GYPSUM IN SALINE AND NON-SALINE ROAD BASES: EFFECTS AND LIMITS DERIVED FR0M LONG-TERM ROAD EXPERIMENTS IN NAMIBIA

F NETTERBERG

Pavement Materials & Geotechnical Specialist; 79 Charles Jackson Street
Weavind Park, Pretoria 0184, South Africa; Tel: 012 846 7051
Email: frank.netterberg@gmail.com

ABSTRACT

In parts of Namibia, Botswana and South Africa the only economically available road construction materials often contain excessive amounts of highly soluble salts such as NaCl (common table salt) and/or gypsum ($CaSO_4 \cdot 2H_2O$) and fresh water for compaction is scarce. The Lüderitz and Haalenberg full-scale, long-term road experiments were therefore constructed in 1976 in the Namib Desert in Namibia in order to find ways of successfully using highly saline and gypseous materials as road pavement base course and of using seawater for the compaction of all layers. In this paper only those aspects concerning gypsum are presented. The experiments included a total of eight sections of G3 quality crushed stone bases with 2 – 20% added gypsum and two of G4 calcrete base with 5% (in comparison with the then permitted limit of 3,5%), in addition to their natural gypsum contents of 0,2 and 0,3% respectively, all under a 19 mm Cape seal surfacing. These experiments were monitored both during and soon after construction as well as for any long-term effects over a period of 36 years from 1976 until 2012. During this period the experiment only received two rejuvenation sprays and a minor amount of slurrying, edge patching, crack sealing and shoulder regravelling. For a 30-year design life and a capacity of at least 1,0M E80 under a 19 mm Cape seal, gypsum contents of up to 10% can be permitted in a G3 and up to at least 5% in a calcrete G4 base in this arid environment and probably in most of the southern African arid and semiarid zone.

1. INTRODUCTION

In many parts of Namibia the local road construction materials contain excessive amounts of soluble salts such as halite (NaCl) and/or gypsum ($CaSO_4 \cdot 2H_2O$) and fresh water for compaction is scarce. Although it was known that quite small amounts of more than about 0,2% of highly soluble salts could cause the surface disintegration of primed base courses and blister bituminous surfacings (Weinert & Clauss ,1967; Netterberg, 1970; Netterberg et al., 1974), the necessity of controlling the only slightly soluble gypsum was uncertain. In Namibia gypcretes or gypseous soils occur mostly within about 50 km of the coast (e.g. McG. Miller, 2008). In South Africa most of the gypsum fields occur in the Northern and Southwestern Cape, including one along the west coast (Oosterhuis, 1998).

The Lüderitz and Haalenberg full-scale, long-term road experiments were therefore constructed in 1976 on Trunk Road 4/2 between Aus and Lüderitz in order to find ways of successfully using highly saline and gypseous materials as road pavement base course and of using seawater for the compaction of all layers.

As the solubility of gypsum in pure water is at a maximum at 30ºC and only about 0,2% and is little affected by temperature in comparison with the 36% of NaCl (e.g. Perry & Green, 1984; Lide, 1992), it is relatively immobile and was therefore initially of little concern in materials not treated with cement or lime (Netterberg et al 1974, Netterberg and Maton 1975). Moreover, it was known that bases containing over 30% of fine (30 – 60% passing 75 µm) gypsum had been used in bases in an area of the Sahara receiving an annual rainfall of 50 – 150 mm (Baudet et al., 1959). However, together with halite it had been found in some of the blisters on the Walvis Bay airport (Netterberg, 1970); it was known to reversibly dehydrate and rehydrate (e.g. Klein & Hurlbut, 1999) – with accompanying molar volume decreases of up to 39% and increases of up to 63% – (Zanbak & Arthur, 1986) at temperatures encountered in pavement bases; and its transition temperatures were known to be decreased and its solubility increased by an increasing concentration of NaCl (e.g. Blount & Dickson, 1973), e.g. to about 0,5% in 3% NaCl (approximately that of seawater) and up to a maximum of about 1,0% at about 12% NaCl. In short, gypsum is reversibly unstable above 46ºC (Kuntze, 2009). Sections including both gypsum and NaCl or seawater were therefore included in the experiments.

At the time of construction gypsum somewhat arbitrarily was limited to a maximum of 1,0% calculated as sulfate (SO_4^{2-}) (i.e. 1,8% $CaSO_4 \cdot 2H_2O$) derived from concrete practice. However, as controlled experiments with a naturally gypseous G3 base continuing 0,5 – 1,9% sulfate (0,9 – 3,4% assumed gypsum) on the Trekkoppie – Swakopmund Road constructed in 1966 with 13% sulfate in the subbase and shoulders were only exhibiting shoulder looseness and edge fretting thought to be caused by halite rather than gypsum, the limit was raised to 2,0% sulfate (3,6% assumed gypsum).

The experiments at Lüderitz inside the coastal Namib Desert mist belt consist of 14 sections each 60 m in length of nominal COLTO (1998) G3-quality granite crushed rock base course containing up to 2% added salt (NaCl) and 20% gypsum as well as sections compacted with seawater up to various levels in the pavement.

The experiments at Haalenberg in the inland Namib Desert outside the main mist belt consist of 14 sections each also 60 m in length of similar G3 granite base course and containing similar amounts of added salt and gypsum, as well as seven sections of natural gravel calcrete base course of nominal G4 quality with up to 2% added salt and 5% gypsum.

These experiments were monitored both for their short-term effects during and soon after construction as well as their long-term effects over a period of 36 years from 1976 until 2012. It is the purpose of this paper only to report on the sections containing gypsum and to derive permissible levels of gypsum in both G3 crushed stone and G4 calcrete gravel base. As such it does not include a general review on gypsum in roads and only minimal literature on the use of gypsum in roads is considered.

2. CLIMATE AND WEATHER

2.1 Climate

Both the climate and weather – particularly during construction – are important risk factors for salt damage – the hotter, drier and windier the greater the risk.

The climate at Lüderitz is cold, dry desert with frequent fog with a Köppen classification of BWk'n similar to that of most of the west coast of southern Africa. That at Haalenberg is hot, dry desert without frequent fog (BWh) (Schulze, 1947) similar to that of most of the inland desert. The fog occurs mostly at night, usually clears during the morning, and was never seen by the author at Haalenberg.

Both Weinert's (1980) N-value of over 50 and Thornthwaite's Moisture Index of less than minus 50 (Emery, 1992) indicate an (extremely) dry climate for pavement design (COLTO, 1996) at both sites and a very high risk of salt damage (Obika, 2001). With a gross annual Class A pan evaporation of about 3 000 mm (Dept Water Affairs, 1978, unpub. map) the potential evaporation − and therefore also for salt concentration − is about 100 times the rainfall.

