Evaluation of two nano-silane-modified emulsion stabilised pavements using accelerated pavement testing

F.C. Rust[a,*], M.A. Smit[b], I. Akhalwaya[b], G.J. Jordaan[c] and L. du Plessis[d]

[a]Pavement Engineering Research Consultancy, Pretoria South Africa;

[b]Council for Scientific and Industrial Research, Pretoria South Africa;

[c]University of Pretoria & Jordaan Professional Services, Pretoria, South Africa;

[d]Gauteng Department of Roads and Transport, Johannesburg, South Africa

*CONTACT: F.C. Rust. Email: chris@perc.co.za

ABSTRACT

Upgrading, maintenance and rehabilitation of road infrastructure is expensive, especially in view of the growing scarcity and cost of suitable road building materials. In areas with high mica content and secondary minerals such as smectite in the natural materials, stabilisation with cement is not viable. The Council for Scientific and Industrial Research of South Africa has embarked on a research programme to evaluate the performance of substandard materials improved with anionic nano-silane modified bitumen emulsions for use in base and subbase layers. This work comprises laboratory testing as well as Accelerated Pavement Testing using the Heavy Vehicle Simulator (HVS). The results of a full-scale HVS test on a light pavement as well as initial analysis on a medium traffic road are discussed. It has been shown that stabilisation of available substandard materials using an anionic nano-silane modified bitumen emulsion compared with the standard approach of importing high quality crushed aggregate can lead to savings as high as 40%–50% for equivalent performance. In addition, there was also a significant reduction in construction effort and time.

KEYWORDS: Anionic nano-silane modified bitumen emulsion; modified emulsion-treated materials; HVS testing; Accelerated pavement testing; alternative road materials; marginal materials

Introduction

The cost of upgrading, maintenance and rehabilitation of road infrastructure is increasing due to increasing scarcity and cost of suitable road building materials. In addition, the quarrying of crushed aggregate has a significant environmental impact. The Council for Scientific and Industrial Research (CSIR) has embarked on a research programme to investigate and evaluate alternative road building materials that can be used to upgrade marginal or natural materials to base and subbase standard. The situation is exacerbated when high percentages of mica minerals are present (such as is often the case in South Africa) which makes cement stabilisation problematic. One modifier that can be used for such upgrading is anionic nano-silane. There are various nano-modified road building materials available world-wide and several companies are manufacturing nano-silane modified emulsions. The Central Roads Research Institute (CRRI) in India indicated that the use of nano-modification in both asphalt and soils is beneficial (Mittal *et al*. 2010). They found that modification increased the CBR between 4 and 5 times and to render the material water resistant with a potential reduction in pavement layer thickness. The National Centre for Asphalt Technology (NCAT) also reported on the use of a diluted cationic emulsion with a nano-technology additive in tack coats, the use of nano-materials in asphalt to improve adhesion (anti-stripping), as well as the use of nano-modified emulsion in soil upgrading (Taylor and Willis 2011). They particularly found that nano-silane modified additives are very effective in asphalt to prevent stripping and to improve the performance of tack coats.

In South Africa, some trial sections have been constructed recently using nano-modified emulsions (NMEs) to upgrade sub-standard base and subbase materials, however, no performance data on NMEs was available prior to this study. The main objective of the research study was to determine the performance of two of the constructed roads, road D1884 and road K46, under Accelerated Pavement Testing (APT) using the Heavy Vehicle Simulator (HVS). The testing was conducted on in-service pavements and not on specially constructed trial sections. The work also included laboratory testing to characterise the materials before and after modification. The HVS programme and its impact has been demonstrated both in South Africa (Rust *et al*. 1997, Du Plessis *et al*. 2008) and internationally (Nokes *et al*. 1996, Harvey *et al*. 1999). This article provides a summary of laboratory results as well as the results from HVS testing and measurements on two pavement structures: a light pavement designed for 3 million Equivalent Standard Axle Loads (ESALs) and a medium traffic pavement, designed for 10 million ESALs. It was found that the nano-modified emulsion (NME) technology can be used successfully to upgrade marginal and substandard materials to replace expensive imported crushed aggregate and cement stabilised layers at a significant cost saving.

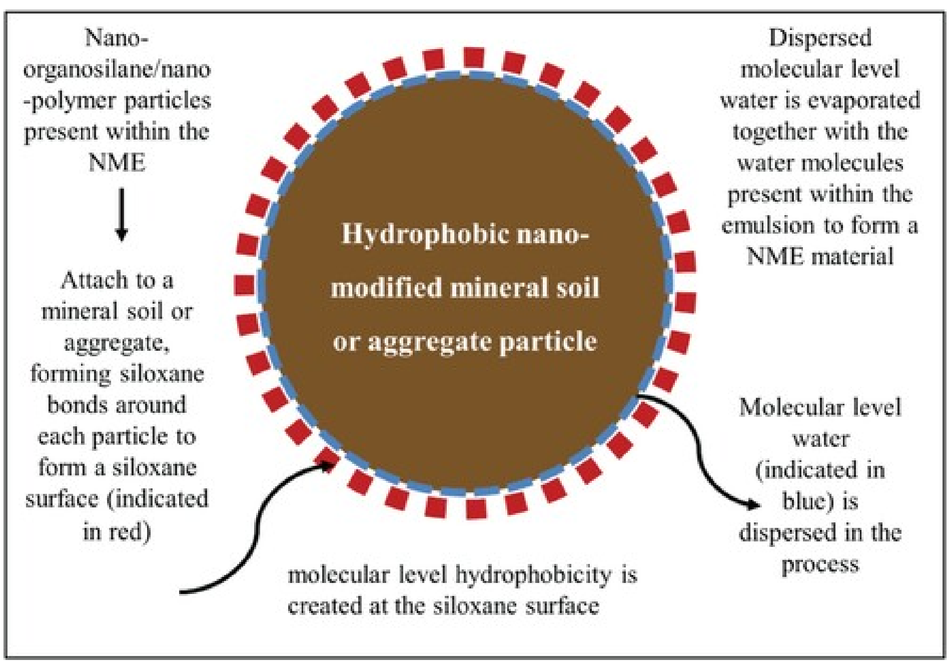
Nano-scale technologies are increasingly being used today. In pavement engineering they are used to modify bitumen binder (Jahromi 2019); to improve self-healing of asphalt (Ganjei and Aflaki 2019); as nano-clays in polymer modified asphalt (Rooholamini *et al*. 2017); as a nano-silica additive to asphalt (Bala and Napiah 2018); to reduce rutting in asphalt (Nejad *et al*. 2014, Ezzat *et al*. 2018) and for fluorescent properties of concrete (Steyn 2009). The macroscopic mechanical behaviour of these materials still depends to a large extent on the microstructure and physical properties on a micro and nanoscale (Partl *et al*. 2004).

Due to scarcity of good quality material in many countries, marginal materials that contain minerology compositions that render them unsuitable for road construction often due to their high mica and clay content are sometimes considered for modification to base and subbase standard (Jordaan *et al*. 2017b). In particular, recent developments in nano-technology mainly in the form of nano-stabilising agents allow for the chemical modification of these marginal materials at low application rates, thus removing the need for an expensive imported crushed stone layer. This enables road agencies to construct roads quicker at lower cost, whilst at the same time maintaining adequate base/subbase layer bearing capacity at an acceptable risk.

Nano-products such as NMEs claim to offer hydrophobic properties and improve marginal materials at a nanoscale, making them directly suitable for road construction whilst simultaneously providing performance superior to good quality materials (Jordaan *et al*. 2017b). The NME is made by adding a nano-silane modifier and/or nano-polymer to bitumen, water and emulsifying agent at high shear to form nano-sized bitumen particles in the emulsion which provide much better cover of the aggregate with bitumen and thus increased water resistance and strength. The nano-silane also provides increased adhesion of the bitumen with the aggregate during stabilisation and actively repels water from the layer.

