THE USE OF SEAWATER IN ROAD CONSTRUCTION: PART 2 – THE LÜDERITZ EXPERIMENT

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

As freshwater is extremely scarce along the desert coast of Namibia ten experimental sections of graded crushed stone base compacted with either seawater or freshwater as controls were constructed in 1976 at Lüderitz. These sections included sections with seawater only up to subbase level and seawater in all layers, with and without 5% added gypsum in the base in order to simulate a gypseous binder, using freshwater base sections with and without 0,5% added NaCl as control sections, as well as certain compaction and construction time constraints. The mean salinity of the bases after compaction and slushing with sea or freshwater as measured by the paste electrolytic conductivity test were 0,4 – 0,5 S/m in the seawater sections in comparison with 0,15 S/m in the freshwater section with seawater only in the subbase and lower layers and 0,09 S/m in the section with freshwater in all layers, and the maximum of 0,15 S/m usually permitted No significant salt damage occurred to the primed base or to the surfacing during or after construction and after 35 years of monitoring it was concluded that at any time of the year under conditions similar to those at Lüderitz seawater can be used in all layers including a G3 base under a 19 mm Cape seal provided that certain precautions are taken.

1. INTRODUCTION

As freshwater is extremely scarce along the desert coast of Namibia experimental sections of G3 quality crushed stone base were constructed during the summer of 1976 at Lüderitz as part of the new road past Haalenberg at about 45 km inland to Aus and Keetmanshoop.

These sections included sections with seawater only up to subbase level and seawater in all layers, with and without 5% added gypsum in the base in order to simulate a gypseous binder, using freshwater base sections with and without 0,5% added NaCl as controls.

In addition, the construction of the left (i.e. Lüderitz-bound) lane was primed and the 19 mm Cape seal completed as soon as practicable up to the first slurry within five days after compaction and the right (i.e. Aus-bound) lane only after 20 days including 18 days before priming in order to simulate more normal construction timing.

The objectives were similar to those of the Swartklip experiment (Netterberg, 2023), but were more comprehensive and included an evaluation of the following factors believed to possibly affect the use of saline materials and compaction with seawater:

- Type of base (crushed stone), with and without added soil binder.
- Content of common salt halite (NaCl) in the base.
- Content of gypsum ($CaSO_4 \cdot 2H_2O$) in the base.
- Use of seawater to the top of the base course, both with and without gypsum.

- Use of seawater for compaction to the top of the subbase.
- Use of seawater in the shoulders.
- Slushing the base and subbase.
- Delay between compaction and priming.
- Delay between priming and sealing.
- Type and application rate of primer, and effect of omitting it completely.
- Surfacing permeability.
- Salt, gypsum and moisture migration during and after construction.

The traffic carried by this road is light and in the critical first five years was only 50 – 70 vehicles per day (vpd) with 15% heavy vehicles and increased to only 160 (13% heavy) with a cumulative 0,2 MESA after the design life of 20 years in 1996. Even after the full analysis period of 30 years in 2006 the traffic was still only 240 vpd with 24% heavies and the road had carried about 0,5 MESA per lane. After the final inspection in 2012 and about 0,75 MESA per lane after 35 years.

With respect to the experimental design, the desert climate, the hot summer season and the light traffic were all factors known to increase the risk, rapidity of onset and severity of salt damage. However, fog may have been a mitigating factor.

The mean saturated paste electrolytic conductivity (EC) of the bases after slushing with sea or freshwater were 0,4 – 0,5 S/m in the seawater sections in comparison with 0,15 S/m in the freshwater section with seawater in the subbase and lower layers and 0,09 S/m in the section with freshwater in all layers, and with the maximum of 0,15 S/m (e.g. Committee of Land Transport Officials (COLTO), 1998) later permitted.

2. CLIMATE AND WEATHER

The climate according to the Köppen classification (Schulze, 1947) at Lüderitz is cool dry desert with frequent fog (BWk'n) and that at Haalenberg hot dry desert (BWh) without frequent fog. The normal annual rainfall at Lüderitz and Haalenberg is about 20 and 70 mm, respectively (Meteorological Services, Windhoek 2012, pers. comm.). Lüderitz has fog or mist on average about 100 days per year, mostly at night. This usually clears during the morning. The experiment is at an altitude of about 20 m and about 1,0 km from the sea.

No measurable rain fell during construction, a total of 42 mm was recorded at Lüderitz during 1976 and an annual average of 13 mm for the period 1976 – 2000, with a minimum of 0,0 and a maximum of 42 mm (Meteorological Services, pers. comm.).

Shade air temperatures taken by the author at Lüderitz during construction varied between 14 and 34ºC and relative humidities between the more usual 18% during the day and a maximum of 100% during the night or morning mist. The mean annual temperature over the period 1976 – 2000 was 15,9ºC with a minimum of 12,7 and a maximum of 19,0ºC (Meteorological Services, Windhoek 2012, pers. comm.).

With a Weinert (1980) N-value of about 90, and a Thornthwaite Moisture Index of about minus 60 (Emery, 1992) the macroclimate is Dry for pavement design purposes (COLTO, 1996).