Further details of the climate are shown in Table 1. Although the rainfall at both sites is almost negligible and only differs by 20 mm, the most significant differences between the two sites are the far fewer days at Haalenberg with fog, and the many days with a relative humidity of less than 10% and with maximum shade air temperatures exceeding 30ºC. The climate at the Lüderitz experiment is similar to that at Diaz point and that at Haalenberg to Gobabeb (Lancaster et al., 1984, not shown).

The findings of these experiments should therefore be applicable to all of the southern African arid zone and, in the absence of seepage, at least conservative elsewhere.

Table 1: Climatic data

Item [1]	**Units**	**Lüderitz Diaz Point**	**Lüderitz Expt**	**Kolmanskop**	**Haalenberg Expt**
Road log [2]	km	(131)	122	113	80
Station No. [3]	-	413/158 X	-	413/403	-
Lat. S / Long. E	Degrees	2638/1506	2639,5/1510,2	2643/1514	2637,1/1529,4
Altitude	m	16	19	124	505
Rainfall, annual		1951-1984	-	15 years	-
Mean	mm	20	(20)	33 [6]	(40)
Max.	mm	60	(60)	-	-
Min.	mm	1	(1)	-	-
>0,1 mm	Days	6	(7)	7 [6]	(7)
Fog, mean / year	Days	117	(100)	(80)	(50 ?)
Relative humidity, mean					
08h00 (mean monthly)	%	86	(80)	(80)	(80)
14h00 (mean monthly)	%	74	(55)	(50)	(35)
20h00 (mean monthly)	%	86	-	-	-
> 90 %	Days	(300)	(200)	-	(50)
< 10 %	Days	(0)	(0)	-	(50)
Temperature, annual daily					
Mean	º C	15,7	(16)	(16)	(17)
Max.	º C	19,3	(19)	(21)	(23)
Min.	º C	12,1	(12)	(9)	(8)
> 30ºC	Days	1,2	(2)	-	(100)
> 35ºC	Days	0,0	(0)	-	(30)
< 10ºC	Days	0,0	(0)	-	(0)
Reference		[4]	[5]	[5]	[5]

Notes:
[1] Bracketed figures are estimates from maps or interpolated
[2] Approximate; Diaz point is approx. 9 km west of Lüderitz Expt and 40 km west of Haalenberg Expt
[3] Weather Bureau / Meteorological Services Reference Number
[4] Weather Bureau (1986)
[5] Estimates, partly from maps in Mendelsohn et al (2009)
[6] Weather Bureau (1963)

2.2 Weather

No measurable rain was recorded at either site during construction of the base and surfacing (March – June 1976) although a total of 10 mm was recorded at Lüderitz during January to June 1976. Shade air temperatures at the Lüderitz site varied between 14 and 34ºC and relative humidities (RH) between 18 and 100%. Haalenberg was hotter (16 – 40ºC) and drier (RH 16 – 50%) and a moderate wind from the southwest was experienced on most days.

The mean annual rainfall recorded at Lüderitz during the period 1976 - 2010 was 13 mm, with a minimum of 0,0 and maximum (in 1976) of 42 mm (Meteorological Services, Windhoek 2012, Pers. Comm). No information was obtainable for Haalenberg, but it is assumed to have had about 30 – 40 mm).

3. TRAFFIC

The traffic carried by this road is very light and after opening amounted to only 55 vehicles per day (vpd) with about 15% heavies. After the 20-year design life and 30-year analysis period the road had only carried about 0,2 and 0,8 ME80/lane respectively (Table 2).

However, this is favourable with respect to the experimental design as salt damage is invariably the worst on pavements carrying the least traffic.

Table 2: Traffic history [1]

Year	AADT vpd	Heavies %	E 80 / Heavy [2] E80	E80 / lane [3]	
				Annual E80	Cumulative E80
1976	55	15,0	3,5	5 289	10 319
1986	89	15,0	3,5	8 571	80 146
1996	160	12,5	4,0	14 600	217 493
2006	236	24,3	4,5	46 811	516 154
2011	220	24,1	4,5	43 526	745 283

Notes:
[1] Compiled by VKE (Namibia) from Namibia Roads Authority (NRA) data supplied
[2] Assumed from various weighbridge data (none on this road)
[3] Assumed 50% split

4. TERMINOLOGY AND TEST METHODS

The terminology and corresponding test methods used in this paper is as follows, although it was not in use at the time of construction in 1976:

Materials: National Institute for Transport and Road Research (NITRR): TRH14:1985.

Routine test methods: NITRR TMH1:1986.

Special test methods: NITRR TMH6:1984.

Structural pavement design: Committee of Land Transport Officials (COLTO):1996.

Standard specifications including the G classification system: COLTO: 1998.

Routine test methods used during construction: South African Department of Transport (1970) for grading and soil constants (wet AI(a) preparation), soaked 2,54 mm CBR, etc.

Highly soluble salt content: What became TMH1:1986 Method A21T for saturated paste electrical conductivity (EC).

Acid-soluble sulphate here reported as gypsum ($CaSO_4 \cdot 2H_2O$) on the whole grading: what became TMH1:1986 Method A22T.

Visual Assessment: Committee of State Road Authorities (CSRA): TMH9:1992.

Qualitative tests for chloride with silver nitrate, sulphate with barium chloride and carbonate with hydrochloric acid: CSIR CA21; gypsum: Method 22(a) with acetone: Richards (1954), and powder X-ray diffraction (XRD).

5. PAVEMENT AND MATERIALS

The pavement and materials design was as follows:

Surfacing: SC2 (19 mm, split-application, new-type Cape seal with two layers of slurry containing 12 % net bitumen − NITRR 1971); 6,8 – 6,9 m wide with 2,0% crossfalls.

Primer: MC-30 at nominal 0,70 l/m^2 ; 7,40 – 7,60 m wide.

Base (7,40 m wide):

- Lüderitz: 150 mm **granite** (with some dolerite) “**crusher-run**” of AASHTO M-145 A-1-a(0) and nominal modern **G3** quality compacted to ≥ 98% MAASHO.
- Haalenberg: 125 mm nominal G3 as for Lüderitz from same source and traditional **natural gravel calcrete** base of AASHTO M-145 A-1-b(0) and nominal modern **G4** quality, compacted to ≥ 98% MAASHO.
- Natural gypsum content of G3 0,1-0,5%, calcrete 0,3%.

Soil binder for G3 base: + 4% ex BP km 110,0 (75% passing 4,75 mm, grading modulus (GM) 1,29, nonplastic (NP), EC 0,03 S/m) + 4% ex BP 101,0 (97% passing 4,75 mm, GM 1,06, plasticity index (PI) 8, EC 0,47 S/m); gypsum contents unknown.