The implementation of NMEs therefore has the potential to improve the long-term quality and cost efficiency of South African road infrastructure through the enhancement of in-situ material properties at affordable cost. According to Akhalwaya and Rust (2018), NMEs consisting of traditional bitumen-emulsions with the addition of low concentrations of nano-additives used as a stabilising agent on naturally available materials show considerable improvement in especially the wet Unconfined Compressive Strength (UCS) and Indirect Tensile Strength (ITS) of materials evaluated in the laboratory. NMEs are made by adding nano-additives such as nano-organosilanes and/or nano-polymers to a standard anionic or cationic bitumen-emulsion (Akhalwaya 2018). These nano-organosilanes and/or nano-polymers then attach to any silica-based road material whilst making it hydrophobic. The NME is then applied to a mineral soil r aggregate as shown in Figure 1.

Figure 1. Summary of the formulation of a siloxane surface on a NME stabilised mineral soil or aggregate (Akhalwaya and Rust, 2018).



Although interest in nano-emulsions was developed more than 20–35 years ago, it is only until recently that the direct applications of these nano-emulsions in consumer products have been considered (Gutiérrez *et al*. 2008). According to Jordaan *et al*. (2017b), a number of different NMEs are currently available in the global market. These nano-products have different chemical compositions, which may react differently when in contact with different minerals. Furthermore Jordaan *et al*. (2017b) mention that careful laboratory testing is required when selecting a suitable NME to match a specific raw material. The successful modification of marginal materials with nano-products depends on the application of the correct nano-product (Jordaan *et al*. 2017b).

Jordaan and Kilian (2016) reported that the new generation organo-silanes (down to 5 nm in size) chemically interact with natural material molecules to change the surface atom composition of aggregates which drastically reduces the susceptibility of these materials to water. These organo-silanes were used to develop various categories of NME designs reported earlier (Jordaan *et al*. 2017b).

In addition, a variation of nano-based polymers (40–80 nm in size) have been developed and are available to be used as modification to bitumen emulsions. These polymers with or without organo-silanes can also improve the distribution, coverage and stabilisation characteristics of bitumen molecules of ± 5000 nm in size (Jordaan *et al*. 2017b).

Materials and methods

The objective of the research study was to determine the performance of the NME technology on two roads: Road D1884 near Meyerton in South Africa and Road K46 in Johannesburg. A full HVS test was completed on road D1884 and initial HVS measurements were conducted on road K46 with subsequent back calculation of layer moduli. The data was used to predict the life of each of the pavements. The pavement structures for the two roads are shown in Figures 2 and 3.

Figure 2. Conventional vs NME design for Road D1884 (3 million ESALs).

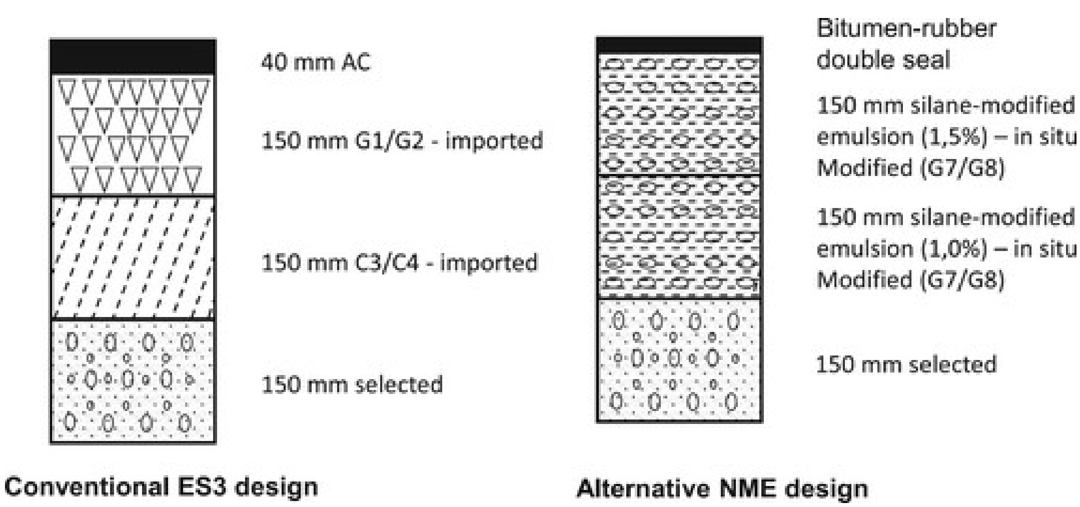
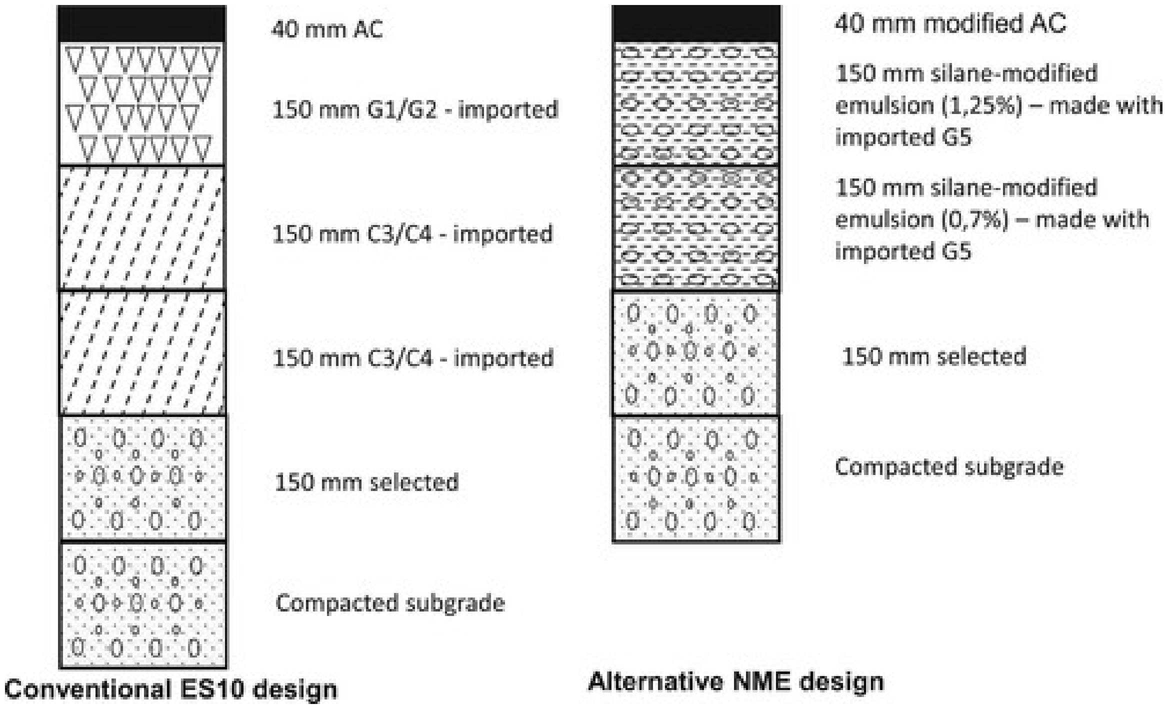


Figure 3. Conventional vs NME design for Road K46 (10 million ESALs).



In the conventional designs in Figures 2 and 3, G1/G2 materials refer to high quality crushed aggregate layers compacted to a high density. For G1 the specification is: sound crushed rock of nominal size 37.5 mm; Liquid Limit less than 35 and Plasticity Index less than 5; Linear shrinkage less than 2%; compacted to 88% of apparent relative density (COLTO 1985). The selected layer is an imported material compacted to provide a working platform for construction of the structural layers. C3 and C4 materials are lightly cement stabilised granular materials with a UCS strength at 7 days of, for C3 between 1.5 and 3.0 MPa and for C4 between 0.75 and 1.5 MPa (COLTO 1985).

