THE ORAPA UNTREATED KALAHARI SAND BASE 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 untreated, Kalahari fine red sand against similar sand treated with 2,5% bituminous emulsion and ferricrete gravel control sections. After 19 years, 0,3 MESA, two reseals and no patching the test and two control sections were still in a good to very good condition. DCP testing indicated that the sand base course had an in-situ CBR of about 160 and the pavement a total capacity in excess of 1,0 MISA and at least 0,5 MESA by a conservative extrapolation of rut depths, in comparison with about 0,8 MESA of the ETB. The high in-situ strength of the base was due to suction-induced apparent cohesion due to the low moisture contents. A specification derived for such an untreated red sand base course on similar red sand lower layers with untreated red sand sealed shoulders and a double seal on the carriageway for up to 0,5 MESA for a South African Category C, 0,6 for a Category D and 0,8 MESA for a Botswana Category II road over 20-30 years includes the following: GM 1,10-1,20; Passing 425 µm 75-85%; PI on P425 µm NP, on P075 µm 2-40; min. soaked MAASHO CBR 60; min. CBD-extractable Fe 0,3% or 1,5% $Fe_2 0_3$ by XRF analysis. Whilst extra care is needed in construction and surfacing, such a pavement has tremendous potential for economical, low-volume, sealed roads in the vast area covered by Kalahari sands in which rock and conventional gravels are scarce.

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 Botswana in order to evaluate the performance of two types of Kalahari sand stabilized with small percentages of bituminous emulsion, using one red unstabilized Kalahari sand and two ferricrete natural gravel bases as control sections.

As details of the whole experiment and references are provided in Netterberg *et al* (This conf.), it is the purpose of this paper only to report on the neat sand section in comparison with the adjacent ferricrete and emulsion-treated control sections and to derive base material and pavement specifications for similar untreated Kalahari sand bases. Only a minimum of information in the companion paper is therefore repeated here for convenience.

This is the second LTPP experiment in southern Africa involving an untreated Kalahari sand base, the first being in South Africa (Netterberg & Elsmere, 2015) and the first to have been regularly monitored for 19 years, virtually the traditional 20-year structural design period of a major rural road, and followed up for the usual 30 year analysis period.

2. LOCATION, LAYOUT, CLIMATE AND SOILS

The Orapa Experiment is located about 20 km on the Serowe side of the village of Letlhakane and the layout of the whole experiment is shown in Table 1 of Netterberg *et al* (This Conf). The neat red sand Section 12 is between the adjacent 2,5% emulsion-treated (i.e. 1,5% net bitumen) red sand Section 11 and the untreated ferricrete gravel control Section 13 at the Serowe end of the experiment. All sections are 150 m in length, of which the middle 100 was monitored. The area lies within the dry macroclimatic region for pavement design purposes and receives a mean annual rainfall of about 400 mm. The roadbed consists of a loose, nonplastic (NP), reddish Kalahari sand to a depth of at least 1,0 m.

3. TRAFFIC HISTORY

The sections were surfaced in late August 1989 and opened to traffic in early September 1989. This is a minor rural road which, at the last available traffic count after 18 years in 2007, carried about 260 vpd of which about 18% were heavy vehicles**.** The left (Serowe-bound) lane had carried about 0,06 and the right (Orapa-bound) lane about 0,27 MESA. After 23 years in 2012 the Orapa lane had carried a projected 0,36 MESA and 0,50 MESA after 30 years in 2019.

4. ALIGNMENT, CROSS-SECTION AND DRAINAGE

The vertical alignment is practically level. The horizontal alignment is straight except on Sections 12 and 13 which are on a slightly superelevated curve to the right. This factor would have contributed some additional loading to the outer wheelpath of the Orapa lane.

The road has a 6,70 m-wide carriageway centrelined in white and the carriageway edge-lined in yellow with 1,2 m-wide sealed shoulders, with a 2,5% crossfall on the carriageway and 3,5% on the shoulders. The initially unclad, later natural grass-covered sand fill side slopes are at about 1 : 6. The edge of the seal is about 0,3 – 0,5 m above the natural ground level of free-draining, nonplastic (NP) sand in which no side drains were cut.

5. PAVEMENT AND MATERIALS

Only TMH 1:1986 test methods were followed, including a MAASHO MDD and OMC and a 2,54 mm 4 day-soaked CBR. Compaction control was by the sand cone replacement method except on the ferricrete Sections 1 where a nuclear gauge was used and on the neat sand Section 12 where both methods were used. All compactions are percentages MAASHO MDD.

The pavement consists of a double seal on a 150 mm-thick base course carried across the shoulders of nonplastic (NP) red sand treated with 2,5% SS 60 emulsion (Section 11), NP neat red sand (Section 12), and NP ferricrete gravel control (Section 13), on a NP red sand subbase, selected subgrade and fill. The shoulders were all sealed, but only the Orapa-bound shoulders of Sections 11 and 13 were treated.

<u>Emulsion treated base (ETB) (Section 11):</u> Min. design laboratory vane shear strength at 40ºC of 200 kPa at 100%, but min. 98% in-situ compaction specified, i.e. a BRDM (1982) and a TRH 14:1985 BT3 material.

<u>Untreated sand base (Section 12):</u> This base is both a test and a control section and 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. A typical profile is shown in Figure 1.