Shoulders (unsealed, 2,5 m wide): Lüderitz 150 mm, Haalenberg 125 mm : calcrete natural gravel of traditional subbase and nominal modern G5 quality, 80% ex BP km 89,8R plus 20% ex BP km 96,0, compacted to ≥ 95% MAASHO. All were A-1-b (0) or A-2-4 (0) materials, with GM 1,8 – 2,1, PI 4–9; EC 0,1 – 0,3 S/m, and 0,2 – 0,5% gypsum.

Subbase: 100 mm, mostly A-1-b (0) and G5 to nominal G4 quality **calcrete** natural gravel mostly ex BP km 89,8R, compacted to ≥ 95% MAASHO; GM 1,8 - 2,2, PI NP-5; natural EC: 0,1 - 0,2 S/m and 0,3 – 0,5% gypsum.

Selected subgrade: 250 mm (100 mm upper and 150 mm lower) G5 and A-1-b (0) calcrete natural gravel ex BP km 89,8 R compacted to≥ 93% MAASHO; GM 1,8 – 2,4, PI 1 – 6, EC 0,1 – 0,2 S/m and about 0,2% gypsum.

Fill: (Lüderitz) approximately 1 m (0,2 – 2,2 m) of rock and G5 granitic gravel (latter compacted to ≥ 90% MAASHO); EC 0,2 - 0,3 S/m; Haalenberg 0,0 – 0,3 m G5 calcrete gravel compacted to ≥ 90% MAASHO; EC 0,1 – 0,3 S/m; GM about 2,0 and PI SP – 8.

Water: Fresh ex Koichab Pan (EC 70 mS/m; TDS @ 180ºC 410 mg/l; pH 8,2); seawater (Lüderitz only) ex Lüderitz harbour (EC 5,3 – 5,5 S/m; TDS 3,4 – 3,5%; pH 7,8 – 7,9).

NOTES:
1. The 'G' classifications used above are those of the Namibian Department of Transport (NDOT) (1995) and Roads Authority (NRA), and COLTO (1996, 1998) although they were not in use at the time (1976) this road was constructed. The traditional Cape and Namibian "crusher-run" bases with or without soil binder and the calcrete bases were inferior to a NDOT and COLTO G3 and G4 respectively mostly only in their gradings. The COLTO G5 is equivalent to the Namibian NDOT (1995) subbase specification.

6. SECTION LAYOUT, ALIGNMENT AND DRAINAGE

6.1 Layout

The layout of the two experiments and a summary of the properties of the base courses being considered here are shown in Table 3.

The Lüderitz Experiment consists of experimental sections of G3 bases each 60 m in length comprising sections with and without added soil binder, 2, 10 and 20% added gypsum ($CaSO_4{\bullet}2H_2O$), one of which (Section 10) had 5% gypsum added, and was also compacted with seawater. A similar length of G3 base with 8% binder compacted with fresh water as used over the rest of the road served as a control section at each end (Sections 1 and 14).

The Haalenberg Experiment is largely similar to that at Lüderitz except that seawater was not used and that both G3 crushed stone and G4 calcrete were evaluated as base course. A section of G3 base with binder also served as a control section at each end (Sections 1 and 21) and in the middle (Section 13).

The left (i.e. Lüderitz-bound) lane was primed and surfaced as soon as practicable after completion of the bases and the right lane primed and surfaced as soon as practicable after a deliberate delay of about two weeks. This actually doubled the number of sections.

In addition, a large number of small-scale priming experiments were also carried out in the right lane in order to evaluate different types of primer (NITRR 1970), i.e. MC-30, MC-70, a RTL 3/12P tar and an invert diesel-fluxed emulsion (NITRR 1986b), their application rates, the delay between priming and surfacing, the effect of not prewetting, and the use of an emulsion tack coat instead of a primer.

6.2 Alignment and Drainage

The total height of the finished road level on the centreline of the Lüderitz experiment above the natural ground level is generally about 2 m, but varies between about 0,7 and 1,5 m over Sections 6 – 9 to 2 – 3 m over Sections 10 and 11 and has an average fall of 1,1% towards Lüderitz. With the possible exception of Section 9 (G3 + 20% gypsum) the base course therefore stands above any possible influence of water standing next to the road (salt water was seen on the left-hand side during the April 2012 inspection).

The Haalenberg experiment is on a low fill resulting in the finished road level on the centreline being 0,6 – 1,0 m above the natural ground level and having at an average fall of 2,8% towards Lüderitz. Although the base course is thus within the influence of the roadbed, at these grades water would not have been able to stand next to the road and none was ever observed.

7. EFFECT OF ADDED GYPSUM

The added salt was a coarse dairy salt containing 99% NaCl and with about 97% passing 2,00 mm and 35% passing 0,425 mm.

The gypsum was a “wet”, neutralized, industrial by-product phosphogypsum powder containing about 93% gypsum, 2% of $CaCO_3$, 3% insolubles, 0,7% P_2O_5, and less than 0,2% readily water-soluble matter, with 100% passing 0,250 mm and 50% 0,053 mm. It was preferred to natural gypsum because the latter was less pure and contained clay.

This gypsum was nonplastic with a linear shrinkage (LS) of 0,0%, but a plastic limit (PL) of 50. However, it did raise the liquid limit (LL) of a nonplastic GI with a LL of 20 by 20% of the amount of gypsum added and, at an addition of 20%, the LS from 0,0 to 0,3%. These effects were probably due to the 16% loss of mass on drying due to the conversion of some or all of the gypsum to bassanite ($CaS0_4$•½H_20), i.e. plaster of Paris, and/or cementation of the soil fines when dried at 105 – 110ºC in the standard wet soil preparation method, and do not indicate a deleterious reduction in material properties.

The 21% **bound** water in gypsum is not available for compaction, but will increase the results of water content determinations by 16% of the gypsum content when dried at 105ºC and 21% when nuclear methods are used, and thus increase the LL and PL and decrease the dry density.

Limited testing on site on the granite G3 only indicated that the addition of gypsum significantly raised the apparent LL by more than the possible 16% due to water loss alone, reduced the PI, LS, MAASHO optimum water content (OWC) maximum dry density (MDD) and with 10 or 20% gypsum the CBR at all levels of compaction, except with 10% where the 98% CBR was unaffected, but had no effect on the swell. These effects were probably also due to the added fineness of the grading but suggested that 10% gypsum might be a suitable limit above which the CBR might be significantly affected. However, in practice much of the natural gypsum present in a material is likely to be coarser.

Whist limited work by the author yielded somewhat erratic results, ASTM Test Method D4318 for LL, PL and PI warns that both the type and amount of soluble salts affect the LL and PL as well as the water contents, and that the degree to which the salts are diluted or concentrated in these tests and the water used must also be considered.

