Review of Surfacings for Low-Volume Roads on the Basis of Experience in South Africa

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Local and overseas specifications and design methods of single, double, slurry, Cape, sand, primer, and Otta seals were compared to investigate potential surfacings for low-volume roads. The following conclusions were drawn: (a) aggregate is rigorously specified for single, double, slurry and Cape seals and little or no relaxation has been considered, whereas the specifications for sand, primer and Otta seals are not as rigorous; (b) binder is rigorously specified by relevant South African Bureau of Standards specifications for all seal types; and (c) formal design methods exist for single and double seals, but the designs of the other seal types are mostly empirical. A calculation of life cycle costs to road authorities over a 20-year period indicated that single and double seals are the most cost-effective over a wide range of traffic volumes. Low unit construction prices do not necessarily mean high cost-effectiveness, as the expected lifetime of the seal is an important consideration.

In many developing regions, traffic volumes are low and consequently local natural materials are usually used for the pavement layers. This process allows cost-effective provision of the road infrastructure, and also helps to stimulate local development. There is, however, one costly item in providing paved roads, namely the surfacing. Surfacing standards appropriate for higher traffic volumes have typically been used in the low-volume environment. This choice has frequently precluded the use of local materials, which may not comply with the rigid specifications required by the surfacing standards. The aim is to critically review the factors that affect the performance of potential surfacing types and, on the basis of experience in South Africa, to present guidelines for the use of these surfacings for low-volume roads. Although many roads in South Africa could be categorized as carrying medium-to-heavy traffic, more than 75 percent of the rural roads are surfaced with chip seals. The performance of surfacings is influenced by the characteristics and quantities of aggregate and binder used for constructing the surfacing, the support beneath the surfacing, and the traffic volume.

SPECIFICATIONS AND DESIGNS OF SEALS

Single and double seal

Aggregate is usually specified by grading, flakiness index, crushing strength (ACV or 10 percent FACT) and cleanliness or dust content. A typical specification (*1*) is presented in Table 1 for stone with a nominal size of 13.2 mm. This specification calls for surfacing stone of a fairly high standard. The strength requirement is the only characteristic that has been relaxed to as low as 80 kN (10 percent FACT) for low-volume roads (*2,3*). No relaxation of specifications for grading, flakiness index, cleanliness or dust content of the surfacing stone could be found in the literature (*4–8*). There are, however, different views on whether particle size and form of the stone should be relaxed at all (*2,9*).

Binder is specified by relevant standards, e.g., South African Bureau of Standards (SABS) specifications, which are often based on ASTM standards. Manufacturers have to comply with these specifications and no relaxation has been considered.

Design methods differ between road authorities. A rational design method was, however, developed by the Division for Road and Transport Technology, which lends itself to the design of surfacings for low-volume roads (*10–13*). With this method, the amount of binder required in a single or double seal is determined as a function of the void volume of the aggregate in the seal. A certain percentage of these voids must be filled with binder. The void volume on the other hand is dependent on the stone size, the embedment into the underlying layer, and the wear of the stone under traffic. Embedment can be determined with the ball penetration test (*14*). Relationships between traffic and embedment exists for traffic volumes as low as 125 vehicles per day (vpd) and bases as soft as 8 mm of ball penetration. The wear of the stone under traffic is a function of the crushing strength of the stone. Relationships between the 10 percent FACT value and wear exist for traffic volumes as low as 125 vpd and 10 percent FACT values as low as 150 kN. If these relationships can be extended for traffic volumes as low as, say, 50 vpd, soft bases (existing gravel road surfaces) and surfacing stone with low 10 percent FACT values, then the rational method developed by the Division for Road and Transport Technology can be used to design seals for low-volume roads with soft bases and aggregates with low crushing strengths.