Road D1884

Prior to rehabilitation, road D1884 was severely cracked with associated water-ingress and damage (Jordaan *et al*. 2017a). The remixed base material was of South African class G8 (COLTO 1985) which is classified as a granular material such as a natural gravel, with grading modulus 2.7–0.75, and CBR at least 10 at 93% mod AASHTO. Detailed gradings and material characteristics of the materials can be found in the publications by Author *et al.* (2019) and Jordaan and Steyn (2019). G8 materials are normally considered as unsuitable for inclusion into base and subbase layers. Furthermore, X- Ray Diffraction (XRD) results of the 0.075 mm fraction (± 22% of the material) of the base-course material contains approximately 36.1% of mica minerals and up to 27.1% of clay minerals (Jordaan and Steyn 2019). This implies that the materials were of low quality and not suitable for standard cement/lime stabilisation of base and subbase material (Jordaan and Steyn 2019). Based on laboratory testing and analysis, to determine a balance between strength and affordability, the base and subbase were treated with 1,5% NME and 1,0% NME respectively (Jordaan *et al*. 2017a). It should be noted that, unlike normal bitumen emulsion stabilisation, no cement was added.

Road K46

Road K46 had also deteriorated severely and parts of it was rehabilitated with NME technology. In this case a G5 material was imported due to the fact that a higher quality material was needed for the higher class of traffic (10 million ESALs). A G5 material (COLTO 1985) is classified as a natural gravel, with a grading modulus between 2.6 and 1.2, a PI less than 12, linear shrinkage of less than 5%, and a CBR of 45 at 95% of modified AASHTO density. In the case of road K46 less modified emulsion was used due to the higher-class imported raw material used – 1.2% in the base-layer and 0.7% in the subbase (with no added cement). The material (class G5) consisted of 34% quartz and had the potential to weather down to approximately 20% mica minerals and approximately 7% clay minerals based on XRD testing.

HVS testing protocol

Road D1884

Based on previous HVS test protocols that have been followed over many years to evaluate road performance the test programme was devised to ensure that the test results will be comparable with previous HVS testing on conventional pavements. The HVS testing wheel load was progressively increased during the test to allow the calculation of the damage factor for the pavement structure:

- 321,350 repetitions of a 40 kN dual wheel load (80 kN axle load)
- 372,600 repetitions of a 60 kN dual wheel load (120 kN axle load)
- 96,882 repetitions of an 80 kN dual wheel load (160 kN axle load) in the dry state, and
- 155,649 repetitions of an 80 kN dual wheel load (160 kN axle load) in the wet state.

The test was initiated in the dry state and towards the end water was applied to the surface of the test section as well as through holes drilled to a depth of 500 mm into the pavement layers. The water is stored in an elevated tank that allows the measurement of the amount of water applied. The water is fed via pipes onto the surface of the test section as well as into the holes drilled to the bottom of the subbase layer. A total of 211 litres of water was applied on the basis of applying as much water as would be absorbed by the pavement layers.

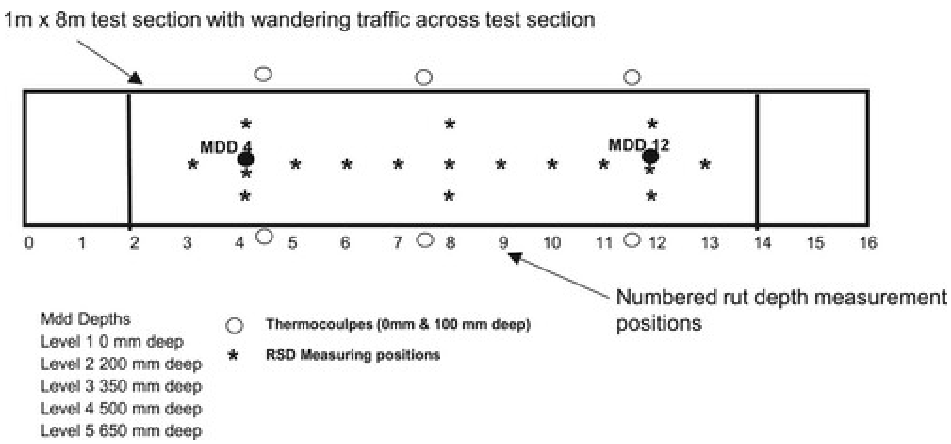
The 155,649 80 kN wheel repetitions equate to 2,008 m ESALS applied in the wet state. Standard HVS measurements were taken that included:

- Profilometer measurements to determine the surface deformation across the test section;
- Road surface deflectometer (RSD) readings to determine the surface deflection characteristics;
- Multi-depth deflectometer (MDD) readings at two points, and

- Temperature readings using thermocouples on the test section as well as a control section.

The layout of the test section with the position of the measuring points is shown in Figure 4.

Figure 4. Layout of the test section on road D1884.



The test section in Figure 4 is located on an in-service road and is uniform in design. The standard designs were not tested in this study, however, these designs had been tested over many years of the HVS test programme and were reported in a significant number of publications and standard design codes (Maree *et al*. 1982, Theyse 2002).

Road K46

The HVS test on road K46 was not completed due to operational challenges with a nearby community. However, a full set of HVS readings were taken after the section had been instrumented, including multi-depth deflectometer and road surface deflection. The layout of the test section was similar to that of road D1884. These readings were used to compute layer moduli and calculate the predicted life of the pavement.

Results of road D1884 HVS testing

Materials testing

A summary of the untreated, in-situ materials testing is given in Table 1. The materials were of inferior quality and would normally not be used in a base and sub-base. The subgrade also contained a high clay content. These results indicate that there had been considerable weathering of the materials over the past 50 years since the road was originally constructed.

Table 1. Materials testing results of the raw material.

		Base layer	Subbase-layer	Upper selected
Sieve analysis (% passing)	63.0	100	100	100
	53.0	100	95	96
	37.5	100	82	89
	28.0	100	76	88
	20.0	93	72	88
	14.0	77	65	88
	5.0	53	56	86
	2.00	46	50	83
	0.475	32	43	75
	0.075	13	22	32
Fine Sand (%)		4	10	17
Silt & Clay (%)		33	44	39
Atterberg Limits	LL (%)	24	23	21
	PI	7	4	3
	LS (%)	3.5	2.1	1.4
GM	GM	2.09	1.85	1.1
Mod-AASHTO	OMC%	7.2	11.4	9.1
	MDD	2170	2030	1967
CBR	Comp MC	7	11.2	8.8
	% Swell	0.16	0.29	0.52
CBR @ density	100%	27	32	20
	98%	22	28	15
	97%	19	26	13
	95%	15	23	9
	93%	12	20	7
	90%	9	16	4
Material classification (COLTO 1985)		G8	G7	G10

The laboratory results of the material containing various percentages of NME are given in Table 2 (Author *et al*. 2019). The test procedures followed are described in detail elsewhere (TG2 2009).

The raw materials were modified with various percentages of an anionic nano-silane modified bitumen emulsion. It can be noted from Table 2 that unusually high (for bitumen emulsion stabilisation; TG2 2009) ITS and UCS values were obtained – with no addition of cement. This is not unusual for anionic NMEs tested on materials throughout southern Africa (Jordaan *et al*. 2017a). The percentage retained strength for both ITS and UCS after soaking was also high for all materials tested. This is explained by the small size (nano size) of the NME particles which provide much better cover for the clay particles causing a hydrophobic effect. A bitumen molecule is in the order of 2–6 μm in size which is significantly larger than clay crystals (< 1 nm). Consequently, at higher percentages of bitumen emulsion, the clay crystals are 'swimming' in the binder resulting in lower tensile strength values (Jordaan *et al*. 2017b). The high retained strength values indicate one of the main advantages of using NMEs – their ability to protect the materials against water ingress (Jordaan *et al*. 2017b).

It is important to highlight two important aspects of using NMEs. Firstly, the required percentage NME to get optimum strength of the modified material (in terms of UCS /

Table 2. Laboratory test results conducted on NME materials.