3. PAVEMENT

- **Surfacing:** “Cape seal”: a 19 mm single seal with two coats of slurry. (National Institute for Road Research (NIRR), 1970) with 2,0% crossfalls.
- **Primer:** MC-30 at the nominal rate of 0,7 ℓ/m.
- **Base:** 150 mm of nominal G3 quality graded crushed stone, mostly with 8% added soil binder by mass, compacted to 98% MAASHO. Completed on 20 – 21 March 1976.
- **Subbase:** 100 mm natural gravel (mostly calcrete) of nominal G5 – G4 quality and an inherent EC of 0,1 – 0,2 S/m compacted to 95% MAASHO.
- **Selected subgrade**: 250 mm G5 calcrete natural gravel with an inherent EC of 0,1 – 0,2 S/m compacted to 93% MAASHO.
- **Fill:** approximately 1 m of rock and soil (latter compacted to 90% MAASHO).
- **Roadbed:** saline soil.
- **Width:** 6,8 – 6,9 m wide seal on 7,4 – 7,6 m base, with 2,5 m G5 gravel shoulders.
- **Alignment:** straight with 1,4% fall towards Lüderitz town.
- **Drainage:** good, centreline 2,0 m above natural ground level; water table deep.

4. MATERIALS AND TEST METHODS

4.1 Materials

Chemical analyses of the waters shown in Table 1 show that the salinity of the seawater was normal at about 3,5%, and that the fresh water was of drinking water quality.

Table 1: Composition of seawater and fresh water used in the Lüderitz experiment

Component	Units	Seawater	Freshwater
Na^+	% m/v	1,00 - 1,06	0,010
$C\ell^-$	% m/v	1,88 - 1,95	0,011
SO_4^{2-}	% m/v	0,21 – 0,25	0,006
TDS at 180ºC	% m/v	3,39 - 3,53	0,041
EC at 25ºC	S/m	5,25 - 5,50	0,069
Salinity from EC [1]	%	3,5 - 3,6 (m/m)	0,045 (m/v)
pH	-	7,8 - 7,9	8,2

Notes:
[1] By NITRR Method CA21-74 (1980)
[2] 1 S/m = 1 000 mS/m = 10 mS/cm; 1% = 10 000 mg/ℓ

Typical material properties after compaction are shown in Table 2. The EC of the graded crushed stone (mostly granite) was 0,05 S/m and that of the two soil binders 0,03 and 0,47 S/m respectively. Four percent by mass of each binder was added to the crushed stone. The measured EC of this mixture as used for most of the road and for the control sections before adding water was about 0,12 S/m. After compaction with freshwater it was 0,09 – 0,15 S/m and 0,3 – 0,6 S/m with seawater. The salt added was a coarse dairy salt containing about 97% NaCl as halite and the gypsum a “wet” neutralised, industrial gypsum containing about 93% $CaSO_4 \cdot 2H_20$.

4.2 Test Methods

The standard indicator and test methods used were those of the South African Department of Transport (DoT, 1970). The wet A1(a) soil preparation method was used for the sieve gradings and the soil constants. All CBRs were determined at a penetration depth of 2,54 mm after four days of soaking.

Samples for compaction and CBR testing were taken from the dumps on the road before compaction and for indicators from the layer after compaction.

The soluble salt, pH and qualitative test methods used during construction are described in the first paper of three to this conference of this series (Netterberg, 2023).

Their current nominal equivalents are those of the SABS SANS 3001 series which, however, may not yield exactly the same results.

The saturated paste EC method provides a very good, rapid measure of only the total very soluble salt content such as NaCl and sea salt and minimises the effect of the only slightly soluble salt gypsum. Up to an EC of about 1,5 the results in S/m are approximately numerically equal to the percentage by mass of NaCl or sea salt in the minus 6,7 mm fraction tested.

What is now TMH1:1986 Method A22T for acid-soluble sulphate was used for the determination of gypsum. The results reported here are as gypsum ($CaSO_4$•$2H_20$).

All water (moisture) contents were determined at the usual 105 – 110ºC without any allowance being made for any possible loss of bound water, such as that in gypsum.

Limited testing of compaction characteristics and CBR with seawater indicated that it had little effect but may have aided compaction slightly.

5. EXPERIMENTAL LAYOUT, CONSTRUCTION TIMING AND SALT CONTENTS AFTER COMPLETION

The Lüderitz experiment consists of twelve sections each 60 m in length comprising sections with and without added binder, additions of 0,2, 0,5, 1 and 2% deliberately added NaCl, 2, 10 and 20% deliberately added gypsum, as well as three seawater sections. Crushed stone with binder compacted with freshwater as used over the rest of the road served as control sections at each end of the experiment.

Details of the seawater sections and the nearest control sections are shown in Table 2. The two seawater bases received a normal slush with seawater and the controls a normal slush with freshwater. Most of the other sections only received a light slush (water roll) with fresh water. Seawater was also used in the shoulders of the two seawater bases and the two seawater subbase sections.