Slurry Seal

Aggregate specifications for slurry seals are given in Table 2 (*15*). The Committee of State Road Authorities (CSRA) specification is used most frequently in South Africa. Aggregate quality is rigorously specified since it has been found that

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TABLE 1 TYPICAL SPECIFICATION FOR 13.2-mm NOMINAL-SIZE SURFACING STONE (*1*)

GRADING		CRUSHING STRENGTH	FLAKINESS
Sieve Size (mm)	Percentage passing by mass	Maximum aggregate crushing value (%)	Maximum flakiness index (%)
19,0	100	21	25
13,2	85-100		
9,5	0-30		
6,7	0-5		

relaxation of the specifications generally led to poor performance (*16*). Specifications permit a sand equivalent (*17*) as low as 35, but experience has shown that the sand equivalent should preferably be not less than 45.

The bitumen emulsion used for slurry manufacture is predominantly of the stable-grade anionic type as specified in SABS 309 (*18*). A variety of bitumens from 60/70 to 150/200 penetration can be used as the base bitumen in emulsion for slurry sealing. However, the bitumen selected is usually between 80/100 and 150/200 penetration, the lower penetration bitumens being used in the hot areas and for heavy traffic conditions, and vice versa (*19*). It is estimated that about 95 percent of emulsions used in South Africa for slurry sealing are of the anionic type and are used mainly with dolerite, dolomite, quartzite, and norite aggregates. This is in contrast to the rest of the world in which cationic emulsions are favored (*15*). The Transvaal provincial administration, for example, uses only anionic emulsion because cationic slurries tend to break too soon.

Cationic bitumen emulsion as specified in SABS 548 (*20*) has also been used in South Africa, mainly with quartzites and natural sands. Cationic emulsions give less stripping and consequently greater durability than anionic emulsions with aggregates that are hydrophilic (*15*).

Design methods are mostly empirical or semiempirical (*15*). Use of these simple design methods (aggregate gradings and bitumen content specified) is appropriate when good-quality aggregate can be obtained. When the use of aggregate that is outside the specification is considered for low-volume roads, the more sophisticated design methods such as the wet track abrasion test (WTAT) (*21–24*) and cohesion test (*25*) are preferred.

Cape Seal

Cape seal is a surface treatment consisting of a 9.5-, 13.2-, or 19-mm layer of stone placed shoulder to shoulder on a tack coat and covered with one or two applications of slurry so that the tops of the stones are left proud (*26,27*).

Aggregate specifications for Cape seals are essentially those for single and slurry seals. Aggregate of a high standard is thus specified and no examples of Cape seals built from lower standard material could be found.

Binder is usually one of, or a combination of, the following (*27*):

- Road tar (RTH 50/55), bottom spray of 19-mm surfacings;
- 150/200 penetration bitumen, bottom or cover spray;
- MC3000 cutback bitumen, bottom or cover spray;
- Cationic spray-grade emulsion, bottom or cover spray;
- Cationic stable-grade emulsion, slurry manufacture; or
- Anionic stable-grade emulsion, slurry manufacture.

Road tar is used in areas where it is cheaper than bitumen, but then only for the bottom spray of 19-mm surfacings with the cover spray consisting of a bitumen product. These binders are also specified by relevant SABS specifications and no relaxation has been considered.

Design of Cape seals is mostly empirical (*1,26,27*). The stone sizes for the single seal are related to traffic volume. The slurry is designed by specifying aggregate properties for a specific bitumen content. Cape seals have never been designed for low-volume road applications. Design methods proposed by Biesenbach and Alexander (*27*) allow for two categories of traffic: less than 1,000 vehicles per day (vpd) and more than 1,000 vpd. Although Campbell (*26*) provides for as low as 200 vpd in his design methods, the minimum traffic volume that Cape seals are normally used for is about 500 vpd (*27*). Aspects mentioned under single and slurry seal design should be considered when designing Cape seals for low-volume roads.

Sand Seal

Sand seals can be described as consisting of a cutback bitumen or emulsion tack coat and a suitably graded sand applied to a base course with or without a prime coat (*28*).

