The two full-depth 1,5% red sand Sections 10 (old emulsion) and 11 (new emulsion) both performed slightly better than Section 7 and were both rated as very good both in 1995 and in 2008, and should be adequate for at least 0,8 MESA for a Category C and 1,0 for a Category II road.

A conservative recommendation would therefore be to use 1,5% net bitumen (2,5% emulsion) in the upper base only as in Section 7 for up to 0,5 MESA and 1,5% in the whole base as in Section 11 for 0,8 MESA for both categories of road.

The two 3% red sand Sections 6 (3% in upper base only) and 9 (3 / 1,5%) both gave a similarly good performance and are recommended for 0,8 MESA for a Category C and 1,0 for a Category II road. The only differences between the two were the extensive Degree 2 - 5 edge breaking on the Orapa shoulder of Section 6 (which led to a downgrading of the general pavement condition from very good to good, and the weaker base in both lanes of Section 9 with a DN of 3,6 (CBR of 80) against the 2,4 and 135 of Section 6, and the mole damage on the Orapa shoulder of Section 9. Disregarding the shoulders (which should be identical), Section 6 is recommended over Section 9 because of its stronger and cheaper base.

The good performance and high strength (DN of 2,1; CBR 160) of the neat red sand base Section 12 – although a slightly different sand – indicates that emulsion treatment of only the upper base is sufficient to raise the capacity from about 0,5 to 0,8 MESA and to provide a safety factor against wetness. Indeed, in every case with both sands in both lanes the average strength of the section which was only treated in the upper base was stronger than the equivalent full-depth section, the only exceptions being of the Orapa lane of Section 4 and the old emulsion Section 10. As this must be due to the high suction-induced strength of the untreated sand, it can only be expected to last as long as it is kept dry.

All such sand bases – whether neat or emulsion-treated – will require protection from the hooves of cattle and large wild animals, both before and after priming until sealed. The use of an electric cattle fence and/or reliable herd guards may therefore prove necessary.

The two untreated ferricrete control sections were both in a very good condition with a probable total capacity of about 2 MESA.

13. CONCLUSIONS

The existing BRDM:1982 and TRH 14: 1985 criterion of a minimum vane shear strength at 40ºC of 200 kPa at 100% MAASHO for a BT3 material is supported.

The following criteria for a Botswana Category II or South African Category C road in Table 8 for the two sands have been derived from the site test results for each section and their subsequent performance. As they have been derived from tests necessarily carried out under less than ideal conditions under temperatures varying from 6 to 24ºC they should be regarded as guidelines rather than as rigid specifications. The raw results have been corrected to an assumed average site laboratory temperature of 20ºC on the assumption that the correction factors derived for vane shear strength are also valid for CBR and UCS.

Table 8: Design guidelines for emulsion-treated Kalahari sand bases [1]

TYPE	GREY SAND						RED SAND					
TEST	**CBR (%) [2]**			**UCS (MPa) [3]**			**CBR (%) [2]**			**UCS (MPa) [3]**		
AGE (DAYS)	7	30	60	7	30	60	7	30	60	7	30	60
NET BITUMEN (%)												
1,5	30	40	50	0,4	0,6	0,8	40	50	70	1,0	1,1	1,5
2,0	-	-	-	-	-	-	60	60	70	1,0	1,5	1,5
3,0	20	35	100	0,4	1,0	1,0	45	60	70	1,0	1,5	1,5
4,0	-	-	-	-	-	-	30	60	80	0,5	1,0	1,5

Notes:
[1] See also discussion of traffic limitations and terminal rut depth limits in Section 12.1
[2] CBR is air-dry and 4-day soak @ 100% MAASHO
[3] UCS is air-dry and 4-hour soak @ 100% MAASHO

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