Table 2: Mean as-built 60-m long base materials test results on Lüderitz seawater and control sections [1]

Section	Additive				EC	Gyp-sum	Percentage passing by mass								GM	PI	COMP. OMC	CBR					Field water content [7]	
																		Lab. & Field @ 98% [5]	Field DCP [6]					
																			LHS		RHS		LHS	RHS
	Binder	NaCl	Gypsum	[2] Water Base / Rest	[3]	[4]	37,5 mm	26,5 mm	19,0 mm	13,2 mm	4,75 mm	2,00 mm	425 µm	75 µm					DN	CBR	DN	CBR	0-25 25-150 mm	0-25 25-150 mm
No.	+ %	+ %	+ %	Type	S/m	%										%	%	%	mm /bl.	%	mm /bl.	%	%	%
4 [8]	8	0,5	-	Fresh / fresh	0,51	0,2	100	90	76	66	43	32	18	7	2,43	NP- SP	99 7,5	75	-	-	-	-	1,2 1,6	1,7 1,0
10	5	-	5	Sea / fresh	0,43	4,4	100	86	67	57	37	28	18	9	2,45	SP -4	101 5,4	200 400	2,7	150	3,2	120	2,9 3,1	2,5 2,4
11	8	-	-	Sea / sea	0,40	0,5	100	82	66	56	35	25	15	6	2,54	SP	101 5,8	300 400	2,9	140	3,4	110	2,1 2,5	1,6 1,4
12	8	-	-	Fresh / sea	0,15	0,3	100	83	64	52	35	25	14	7	2,54	SP	101 5,3	- 320	-	-	-	-	- -	- -
14 [9]	8	-	-	Fresh / fresh	0,09	-	100	88	67	55	34	24	14	6	2,56	SP	100 5,1	200 270	3,5	105	2,1	210	- -	- -

Notes:

[1] Sampled on 20-21 March 1976 after compaction, but before slushing for indicators and CBR; gradings are means and soil constants min. and max. of three Namibia Roads Branch central lab. results at 20L, 30CL and 40 mR points

[2] Seawater was used in the shoulders of Sections 10 - 13 only (mean shoulder GM 1,79; PI 6). Except for Section 10 'rest' means all other layers including shoulders

[3] EC after slushing with sea or fresh water as appropriate (means of 4 - 7 central lab. results)

[4] Gypsum as $CaSO_4{\bullet}2H_2O$. Means of 2 - 6 central lab. results on same samples for EC after slushing with sea or freshwater as appropriate, using what became TMH1:1986 Method A22 (NITRR, 1986a)

[5] Laboratory soaked CBR at 98% and field compaction. Central lab. results on one sample from middle of each section

[6] In-situ DN in mm/blow and CBR estimated from Fig. 10 average in Kleyn (1975) using CSIR 30 º cone at in-situ water content after surfacing (first slurry LHS 24 March, RHS 10 April); three per lane near middle of sections

[7] Just before priming: LHS 21 March, on day after bases completed on 20-21 March**; RHS 08 April 1976 after 18 days of exposure;** from near middle of section; all 0-25 mm and 25-150 mm; Sections 4 and 11 midlane (1,7 m L or R) only; Section 10 means of 0,5 and 2,5 m from edge of future seal. All after drying at 110º C. Results for Section 10 with 5% gypsum added all about 1% point lower after drying at 50º C

[8] Control section with 0,5% added NaCl but with freshwater in all layers

[9] Control section of normal construction with freshwater in all layers. Seawater used in lower selected and shoulders of adjacent Section 13 (Table 4)

Although the stone and additives were not always well-mixed, the base was thoroughly broomed and very little fines were present on the base after brooming. A normal light spray of water was usually used before priming.

It was intended that one lane should be primed and sealed as soon as possible and the other when convenient a few weeks later. The actual timing achieved is shown in Table 3. The effect of a longer delay of up to 18 days between priming and sealing and the effect of different primers and application rates was studied by means of small-scale (1 m x 2 m) priming experiments with MC-30, MC-70, 3/12 evt tar and invert emulsion (MSP1) primes (NIRR, 1970; NITRR, 1986b) and a spray grade emulsion tack (i.e. with no prime) in the otherwise unprimed right lane. Short sections of base were also left completely unprimed.

Table 3: Construction timing of the Lüderitz experiment

Delay Between:	Left Lane [1]	Right Lane [1]
Base [2] and priming	1 day	18 days
Priming and tacking and chipping	3 days	1 day
Tack and top sprays	0 days	0 days
Top spray and first slurry [3]	1 day	1 day
First and second slurry	9 weeks	7 weeks

Notes:
[1] Stake value (SV) zero at Aus; left lane Lüderitz-bound, right Aus-bound
[2] Base completed on 21 March 1976
[3] Slurry rolled (2 passes), construction trafficked and opened to general traffic within the following few days

The Contractor estimated that 6% water was added for compaction plus a 2% allowance for evaporation plus another 2% for slushing, i.e. 10% by mass in all. The measured EC of about 0,5 S/m for the seawater bases was about the same as those at Swartklip and Lambert's Bay (Netterberg, 2023).

The average EC of the seawater bases did not change significantly between completion and surfacing. However, the EC of the right-hand lane of Section 12 with freshwater in the base only, doubled from the expected 0,09 as in Section 14 to 0,18 S/m after completion, indicating pickup during construction from the seawater subbase. It then almost trebled to 0,25 S/m after two weeks of exposure (Table 4), during which the ratio of the EC of the upper 25 mm to the rest of the base increased (not shown), indicating upward migration within the base, and/or the addition of windblown sea salt, which can penetrate up to about 10 km inland (Callaghan, 1984). The ECs in the sealed lane did not change significantly.