Aggregate gradings for sand seals are given in Table 3, which indicates that the TRH14 (*4*) and Mitchell (*28*) gradings are almost identical. These two gradings fall between the ideal and average grading proposed by Marais (*5*). Grading is the only aggregate property specified in the literature studied. The gradings proposed in Table 3 fall within a wide envelope; therefore, the aggregates that can be used in sand seals are not rigorously specified. However, some sand seals last longer than others. This can probably be attributed to the aggregate used for the construction of the seal. Further investigation

TABLE 2 STANDARD SOUTH AFRICAN SPECIFICATIONS FOR SLURRY AGGREGATES (*15*)

Requirement	SABS 1083	CSRA*			TRH3&TRH7 NITRR	CPA+	TPA+		NPA+	OTHER(21)		
		Coarse	Medium	Fine			Coarse	Fine		General Medium	Normal Coarse	Extra Coarse
Grading												
9,5mm	100	100	100	100	100	100	100	100	100	100	100	85-100
6,7mm	100	100	100	100	100	100	100	100	100	100	85-100	70-90
4,75mm	100	70-90	82-100	100	100	100	70-90	100	100	85-100	70-90	60-83
2,36mm	90-100	45-70	56-95	90-100	90-100	90-100	45-70	90-100	90-100	65-85	45-70	40-60
1,18mm	65-95	28-50	37-75	65-95	65-95	65-95	28-50	65-95	65-95	45-70	28-50	28-45
0,600mm	42-72	19-34	22-50	42-72	42-72	42-72	19-34	42-72	42-72	30-50	19-34	19-34
0,300mm	23-48	12-25	15-37	23-48	23-48	23-48	12-25	23-48	23-48	18-30	12-25	14-25
0,150mm	10-27	7-18	7-20	10-27	10-27	10-27	7-18	10-27	10-27	10-21	7-18	8-17
0,075mm	4-12	2-8	4-12	5-12	5-12	3-12	5-15	4-12	4-12	5-15	5-15	4-8
Maximum addition of suitable sand	25%		25%		25%	25%	25%		50%		N.S	
Fineness modulus**	2,0-3,8		N.S.		N.S.	N.S.	2,0-3,8		2,0-3,8		N.S.	
Minimum sand equivalent	35		35		N.S.	N.S.	35		35		N.S.	
Maximum ACV (Parent rock)	N.S.		30		N.S.	N.S.	30		30		N.S.	

N.S. - not specified

* Committee of State Road Authorities.

** Sum of cumulative percentages retained on the 4,75; 2,36; 1,18; 0,600; 0,300 and 0,150 mm sieves divided by 100.

\+ CPA; TPA & NPA - Cape; Transvaal & Natal Provincial Administrations

TABLE 3 PROPOSED GRADING FOR SAND TO BE USED IN SAND SEALS (*4,5,28*)

Sieve Size (mm)	PERCENTAGE PASSING BY MASS				
	MARAIS			TRH 14	MITCHELL
	Ideal	Average	Fine		
9,5	100	100	100	-	-
6,7	-	-	-	100	100
4,75	85-100	85-100	100	-	-
2,36	-	-	85-100	-	-
1,18	25-50	50-85	-	-	40-65
0,600	0-20	20-50	50-85	-	10-35
0,300	0-5	0-10	-	0-15	0-15
0,150	-	-	-	0-2	0-2
0,075	0-2	0-2	0-2	-	-

into the relation between the properties of the aggregate and the performance of the seal is thus warranted. This would enable designers to relate the expected performance of the sand seal to the quality of the aggregate used. Although sand seals were popular about 10 years ago in South Africa, variable performance and the difficulty in obtaining suitable sands has led to a preference for small-size single seals.

Binders used for sand seals are again rigorously specified by the relevant SABS specifications and no relaxation has been considered.

No formal method of design exists. Application rates for tack coat and aggregate proposed by two researchers are presented in Table 4 (*28,29*).