Test method ASTM D2216 for water (moisture) content also contains a warning that the mass after drying includes the mass of previously soluble salts and that it may be desirable to dry soils containing gypsum at 60ºC (BS1377:1990 advises no more than 80ºC) or in a desiccator at room temperature as gypsum slowly dehydrates at the standard drying temperature of 110ºC and at a very low humidity. Test method ASTM D471 for the **free** water in gypsum requires drying at 45ºC for 2h. Only the usual method of drying at 105 – 110ºC was used for this project and no corrections according to the gypsum or highly soluble salt contents were applied.

Table 3: Layout and mean as-built base test results

Experiment Name / Date completed [1] / Base Thickness	Section No.	Construction Stake Value [2] km	Type and % added soil binders [4] [5]	Additive Type [6]	Additive Net m/m + %	EC [7] S/m	Gypsum [8] %	GM [9]	PI [9] %	CBR at 98 % MAASHO [10] %	MAASHO MDD [10] kg/m³	MAASHO OMC [10] %	Compaction [11] MAASHO [12] %	Compaction [11] In-situ water content %	Remarks
	1	123,440 - 123,500	Grt G3 + 8%	-	0	0,13	0,1	2,48	2	230	2 370	5,7	100,0	3,2	East G3 Control
Lüderitz	7	123,800 - 123,860	Grt G3	Gypsum	2	0,13	3,0	2,42	5	160	2 311	4,5	101,2	3,3	
03 June 1976	8	123,860 - 123,920	Grt G3	Gypsum	10	0,09	18 ?	2,43	1	200	2 298	5,9	99,0	5,0	
	9	123,920 - 123,980	Grt G3	Gypsum	20	0,08	16	2,45	2	140*	2 280*	6,8*	99,8	4,0	20 % Gypsum
150 mm	10	123,980 - 124,040	Grt G3 + 5%	Gypsum	5	0,43	4,4	2,42	4	200	2 247	5,4	100,6	3,7	**Seawater base & shoulders only**
	14	124,220 - 124,280	Grt G3 + 8%	-	0	0,09	-	2,52	2	200*	2 376*	5,1*	99,6	2,0	West G3 control
	1	82,700 - 82,760	Grt G3 + 8 %	-	0	0,20	0,2	2,48	4	200	2 313	6,1	100,3	2,4	East G3 control
	6	83,000 - 83,060	Grt G3	Gypsum	2	0,17	1,2	2,46	3	200	2 360	5,0	103,4	1,3	
	7	83,060 - 83,120	Grt G3	Gypsum	5	0,76	3,8	2,45	1	180	2 297	6,2	97,6 (99,3)	2,7	**Plus 0,5 % NaCl**
Haalenberg	8	83,120 - 83,180	Grt G3	Gypsum	10	0,08	6,4	2,45	2	200	2 272	5,5	98,8	1,8	
30 July 1976	9	83,180 - 83,240	Grt G3	Gypsum	20	0,08	16	2,31	4	150	2 198	7,3	98,0	5,3	20 % Gypsum
	13	83,360 - 83,420	Grt G3 + 8 %	-	0	0,14	0,2	2,48	3	140	2 304	6,3	98,7	2,9	Middle G3 control
	14	83,420 - 83,480	Calcrete G4	-	0	0,08	0,3	2,15	NP	160	2 114	7,5	99,7	3,1	Calcrete G4 control
	19	83,720 - 83 780	Calcrete G4	Gypsum	5	0,20	4,9	2,14	3	220	2 120	8,2	98,8	4,4	
	20	83,780 - 83,840	Calcrete G4	Gypsum	5	0,39	5,3	2,02	3	170	2 137	8,2	95,4 (96,3)	3,6	**Plus 0,5 % NaCl**
125 mm	21	83,840 - 83,900	Grt G3 + 8 %	-	0	0,13	0,7	2,37	3	230	2 332	6,1	101,4	3,1	West G3 control

Notes:

[1] Final slurry. Bases completed : Lüderitz 20-21 March 1976; Haalenberg 13 – 14 March 1976

[2] **Construction stake values (SV) are the definitive positions.** SV zero was at Aus and km 124 at Lüderitz

[3] G3 bases lightly slushed with freshwater except Lüderitz Section 10 (seawater). Calcretes not slushed

[4] Original seal SC2 (Cape seal) on all sections. "Crusher- run" granite and dolerite mixture (Grt) ex Q2 at Haalenberg+ 4% binder ex BP 110 + 4% ex BP 101,0 except where indicated. EC without binder about 0,05 S/m and with 8% binder about 0,12 S/m

[5] Calcrete natural gravel: ripped and gridded honeycomb calcrete of nominal G4 quality from BP 89,8 R.   EC of calcrete alone 0,07 – 0,10 S/m

[6] The salt added was coarse dairy salt ex Swakopmund containing 99% NaCl. Gypsum added was fine industrial gypsum ex Johannesburg containing 93 % $CaSO_4{\cdot}2H_2O$

[7] Roads Branch (RB) central lab. results: 20 m LHS midlane, 30 m CL, 40 m RHS midlane on the 60 m sections, usually $n = 3 – 7$. Haalenberg Section 20 EC estimated from other results (only one result after compaction (middle CL), both JG & RB of 0,16 S/m apparently too low. Means reported here to two decimal places; rounded off to one place for values above 1,0 S/m in most subsequent tables

[8] **Gypsum calculated as $CaSO_4.2H_2O$**. RB results (usually $n \geq 3$ on same samples as for EC). Six results for Lüderitz Section 8 (10% gypsum added) : 3 of 9,2 – 12,8%; 3 of 23,1 - 27,2%, yielding a mean of 17,7%, or 10,6% if those over 20% rejected; about 11% more likely. Means rounded to nearest 0,1% up to 10% and to nearest percent above 10 %

[9] Jeffares & Green (JG) site laboratory results (one sample on CL near middle of section)

[10] Roads Branch central laboratory results except where * for JG results (all one per section). MAASHO CBR swells when done 0,00 – 0,18%

[11] JG site results; by sand cone replacement method relative to their MDDS (one per section, MDDs not shown)
Field (in-situ) water content at time of test by drying excavated material in laboratory at 105 – 110ºC. Tested (Lüderitz) 20 March 1976; Haalenberg 13 March 1976.

[12] Compactions less than 98% accepted because of experimental time constraints and density holes sited in localized rough areas, but rest appeared and sounded good. Recalculated compactions using Roads Branch MDDs bracketed. On this basis only Haalenberg Section 20 at 96,3% failed

8. CONSTRUCTION

The soil binder was first mixed into the crusher-run and the gypsum mixed in with a disc harrow in an initially dry condition before the addition of water. A substantial loss of gypsum from the 10 and 20% G3 sections occurred due to a strong wind.