Figure 1: Profile at CH. 65 CL on Section 12
(Photo: Mr S Pilane)

<u>Untreated ferricrete gravel base (Section 13):</u> A length of normal construction at the Serowe end: min. 98% CBR 80, max. PI 6, i.e. essentially a COLTO : 1998 G4 material.

<u>Surfacing:</u> Carriageways: 9+13 mm (i.e. 13,2 on 9,5 mm) inverted seal, a 90 m length of 19 + 9 mm across the joint between Sections 11 and 12, and 10 m lengths of 13 mm on crusher dust, and a 19 mm single seal intended as the lower layer of a Cape seal (which was never completed) on Section 12. Shoulders: 9 mm single seal, initially without a fog.

6. MATERIAL AND AS-BUILT PROPERTIES

A summary of site laboratory test results on both the grey and red sands used on the Orapa experiment is shown in Table 3 of Netterberg *et al* (This Conf.)

The red sand used for Section 12 had a MAASHO (i.e. at 100%) soaked CBR of 55 (58 unsoaked at optimum moisture content (OMC) and 100 at about 0,5 OMC) a GM of 1,08, was NP on the P425 but had a PI of 9 on the P075, classified as an AASHTO A-3(0) and a COLTO:1998 G7 material and, according to the Mainwaring (1968) fineness index (FI) criteria, had good compactability. Its MDD and OMC of 1 842 kg/m^3 and 8,5% were respectively lower and higher than those of the 1 922 kg/m^3 and 7,8% achieved with the BS 1377:1990 Vibrating Hammer method.

The unsaturated CBRs at OMC were probably too low because they were tested too soon after compaction, but those at about half OMC appear more reasonable.

During the CBR tests, all the sands peaked sharply at a 3 - 4 mm penetration and a true 5,08 mm CBR would have been lower than at the standard 2,54 mm. Only the Sample 12 in Table 3 of Netterberg *et al* (This Conf.) at about 0,5 OMC achieved a valid 5,08 mm CBR – of about 200. However, this may be misleadingly high, because with a moisture content in the upper 25 mm of 1,9% and 4,6% in the whole specimen, it was clearly not fully equilibrated

The red sands were a yellowish red colour (Munsell 5 YR 4/6) dry, and reddish-brown (2,5YR 4/4) moist. Chemical, mineralogical and microscopic analyses confirmed that they were composed of about 93-98% SiO_2 mostly as quartz, with 1,8 – 2,1% Al_2O_3 as 1 – 2% felspar, 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. Under the microscope, the sands were seen to be composed almost entirely of clear quartz grains, spheroidal and subrounded in the larger sizes and becoming more irregular in shape and more angular as the particle size decreased. Two red sand samples tested for their combined particle shape and angularity according to ASTM C 1252-93 (Method C, whole grading) yield uncompacted voids contents of 46 and 48% respectively, indicating an average angularity.

7. CONSTRUCTION

The potentially collapsible sand roadbed was impact-compacted to 90% to a depth of 600 mm as described by Pinard *et al* (1988).

The emulsion-treated red sand Section 11 was mixed and compacted on April 04, 1989 at about its MAASHO optimum fluid content (OFC) of 8,0% to a mean of 98,8% (n = 8), with an as-built laboratory 98% CBR of 42, a mean in-situ Clegg CBR of 60 (n = 40) and a vane shear strength of 410 kPa at road temperature at 14 days, respectively. The compaction and CBR achieved on the subbase lot was a mean of 99,4% (n = 4) with 98,5% on Section 11 (n = 2) and a 95% CBR of 37 for Section 11 (n = 1); those on the upper selected were a mean of 93,4% for the lot (n = 4) and a 93% CBR of 26 for Section 11 (n = 1), respectively.

The neat sand Section 12 was mixed by grader at about its MAASHO OMC of 7,4% and compacted with five passes of the VBR and eight of the PTR on April 12, 1989. The compaction achieved relative to a rather low (see Tables 5 and 7 later) MDD of 1 829 kg/m^3) is shown in Table 1. If the higher mean MDD of 1917 kg/m^3 (n = 11) from Table 5 is used, the mean sand cone- and nuclear gauge- determined compactions would only be 102,0 and 96,2%, respectively. Whilst it is not known which is correct, a relative compaction of 100 – 102% seems likely.

Table 1: Comparison between sand cone and nuclear density tests on Section 12

METHOD	FDD	FMC	RELATIVE COMPACTION					MDD	OMC
			MEAN	SD	MIN.	MAX.	RESULTS		
	kg/m^3	%	%	%	%	%	No.	kg/m^3	%
Sand Cone	1 955,1	4,4	106,9	0,94	105,8	108,5	7	1 829	7,4
Nuclear	1 844,1	3,6	100,8	1,09	98,7	102,2	8	1 829	7,4

Notes:

[1] Field dry density; field moisture content

[2] Troxler, with probe at 150 mm and -10 moisture correction

A rather high 98% as-built laboratory CBR of 102 was also recorded and a good vane shear strength of 385 kPa at 7 days at road temperature, but an in-situ Clegg CBR of only 40.

The compaction and CBR achieved on the subbase lot was a mean of 97,3% (*n* = 4), with 101% on Section 12 (*n* = 1) and a 95% CBR of 39; those on the upper selected were 94,5 % for the lot (*n* = 4) and a 93 % CBR for Section 12 of 26 (*n* = 1).