The proposed binder application rates do not correlate well. It is assumed that both rates are actual hot spray rates. Performance is most likely also subject to the amount of binder in the seal, although this has not been fully investigated. Further investigation into this aspect could lead to different application rates for different traffic volumes and consequently more cost-effective designs for low-volume roads.

Primer Seal

Primer seal is a combination of a priming and sealing operation and consists of the application of a primer binder with a viscosity midway between that of a primer and a seal bitumen covered by a layer of aggregate. This can be a single-size aggregate of nominal size 5, 7, or 10 mm or a graded crushed-rock aggregate or natural sand that mostly passes the 4.75-mm sieve (*6*).

Aggregate gradations for primer seals are presented in Table 5 (*5,30*). A comparison of the grading proposed by Marais for the sand seal and the primer seal reveals that the grading for the primer seal is much coarser than for the sand seal. However, the National Association of Australian State Road Authorities (NAASRA) primer seal grading (*30*) appears to correspond with the Marais sand seal grading (*5*), whereas the grading for the primer seal proposed by Marais is much coarser than even the ideal primer seal grading proposed by NAASRA.

There may be a small difference between the grading proposed for sand and primer seals, and Marais, in fact, uses the NAASRA primer seal grading for a sand seal. However, the primer seal grading proposed by Marais is considerably coarser than the grading proposed by NAASRA. As far as the aggregate is concerned, sand seals and primer seals are identical. Judging by the wide range of proposed gradings, the grading for a sand or primer seal may not be critical. It is also the only aggregate property specified. This then is the ideal type of surfacing for low-volume roads, as a wide range of materials can be used. However, the grading and strength of the aggre-

TABLE 4 TACK COAT AND AGGREGATE APPLICATION RATES FOR SAND SEALS (*28,29*)

	VISSER(28)	MITCHELL(27)
Tack coat (l/m^2)	1,25	1,5 - 2,0
Aggregate (m^2/m^3)	-	200

TABLE 5 AGGREGATE GRADING PROPOSED FOR PRIMER SEALS (*5,30*)

Sieve size (mm)	Percentage passing by mass				
	NAASRA			MARAIS	
	Ideal	Average	Fine	10 mm	7 mm
13,2	-	-	-	100	100
9,5	100	100	-	85-100	100
6,7	-	-	-	0-40	85-100
4,75	85-100	85-100	100	0-10	-
3,35	-	-	-	-	0-30
2,36	-	-	85-100	0-1	0-10
1,18	25-50	50-85	-	-	-
0,600	0-20	20-50	50-80	-	0-2
0,300	0-5	0-10	-	-	-
0,075	0-2	0-2	0-2		

gate must in some way influence the performance of the surfacing, and this aspect should be investigated further.

Binders for primers seals are again specified by the SABS and no relaxation has been considered.

Binder and aggregate application rates are presented in Table 6 (*5,6*). These rates correlate well with the application rates for the sand seal given in Table 4. The application rates proposed by Marais (*5*) allow for traffic volumes of less than 250 vpd and higher than 2,000 vpd, but do not accommodate the intermediate traffic volumes. The rates proposed by Dickinson (*6*) agree with the rates proposed by Marais for the RTH/RTL 35/40 and MC800 binder types. These binder types require less binder for the same aggregate application rate than the RTH/RTL 40/45 and MC3000 types. The binder application rates are well defined by Marais and Dickinson and correlate well. Because of the similarity in aggregate grading between the two seal types, the rates proposed for primer seals could probably be applied to sand seals as well.

TABLE 6 BINDER AND AGGREGATE APPLICATION RATES FOR PRIMER SEALS (*5,6*)

	Binder Type	Traffic Volume (vpd)	Application rates Binder (l/m^2)	Aggregate (m^2/m^3)
MARAIS (5)	RTH/RTL 35/40	<250	1,35	170-200
	MC800	>2000	1,10	170-200
	RTH/RTL 40/45	<250	1,50	125
	MC3000	>2000	1,20	125
DICKINSON (6)	-	<250	1,30	100-200
	-	250-2000	1,20	100-200
	-	>2000	1,10	100-200

Otta Seal

Otta seal is a surface dressing method using traditional equipment, working techniques, and binder. However, the covering aggregates are quite different from those conventionally used.