The construction procedure was first to grid-roll, then cut initial levels, grid-roll again, and cut final levels, roll first with a vibrating roller and then with an eleven-wheel pneumatic and steel-wheel rollers working together. The crusher-run sections were very lightly slushed (a so-called water-roll) but the calcrete was not slushed. The normal light spray of water was used on all sections before priming with the MC-30.

The time delay between pavement layers is an important risk factor with respect to the prevention of salt damage: the longer a wet compacted layer is exposed during dry weather the greater the likelihood of salt being drawn up by capillarity both from within this layer as well as from the layers below. This applies to any layer, not just the base course. In the case of these two experiments the time factor was only deliberately varied in the case of the delays between the completion of the base and priming and priming and surfacing. The delay between completion of the subbase and the base was 15 – 17 days for both experiments except for the control section 14 at Lüderitz which was only 7 days.

It was intended that the left lane on both experiments would be primed as soon as practicable and that the right lane be left open for about two weeks in order to simulate a short but more convenient delay (In practice a base might stand far longer) and that the Cape seal surfacing would be applied on both lanes as soon as practicable. The actual delays achieved on both experiments between completion of the base and priming were 1 – 3 days in the left lane and 15 – 19 days in the right lane The delay between priming and tacking and chipping were 1 – 3 days in all cases except for Section 20 (calcrete G4 with 5% gypsum plus 0,5% NaCl) which was reprimed after 3 days because of salt damage. The final spray was applied on the same or the following day on all sections except the G3 control sections and the calcrete G4 control Section 14 and the 5% gypsum calcrete Section 19 at Haalenberg. The first slurry at Lüderitz and on Section 20 at Haalenberg was applied on the same or the following day, but at Haalenberg this was only 6 – 8 days later on the other sections. The delay between the first and final slurry was 8 – 10 weeks at Lüderitz and 16 – 18 weeks at Haalenberg.

The slurries only received normal rolling with an eleven-wheel pneumatic roller before opening to traffic, which was very light.

Determination of the gypsum contents of both the upper 25 mm and the rest of the base after two weeks and 14 months were found to be similar, indicating that no significant migration of gypsum had take place even in the presence of NaCl or seawater. However both testing and visual inspection showed that both the vertical and longitudinal distribution was generally poor, in spite of the use of two graders, working in opposite directions on some sections. In spite of this and the grader operator being instructed to lift his blade at the end of each section, there was also a substantial amount of carryover from one section to another in places. This meant that only the middle 20 – 40 m of some sections was sampled and inspected.

9. PERFORMANCE AND DISCUSSION

9.1 Methods

The performance of these experiments during and after construction was monitored by regular visual inspection of a panel consisting of members of the then roads authority and the author, who was also present during construction of the base course and the seal. During construction representatives of the site staff were also usually present.

Monitoring consisted of mostly visual descriptions according to the methods of the time which have been converted into those of TMH9:1992 supplemented by occasional rut depth, smoothness, dynamic cone penetrometer (DCP) according to TMH6:1984) and radius of curvature (RC) measurements according to what became TMH6:1987.

In addition to the usual indicators of pavement distress such as shear failures, rutting and cracking, particular attention was given to the known indicators of soluble salt damage such as looseness and/or blistering of the primed base, blistering and cracking on a starburst pattern of the seal and/or the slurry overspread, and premature edge breaking and looseness of the gravel shoulders (Netterberg 1970, 1979, 1994; Netterberg et al 1974).

9.2 During Construction

No negative effects were apparent on the gypsum sections at Lüderitz with a maximum of 18% gypsum together with an EC of 0,09 S/m as in Sections 8 and 9 or 4,4% gypsum together with an EC of 0,43 S/m as in the seawater gypsum base Section 10, except that the prime took somewhat longer to dry, especially with more than about 10% gypsum.

The performance of the Haalenberg sections was similar to those at Lüderitz and it was conservatively concluded that 15% gypsum together with an EC of up to 0,10 S/m or 4% gypsum together with an EC of up to 0,80 S/m could be permitted in a G3, at least in the short term (i.e. during construction), provided that the base was primed and sealed with the time constraints used.

Neither the primed nor unprimed lanes of the gypseous G3 sections experienced any salt damage. However, about 30% of the area of the G4 calcrete Section 20 with 5% gypsum and 0,5% NaCl suffered severe prime damage starting the same day and had to be broomed and reprimed. The unprimed right lane remained undamaged and after 15 days was primed, tacked and chipped, all on the same day.

Small-scale priming experiments with different types and application rates of primers did not reveal any great differences in performance at either site although the diesel-fluxed, invert cationic emulsion primer was preferred. None of them became damaged at Lüderitz. However, the presence of gypsum increased the drying time and it appeared desirable to limit the gypsum content to about 10% in order to limit the drying time of the emulsion and MC-30 to about 3 and 9 days respectively at the usual application rate of 0,70 l/m^2. As at Lüderitz, none of them on the G3 bases at Haalenberg became damaged. However, on Section 20 at Haalenberg all except the emulsion became damaged within 24 hours and after 9 days only the non-prewetted emulsion was acceptable.

9.3 After Construction

Formal panel inspections were held after completion of the seal, after about one year (by which time salt damage usually appears), three, five, 11, 15 and 36 years, with informal reporting at irregular intervals.

No conventional distress or salt damage appeared on the gypsum or control sections except that after 15 years about 75% of the slurry overspread had gone on those sections containing 10% or more gypsum (in comparison with about 50% on the control sections) and most of the upper layer of slurry had worn off all sections. TMH 9:1992-type Degree 1 – 2 Extent 5 age-related shrinkage "hair" cracking of the lower slurry was present on all sections including the controls, and edge fretting had not extended to the loss of the chamfer at the edge of the seal on any section.

In 2012, after 36 years all the sections at both Lüderitz and Haalenberg were found to be in an acceptable and indeed remarkably good condition considering their age, with remarkably little deterioration since 1991, in spite of all of the top slurry having worn off. The only maintenance recommended at Lüderitz was a reseal or slurry on all the sections including the controls at a B priority.

At Haalenberg no maintenance at all was recommended on the G3 control sections 1, 13 and 21, the calcrete G4 control 13 and the calcrete G4 with 5% gypsum (Section (19). Only rejuvenation and rolling was recommended for Sections 6 (2% gypsum G3) and 20 (5% gypsum plus 0,5% NaCl calcrete G4) – the latter only in the outer 0,5 m. Rejuvenation, reseal or a slurry was recommended for the 5,10 and 20% gypsum G3 sections (7,8 and 9) and attention to edge breaking and/or regravelliing the shoulders on the gypsum calcrete sections 19 and 20 as well as the calcrete control (14), all at a B priority. In short, a rejuvenation spray alone was considered sufficient on the seal on these sections.