Material	Avg ITS_{dry} (kPa)	Avg ITS_{wet} (kPa)	Retained ITS (ITS_{wet}/ITS_{dry})	Avg UCS_{dry} (kPa)	Avg UCS_{wet} (kPa)	Retained UCS (UCS_{dry}/UCS_{wet})
Base layer: 1.5% nano- modified emulsion (32 L / m^3)	232	184	79%	2620	1865	71%
Sub-base layer: 1.2% nano- modified emulsion (24 L / m^3)	268	206	77%	4947	1670	34%
Sub-base layer: 1.0% nano-modified emulsion (20 L / m^3)	420	321	76%	4807	831	17%

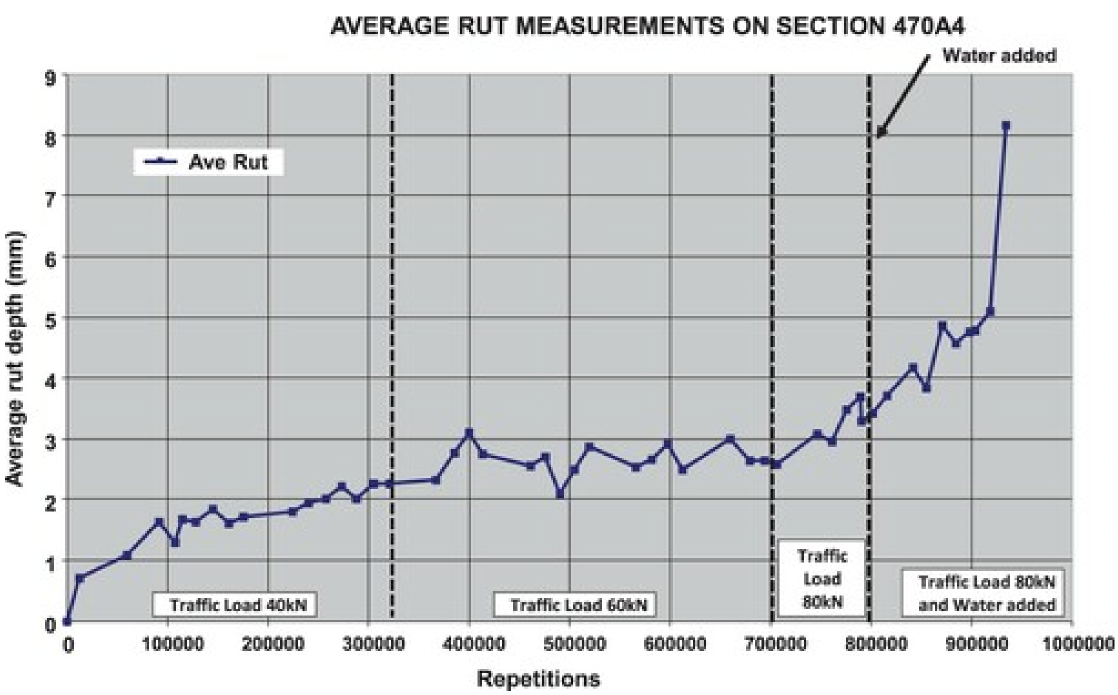
ITS) is roughly reduced by a factor two to three. Conventional ETB mixes (depending on the quality of the parent granular material) may require 2.5–3.5 percent of emulsion to get to optimum strength. With the addition of organo-silanes to the emulsion, the optimum percentage of the modified emulsion drops to 1–1.5% with a significant strength gain as shown in Table 2. Secondly it is worth highlighting the extremely low concentrations of organo-silanes used in the modified emulsion. It can be as low as 1 L organo-silane per 1000 litres of emulsion but is dependent on the minerology of the raw material.

Results from accelerated pavement testing

Permanent deformation

The average rut depth as measured with an HVS laser profilometer on 12 points across the test section is depicted in Figure 5. At the end of the test, after 946,481 applications of a variety of wheel loads, the average rut depth was 8 mm. This is excellent performance after about 7 million ESALs (using a damage coefficient of 4.2) as opposed to the design life of 3 million ESALs. The maximum rut depth measured was 10.6 mm.

Figure 5. Average rut depth measurements on the total section.



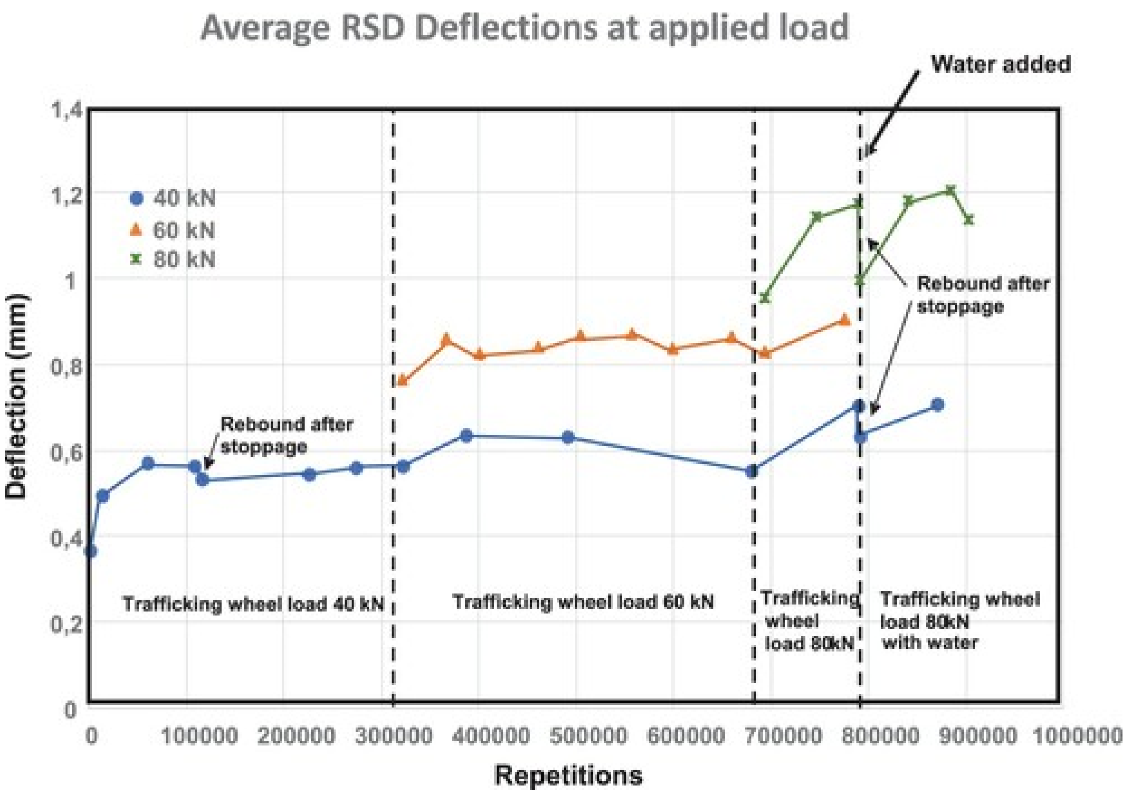
The original design was based on transfer functions developed for normal bitumen emulsion stabilised materials (Jordaan 2011) and was expected to be conservative. The NME stabilised base and sub-base was carefully monitored during the APT using the HVS on the D1884 and performed excellently and exceeded all expectations.

The main mode of failure was rutting and no fatigue cracking was observed during the test. In some cases, bearing capacity loss can be associated with a reduction in modulus of the base layer as discussed below. This could eventually lead to additional rutting (and associated cracking) due to less protection of the subgrade, However, the design bearing capacity was exceeded well before the end of the test without reaching a 'warning' stage for the category of road (10 mm rut depth).

Road surface deflection

The surface deflection of the section was measured using the HVS road surface deflectometer (RSD) which is a modified Benkleman beam. The results are shown in Figure 6. Deflections were measured under the slow rolling wheel of the HVS at 40, 60 and 80 kN wheel loads with an 800 kPa tyre pressure.