The measured salt contents of the Lüderitz bases and lower layers after compaction and with time are shown in Table 4. Once again, the ECs of the added salt sections are lower than expected. Although a large variation in the ECs is evident and was expected, the mean for each section agreed well with the nominal salt content added. As the solubility of NaCl is about 36% m/v, some 2,0% salt could be held in solution at the MAASHO OMC of 5,5%. At about half this, which is a likely equilibrium moisture content for a base in an arid area (Emery, 1992) only about 1,0% could be held. Any excess salt built into the base will thus tend to crystallize, with resultant possible damage, as the base tends towards equilibrium.

Table 4: As-built salt (as EC) and gypsum contents and changes in EC with time

Section no.					**10**	**11**	12	**13**	14
Base [1]		Units							
		Binder		+%	5	8	8	-	8
		Gypsum		+%	5	-	-	-	-
		NaCl		+%	-	-	-	-	-
		Water		Type	**Sea**	**Sea**	Fresh	Fresh	Fresh
Gypsum and EC at	Completion	**Gypsum** [9]							
			Mean	%	4,4	0,50	0,30	0,19	-
			Min.	%	3,1	0,44	0,25	0,17	-
			Max.	%	5,9	0,67	0,34	0,20	-
		EC [10]							
			Min.	S/m	0,37	0,21	0,13	0,06	0,09
			Max.	S/m	0,47	0,54	0,23	0,09	0,10
			Mean	**S/m**	**0,43**	**0,40**	**0,15**	**0,07**	**0,09**
		LHS	Mean	S/m	0,40	(0,51)	(0,13)	0,07	0,09
		RHS	Mean	S/m	0,47	0,35	0,18	0,08	0,09
	2 Weeks [6]	LHS		S/m	0,34	-	0,16	0,15	-
		RHS		S/m	-	-	0,25	0,11	-
	2 Months [7]	LHS		S/m	0,51	-	0,16	0,08	-
		RHS		S/m	0,40	-	0,29	0,07	-
	7 Months [7]	LHS		S/m	0,40	-	0,15	0,07	-
		RHS		S/m	0,36	-	0,27	0,08	-
	14 Months [7]	LHS		S/m	0,33	-	0,24	0,08	-
		RHS		S/m	0,42	-	0,33	0,11	-
	36 Years [8]	LHS		S/m	0,45 0,39	1,77	-	-	0,49
		RHS		S/m	0,39	1,24	-	-	-
Subbase [2]			Water	Type	Fresh	**Sea**	**Sea**	Fresh	Fresh
EC at:	Completion			S/m	0,09	0,37	0,40	0,08	0,09
	2 Weeks [6]			S/m	0,20	-	0,38	0,09	-
	14 Months [7]			S/m	0,22	-	0,37	0,11	-
Upper Selected [3]			Water	Type	Fresh	**Sea**	**Sea**	Fresh	Fresh
EC at:	Completion			S/m	0,09	0,54	0,59	0,14	0,08
	2 Weeks [6]			S/m	0,21	-	0,39	0,15	-
	14 Months [7]			S/m	0,28	-	0,69	0,26	-
Lower Selected [4]			Water	Type	**Sea**	**Sea**	**Sea**	**Sea**	Fresh?
EC at:	Completion			S/m	**-**	**-**	**-**	**-**	-
	2 Weeks [6]			S/m	0,49	-	0,63	0,49	-
	14 Months [7]			S/m	0,41	-	0,53	0,48	-
Shoulders [5]			Water	Type	**Sea ?**	**Sea**	**Sea**	**Sea ?**	Fresh
EC at:	Completion			S/m	0,15	0,31	0,25	-	-
	2 Weeks [6]			S/m	0,34	-	0,23	0,17	-
	14 Months [7]			S/m	0,27	-	1,15	0,24	-

Notes:

[1] Base completed on 20 - 21 March; LHS primed 21 March; RHS 08 April 1976. Small priming experiments in right lane on Sections 4, 10, 11 and 13 **(embolded)** on 22 March 1976

[2] Subbase completed on 4 - 5 March (Sections 1-13), 13 March 1976 (Section 14). ECs means of mostly 2 - 3 samples

[3] Upper selected subgrade completed on 28 Feb. (Sections 1-13), 04 March 1976 (Section 4). ECs mostly single samples initially and means of 3 - 4 later

[4] Lower selected subgrade completed on 06 Feb. (Sections 1-13), 03 March 1976 (Section 14). ECs mostly on single samples. after initially and means of 3 - 4 subsequently. Final fill completed 14 - 24 Jan. 1976, with EC of 0,2 – 0,3 S/m (not tested subsequently). Figures bracketed estimated from results on passing 0,425 mm fractions

[5] Shoulders tested for compaction on 16 March 1976

Table Notes: Cont'd

[6] Two **weeks,** after surfacing (to first slurry). (LHS primed; RHS still unprimed)
[7] Time periods in **months** are after first **slurry** on LHS 24 March, RHS 19 April 1976
[8] Sampled on 29-30 March 2012. All VKE Namibia results except for 1,24 S/m on Section 11 by ANALAB, Windhoek; pH according to TMH 1 Method A20 but on minus 2,00 mm fraction 7,0 – 8,1
[9] Base gypsum (as $CaSO_4.2H_2O$) means of mostly 2 – 4 samples. Neat gypsum ccontent of G3 base mostly 0,1 – 0,2%; calcrete subbase 0,3 – 0,4%; calcrete shoulders 0,3 – 0,5%
[10] EC means of 5 – 7 samples. Neat EC mostly about 0,10 S/m. Min., max. and mean for section (i.e. both lanes) **include** centreline results. LHS and RHS lane results **exclude** them. Results bracketed in lanes at completion include one or more estimated from results on minus 0,425 mm fraction
[11] **Not in table**: Water contents in March 2012: Upper 25 mm: mean 2,5% (0,8 – 8,6%; *n* = 5); Rest of base: mean 1,5% (0,7 – 2,2%; *n* =14); whole base from Sections 9 and 10 **at 60ºC**: mean 1,9% (1,4 – 2,5%; *n* = 9), at 107ºC: mean 3,0% (2,1 – 4,9%; *n* = 9)