Apart from the general loosening of the shoulders and the loss of the prime overspray on all sections including the controls due to the generally high EC, the only possible incipient, slight blistering seen was on the 20% gypsum and the 5% gypsum plus seawater sections at Lüderitz. The Haalenberg mixed gypsum and salt Sections 7 (G3) and 20 (calcrete G4) with 5% gypsum plus 0,5% exhibited no salt damage to their surfacings.

The only section on either experiment which was in a warning condition after 36 years was Section 9 at Haalenberg (20% gypsum G3) with Degree 3 / Extent 3 crocodile cracking in the wheelpaths.

In spite of "hygroscopical cracks" gypcrete-based pavements in Algeria performed well for more than 20 years even with more than 300 heavy vehicles per day (the legal axle load was 130 kN) – "provided that the subgrade water content remains low" (Horta 1987). The gypsum content of materials used in hydraulic structures should be limited to a maximum of 2% (Brune 1965, Van Alphen and Rios Romero 1971), although up to 10% has been used in the outer sections above the sediment pool elevation (WL Vaught, United States Soil Conservation Service 1973, pers. comm).

No potholing, shoving, shearing or significant rutting was present on any sections on either experiment and all patching represented sample holes.

10. PAVEMENT EVALUATION

A pavement evaluation carried out in February 1979 after about 20 months after the final slurry showed little difference between any of the sections in visual condition, rut depth or longitudinal smoothness and that the addition of gypsum or NaCl or compaction of the gypseous section 10 at Lüderitz with seawater had not compromised the expected structural capacity (Tables 4 and 5).

Dynamic cone penetrometer (DCP) testing using the then standard 30º cone was abandoned as the instruments refused and broke at a depth of about 50 mm on the G3 and calcrete G4 control sections.

Radius of curvature (RC) measurements of the deflection bowl using a Dehlen MkII curvature meter (Dehlen 1962a) were then used in preference to the maximum surface deflection for the comparison of different base courses, as from Dehlen (1962b) and other sources about 60% of the RC is due to the upper 150 mm of a pavement in comparison with about only 20% for deflection.

It is clear that the presence of gypsum actually increased stiffness and thereby the structural capacity and, with RCs in excess of the 200 m usually only associated with cemented or bitumen-bound bases, appeared to have cemented the bases at both Lüderitz and Haalenberg without the block cracking usually associated with cementation.

As the gypseous bases did not appear to be cemented when sampled in 2012 but compacted gypsum has been known to develop unexpectedly high in-situ undisturbed strengths, with a sensitivity ratio of 3 to 6 (Blight 1969), it seems likely that the stiffness was due to interlocking needles of gypsum or bassanite (hemihydrate) as in plaster of Paris (Carman, 1949; Kuntze, 2009), which is lost on disturbance.

Repeat measurements on a few sections at different times of the day showed the RC to be strongly temperature-dependent, the highest values being obtained when the road was at its hottest (40 – 50ºC at about 15h). These results enabled estimates to be made of the RCs at the same arbitrary temperature of 25ºC at Haalenberg (Table 5) – all the corrected values were lower than the uncorrected ones, but higher than those of their control sections. Contrary to normal practice, the temperature of pavements with thin surfacings may therefore need to be taken into account when carrying out deflection surveys (Netterberg & Haupt, 2003). For example, assuming that the 0,5% NaCl plus 5% gypsum (measured EC 0,80 S/m and 4,3% gypsum) caused the G3 base of Section 7 to exhibit some cementation, the NGM-C curve of Figure 31(b) of TRH 12 (COLTO 1997) indicates a structural capacity of about 40M E80 for an uncorrected inner wheelpath RC of 190 m, but only about 10M E80 for the corrected value of 135 m, illustrating the large errors that can be made if uncorrected RCs are used.

Although no percentiles were calculated, the means shown and the lowest RCs (not shown) of 110 m in the outer wheelpath at Lüderitz and 130 m at Haalenberg (as well as the temperature – corrected inner wheelpaths) were all in excess of the minimum 90- % ile of 80 m (COLTO 1997) expected for Category B pavements in a sound condition.

This temperature-dependence of the RC suggested that the higher temperatures during the day partially dried out the upper pavement, thus increasing both the matric and the solute suction, and driving some of the water downwards, from which it rose again during the night.

Table 4: Summary of pavement evaluation survey at Lüderitz after two years [1]

Section No.	Base		Additive			Actual [2] [3]				Radius of curvature [4]			Left lane				Right lane			
	Classification	Water	Binder	NaCl	Gypsum	Left Lane		Right Lane		Right Lane Wheelpath			Rut Depth [5] Wheelpath		Smoothness [6]		Rut Depth [5] Wheelpath		Smoothness [6]	
						EC	Gypsum	EC	Gypsum	Inner	Mean	Outer	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
		Type	+%	+%	+ %	S/m	%	%	%	m	m	m	mm	mm	mm	mm	mm	mm	mm	mm
1	G3	Fresh	8	-	-	0,19	(0,1)	0,11	(0,1)	215	175	140	5	4	5	4	2	2	6	5
7	G3	Fresh	-	-	2	0,15	3,9	0,11	2,4	550 [7]	380	220 [7]	5	4	5	5	6	3	5	5
8	G3	Fresh	-	-	10	0,09	19	0,10	20	350	270	190	2	4	4	5	3	4	4	4
9	G3	Fresh	-	-	20	0,08	16	0,09	15	310	260	215	4	6	4	6	2	4	4	4
10	G3	**Sea**	5	-	5	0,40	5,8	0,47	4,4	205	175	150	4	3	4	4	4	4	4	3
14	G3	Fresh	8	-	-	0,09	-	0,09	-	145	145	145	3	4	5	5	6	2	4	4

Notes:

[1] On 06-07 Feb. 1979.