Although the traditional surface dressing requires more or less single-sized, dust-free stone, the Otta surfacing method prescribes the use of naturally occurring sandy gravel, including fines. The maximum size of the gravel can vary from 12 to 20 mm. The gravel is used at its natural water content, which usually varies from 3 to 5 percent by mass. Compaction is carried out by the combined effect of rolling and the addition of an adhesion-active agent (fatty amine) to the binder. The subsequent traffic also contributes substantially to the compaction.

Aggregate grading for Otta seals proposed by Marais (*5*) and Thurmann-Moe and Ruistuen (*31*) is presented in Table 7. The material is more uniformly graded and much coarser than aggregate used for primer and sand seals. The gradings proposed by the two researchers are similar. The grading requirements for the covering aggregate are modest and are normally the same as for base course material, although the maximum size is smaller.

Binder and aggregate spray rates proposed by Thurmann-Moe (*31*) and Marais (*5*) are presented in Table 8. No distinction is made between different traffic volumes in the design procedure.

As natural aggregates are used, the Otta seal has great potential as a surfacing option for low-volume roads. However, binder application rates for low traffic volumes will have to be established by further investigation.

COST-EFFECTIVENESS OF VARIOUS SURFACING TYPES

Cost-effectiveness should take cognizance of the costs to road authorities as well as to the road user. Costs to the authorities comprise initial construction as well as maintenance costs. User costs comprise vehicle operating, time, and collision

TABLE 7 GRADING OF NATURAL AGGREGATES FOR OTTA SEAL AS PROPOSED BY MARAIS (*5*) AND THURMANN-MOE (*31*)

Sieve Size (mm)	PERCENTAGE PASSING BY MASS		
	MARAIS		THURMANN-MOE
	Nominal 0-12 mm	Nominal 0-20 mm	
19,0	100	100	100
13,2	100	60-100	50 - 100
9,5	70-100	40-70	31 - 90
4,75	40-70	15-40	18 - 68
2,36	30-50	8-30	10 - 52
1,18	20-40	5-20	5 - 40
0,600	15-30	3-15	3 - 32
0,300	12-22	2-12	2 - 20
0,150	8-15	1-8	0 - 15
0,075	5-10	1-5	0 - 10

TABLE 8 BINDER AND AGGREGATE SPRAY RATES FOR OTTA SEALS RECOMMENDED BY THURMANN-MOE (*31*) AND MARAIS (*5*)

Nominal Size (mm)	Aggregate Spread Rate (l/m^2)	Binder Spray Rate (l/m^2)
0-12	12-15	1,5
0-20	20-25	2,0

costs. However, user costs are not considered in this analysis, which is assumed to be the same for all surfacing types. This assumption will, however, not be valid when surfaced roads are compared to gravel roads. The cost of resealing is considered to be the maintenance cost of the surfacing over the analysis period.

The life of a surfacing is a function of the following:

- Type of surfacing;
- Volume and type of traffic;
- Support from pavement structure;
- Quality of surfacing construction; and
- Environmental conditions, e.g., temperature and rainfall.

Table 9 presents estimates of the expected life of the surfacing types under the traffic volume ranges for which the surfacings are normally used. These data (except for the Otta seal) were collected by the Transvaal provincial administration over a number of years and assume a good-to-reasonable pavement condition. They represent about 70 percent of all the cases encountered (G. D. van Zyl, unpublished data). The factors influencing surfacing life must also be considered when a life cycle cost analysis is conducted using the information presented in Table 9.

Table 10, which presents the life cycle costs to the authorities over a period of 20 years [defined as the present worth of cost (PWOC)], was compiled from the unit costs presented in Table 10 and the expected lifespans and traffic volumes presented in Table 9.