It may therefore be risky to seal a crushed stone base in an arid or semiarid climate with a content of NaCl greater than about 1,0%, equivalent to an EC of 1,1 S/m with NaCl or 1,05 S/m with sea salt according to NITRR Method CA-21. According to this concept the amount of salt tolerable should be proportional to the equilibrium moisture content, which in turn is proportional to the OMC. If the upper base dried out, less would be tolerable.

Although the full length was always inspected, most work and all sampling were limited to the central 20 – 40 m of these short 60 m sections in order to allow for contamination between sections.

In the case of the Section 10 seawater base, the EC of the full thickness of base was not found to change significantly between completion and surfacing, nor was there much difference between the lanes over the 14-month period of testing and even after 35 years.

As halite (NaCl) does not form hydrates at the temperatures involved, and as its solubility in water is almost independent of temperature, ranging only between 35,7 g/100 g water at 0ºC and 37,8 g/100 g water at 70ºC (Perry & Green, 1984; with similar data in Lide, 1992), the main factor controlling the amount of salt tolerable in a pavement layer is the amount of **free water** it contains. (Free water is water present as liquid and not part of a mineral such as gypsum ($CaSO_4{\bullet}2H_20$) or clay minerals and is thus available for compaction and plasticity).

The water contents of the density samples of the Lüderitz base courses after compaction ranged between 2,0 and 5,0%. If the result is corrected for the gypsum content, then the average **free** water content was 2,0 – 3,6%, with an average of 2,8%, thus supporting the suggested maximum of 1,0% NaCl or an EC of about 1,7 S/m, during construction, at least.

As, in contrast to NaCl, the solubility of natural gypsum is only 0,22 g $CaSO_4{\bullet}2H_2O$ / 100 g pure water at 0ºC and 0,25 g / 100g at 70ºC (calculated by author from data as $CaSO_4$ in Perry and Green, 1984) very little can be dissolved in pure water and its migration and crystallization in significant amounts is therefore unlikely under most conditions. Like NaCl, its solubility is little affected by temperature. Although its solubility is increased in the presence of NaCl, this effect is not great and the added amounts of up to 20% were not found to be detrimental in the G3 bases at Lüderitz and Haalenberg (Netterberg, 2021). Water content determinations on Sections 4, 10 and 11 at Lüderitz, two months after the first slurry seal ranged between 1,2 and 3,1% or 1,3 – 2,3% with a mean of 1,8% **free** water when corrected for the gypsum content. Such an average water content could only hold about 0,6% NaCl in solution in the base as a whole. As the water contents of the upper 25 mm of the base were mostly 0,1 – 0,4% lower, a maximum of about 0,5% NaCl would be indicated for this critical upper part of the base.

Water contents of five samples of the upper 25 mm of base at Lüderitz after 35 years ranged between 0,8 and 8,6% (both extremes on Section 14, others 2,3 – 6,8%), averaging about 2,5% and 0,7 – 2,2% (average 1,5% for 14 samples of the rest (i.e. 25 – 150 mm) of the whole of the 150 mm base were similar to the 1,4 – 3,1% found after two months. At a solubility of 36 % and round figures of water content of 1,0 and 1,5 %, about 0,35 and 0,5% NaCl could be held in solution, respectively. Checks on Sections 9 and 10 to which gypsum had been added yielded water contents of 1,4 – 2,6% with a mean of 1,9% after drying to constant mass at 60ºC and 2,1 – 4,9% (mean 3,0%) after the usual overnight drying at 105 - 110ºC, differences of 0,4 - 2,4 percentage points.

From the water content determinations and solubility considerations it is **concluded** that an upper limit of about 0,5% NaCl in the whole base course (equivalent to a < 6,7 mm EC of about 1,0 S/m) should be safe under conditions similar to those at Lüderitz.

After about one year the average EC of the gypsum-seawater base (Section 10, initially at 0,43 S/m) and the freshwater base with the seawater lower layers (Section 12, initially at 0,15 S/m) was found to be about the same at about 0,3 – 0,4 S/m in both lanes, the left and right lanes being 0,33 and 0,42, and 0,24 and 0,33 S/m of the two sections, respectively. The EC ratios, i.e. the ratios of the EC of the upper 25 mm to the EC of the rest of the layer (not shown), had dropped to about unity, indicating that the salt was evenly distributed vertically within the base. From this it is **concluded** that there is little long-term value in restricting the seawater to the top of the subbase, although it should help to prevent any salt damage to the primed base if it has to stand for long before sealing. The plain seawater base (Section 11) was not tested, but probably behaved similarly.