Showers of rain after 9 days on April 21 greatly softened Section 12 to a Clegg CBR of 6 and a shear strength of 90 kPa on the following day (Table 2). At 30 days the Clegg CBR had only improved to 20 and the shear strength to 160 kPa and it took nearly two months to recover. In contrast, although only tested 11 days after the rain, with a CBR of 55 and a shear strength of 285 kPa, Section 11 was far less affected. After allowing it to dry out, Section 12 was recompacted by six passes of the PTR and primed with MC-30 at the high rate of 1,4 l/m^2 in order to achieve penetration and strengthen the upper base. However, it remained soft and was skimmed and reprimed with MC-30 at 0,8 l/m^2 on July 22 with moisture contents of 4,1% in the base and 6,8% in the subbase two days later, prior to surfacing on August 30, 1989.

Table 2: Strength development [1] with time and effect of rain on unprimed bases

SECT-ION No.	NUMBER OF DAYS AFTER COMPACTION IN APRIL 1989															
	7		10 [2]		14			± 30 [3]			± 60			20 weeks		
	CBR %	S kPa	CBR %	S kPa	CBR %	S kPa	TEMP °C	CBR %	S kPa	TEMP °C	CBR %	S kPa	TEMP °C	CBR %	S kPa	TEMP °C
11	50	-	-	-	60	410	24	55	285	16	-	320	15	85	565	31
12	40	385	6	90	-	-	-	20	160	-	-	440	-	85	440	30

Notes:

[1] Means of both lanes (shoulders excluded): Clegg (1983) Hammer using 1999 relationship CBR = $(0{,}24\ \text{CIV} + 1)^2$, 8 sites, 5 positions (*n* = 40) except at 20 weeks just before surfacing on Aug. 30 (2 sites, *n* = 10; TMH 6: 1984 vane shear strength (S) at test temp., 8 sites, 5 positions (*n* = 40) except at 20 weeks (2 sites, *n* = 10).

[2] 1 Day after rain showers (on April 21)

[3] 11 Days after rain in case of Section 11 and 24 in case of Section 12

The ferricrete control Section 13 was compacted on May 02, 1989 at about its MAASHO OMC of 7,7% to a mean of 101,1% (*n* = 8), with an as-built 98% laboratory CBR of 104 (*n* = 1), GM of 2,40 and NP on the P425, but 14 on the P075. The compaction and CBR achieved on the subbase lot was a mean of 97,3% (*n* = 4) with 95% on Section 13 (*n* = 1) and a 95% CBR of 39 (*n* = 1); those on the upper selected lot were 94,5% (*n* = 4) and a 93% CBR of 49 (*n* = 1).

Ball penetration tests uncorrected for seal design temperature carried out on the bases just before surfacing in order to allow for embedment (Table 3) showed that this needs to be taken into account in seal design for both ETB and neat sand bases.

Table 3: Results of as-built compaction and CBR tests in April-May and ball penetration tests before surfacing on 30 August 1989

SECTION	BASE	COMPACT-ION [1]	OFC or OMC	CBR [2]	PENETRATION [3]	SURFACE TEMP. [3]	FFC or FMC [4]
No.	Type	%	%	%	mm	º C	%
11	ETB	99	8,0	42	9,5	31	2,8
12	Red sand	99	7,4	103	6,2	30	3,4
13	Ferricrete	101	7,7	104	3,0	34	3,2

Notes:
[1] Mean (*n* = 8).
[2] Laboratory soaked @ 98% (*n* = 1).
[3] According to TMH6:1984: mean, as measured (T1), 5 per lane (*n* = 10).
[4] Mean FMC and FMC contents on centreline (*n* = 3). Mean subbase FMCs 6,0 – 6,6 % (*n* = 3)

Surface preparation for priming required great care and the neat sand section was greatly softened by rain, but the greatest problem was the severe damage caused by cattle. All of the sand sections had to be skimmed − losing about 20 mm in thickness − rerolled and reprimed, finally on the 22 July 1987 together with the controls, with MC-30 at 0,8 l/m^2.

8. PERFORMANCE

In 1995 after six years and about 0,06 MESA in the Orapa lane, all three sections and their shoulders were all still in a very good condition with negligible cracking and an average rut depth of Degree 1 (< 5 mm) on Sections 11 and 13 and Degree 2 (5 -10 mm) on Section 12.

The results of this and a more detailed pavement evaluation of all 13 sections in 2008 after about 0,30 MESA in 19 years in the Orapa and 0,07M in the Serowe lane are shown in Tables 5 and 6 of Netterberg *et al* (This Conf.) and partly summarised in Table 4.

Table 4: Comparison of carriageway condition of Orapa lane in mid-2008 after 0,3 MESA in 19 years

SECTION		GENERAL PAVEMENT CONDITION	OUTER WHEELPATH					RIDING QUALITY	TOTAL CAPACITY PROJECTED TO : [4]		
			RUTTING			MEAN DCP					
			50	80	90	DN	CBR		20 mm		25 mm
			%-ile	%-ile	%-ile				50%-Iie	80%-ile	90%-ile
		[1]	[2]	[2]	[2]	[3]	[3]	[1]	(Cat. D)	(Cat. C)	(Cat. II)
No.	Type	Rating	mm	mm	mm	mm/b.	%	Rating	MESA	MESA	MESA
11	ETB	V. good	7	8	9	3,0	100	V. good	1,3	1,2	1,5
12	Sand	Good	10	12	13	2,1	160	Fair	0,8	0,7	1,0
13	Ferricrete	V. good	8	10	11	1,8	185	V. good	1,4	1,3	1,7