Figure 6. Average surface deflections measured with the RSD.



The average deflection increased from an initial value of 0.36 mm to 0.71 mm under a 40 kN wheel load. The maximum deflection measured during the test under 40 kN was 0.89 mm.

Multi-depth deflectometer measurements

The multi-depth deflectometer (MDD) (De Beer *et al*. 1989) was used to measure permanent deformation as well as in-depth elastic deflections at two points on the test section (point 4 and point 12). The device is used to measure the permanent deformation and deflection within a layer, which allows for the isolation of distress for each layer in the pavement structure. The data series in these graphs refer to the modules of the MDD installed at depths of 0 mm, 200 mm, 350 mm, 500 mm and

650 mm at the interfaces of the pavement layers to allow for isolation of each layer in data analysis.

The results are shown in Figures 7–10. It can be noted that most of the permanent deformation occurred in the base layer due to post-construction compaction as the layer settled in under traffic. The total deformation at the top of the base layer was 5 mm which is low compared to the warning criterion of 10 mm and failure criterion of 12 mm. A significant portion of the elastic deflection occurred in the subbase layer.

Figure 7. MDD Permanent deformation at point 4.

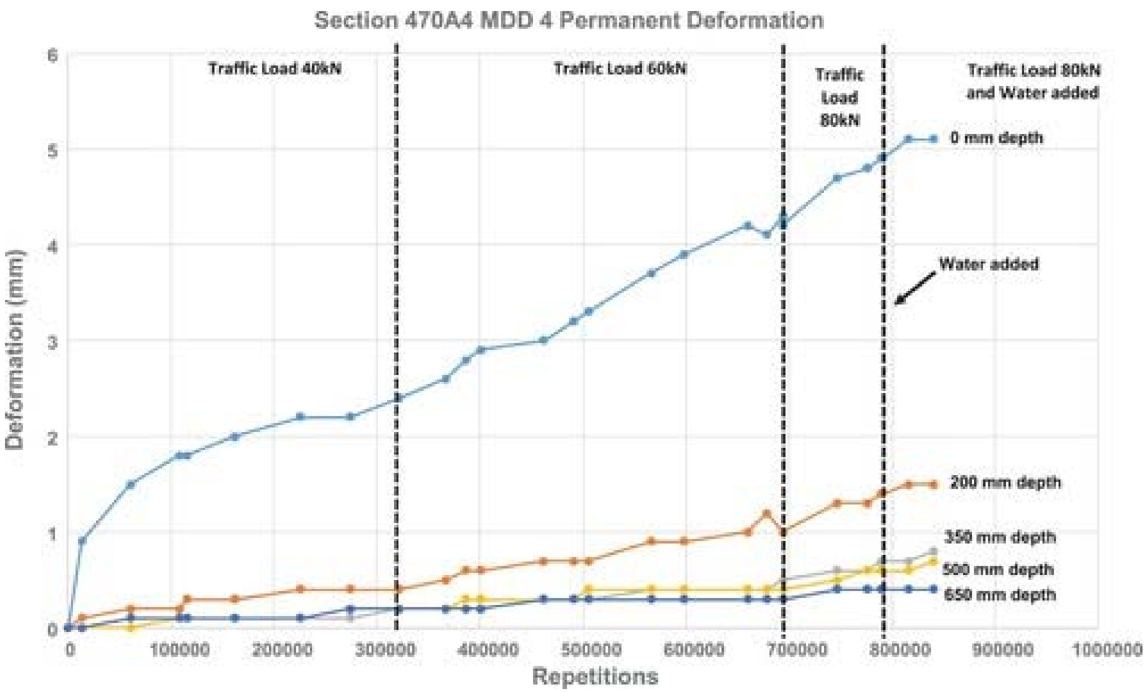


Figure 8. MDD Permanent deformation at point 12.

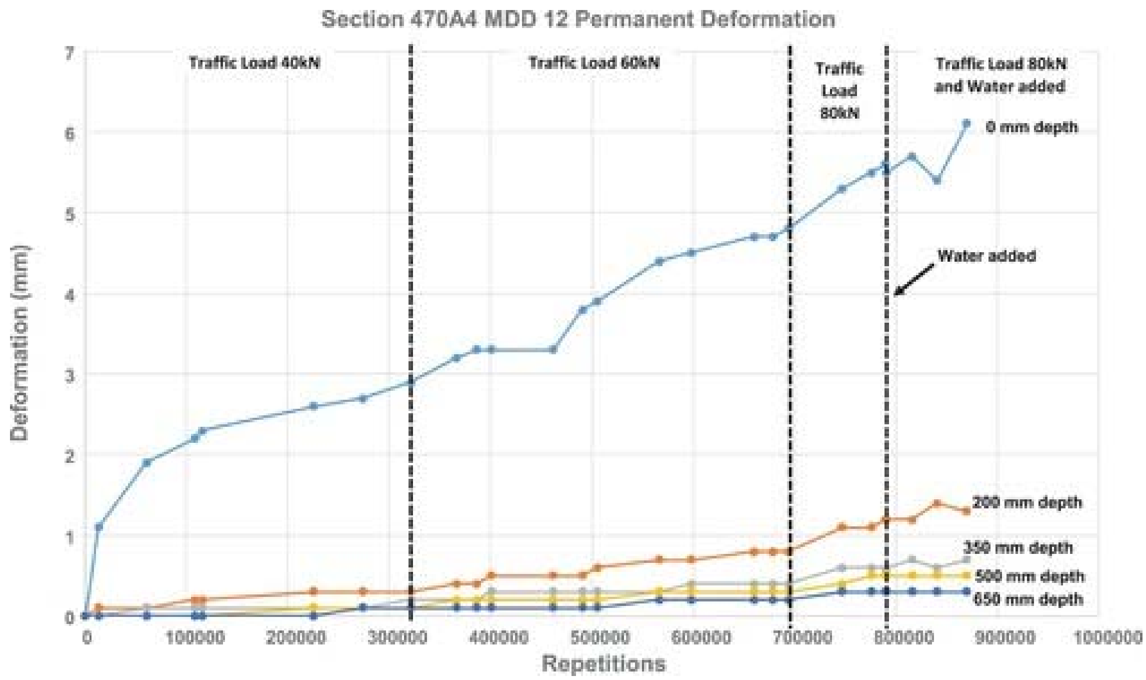


Figure 9. MDD elastic deflection at point 4.