The EC of the base of Section 2 without added binder on a saline dorbank subbase with an EC of 0,52 S/m approximately doubled from an initial 0,08 S/m to about 0,18 S/m within less than a year (not shown), whilst that of the subbase had decreased and those of the selected layers had increased. This, together with the findings from the seawater subbase of Section 12 and the decrease with time of the EC of the seawater base of Section 10 together with the increase in EC of the selected layers, show that significant salt migration can take place both upward from the subbase into a sealed base over a distance of about 150 mm, as well as downward from the base or subbase to a distance of at least 300 mm. In the case of Section 10 one cannot of course say whether the increase of EC in the upper selected was due to migration from the base or the lower selected, which latter is more likely.

The average salt content of the **seawater shoulders** on Sections 10-13 at Lüderitz had at least doubled from about 0,15 - 0,3 S/m after compaction to as much as 1,2 S/m in the case of Section 12 after one year and they also became loose to a depth of about 10 mm. Experience elsewhere on this road was that the surface of similar subbase started to become loose when the EC of the subbase rose above about 0,4 S/m. The source is presumed to have risen from the lower layers and/or been added by windblown salt.

6. PERFORMANCE DURING AND SOON AFTER CONSTRUCTION

The performance of this experiment was monitored by regular inspections of a panel consisting of members of the Namibian Department of Transport and the author, who was also present throughout construction. Salt stains and/or salt glazing were evident both before and after priming on all the sections of base containing 0,5% or more of added salt and also to a much lesser degree on the seawater sections. This did not receive any special attention. The salt and seawater sections retained their moisture longer and did not dry out as rapidly as the control sections. The depth of primer penetration on these sections was also reduced and the primer took longer to dry.

When the right lane was primed 18 days after completion of the base neither the bare base nor any of the small-scale patches of primer had become significantly damaged by salt. However, in general, within the first ten days the upper 1 mm of the base had become loose on the seawater sections and also where the primer had penetrated most on the small-scale priming experiments. This was regarded as negligible and acceptable and did not require any special treatment. The primer overspray (i.e. that part of the primer on the edge of the base not intended to be sealed) along the outer edge of the seal of the south lane had become very slightly loose in a few places within about ten days of spraying. This occurred on most sections except the controls. By 14 April 1976 about 5% of the area of the overspray on the 0,5% salt section was affected but less than 1% on the control sections. This overspray always became loose when it was on the shoulder.

7. LONG-TERM PERFORMANCE

An inspection one year after sealing showed no significant damage to any section. However, rare hair cracks, salt stains and/or wet patches were noticed on the seawater base and the 0,5% salt sections, suggesting that the seal was not impermeable. These were limited to the areas of the seal outside the wheel tracks. All signs of the primer overspray had disappeared even on the freshwater control sections. However, most of the full 300 to 500 mm width of the normally exposed base at the edge of the seal had received a slurry seal (here called slurry overspread) that would have covered most of the overspray. This slurry became loose where it was on the shoulder.

In 1979, three years after sealing, similar, barely noticeable hair cracks were observed over the full width of **all** sections including the freshwater controls. About 10% of the area of the slurry overspread on the seawater sections had become loose. The gravel shoulders of the seawater sections had become loose to a depth of about 25 mm. All of this was considered acceptable by the panel in this environment.

The inspection panel concluded that – with precautions – seawater could be used for the compaction of all layers including the shoulders and crushed stone base course. (It was known that salt damage normally appeared within about one year of surfacing.) However, blanket permission for the use of seawater should **not** yet be given. No significant further deterioration had occurred at Lüderitz or Haalenberg when inspected by the author in 1981, i.e. after five years of service and all sections were regarded as acceptable. In 1986 it was reported that no further deterioration had taken place, that none of the sections had been patched or resealed, that the road was not on the programme for resealing, and these reports were confirmed by panel inspections carried out both in1991 and after 36 years in 2012.

8. PAVEMENT EVALUATION

A pavement evaluation carried out in 1979 showed little difference between any of the sections, in either condition or expected structural capacity.

Radius of curvature measurements of the deflection bowl under an 80 kN wheel load using a Dehlen (1962) curvature meter according to TMH6:1984 showed values averaging about 180 m for the seawater sections and 150 m for the control sections. In general, those sections containing salt and/or gypsum showed higher radii of curvature than the control sections, indicating that the former base courses were stiffer. The lowest reading anywhere on any section was 102 m. These measurements showed that the structural condition of the upper pavement (especially the upper 300 mm) was good and that the salt, gypsum and seawater had **not** reduced the expected structural capacity life of the pavement. All radii of curvature were also well above the 25 to 30 m below which fatigue cracking of the surface would be expected, supporting the view of the inspection panel that the surfacing cracking seen on **all** of the sections was due to shrinkage cracking (crazing) of the slurry and not flexure-related fatigue cracking.

There was no significant difference between the average rut depth (about 5 mm), smoothness (about 5 mm) and riding quality (about 3,3 PSR) between any of the sections.

The in-situ permeability of the surfacing to air measured according to ASTM D3637-84 with the grease gun sealer but without the weight at a head of 6,4 mm of water varied between 0,9 and 2,6 mℓ/cm^2/minute on the control sections and 1,1 and 6,2 mℓ/cm^2/minute on the gypsum-seawater base section. All except two readings on the latter section were below 1,9 mℓ/cm^2/minute. The three spots on the seawater section with permeabilities in excess of the 1,7 mℓ/cm^2/minute suggested by the work of Netterberg (1979) as necessary to prevent salt damage to asphalt-surfaced pavements with an excess of highly soluble sulphates in the base course were not damaged, suggesting that the salt contents (EC of about 0,5 S/m) of the seawater section were insufficiently high to cause damage to a 19 mm Cape seal with two coats of slurry, even when relatively permeable. However, an upper limit for permeability of about 2,5 with an average of 2,0 mℓ/cm^2/minute is suggested.