Notes:
[1] Best average on five-fold basis on April 08, 2008 according to TMH9:1992. Both sealed shoulders in good condition (three-fold basis) with D4/E1 mole damage and D5/E1 edge breaks on the left shoulder of Section 11 and D2/E4 breaks on the right.
[2] Straight edge (2,0 m) and wedge (25 mm wide); *n* = 21 on July 03, 2008; respective 80%-iles 7, 12 and 9 mm in May 1990.
[3] Including surfacing according to TMH 6:1992; weighted mean of upper 160 mm of pavement using CSIR program WinDCP 5.1; DSN_{800} all >290 blows; *n* = 6 in outer wheelpath on 05 – 08 Sept. 1989.
[4] Based solely upon rut depth

A view towards Orapa of Section 12 in April 2008 and 0,3 MESA with an 80 %-ile rut depth of 12 mm in the Orapa lane and 13 mm under the straight edge is shown in Figure 2.

Figure 2: View of Section 12 in Orapa lane after 0,3 MESA in 19 years

Although the general pavement condition of Sections 11 – 13 was still mostly very good, the right-hand (Orapa) lane of Section 12 was downgraded to 'good' because of only a fair riding quality owing to some corrugations caused by the shifting of the seal in places, and an 80%-ile outer wheelpath rut depth of 12 mm, i.e. just within the TRH 12:1997 warning range of 10 – 20 mm, although not within the 15– 25 mm of the BRD (2000). Whilst this was the most heavily loaded wheelpath, stringline and straight edge measurements in May 1990 indicated that some of this had been built in on both the slightly superelevated Sections 12 and 13. (The grader blade was also suspected to have been worn.) The 80%-ile rut depths were practically unchanged from the respective 7, 12 and 9 mm in 1990 and those of 12 mm on the neat sand Section 12 in 2008 were practically the same as the 10 mm on the adjacent ferricrete control Section 13, and both were slightly greater than the 8 mm of the non-superelevated ETB Section 11.

The average in-situ DCP-indicated strengths of all three bases in both their outer wheelpaths were all very good with the neat sand stronger than the ETB and, with a DSN_{800} of over 290 blows, all with pavements well within the sound range of over 190 for a South African Category C road in an M2 (approx. OMC) moisture environment (TRH12:1997) and the 155 for a Botswana Category II road (BRD, 2000).

Table 5 shows the individual rut depth, in-situ DCP and laboratory test results on 15 samples of the base from Section 12 after 19 years during the last full pavement evaluation in 2008. Unfortunately, the field moisture contents were lost, but the excavated base was dry, hard and blocky, DCP penetration was difficult, with refusal in many cases, with base course DNs of 0,9 – 3,5 equivalent to in-situ CBRs of 320 – 84 indicated by the Kleyn (e.g. Kleyn & Van Heerden, 1983) relationship and all at least 150 according to the Hoopstad Kalahari sand relationship of Netterberg and Elsmere (2015).

Table 5: Rut depth, DCP and BRD Central Laboratory test results on neat sand base on Section 12 in Aug. – Sept. 2008 after 19 years and 0,3 MESA in Orapa lane