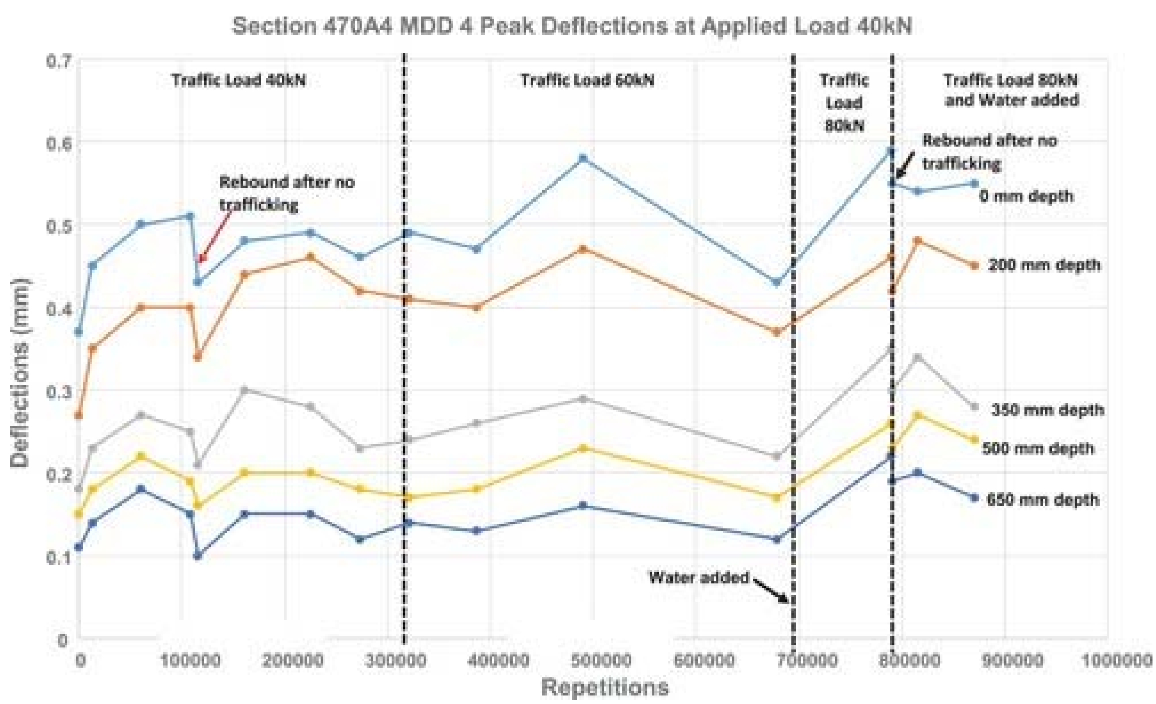
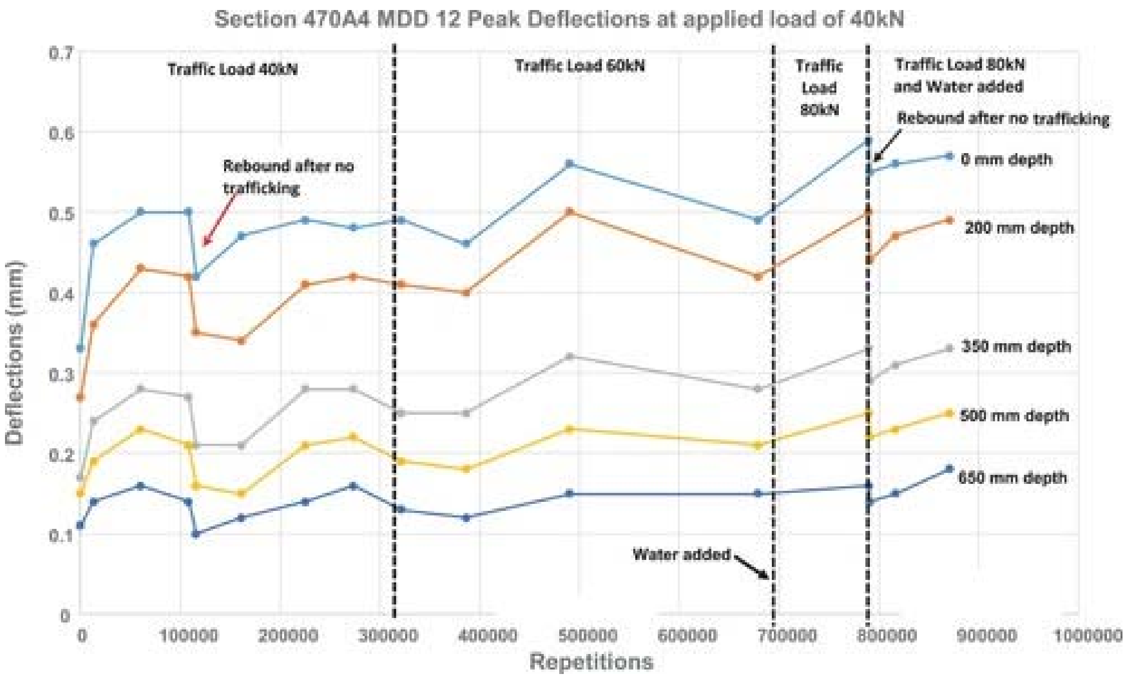


Figure 10. MDD elastic deflection at point 12.



Calculation of damage factors

The damage factor is used to calculate equivalent traffic for various wheel loads higher than the standard axle load of 80 kN (40 kN wheel load). The slope of the deformation graph in Figure 5 is used (Rust *et al*. 2019) with a formula for the

calculation of the damage factor provided by Kekwick (1985):

$$d = \log(M1/M2)/\log(P1/P2) \quad (1)$$

where:

- M1 and M2 are the slope gradients on the rutting graph for loads P1 and P2, in rut (mm) per repetition,
- P1 is the applied load, and
- P2 is the standard 40 kN wheel load.

The damage factors for this HVS test were calculated as 1.63 (60 kN wheel load), 2.26 (80 kN wheel load) and 3.69 (80 kN wheel load in the wet state) (Rust *et al*. 2019). This is significantly lower than the often-used average damage factor of 4.2 which indicates that the pavement is a well-balanced, deep structure and insensitive to overloading (which is of importance especially where little law-enforcement in terms of over-loading exists). Using the 4.2 damage factor, the pavement carried an equivalent of 7 million ESALs and using the damage factors for each stage as calculated from the HVS test, the pavement carried 3.5 million ESALs without reaching failure conditions.

Table 3. Summary of Moduli back-calculated for road D1884 (MPa).

DEPTH	Moduli (MPa) MDD 4 Average	MDD4 range	MDD 12 Average	MDD 12 Range
Base	173	69–797	127	71–214
Subbase	93	40–142	98	71–134
350 - 500 mm deep	154	75–316	174	82–606
500 - 650 mm deep	205	136–268	198	160–268

Moduli calculations

Moduli were back-calculated from the MDD data, using the Council for Scientific and Industrial Research (CSIR) back-GAMES programme. The average moduli for the base layer were 173 MPa and 127 MPa for MDD 4 and MDD 12 respectively. The subbase moduli average was 93 MPa and 98 MPa for MDD 4 and MDD12 respectively. This is summarised in Table 3 below. Apart from one outlier, the moduli did not change significantly during the HVS test (Rust *et al*. 2019). The base layer showed some stiffening behaviour initially due to the post-construction compaction under the HVS loading. At the end of the test the base layer modulus decreased to an average of 104 MPa as the layer started to fatigue under HVS testing, thus indicating the initiation of loss in bearing capacity.

Results of road K46 HVS testing

Materials testing

The materials laboratory test results are given in Table 4 below.

Table 4. Material properties of the imported G5 material on road K46.

Atterberg Limits	LL (%)	20
	PI	3
Grading Modulus	GM	2.28
Mod-AASHTO	OMC%	6.4
	MDD	2132
CBR	100% Mod AASHTO	85
CBR @ density	100%	85
	98%	55
	95%	30
	93%	10
Material classification (COLTO 1985)		G5/G6

It can be noted that this material is of better quality than that used on road D1884.

The NME mix properties were compared with that of samples modified with normal emulsion as well as samples with normal emulsion plus 0,5% cement. The test results of the nano emulsion modified material are shown in Table 5.

Table 5. Laboratory test results of NME material on road K46.

Mix	UCS (kPa) (Dry)	UCS (kPa) (Wet)	Retained UCS % (UCS_w/UCS_d)	ITS (kPa) (Dry)	ITS (kPa) (Wet)	Retained ITS % (ITS_{wet}/ITS_{dry})
0.7% NME	2430	1923	79%	179	158	88%
0.7% standard SS60 anionic bitumen emulsion - no NME or modification	2218	558	25%	145	36	25%
0.7% standard SS60 anionic bitumen emulsion– no NME plus 0.5% Portland cement	1399	943	67%	76	39	51%

The data in Table 5 indicates that the addition of the nano-modifying emulsion stabilising agent is very beneficial in terms of laboratory strength measurements, particularly in the wet condition (as indicated by the retained % in terms of both the ITS and the UCS).