[2] EC means of usually two Roads Branch central lab. results from 20 and 40 m midlane positions per lane

[3] Gypsum means of 1 - 2 Roads Branch central lab. results from 20 and 40 m per lane. Bracketed results were centreline at 30 m

[4] Means of 11 duplicate results on 10 – 50 m positions in RHS (Aus-bound) lane using Dehlen curvature meter under 40 kN wheel load and constant 520 kPa tyre pressure. Temperatures at depth of 25 mm ranged from about 23 ºC at 07 h to 46 º C at 15 h to 32 º C at 19 h. Surface temps usually 2 – 3 º C higher. Means of 11 duplicate Benkelman beam deflections on Section 14 : 0,23 mm (inner and outer wheelpaths). Means of 3 duplicates on Sections 9 and 14 : 0,20 – 0,29 mm (inner), 0,16 – 0,23 mm (outer)

[5] Maximum deviation in wheelpaths under 2,0 m straight edge measured with calibrated wedge. (Means of 6 single results on 10 – 50 m positions)

[6] Maximum deviation under 3,0 m straight edge parallel to centreline at about 300 mm in from outer edge of seal (“outer”) and 300 mm on either side of centreline (“inner”), as measured with a calibrated wedge. (Means of 6 single results on 10 – 50 m positions)

[7] Range of ROC : Inner 330 – 800 m, C.O.V. = 23 %, temperature at 25 mm = 29 ºC ; Outer 145 – 280m, C.O.V. = 24 %

Table 5: Summary of pavement evaluation survey at Haalenberg after two years [1]

Section No.	Classification	Additive			Actual [2] [3]				Radius of Curvature [4]				Left Lane				Right Lane			
					Left Lane		Right Lane		Wheelpath				Rut Depth [6] Wheelpath		Smoothness [7]		Rut Depth [6] Wheelpath		Smoothness [7]	
		Binder	NaCl	Gypsum	EC	Gypsum	EC	Gypsum	Inner	Mean	Outer	Inner Corrected [5]	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
		+%	+%	+%	S/m	%	S/m	%	m	m	m	m	mm	mm	mm	mm	mm	mm	mm	mm
1	G3	8	-	-	0,13	0,2	0,25	0,2	165	175	185	135	2	2	2	4	3	5	4	5
6	G3	-	-	2	0,19	1,1	0,18	0,9	200	255	310	150	1	3	7	4	3	3	5	5
7	G3	-	0,5	5	0,68	3,0	0,80	4,3	190	185	185	135	2	6	6	4	6	2	4	4
8	G3	-	-	10	0,08	(7,5)	0,07	5,3	370	310	245	290	2	3	4	3	6	3	4	4
9	G3	-	-	20	0,09	16	0,07	-	430	370	310	360	2	2	4	4	2	2	4	3
13	G3	8	-	-	0,14	(0,2)	0,15	(0,2)	155	160	170	150	3	5	5	4	4	5	5	4
14	G4	-	-	-	0,08	-	0,09	(0,3)	225	250	280	210	3	4	6	5	5	3	5	5
19 [8]	G4	-	-	5	0,17	4,9	0,28	5,3	620	580	550	480	4	3	6	5	5	4	4	4
20	G4	-	0,5	5	0,29	(3,1)	0,54	7,3	590	540	490	430	4	3	5	4	8	4	5	4
21 [9]	G3	8	-	-	0,15	1,0	0,09	0,7	310	300	290	245	2	3	6	4	5	4	4	5

Notes:

[1] On 08-09 Feb. 1979. [2] EC means of 2 - 3 Roads Branch central lab. results from 20 to 40 m midlane positions per lane

[2] EC means of usually two Roads Branch central lab. results from 20 and 40 m midlane positions per lane

[3] Gypsum means of 1 - 3 Roads Branch central lab. results from 20 to 40 m midlane positions per lane. Bracketed results from centreline at 30 m

[4] Means of 10 duplicate results from 10 – 50 m positions in RHS (Aus-bound) lane using Dehlen curvature meter under 40 kN wheel load and constant 520 kPa tyre pressure. Means of duplicate Benkelman beam deflections on the same 10 positions on Control Sections 1 and 21 yielded results of 0,20 and 0,13 mm respectively in both wheelpaths and 0,13 mm on one position in outer wheelpath of Section 9 and calcrete Control Section 14. Mean of mean for all 7 G3 Sections: 250 m; all 3 calcrete G4 sections: 460 m

[5] Corrected to 25 º C at depth of 25 mm at appropriate time of day. Temperatures at depth of 25 mm ranged from about 24 º C at about 07 h to about 56 ºC at about 15 h. Surface temps usually 3 – 6 º (higher). Mean of all 7 G3 Sections: 210 m ;all 3 calcrete G4 Sections: 370 m

[6] Maximum deviation in wheelpaths under 2,0 m straight edge measured with calibrated wedge. (Means of 6 single results on 10 – 50 m positions).

[7] Maximum deviation under 3,0 m straight edge parallel to centreline at about 300 mm in from outer edge of seal ("outer") and 300 mm on either side of centreline ("inner"), as measured with calibrated wedge. (Means of 6 single results on 10 – 50 m positions)

[8] Range of ROC : Inner 370 – 930 m, C.O.V. = 27 %, temperature at 25 mm = 48 ºC ; Outer 310 – 700m, C.O.V. = 24 %

[9] Contamination with NaCl and gypsum noted during construction

11. MAINTENANCE

As at April 2012 neither the road from Haalenberg to Lüderitz nor any of the test sections had been resealed, and only a 3 m and 44 m length of slurry had been placed for unknown reasons on the respective Section 1 and 14 control sections at Lüderitz and a 2 m and 5 m length on Sections 1 and 21 at Haalenberg.

The only spray maintenance had been invert emulsion rejuvenator sprays at 0,5 l/m^2 in 1997 (after 20 years) and 2007 over the whole length of road from Aus to Lüderitz.

The shoulders were regravelled in places on both experiments during 1987 and it appeared that some subsequent regravelling had also been done in places.

12. CONCLUSIONS AND RECOMMENDATIONS

- Preliminary laboratory testing suggested that more than about 10% of added fine gypsum detracted significantly from the engineering properties of the G3 material evaluated.

- The bound water in gypsum is not available for compaction but will increase the results of water (moisture) content determinations by both drying at 105 – 110ºC and by nuclear means and thereby affect all tests which rely on such determinations.

- The long-term water content of both the Lüderitz and Haalenberg bases was only about 1,5%, i.e. about one-quarter of MAASHO OWC.

- As the solubility of gypsum is only about 0,2% and is also little affected by temperature or the presence of other salts the probability of it causing damage is low.

- No upward migration of gypsum took place during construction or within about one year of sealing (no further such testing was carried out).

- The performance of the gypsum sections at Haalenberg was similar to or slightly better than those at Lüderitz, although the edge breaking and gravel shoulder looseness were generally worse.

- The drying times of the MC-30, MC-70 and tar primers were extended to an undesirable degree on the G3 bases at Lüderitz by an EC in excess of about 0,4 – 1,5 S/m or a gypsum content in excess of about 10%, but the invert emulsion was little affected.

- As the panels which were not prewetted performed best, the necessity for and possible avoidance of prewetting should be considered.

- The only sections considered to be in a “warning” condition were parts of the 2% salt sections and the 20% gypsum sections on both experiments, leading to the conclusion that these were acceptable for a 20-year design life, but conservatively should be excluded for a 35-year design life.