SECTION CH. (m), POSITION			35 LO	35 LM	35 RO	45 [1]	65 LO	65 CL	65 RO	85 LO	85 RO	95 CL	95 RO	113 LO	113 LM	113 RM	113 RO
DEPTH		mm	25-160	25-170	25-160	25-150	25-160	25-160	25-165	25-150	25-150	25-140	25-150	25-150	25-145	24-145	25-150
		UNITS															
RUT DEPTH 1990 / 2008		mm	8 / 7	-	6 / 6	5 / 10	11 / 8	-	7 / 10	10 / 6	3 / 9	-	4 / 7	11 / 5	-	-	7/ 13
DCP	[2]																
Base DN	[3]	mm/bl.	1,2	1,4	2,3	2,7	2,6	3,5	2,8	1,8	1,6	2,0	0,9	0,9	1,1	1,9	1,2
Base CBR	[4]	%	270	240	142	115	120	84	110	190	210	170	320	320	280	180	270
Refused / stopped @		mm	174	252	800	800	800	800	800	196	325	254	151	116	209	353	800
Refused / stopped @		blows	175	275	356	406	505	310	345	145	360	125	155	125	275	220	585
PASSING	(mm)																
4,75		%	98	97	-	98	97	97	99	98	98	99	96	97	97	98	99
2,00		%	97	95	-	97	95	97	98	97	97	98	94	95	96	97	97
1,18		%	97	95	-	97	95	96	98	97	96	98	93	95	95	97	97
0,425		%	77	78	-	79	79	78	79	79	78	81	77	77	78	79	78
0,250		%	57	58	-	59	59	58	60	60	60	60	58	56	58	58	58
0,150		%	32	33	-	37	35	34	35	38	38	34	37	29	28	31	30
0,075		%	8	9	-	8	9	8	9	9	8	9	9	8	8	9	8
LL / PI	P425	%	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
LS	(P425)	%	-	-	-	-	-	-		-	-	-	-	-	-	-	-
LL / PI	(P075)	%	81 / 34	79 / 37	76 / 38	-	79 / 35	-	85 / 31	-	-	19 / 3	-	67 / 25	20 / 2	82 / 41	79 / 23
LS			20,5	19,7	18,7	-	16,7	-	21,3	-	-	1,0		13,3	0,7	19,3	18,9
MAASHO	MDD	kg/m^3	1 925	1 921	1 925	-	1 920	1 901	1 923	-	-	1 922	-	1 922	1 915	1 915	1 894
	OMC	%	8,0	8,4	5,4	-	7,7	8,3	5,3	-	-	7,9	-	8,5	5,6	5,7	6,4
CBR [5] @ %	MAASHO																
Soaked	102		130	130	32	-	54	140	120	-	-	>200	-	130	60	130	100
	100	%	73	90	20	-	50	74	64	-	-	130	-	100	50	60	56
	98	%	40	65	14	-	46	38	40	-	-	50	-	71	45	24	31
	95	%	16	38	6	-	40	13	9	-	-	10	-	44	36	5	12
	93	%	8	25	4	-	35	7	4			4		25	30	2,5	6
Soaked MC [6] @	100	%	11,0	11,6	11,5	-	9,5	11,0	11,3	-	-	11,5	-	11,3	10,8	11,1	11,3
DERIVED DATA																	
GM		-	1,18	1,18	-	1,16	1,17	1,17	1,14	1,15	1,17	1,12	1,20	1,20	1,20	1,14	1,17
Dust ratio (DR)	[7]	-	0,10	0,12	-	0,10	0,11	0,10	0,11	0,11	0,10	0,11	0,12	0,10	0,10	0,11	0,10
TMH FI075	[8]	-	272	333	-	-	315	-	279	-	-	27	-	200	16	369	184
Approx. LS(075) / mean Ø	[9]	-	9	9	8	-	7	-	9	-	-	0,4	-	6	0,3	8	8
CLASSIFICATION																	
Unified (ASTM D2487)	[10]	-	SP-SM	SP-SM	-	SP-SM	SP-SM	SP-SM	SP-SM	SP-SM	SP-SM	SP-SM	SP-SM	SP-SM	SP-SM	SP-SM	SP-SM
AASHTO M145-91	[11]	-	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)	A-3(0)	A-3(0)	A-3(0)	A-3(0)
COLTO : 1994, 1998	[12]	-	G9	G6	G10	-	G6	G9	G9	-	-	G10	-	G6	G6	(G10)	G10
Compactability	[13]	-	Fair	Fair	-	-	Fair	-	Fair	-	-	Good	-	Fair	Good	Poor	Fair
Road sand subbase	[14]	-	No	No	-	-	No	No	No	-	-	No	-	No	Yes	No	
BRD sand base	[15]		Yes?	Yes?	No	-	No?	Yes?	Yes?	-	-	No	-	Yes?	No	Yes?	Yes?

Notes:

[1] Sample position uncertain; DCP in right outer wheelpath (RO) 45 RO. [2] Up to three tries at each position. [3] For approx. thickness as sampled; surfacing "removed" when processing. [4] CBR = 410 DN $^{-1,27}$ (Kleyn and Van Heerden, 1983). [5] At 100%, $\bar{X}$ = 68,6; s = 17,5; 20% - ile = 52,9 if outliers of 20 and 130 omitted. CBRs @ OMC only for 35LO : 120 @ 102%, 80 @ 100%, 57 @ 98%, 34 @ 95%, 23 @ 93%. [6] By weighing whole specimen in mould after testing before and after soaking. All swells 0,0%. [7] DR = P075 / P425. [8] FI075 = PI(075) x P075. $\bar{X}$ = 221,7; s = 127,8; 80 % ile = 336,7. [9] See BRD (2010) Guideline 11. [10] Poorly graded sand with silt, all with uniformity coeffs ≈ 3. [11] A-3(0) = Nonplastic fine sand. [12] G10 only in TRH 4: 1996, TRH14 : 1985. [13] Modified from Mainwaring (1968) for TMH 1 (=ASTM) Cup PI = BS (1990) Cup PI minus 4), i.e. for BS FI075 Good 0-200, equiv. TMH FI075 = 0 to (200 minus 4P075), e.g. 0 - 180 for P075 = 5 %. [14] Serowe-Orapa sand subbase spec: P075 ≤ 20%; CBR ≥ 35 @ 95%; P075 = 5 - 20; FI075 = 30 - 200. [15] RD (2010) Guideline 11 sand base spec : LS075 / Ø mean = > 5 – <10; soaked CBR @ 10-0% BSVH MDD ≥60; $Al_2O_3 + Fe_2O_3 > 8$

The only long-term field moisture contents available are from two cross-sections taken on Section 12 on Sept. 01, 1995: these varied only from 2,6 to 3,5% in the carriageway (n = 8 triplicates), 2,8 to 4,1% in the shoulders (n = 4), with 2,6 and 3,4% (n = 2) in the Orapa outer wheelpath. Comparison with the OMCs in Table 5 indicates this section to have been operating at about 0,5 OMC, during the winter, at least.

At all six sites where full penetration was achieved, the DSN_{800} was in excess of 290, indicating a residual structural capacity in excess of 12 MISA (Kleyn & Van Heerden, 1983) uncorrected for the existing rut depth, and at least 4,2 MISA when corrected. The rut depths at the six DCP and sample sites in the critical right-hand outer wheelpath of 6 - 13 mm averaged 9,2 mm, with only one (13 mm at CH. 113 R0) over 10 mm. The three laboratory CBRs at 100% of 20 (rut depth 6 mm), 56 (13 mm) and 64 (10 mm) averaged 47.