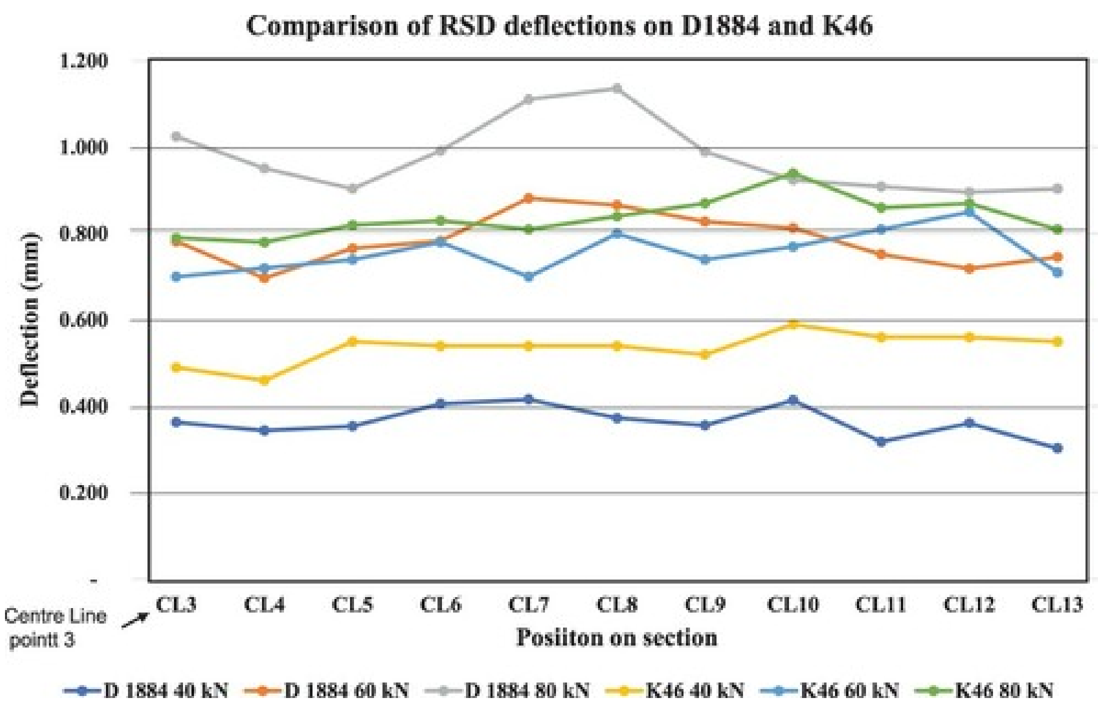
Limited tri-axial testing was done on the 0.7% NME material. The results indicated a resilient modulus increase from 260 MPa for the unmodified material to 1,450 MPa for the NME and an increase in cohesion from 32.3 kPa to 1818.0 kPa.

HVS measurements

Surface deflection

The RSD surface deflections for both road D1884 and road K46 taken on the centre line of the test sections are shown in Figure 11. The maximum defection measured on K46 under the 40 kN, 60 kN and 80 kN load respectively was 0.59 mm, 0.85 mm and 0.94 mm. The effect of increased loading on the pavement structure is clear.

Figure 11. Comparison of cross section RSD deflections on D1884 and K46 at different wheel loads (800 kPa tyre pressure) and FWD 40kN measurements (Positions indicated as CL (Centre Line) plus point number).



The 40 kN RSD deflections on road K46 ranged from 0.47–0.59. This is slightly higher than the FWD deflections as can be seen in Figure 11. This is to be expected due to the fact that the FWD is a dynamic impact loading. Impact loading will render a bitumen emulsion layer stiffer than that under a slow rolling wheel deflection (static loading) due to, *inter alia*, the visco-elastic nature of bitumen and its dependency on the frequency of loading and the inertia effect on the sub-grade due to dynamic

Table 6. MDD in-depth deflections measured at point 8 on road K46.

DEPTH	Deflection (mm)					
	Deflection 40 kN (mm)	% deflection from layer	Deflection 60 kN (mm)	% deflection from layer	Deflection 80 kN (mm)	% deflection from layer
Surface	0.44		0.7		0.84	
Base (180 mm)	0.34	22.7%	0.52	25.7%	0.64	23.8%
Subbase (330 mm)	0.2	31.8%	0.32	28.6%	0.42	26.2%
480 mm	0.13	15.9%	0.23	12.9%	0.31	13.1%
680 mm	0.07	13.6%	0.11	17.1%	0.15	19.0%

Table 7. MDD in-depth deflections measured at point 12 on Road K46.

DEPTH	Deflection (mm)					
	Deflection 40 kN (mm)	% deflection from layer	Deflection 60 kN (mm)	% deflection from layer	Deflection 80 kN (mm)	% deflection from layer
Surface	0.46		0.65		0.82	
Base (180 mm)	0.37	19.6%	0.53	18.5%	0.67	18.3%
Subbase (330 mm)	0.24	28.3%	0.36	26.2%	0.46	25.6%
480 mm	0.15	19.6%	0.12	36.9%	0.16	36.6%
680 mm	0.06	19.6%	0.09	4.6%	0.12	4.9%

loading. The deflections measured on road K46 were higher than that measured on the D1884 at 40 kN (see Figure 11).

The initial in-depth deflections measured with the MDD at point 8 and point 12 are shown in Tables 6 and 7.

Moduli from back calculation

The FWD and MDD data above were used to back calculate moduli for the various layers. Table 8 shows the moduli back calculated from the FWD measurements.

Table 8. Moduli back calculated from FWD data.

DEPTH	Moduli (MPa) Range	Avera
Base	523–935	684
Subbase	81–169	137
330–480 mm	51–77	61
480–680 mm	361–491	441

Tables 9–11 indicate the moduli back calculated from MDD data for wheel loads of 40, 60 and 80 kN using the CSIR back-GAMES programme.

Table 9. Back-calculated moduli for both MDDs at 40 kN wheel load.

	MDD 8		MDD 12	
DEPTH	Range (MPa)	Average (MPa)	Range (MPa)	Average (MPa)
Asphalt	2732–4315	3769	10248–25841*	16286*
Base (0–180 mm)	179–332	243	305–329	316
Subbase (180–330 mm)	135–226	189	177–188	182
330–480 mm	291–400	352	190–263	227
480–680 mm	261–314	282	293–349	312
Subgrade	862–1258	1002	571–731	624

*The high asphalt moduli calculated by the software is due to the limitations of back calculation processes

Table 10. Back-calculated moduli for both MDDs at 60 kN wheel load.

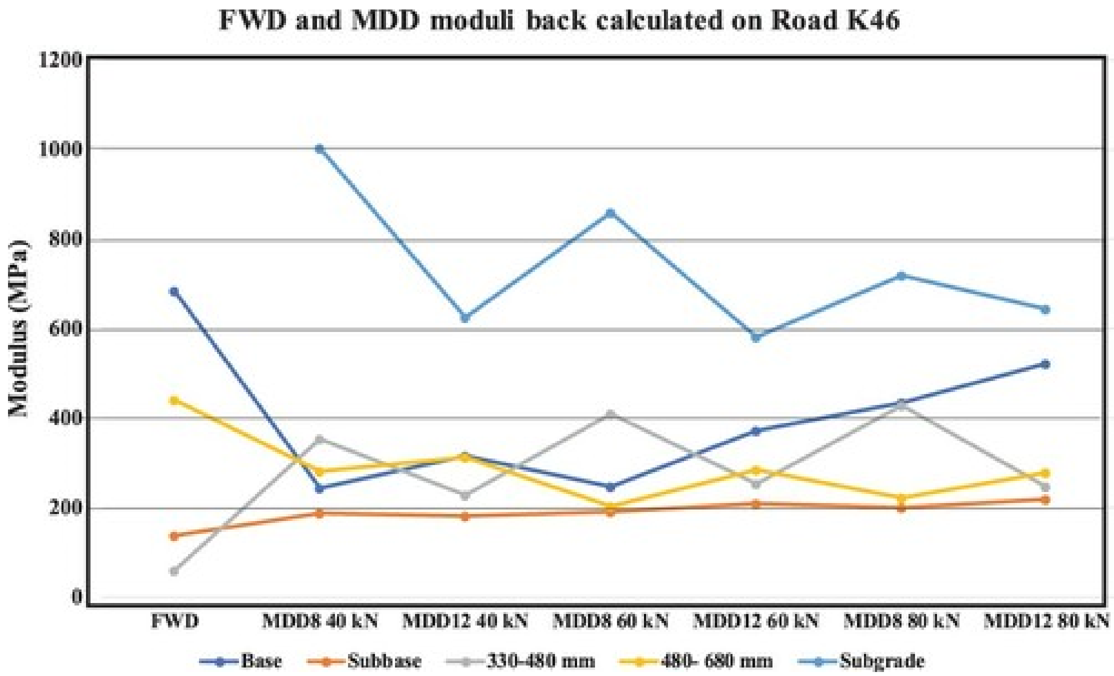
	MDD 8		MDD 12	
DEPTH	Range (MPa)	Average (MPa)	Range (MPa)	Average (MPa)
Asphalt	1351–2556	1888	2072–3363	2552
Base (0–180 mm)	243–252	247	340–398	371
Subbase (180–330 mm)	180–195	190	194–221	210
330–480 mm	408–412	410	252–259	255
480–680 mm	196–214	202	283–288	285
Subgrade	746–914	860	566–612	582