A discount rate of 8 percent was used. In those cases for which 20 years was not a multiple of the lifespan of the seal, the salvage value at 20 years of the last reseal was taken as the unit price multiplied by the proportion of the surfacing life that still remains.

Table 10 can be used as a guideline for the type of seal to be selected for specific situations. However, the factors influencing surfacing life mentioned earlier must be kept in mind when a selection is made. This table indicates that single- and double-chip seals are cost-effective in most situations. Low unit prices do not necessarily mean high cost-effectiveness, because the expected lifespan of the seal has to be taken into account. Although this table is applicable to South African conditions, the logic used in developing the table as well as the surfacing lives can guide practitioners in other environments.

CONCLUSIONS

In South Africa, a proud and successful tradition in the use of surfacing seals has been established on low-to-medium-heavily trafficked roads. This approach could serve as a model for low-volume roads in a similar environment. In this review, the potential surfacing types were evaluated and the following conclusions regarding specifications, design methods, and use of surfacings for low-volume roads can be made:

- Binder to be used for the construction of the surfacing types is well specified from long-term experience, and no

TABLE 9 EXPECTED LIFESPANS AND ASSOCIATED TRAFFIC VOLUMES OF CERTAIN SURFACINGS (*31* AND G. D. VAN ZYL, UNPUBLISHED DATA)

SEAL	LIFESPAN (years)	TRAFFIC VOLUME (corrected vpd)*	TRAFFIC CATEGORY
Sand	3-5	400-2 000	1
Slurry (fine)	3-5	2 000-4 000	1-2
Single (9,5 mm)	10-12	2 000-4 000	1-2
Double Otta	10	1000 ADT**	1-2
Single (13,2 mm)	10-14	4 000-20 000	1-3
Slurry (coarse)	4-8	4 000-20 000	1-3
Cape (13,2 mm & slurry)	8-12	4 000-20 000	1-3
Double (13,2 mm & 6,7 mm)	10-14	4 000-20 000	1-3

* vpd: vehicles per day

corrected vpd: 1 heavy vehicle = 20 vehicle units

** ADT: Average Daily Traffic - assumed to be vehicles only with no correction for heavy vehicles. If 15 per cent heavies are further assumed, 1000 ADT will be category 2 traffic.

TABLE 10 LIFE CYCLE COST TO AUTHORITIES OVER 20 YEARS (PWOC, DISCOUNTED AT 8 PERCENT) FOR VARIOUS SURFACING TYPES

SEAL	LIFESPAN (years)	UNIT PRICE (R/m^2)	PWOC (8%) (R/m^2) TRAFFIC CATEGORY 1	2	3
Sand/primer	4	1,55	4,59*	-	-
Slurry (fine)	4	1,61	4,77	4,77	-
Single (9,5 mm)	10	1,75	2,56	2,56	-
Otta (double)	10	3,30	4,83	4,83	-
Slurry (coarse)	6	3,26	6,96	6,96	6,96
Cape (13 mm & slurry)	10	3,69	5,40	5,40	5,40
Double (13,2 mm & 6,7 mm	12	3,38	4,48	4,48	4,48

* Example: $PWOC = 1{,}55\{1 + 1/(1{,}08)^4 + 1/(1{,}08)^8 + 1/(1{,}08)^{12} + 1/(1{,}08)^{16}\}$

$= 4{,}59$

relaxation is considered possible without jeopardizing performance.

- Aggregates for single and double seals are well specified and carefully developed design methods exist. However, the specifications and rational design method could be extended to cater for lower traffic volumes.
- Aggregates for sand, primer, and Otta seals are generally not well specified, which may account for the considerable differences in performance of these surfacing types.
- Binder application rates for sand, primer, and Otta seals are also not well defined. This fact may also account for differences in performance.
- Single- and double-chip seals are cost-effective in most situations, as was demonstrated by the South African experience.
- The expected lifespan of the seal is an important consideration when determining cost-effectiveness.