The AASHTO of A-3(0) and Unified of SP-SM classifications of all 15 samples were all the same, but the COLTO: 1998 ranged between G6 (the best) and G10 (the worst) – the poorer because of the poor CBRs at 93%. The CBR-density relationships showed that some samples that classified only as G9 or G10 were extremely density-sensitive. Although it is probably wise to avoid such materials, as at 2008 none of them had failed. However, the necessity of avoiding disturbance and maintaining confinement of such material is critical. On this basis, the best materials would be 35LM, 65LO, 113LO and 113LM, with CBRs of 50-90 at 100% and 25 – 35 at 95, all classifying as G6.

A summary of the laboratory test results on the lower layers is shown in Table 6.

Table 6: Summary of BRD Central Laboratory test results on lower layers [1] on Section 12 after 19 years

LAYER		SUBBASE	SELECTED SUBGRADE	ROADBED
POSITION	CH.(m)	35LO - 113RO	35LO - 113RO	65CL
DEPTH	mm	150 / 160 –240 / 270	240 / 270 -390 / 400	480 - 730
DESCRIPTION	UNITS	Red sand	Sand + calcrete + silcrete	Orange sand
PASSING (mm)	%			
4,75	%	95 - 96	75 - 97	100
2,00	%	93 - 94	71 - 90	99
0,425	%	68 - 72	53 - 75	73
0,075	%	11 - 12	8 - 10	8
PI (P425)	%	NP ; 9	NP ; 2	NP
PI (P075)	%	12 - 20 ; 39	30 - 44	30
CBR @ % MAASHO				
Soaked 100	%	60 - 92	20 - 72	48
98	%	40 - 55	19 - 46	35
95	%	20 - 29	14 - 25	20
93	%	12 -23	2 - 17	15
Swell @ 100	%	0,01 – 0,02	0,01	0,00
GM	-	1,21 – 1,28	1,20 – 1,67	1,20
TMH FI075 [2]	-	132 - 288; 429	270 - 440	240
AASHTO Class.	-	A-2-4(0)	A-3 (0) - A-2-4(0)	A-3(0)
COLTO Class.	-	G6 - (G7); G8	G7 - G9; (G10)	G7

Notes:

[1] Subbase & subgrade n = 5 CBRs & indicators (3 on P075); roadbed n =1. Results on one subbase sample (ferricrete: GM 2,33; NP, A-1a(0), G6 omitted)

[2] FI075 = PI on P075 x P075 (TMH 1 methods)

The results of laboratory tests on three further samples of base course taken in late July 2013 from the left shoulder at CH. 56, 80 and 105 m are shown in Table 7. Although the usual indicator results and the classification of this combined sample taken in an almost untrafficked area agreed well with those in Table 5, the soil constants on the P075 and the

FI (075) were lower than most of them, and the MAASHO CBR higher than most, and the MDD lower than all.

The mean of two DCP tests in the outer wheelpath of the Orapa lane at Ch. 40 and 83 in July 2013 yielded a DN of 2,8 mm (Kleyn CBR of 110) and a DSN_{800} of 148, indicating a residual capacity of 1,2 MISA and at least 0,3 MISA corrected to a terminal rut depth of 20 mm.

The very dense, reddish-orange sand base was dry and the dense, dusky red sand subbase moist. The base came out in hard, blocky pieces 50 100 mm in size and disintegrated (but did not disperse) readily in water, showing that they were not cemented, (and non-dispersive) and that the high in-situ strength was therefore due to suction-induced apparent cohesion due to the low moisture contents and the small clay and free iron oxide/hydroxide content. (From Netterberg & Haupt (2003) this means that pavements with such bases will probably exhibit marked diurnal and seasonal changes in pavement response.)

Similar tests carried out in the laboratory using up to 7 days of soaking on small (20 - 25 mm) specimens from Sections 11 and 12, confirmed these findings and showed that the addition of only 1,5% of not very well-mixed bitumen greatly increased their water-resistance. After 24 hours the emulsion-treated red sand specimens from Section 11 had been softened, but had not disintegrated even after one week of soaking.

Table 7: Summary of further laboratory test results on Section 12 neat sand base course [1]

PROPERTY	RESULT
PERCENT PASSING (mm)	
4,75	98 - 99
2,00	96 - 98
1,180	96 - 98
0,425	79 - 83
0,250	65 - 70
0,150	38 - 46
0,075	6 - 9
0,002	3
MAASHO MDD / OMC	1 864 kg / m^3 / 7,4 %
CBR @ 100; 98; 95; 93 % MAASHO	96; 58; 29; 21 (soaked) 90; 71; 49; 35 (OMC)
LL / PI / LS (P425)	NP / 1 / 0
LL / PI / LS (P075)	25-27 / 6-9 / 2,5-5,5
Sand equivalent	21 - 24
GM	1,13 -1,15
TMH FI075	48 - 64
AASHTO M-145 Class.	A-3(0)
Unified Class.(ASTM D 2487)	SP - SM
COLTO:1994, 1998 Class.	G7
BRD (2010) sand base	No (LS (075) / mean *Φ* too low)

Note: [1] Three samples combined into one for CBR. Laboratory testing by Geostrada, Pretoria

Unfortunately, no further pavement evaluation or even complete visual inspection on foot was carried out subsequent to 2008. However, Google Earth road survey photos taken after 23 years in May 2012 after about 0,36 MESA showed all three sections to be in good condition with no new patching and the 2008 section paint markings on the seal to be still visible. During the 2013 sampling (after 25 years and about 0,40 MESA) Section 12 was still in a good condition, and subsequent twice-yearly drive-over inspections by one of us (KJRM) indicated these three sections still to be in good condition up to at least 2018.