9. CONCLUSIONS

- Seawater can be successfully used for the compaction and slushing of a G3 crushed stone base whether containing gypsum or not, as well as for the underlying layers under a 19 mm Cape seal and for the unsealed shoulders, in a climate such as at Lüderitz (BWk'n: cool dry desert with frequent fog), for a road pavement with a design life of at least 20 years.
- The performance of the seawater bases was similar to that of sections of similar EC (about 0,5 S/m) to which 0,5% salt (NaCl) had been deliberately added.
- The performance of the crushed stone base sections containing added salt at Haalenberg (40 km inland) (not shown here).was similar to that at Lüderitz.
- Seawater could therefore also have been used for compaction of all layers at Haalenberg (BWh: hot dry desert) and therefore for the whole road as far as would have been economic, and probably under any climatic conditions anywhere.

- At any time of the year under conditions similar to those at Lüderitz a crushed stone base with soil binder compacted with seawater can be left unprimed for at least 18 days (at least 15 days at Haalenberg) without suffering significant loss of density. The presence of seawater and/or other salt will cause the base to dry out more slowly.

- Also under Lüderitz conditions a primed crushed stone base with soil binder compacted with seawater and/or with a similar EC can be left for at least 17 days (14 days at Haalenberg) without suffering significant primer damage. However, very slight and acceptable looseness may occur within ten days when the EC is more than about 0,5 S/m. This should not require any special treatment. [However, experience on other roads indicates that provision for sealing within one week is advisable at an EC of more than 0,5 S/m, especially (and possibly only) if excess fines are present on the top of the base.] The presence of seawater and/or salt may cause the depth of primer penetration to be less than normal, the primer to take longer to dry and to a reduced application rate of primer being desirable. Any reduction in the primer rate should be compensated for by increasing the tack rate in order not to compromise surfacing permeability, durability and bond.

- Under Lüderitz conditions a highly saline crushed stone base can be left for a total of at least 19 days after compaction before sealing without suffering damage, whether primed or unprimed. At Haalenberg (40 km inland) at least 15 days is allowable.

- Little difference was found between the performance of the different types and application rates of the primers tried. However, none became significantly damaged.

- Under these conditions a prime coat can be omitted. However, the tack spray should then be increased by 0,15 ℓ/m^2 (NITRR, 1986b).

- Salt damage to such bases is likely to be limited to looseness or loss of all or most of the primer overspray within one year and, within three years, some looseness, cracking or loss (10%) of the slurry overspread on the base, general looseness of the gravel shoulders to a depth of about 25 mm and, at salt contents of more than about 1% NaCl, (< 0,67 mm EC of 1,5 S/m) some hair cracking (possibly representing incipient blistering and / or simply crazing of the slurry). No additional maintenance of the seal should be necessary within the first ten years.

- In order to avoid any risk of salt damage within the critical first few years to a 19 mm new-type Cape seal used with or without a primer on a 150 mm G2 or G3 quality crushed stone base with or without soil binder the EC of the completed base should be limited to a maximum of about 1,5 S/m when sealed. EC tests should be carried out on all samples taken for gradings and indicator tests and the average value for each lot of base (say 6 000 to 8 000 m^2) should not exceed about 1,2 S/m. In addition, the air permeability of the surfacing, as measured with a Soiltest Asphalt Paving meter according to ASTM D3637 at a pressure head of 6,4 mm of water, should probably not exceed an average value of 2,0 and a maximum of 2,5 m ℓ/cm^2/min.

- The foregoing conclusions do not apply to more finely graded or natural gravels such as calcrete, which may suffer severe primer (and possibly some surfacing) damage under these conditions (not discussed here).

- A primer alone or a slurry seal on a primer are inadequate surfacings even on a crushed stone base under these conditions and will be rapidly destroyed on a gravel base or shoulder.

- Gypsum was not harmful in base courses under the conditions of the experiment and may actually exert a weak cementing effect (Netterberg, 2021).
- The use of seawater and/or high salt contents and/or high gypsum contents does not reduce the structural life of a pavement under these conditions.
- The salt content of a base of initially low salinity will increase both during exposure and after sealing if placed on a subbase of higher salinity.
- Salt from a seawater subbase may be picked up during construction and will also migrate into the base course and within one year the salt content of the base course will be nearly as high as that which it would have been if it had been compacted with seawater in the first place. The addition of windblown sea salt to exposed layers during construction must also be considered.
- There is little long-term value in restricting the use of seawater or excessively saline materials to the subbase unless an intervening impermeable membrane is utilised. However, in the short term (i.e. during construction) such restrictions may prevent or minimise damage to the primed base if it is left exposed for more than two to four weeks before sealing.
- Under a relatively impermeable surfacing the salt in a base becomes evenly distributed vertically within the base within one year.
- Under the conditions of the experiment at Lüderitz any thermal salt pumping action, diffusion or any other process was acting to even out and not to concentrate the salt in the upper base.
- Calcrete natural gravel shoulders compacted with seawater on lower layers also compacted with seawater became loose to a depth of 10 mm within one year and to 25 mm within three years.
- The salt content of these shoulders increased from an initial EC of 0,3 S/m after compaction to 0,6 S/m after one year. (Experience elsewhere on this road was that the surface of similar subbase started to become loose when the EC of the full thickness of subbase rose above about 0,4 S/m.) Seawater should not be used for the compaction of gravel shoulders if such looseness is not tolerable.