RECOMMENDATIONS

The effect of aggregate properties and binder application rates on the performance of sand, primer, and Otta seals should be further evaluated to use these surfacing types for low-volume roads most cost-effectively.

The relationship between traffic and embedment of aggregate into road bases used in the rational design method of the Division for Road and Transport Technology should be extended to allow for traffic volumes lower than 125 vpd and bases softer than 8 mm of ball penetration. Furthermore, the relationship between the wear of stone under traffic and the crushing strength of the stone should be extended to allow for traffic volumes lower than 125 vpd and for aggregate with 10 percent FACT values of less than 150 kN. This condition will allow the rational design method to be used cost-effectively in the design of single and double seals for low-volume roads.

The following additional factors for defining appropriate seals for a specific project should be considered:

- In cases of no or irregular maintenance, seals which do not need regular maintenance, such as Cape seal, should be used.
- Because no general seal that would be most economical for all situations exists, each situation should be evaluated individually.
- Aggregate properties and binder application rates should relate to performance required.

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REFERENCES

1. Committee of State Road Authorities. *Standard Specifications for Road and Bridge Works*. CSRA Secretariat, Pretoria, South Africa, 1988.
2. M. P. O'Reilly and R. S. Millard. *Roadmaking Materials and Pavement Design in Tropical and Subtropical Countries*. Report LR 279, Road Research Laboratory, Crowthorne, Berkshire, U.K., 1969.
3. F. Netterberg and P. Paige-Green. *Pavement Materials for Low Volume Roads in Southern Africa: A Review*. South African Institution of Civil Engineers Annual Transportation Convention 88, Vol. 2D, Pretoria, South Africa, July 1988.
4. National Institute for Transport and Road Research. *TRH 14: Guidelines for Road Construction Materials*. CSIR, Pretoria, South Africa, 1985.
5. C. P. Marais. *Low Volume Roads in Developing Areas: Proposed Synthesis of Design, Construction and Maintenance*. Division of Roads and Transport Technology, CSIR, Pretoria, South Africa, 1989.
6. E. J. Dickinson. *Bituminous Roads in Australia*. Australian Road Research Board, Vermont South, Victoria, 1984.
7. S. W. Hudson, B. F. McCullough, and R. F. Carmichael. *Surface Design and Rehabilitation Guidelines for Low Volume Roads*. Report FHWA-TS-87-225. U.S. Department of Transportation, June 1987.
8. C. Overby. *Sebina-Tutume Road: Upgrading to Bitumen Standard 1979–1981*. Report 25. Botswana Roads Department, Gaborone, Africa, Nov. 1981.
9. B. H. Spottiswoode and R. W. V. Graham. *Design and Construction of a Low Cost Road at the West Coast*. Annual Transportation Convention, Session H, Johannesburg, South Africa, Aug. 1982.
10. National Institute for Transport and Road Research. *TRH 3: Surfacing Seals for Rural and Urban Roads and Compendium of Design Methods for Surfacing Seals Used in the Republic of South Africa*. CSIR, Pretoria, 1985.
11. C. P. Marais and C. J. Semmelink. A Rational Design Approach for Single and Double Surfacing Seals Based on the Modified Tray Test. *Proc., International Conference on Roads and Development*, Vol. 2, Paris, May 1984.
12. C. P. Marais. Design of Single Surface Treatments for Road Maintenance. *Proc., New Zealand Roading Symposium*, Session N. Road Research Unit, National Roads Board, Wellington, New Zealand, 1971.
13. C. J. Semmelink. A Rational Design Approach for Single and Double Surfacing Seals Based on the Modified Tray Test. In *Transportation Research Record 1106*, TRB, National Research Council, Washington, D.C., 1987, pp. 202–207.