The whole experiment was overlaid with 30 mm of asphalt in 2020, unfortunately without prior inspection.

9. MAINTENANCE

The only maintenance applied to the sections over the first 20 years was a fog spray due to initial ravelling, two reseals, patching of edge breaks due to shoulder erosion, and early flattening of the unclad Kalahari sand side slopes from 1 : 4 to 1 : 6 or flatter. The 2012 Google Earth road survey showed that no reseal or further patching had been carried out up to then.

10. DERIVED SPECIFICATIONS

On the basis of monitoring both during and for 25 years after construction involving visual condition, rut depth and DCP surveys, the total capacity of the ETB, neat sand and ferricrete sections are conservatively estimated at about 0,8, 0,5 and 1,0 MESA respectively to an 80%-ile terminal rut depth limit of 20 mm for a South African (COLTO, 1996, 1997) Category C road, and to a 90%-ile limit of 25 mm (BRD, 2000), a respective 1,0, 0,8 and 1,5 MESA for a Botswana Category II road. A mean 20 mm limit as for a South African Category D road indicates a capacity of about 0,6 MESA for the neat sand section and a mean 30 mm limit for low volume roads in general. Otto *et al* (2019) would indicate an even greater capacity unless limited by other modes of distress.

10.1 Pavement Required

The following specifications for a Botswana BRD (2000) Category II or a South African TRH4:1996 Category C road have been 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, i.e:

Roadbed: "Red" Kalahari sand, precollapsed to 90% down to 600 mm by impact or other rolling if potentially collapsing.

Fill: "Red" Kalahari sand, minimum 95% CBR of 25 compacted to 95% if A-2-4(0) and 100% if A-3(0).

Subgrade: "Red" Kalahari sand or mixture similar to that found (Table 6), min. 100 mm, preferably 125 mm in thickness; min. GM 1,20, TMH FI075 10 - 400; min. 93% CBR 15 as for COLTO: 1998 G7 (upper) and 10 as for G8 (lower), compacted to 95% if A-2-4(0) and 100% if A-3(0). (Mean of 93 - 95% achieved where 95% specified.)

Subbase: **"**Red" Kalahari sand as found (Table 6), min. 100 mm, preferably 125 mm in thickness: min. GM 1,20 TMH FI075 10 - 400; min 95% CBR 20, preferably 25 as for COLTO G6, compacted to 98% if A-2-4(0) and 100% if A-3(0). (Mean of 99,1% achieved on Sections 2 -12 where 95% specified.) For a 0,2 MESA Category D road a minimum GM of 0,70 with a CBR of 25 should be adequate, as found by Maree and Visser (1994) for Kalahari sand subbase in the western Free State.

Base course: "Red" sand 150 mm in thickness complying with the base specification in Section 10.2 to follow compacted to refusal or 100%.

Shoulders: As per base course compacted to 100% and sealed with at least a fogged single seal

Surfacing: Prime at about 0,8 l/m, followed by either a 19 + 9 mm or crusher dust + 13 mm double seal, or a Cape seal (not fully evaluated). Allowance must be made for embedment. If the chippings are calcrete or silcrete they must be precoated and/or allowance made for absorption.

For a South African Category D road it is suggested that deep precollapsing of the roadbed be omitted and that the pavement designs for dry regions in TRH4:1998 be used except that the Kalahari sand subbase and base be as specified above.

10.2 Untreated Kalahari Sand Base

The following is recommended as a specification for a Kalahari sand base course material for sealed low volume roads with sealed shoulders in a similar environment designed to carry up to about 0,5 MESA over 20 years for a South African Category C, 0,6 MESA for a Category D and 0,8 MESA for a Botswana Category II road. As it has only been derived from one type of Kalahari sand from one borrow pit it should not be regarded as a generic specification for all sands, or even all Kalahari sands. As no failures took place, the specification simply attempts to circumscribe what are apparently the most important properties of the sand actually used and is not intended to exclude other proven sands.

Apparently essential:

- Colour: reddish brown, orange or red (**not** white or grey)
- AASHTO classification; A-3(0) or, probably, A-2-4(0)
- Unified classification : SP-SM
- P4,75 mm : 95 - 100
- P2,00 mm : 95 - 100
- P425 µm : 75 - 85
- P075 µm : 5 -10, possibly up to 15%
- GM : 1,10 - 1,20, possibly down to 1,00
- TMH 1 PI on P425 fraction : NP, possibly SP
- TMH 1 PI on P075 fraction : 2 - 40
- TMH 1 FI075 : 10 - 340. (When PI075 = NP or 0, then IF075 = P075.)
- Min. soaked 2,54 mm MAASHO CBR: 55
- Min. CBD-extractable Fe : 0,3% or, less reliably, minimum Fe_2O_3 content by XRF analysis : 1,5% Fe_20_3

Probably desirable:

- COLTO classification: G6, possibly G7
- Min. unsoaked 2,54 mm MAASHO CBR at OMC: 60
- Max. MAASHO CBR swell : 0,1%
- Sand equivalent : 20 - 30
- Dust ratio : 0,10 - 0,12
- Particle angularity : Min. uncompacted voids (ASTM C 1252) on whole grading : 45%

The purpose of specifying colour is to ensure that there is some suitable free iron oxide/hydroxide mineral(s) present and to act as a proxy for chemical analysis, which is difficult to get done by the more desirable CBD method (Soil Analysis Committee, 1990), and which cannot be done on site. (An adequate semiquantitative test for free iron could be developed and portable XRF analysers for total iron are now available.) The generally better CBRs and much better unsoaked CBRs of the red sand than the otherwise similar grey sand indicate even the small free iron oxide/hydroxide content found to be beneficial.