10. ACKNOWLEDGEMENTS

These experiments were constructed to the author's design with the enthusiastic support of the Chief Roads Engineer Mr HJM Williamson for the Roads Branch of the then South West Africa Administration as part of the Lüderitz-Haalenberg contract. The Consulting Engineers were Messrs Jeffares and Green and the Contractor LTA. The author was present throughout construction of the base courses and surfacing and led practically all of the subsequent monitoring. Mr H Rakow of the Department assisted with much of the work and the inspection panel generally consisted of Messrs L von Solms and H Rakow of the Department and the author. During construction and for some years thereafter the author was in the employ of the NITRR of the CSIR. Mr F J Haupt of the NITRR assisted with the radius of curvature measurements in 1979. The 2012 team consisted of Messrs C Silombela, D Gawaseb and L Shikongo of the NRA, P du Toit, B Boshoff and J Dongwi of VKE Namibia, and the author. This report is mostly based upon a more comprehensive report by the author in 2013 to the Roads Authority of Namibia, and a summary to the Water Research Commission (Netterberg, 2022) which are used with their permission.

However, the findings and opinions expressed are those of the author and not necessarily those of the Authority, or any of the above.

11. REFERENCES

American Society for Testing and Materials. 1998. ASTM D3637-84 (Reapproved 1991): Standard test method for permeability of bituminous mixtures. In: Ann. Book ASTM Standards 04.03, 356-361.

Callaghan, BG. 1984. Long-term atmospheric corrosion programme results after 10 years of exposure. National Building Research Institute Reprint R/BOU1146.

Committee of Land Transport Officials. 1996. TRH4:1996: Structural design of flexible pavements for interurban and rural roads. DoT, Pretoria.

Committee of Land Transport Officials. 1998. COLTO:1998: Standard specifications for road and bridge works for state road authorities. S. Afr. Instn Civil Engrs, Yeoville.

Dehlen, GL. 1962. Flexure of a road surfacing, in relation to fatigue cracking, and factors determining it severity. Highway Res. Road Bull, 321:26-39.

Department of Transport. 1970. Standards methods of testing materials. DoT, Pretoria.

Emery, SJ. 1992. The prediction of moisture content in untreated pavement layers and an application to design in southern Africa. Div. Roads Transp. Tech. Bull. 20, CSIR, Pretoria.

Kleyn, EG. 1975. The use of the dynamic cone penetrometer (DCP). Transvaal Roads Dept. Rep. 2/74, Pretoria.

Lide, DR. (ed.) 1992. CRC handbook of chemistry and physics. 73rd edn. CRC Press, Boca Raton, Sec. 4, p. 98.

National Institute for Road Research. 1970. TRH1:1970: Guide on prime coats, tack coats and temporary surfacings for the protection of bases. NIRR, CSIR, Pretoria.

National Institute for Road Research. 1971. TRH3:1971: Bituminous surface treatments for newly constructed rural roads. NIRR, CSIR, Pretoria.

National Institute for Transport and Road Research. 1980. Determination of the electrical conductivity and pH of a soil paste or water and qualitative tests for sulphate, chloride and carbonate or bicarbonate. NITRR Test Method CA 21-74 (1980), CSIR, Pretoria.

National Institute for Transport and Road Research. 1984. TMH6:1984: Special methods for testing roads. NITRR, CSIR, Pretoria.

National Institute for Transport and Road Research. 1986a. TMH1:1986: Standard methods of testing road construction materials. NITRR, CSIR, Pretoria.

National Institute for Transport and Road Research. 1986b. TRH1:1986: Prime coats and bituminous curing membranes. NITRR, CSIR, Pretoria.

Netterberg, F. 1979. Repair of salt-damaged asphalt surfacings on the Witwatersrand. Proc. 3rd Conf. Asphalt Pavements S. Afr., Durban, 1:137-141; 2:42-43.

Netterberg, F. 2021. Gypsum in saline and non-saline road bases: Effects and limits derived from long-term road experiments in Namibia. Proc 39th Southern Afr. Transp. Conf., Pretoria, Session 2A, 19 pp.

Netterberg, F. 2022. The use of non-potable water in road construction. Water Res. Comm. Rep. No. 3035/1/22. WRC, Pretoria.

Netterberg, F. 2023. The use of seawater in road construction: Part 1. The Swartklip and Lambert's Bay Experiments. Proc. 40th Southern Afr. Transport Conference, Pretoria, Session 1A, 16 pp.

Perry, RH & Green, DW. (Eds). 1984. Perry's chemical engineers' handbook. 6th edn, McGraw-Hill, New York.

Schulze, BR. 1947. The climates of South Africa according to the classification of Köppen and Thornthwaite. S. Afr. Geog. J., 29:32-42.

Weinert, HH. 1980. The national road construction materials of southern Africa. Academica, Pretoria.