14. C. P. Marais. *Advances in the Design and Application of Bituminous Materials in Road Construction*. Ph.D. dissertation, University of Natal, Republic of South Africa, Nov., 1979.
15. H. Wolff, C. P. Marais, and R. N. Walker. *Slurry Seals: A Survey of Material, Design, Construction and Performance Aspects*. Technical Note LVRN/1/90, Division for Road and Transport Technology, CSIR, Jan. 1990.
16. Zimbabwe-Rhodesia Government Ministry of Roads and Road Traffic. *The Use of Sand in a Slurry Seal*. Laboratory Record 2/80, Materials and Training Branch, Central Laboratory, Salisbury, Zimbabwe, March 1980.
17. F. N. Hveem, Sand Equivalent Test for Control of Materials During Construction. *Proc., 32nd Annual Meeting, Highway Research Board*, Publication 271, HRB, National Research Council, Washington D.C., 1953.
18. The Council of the South African Bureau of Standards. *Standard Specification for Anionic Road Emulsions*. SABS 309-1972 (as amended 1976), Pretoria, South Africa, 1972.
19. National Institute for Road Research. *TRH 7: The Use of Bitumen Emulsions in the Construction and Maintenance of Roads*. CSIR, Pretoria, South Africa, July 1984.
20. The Council of the South African Bureau of Standards. *Standard Specification for Cationic Bitumen Road Emulsions*. SABS 548-1972 (as amended 1974 and 1976), Pretoria, South Africa, 1972.
21. L. K. Davidson. Specification for the Construction of a Surface Treatment Consisting of a Single Layer of Thick Slurry Seal. Presentation at SABITA seminar, Bloemfontein, South Africa, Aug. 1981.
22. R. T. Young, R. J. Province, and E. F. Flock. *Bituminous Slurry Surfaces Handbook*. Slurry Seal Inc., Waco, Tex., 1973.
23. *Design Technical Bulletins*. International Slurry Seal Association, Washington, D.C., 1980.
24. C. R. Benedict. *Laboratory Tests and Testing Trends for Slurry Seal and Cold Overlay Design and Research: A State-of-the-Art Report*. ISSA Second World Congress, Geneva, Switzerland, March 1987.
25. J. Gordillo. *Road Maintenance—Slurry Seal*. E.S.M. Group of Companies, Madrid, Spain.
26. R. Campbell. Slurry Seal in New Construction. *Shell Bitumen Review*, Vol. 56, Sept. 1977.
27. W. J. Biesenbach and B. J. Alexander. The Design, Construction and Performance of the Cape Seal. *Proc., 3rd Conference on Asphalt Pavements for Southern Africa*, Durban, Republic of South Africa, 1979.
28. M. F. Mitchell, E. C. P. Petzer, and N. Van der Walt. The Optimum Use of Natural Materials for Lightly Trafficked Roads in Developing Countries. In *Transportation Research Record 702*, TRB, National Research Council, Washington D.C., August, 1979.
29. A. T. Visser and T. Van Niekerk. The Implementation of Appropriate Technology in the Design of Light Pavement Structures. In *Transportation Research Record 1106*, TRB, National Research Council, Washington D.C., 1987.
30. *Pavement Materials, Part 4—Aggregates*. National Association of Australian State Road Authorities, Sydney, 1982.
31. T. Thurmann-Moe and H. Ruistuen. Graded Gravel Seal (Otta Surfacing). In *Transportation Research Record 898*, TRB, National Research Council, Washington D.C., 1983.
32. A. T. Visser, J. H. Maree, and C. P. Marais. Implications of Light Bituminous Surface Treatments on Gravel Roads. In *Transportation Research Record 898*, TRB, National Research Council, Washington, D.C., 1983.
33. A. J. Van Wijk, G. D. Van Zyl, and J. Joubert. Light Pavements: Design, Performance and Cost Effectiveness. Volume 2A, *Proc., of the Annual Transportation Convention*, Pretoria, South Africa, Aug. 1987.
34. *Bituminous Products for Road Construction*. Manual 2, South African Bitumen and Tar Association, Cape Town, South Africa, 1987.