As, except for the $Al_2O_3 + Fe_2O_3$ contents and the LS / Φ ratio, most of the samples would probably satisfy the BRD (2010) Guideline sand base and subbase specification, a modified version of this specification also appears appropriate.

This specification is comparable with that derived by Netterberg and Elsmere (2013) for the neat Kalahari base section in the Hoopstad LTPP experiment, although the allowable P075 is lower and the PI on the P075 and the TMH FI075 are higher. These differences are within the expected reproducibility of the test methods used.

Whilst the Texas triaxial test is used there for base materials, on an equivalent CBR and plasticity basis this specification may qualify as sand base course for up to 0,1 MESA in Zimbabwe (Mitchell et al., 1976; Mitchell, 1982), but Kalahari sands are too fine to qualify there even as subbase.

Coarser, granitic sand bases used in Zimbabwe were highly susceptible to rapid failure due to perched water tables and a suspected loss of density due to vibration. As a Kalahari sand base might be even more so, G8 and worse sands have been excluded from the specification.

The most essential requirements would appear to be to have at least about 5% P075 with just enough plasticity to develop sufficient cohesion for easy compaction, lateral confinement, stability during construction and an adequate CBR, both soaked and at OMC, as well as a sufficiently stiff compaction platform. The necessity for a CBR requirement at OMC as well as after soaking is uncertain, but it should ensure that the sand is capable of developing sufficient apparent cohesion for shear strength and lateral confinement when operating under the usual field water contents of OMC or less. A minimum CBR additional requirement at about half OMC of 80 could also possibly be added. Vane shear strength or Clegg CBR tests in CBR moulds and/or in-situ are convenient supplements to the CBR (Netterberg, This Conf.).

A sand equivalent might be a good substitute for a PI on the P075 and the TMH IF075. It is also a convenient test for a field laboratory and quicker and cheaper than a PI on the P075.

<u>Construction:</u>

- Compaction:
  - Roadbed to at least 95% to a depth of 600 mm, by impact, vibrating and / or heavy pneumatic roller if potentially collapsing.
  - Shoulders, subbase, selected subgrade and fill of similar sand to 100%.
  - Base to refusal or 100% (do not allow to dry or over-use vibrator).
- Trafficability of base and subbase: Satisfactory provided not allowed to dry out and powder, or after heavy rain, and dump trucks not permitted to turn on it.
- Resistance to softening and erosion by rainfall: Poor.
- Unclad Kalahari sand side slopes: 1 : 6 or flatter (wild grass should follow).
- Drainage: Good
  - Permanent or seasonal perched water table (e.g. due to rock bars): at least 1,0 m below top of roadbed.
  - Side drains: if provided, at least 5 m from edge of seal and inverts at least 0,5 m below finished road at centreline (usually unnecessary on Kalahari sand).

- Drying back of base to about 0,5 OMC: Recommended (as is usual for untreated base).
- Protection from cattle and large wild animals: Required.
- Prime: Required (also for protection from rain) – MC-30 at about 0,8 l/m^2.
- Seal: At least a double seal on the carriageways and a single seal with precoated chips or fog on the shoulders to ensure confinement of the base and to prevent ingress of water.

Seal maintenance: Critical.

Alignment: Relatively flat, with no significant gradients, curves, superelevations, stopping or turning areas without consideration of a stronger seal and/or emulsion treatment or armouring of the upper base in such areas.

Further details of and precautions on the use of Kalahari sands are available (Mgangira, 2007; BRD, 2010; Paige-Green et al., 2011; Infra Africa et al., 2014).

11. CONCLUSIONS

Although requiring greater care during construction and finishing, a selected, red, nonplastic Kalahari sand base coarse with a minimum soaked MAASHO CBR of about 55 compacted to 100% MAASHO under a double seal and with sealed shoulders provided good service for at least 20 years and 0,3 MESA and, on the basis of visual assessment, rut depth and DCP testing, appeared good for about 0,5 MESA for a South African Category C, 0,6 for a Category D and 0,8 MESA for a Botswana Category II road over 20-30 years. Such an economical base material has tremendous potential for the provision of low-cost, low-volume, all-weather, sealed roads in the huge area of southern Africa covered by Kalahari sands where gravels and rock are scarce.

Whilst such a base would not be permitted for any class of pavement or category of road according to the South African TRH 4:1996 or Botswana BRD (1982) catalogue design method, the use of proven innovative designs is not prohibited and indeed are invited for possible inclusion in a future edition.

12. ACKNOWLEDGEMENTS

Full acknowledgements are provided in Netterberg *et al* (This Conf.) This paper is based upon reports by the first author to the BRD and is published with the permission of the Director. However, the opinions expressed are those of the authors and not necessarily any of the above.

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