- Their long-term performance was found to be the only – albeit small – limiting factor in the case of the **granite G3** bases, whereas in the case of the **calcrete G4** bases their short-term performance during construction in the form of severe blistering of the primed base was the major limiting factor, and blistering of the incomplete seal a minor factor.

- A pavement evaluation carried out in 1979 after about two years showed little difference between any of the sections and the controls in visual condition, rut depth or longitudinal smoothness and, from radius of curvature (RC) measurements, that the presence of salt, gypsum or compaction with seawater had not compromised the expected structural capacity of any of the sections and that both the G3 and calcrete G4 sections were actually stiffer than the control sections and had RCs normally only associated with cemented bases.

- As this − whether due to cementation or crystal interlock − did not give rise to reflection cracking the use of gypsum as an inexpensive stabilizing agent should be investigated.

- The RC measurements at Haalenberg were highly temperature-dependent, indicating that, contrary to normal practice, the temperature of pavements with thin surfacings may need to be taken into account when carrying out any kind of deflection survey when the upper pavement is of the most concern.

- The maintenance over the 36 years on the sections was limited to rejuvenation sprays of invert emulsion in 1997 and 2007 (over the whole road), a negligible amount of crack sealing and patching, some edge patching and shoulder regravelling, and some slurrying on parts of the control sections at both Lüderitz and Haalenberg and on the 2% salt G3 Section 6 at Lüderitz.

- Under conditions similar to those at Lüderitz or Haalenberg the following construction time constraints are recommended for a granite crushed rock base of nominal **G3** quality with a mean EC of 1,0 S/m and a maximum of 1,5 S/m under a 19 mm Cape seal with two rich slurries for a design life of 30 years: prime as soon as practicable, but within 14 days of completion of the base, preferably tack and chip the following day but no later than 7 days, and complete the seal as far as the first slurry within 2 days after tacking and chipping. The slurries must be applied in the traditional Cape manner, well-rolled and opened to traffic as soon as practicable, and the second one applied not later than 8 weeks after the first. No construction time constraints are necessary for gypsum alone (i.e. with a mean EC of ≤ 0,10 S/m), but are governed by the highly soluble salt content (e.g. NaCl) as indicated by the EC.

- Under conditions similar to those at Haalenberg the following **additional** construction time constraints are recommended for a natural gravel **calcrete** base of nominal **G4** quality: with an EC of ≤ 0,15 S/m the base can be left for at least 14 days but should then be primed and tacked and chipped within 7 days thereafter and the seal completed as far as the first slurry within 4 days of tacking. At an EC of 0,26 - 0,50 S/m the base can be left for up to 10 days, but must be then tacked and chipped the following day. No construction time limits are necessary for the gypsum alone (i.e. with a mean EC of ≤ 0,10 S/m), but are governed by the EC.

- For a life of up to at least 35 years without resealing but with two rejuvenation sprays, the following combinations are regarded as tolerable in a **G3 base** under Lüderitz conditions:

- up to 5,0% gypsum **together** with an EC of up to 0,5 S/m due to intrinsic NaCl or due to seawater as in Section 10 (4,4% mean, 5,9% max.; EC 0,43 S/m mean, 0,47 S/m max.);

- up to 10 – 15% gypsum **together** with an EC of at least 0,10 – 0,15 S/m supposedly as in Section 8 (18%) or the right lane of Section 9 (15%).

- Similarly, under Haalenberg conditions the following are regarded as tolerable:
    - for a **G3**, up to at least 5% gypsum with an EC of up to about 0,80 S/m as in Section 7 (3,8% mean, 4,6% max; mean EC 0,76 S/m, max. 0,88 S/m;
    - for a **G3**, up to at least 10% gypsum **together** with an EC of at least 0,10 S/m as in Section 8 (10% added, but mean of 6,4%, max. 7,5%, but less than Section 9 (20% added, but only one result of 16%);
    - for a **calcrete G4**, up to at least 5% gypsum **together** with an EC of up to about 0,20 S/m with no time constraints as in Section 19 **or** 0,21 - 0,50 S/m as in Section 20 (5% gypsum plus 0,5% NaCl) **with** construction time constraints.

- As it is clear that gypsum itself was not deleterious under these conditions, but that both gypsum and NaCl are usually present in the natural materials they are in reality the worst adverse combinations recommended. For example, at least 10% gypsum on its own is tolerable under both Lüderitz and Haalenberg conditions in a G3 and at least 5% in a calcrete G4.

- Although from these experiments only a limit of 0,5% gypsum (with an EC of 0,1 – 0,3 S/m) can be suggested for the subbase and shoulders, experience on the Trekkoppie road showed that up to at least about 20% can be allowed and that it was the NaCl (as indicated by a high EC) which caused the looseness.

- Pavement layers containing more than about 2% gypsum should not be subjected to long-term seepage conditions.

- The findings at Lüderitz should be applicable to the whole of the arid coastal fogbelt and those at Haalenberg to the whole inland arid and − although probably conservative – to the whole semiarid zones of southern Africa.

- The Lüderitz and Haalenberg experiments probably represent the most comprehensive and longest-lasting study ever undertaken on the use of saline and gypseous materials in road construction. As such they have provided definite proof of what works and what does not, both during construction and in the long term beyond the normal 20- or 30- year design life. They are also unique in that the designer (the author) has been involved throughout this period.

13. ACKNOWLEDGEMENTS

These experiments were designed by the author, constructed for the then Roads Branch of the then Administration of South West Africa (Chief Roads Engineer Mr HJM Williamson) by LTA (Site Agent Mr G Ruppel) as part of the Haalenberg-Lüderitz road contract. The Consulting Engineers were Messrs Jeffares and Green (Resident Engineer Mr WR Mahlendorf, Assistant Resident Engineer Mr DC Johnson), Mr H Rakow of the Roads Branch assisted with much of the research work and the inspection panel generally consisted of Messrs L von Solms and H Rakow of the Roads Branch and the author. The 2012 field team consisted of Messrs C Silombela, D Gawaseb and L Shikongo of the NRA, Mr P du Toit of VKE Namibia, and the author. Messrs B Boshoff and J Dongwi of VKE Namibia also assisted with various aspect of the office and laboratory work. Some of this work was carried out whilst the author was employed at the then National Institute for Transport and Road Research of the CSIR in Pretoria and Mr FJ Haupt of the Institute assisted with the radius of curvature measurements in 1979. The laboratory work was carried out by the construction site, Roads Branch and the NITRR laboratories. The final evaluation and report by the author were sponsored by the German Kreditanstalt für Wiederaufbau for the Namibian Roads Authority and this and other reports by him have been drawn upon. However, the opinions expressed are those of the author and not necessarily any of the above. Some of the findings of this work have been included in the Roads Authority's (2014) materials manual.

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