Table 11. Back-calculated moduli for both MDDs at 80 kN wheel load.

	MDD 8		MDD 12	
DEPTH	Range (MPa)	Average (MPa)	Range (MPa)	Average (MPa)
Asphalt	402–534	480	1001–1130	1068
Base (0–180 mm)	416–448	434	517–524	521
Subbase (180–330 mm)	193–203	200	208–233	219
330–480 mm	410–464	429	226–257	247
480–680 mm	215–238	223	229–302	277
Subgrade	687–737	720	559–780	644

The moduli are represented graphically in Figure 12.

Figure 12. Back calculated FWD and MDD moduli for road K46.



The analysis of the moduli above indicates the following:

- The FWD moduli are higher for the base material than the MDD moduli, possibly due to the impact loading used for FWD measurements (higher frequency of loading) and the visco-elastic behaviour of the bitumen emulsion;
- Both the FWD and the MDD analysis indicate a stiff layer in the subgrade, and
- The modulus of the base layer is sensitive to loading and stiffened with increasing load.

A comparison of the moduli for road D1884 and road K46 is shown in Table 12.

It can be noted that the average moduli for road K46 were higher than that for road D1884, mainly due to the better-quality raw material used. The three phases of the base in the HVS test of road D1884 can be noted. The D1884 base stiffened significantly during the initial compaction period and then decreased as the base started to fatigue under traffic.

Table 12. Comparison of back calculated moduli for road D1884 and K46.

	D1884 Average calculated moduli				K46 Average calculated moduli			
Stage of testing	MDD4 Base (MPa)	MDD4 Sub-base (MPa)	MDD12 Base (MPa)	MDD12 Sub-base (MPa)	MDD8 Base (MPa)	MDD8 Sub-base (MPa)	MDD12 Base (MPa)	MDD12 Sub-base (MPa)
Phase 1 up to 108,000 repetitions	91	112	125	109	243	189	316	182
Phase 2 from 108,000–679,000 repetitions	258	81	139	97	n/a	n/a	n/a	n/a
Phase 3 from 679,000–903,000 repetitions	104	96	104	88	n/a	n/a	n/a	n/a

Pavement life calculation

The back calculated moduli were used to calculate the horizontal strain at the bottom of the base and subbase as well as the vertical strain at the top of the subgrade. These values were then used to predict the life of the pavement, using the following transfer functions (damage models):

For ETBs (Jordaan 2011):

$$\varepsilon_h = 124208 \times E^{-0.488} \times Nf^{-0.169} \tag{2}$$

For the subgrade (Jordaan 1994):

$$Nf = (\varepsilon v/(102.37 \times 12\,\mathrm{mm\ Rut})) - 10 \tag{3}$$

The 12 mm rut depth is selected based on probabilistic analysis (Jordaan and Steyn 2015) allowing for a distribution of performance over the length of a pavement.

Life prediction for D1884

The above data and damage models were used to calculate the predicted life of the HVS test section (based on initial HVS test readings). The case for the strain levels directly under the one tyre of the dual wheel as well as between the tyres of the dual wheel was calculated. The result is shown in Tables 13 and 14 for both MDD 4 and MDD 12. The CSIR back-GAMES software was used to calculate the moduli and the CSIR me-GAMES software was used to calculate the relevant strains. The thin seal on the surface was ignored for these calculations.

Tables 13 and 14 indicate that the prediction of repetitions to failure was between 3 and 5 million equivalent standard axles (MESA) to a state of 12 mm rut depth. This correlates very well with the actual HVS test where 8 mm rut was measured after 3.5 million standard axles and the pavement design life of 3 MESA.

Life prediction for K46

Similar to the case of D1884, the moduli and prediction of repetitions to failure calculations were conducted for K46. In this case the 30 mm asphalt, with a modified binder, was taken into consideration. The result is shown in Tables 15 and 16. It can be noted that, using the GAMES software and the calculated moduli with the damage models indicated above, the analysis predicts a life of in a range between 25 MESA and >100 MESA which is significantly more than the design life of 10 million.

Table 13. Predicted life of D1884 based on initial HVS test readings (MDD 4).

Layer	Modulus (MPa)	Micro strain between tyres	Repetitions to failure (MESA)	Micro strain under tyre	Repetitions to failure (MESA)
Base	173	742	5	806	3
Subbase	93	291	7,577	284	5,751
Selected	154				
Subgrade	205	399	303	384	445

Table 14. Predicted life of D1884 based on initial HVS test readings (MDD 12).

Layer	Modulus (MPa)	Micro strain between tyres	Repetitions to failure (MESA)	Micro strain under tyre	Repetitions to failure (MESA)
Base	127	801	8	877	5
Subbase	98	284	7,523	278	8,537
Selected	174				
Subgrade	198	370	645	357	923

Table 15. Predicted life of K46 based on initial HVS test readings and using the CSIR GAMES software (MDD 8).

	E (back-GAMES)		Micro Strain (me-GAMES: Between tyres)		Repetitions to failure (MESA)		Micro Strain (me-GAMES: Under tyre)		Repetitions to failure (MESA)	
Layer	Range (MPa)	Average (MPa)	Range (MPa)	Average (MPa)	Range (MPa)	Average (MPa)	Range (MPa)	Average (MPa)	Range (MPa)	Average (MPa)
Asphalt	2732–4315	3769								
Base	179–332	243	307–527	399	34–175	>100	325–556	421	25–131	85
Subbase	135–226	189	110–159	132	>100	>100	108–155	129	>100	>100
Selected	291–400	352								
Subgrade 1	261–314	282	189–244	219	>100	>100	182–235	211	>100	>100
Subgrade 2	862–1258	1002								

Table 16. Predicted life of K46 based on initial HVS test readings and using the CSIR GAMES software (MDD 12).

Layer	E (back-GAMES)		Micro strain (me-GAMES: Between tyres)		Repetitions to failure (MESA)		Micro strain (me-GAMES: Under tyre)		Repetitions to failure (MESA)	
	Range (MPa)	Average (MPa)	Range (MPa)	Average (MPa)	Range (MPa)	Average (MPa)	Range (MPa)	Average (MPa)	Range (MPa)	Average (MPA)
Asphalt	10248–25841	16,286								
Base	305–329	316	287–349	322	84–214	>100	288–358	327	72–210	>100
Subbase	177–188	182	129–179	154	>100	>100	125–174	150	>100	>100
Selected	190–263	227								
Subgrade 1	293–349	312	163–195	184	>100	>100	156–185	175	>100	>100
Subgrade 2	571–731	624								

Cost benefits

The construction cost for the project at D1884 in the order of R 4 million (US$ 233,000 at R17.2/$) per km for a 3 million ESAL design (Jordaan 2020). The equivalent conventional design for the project would consist of a 40 mm asphalt layer, a 150 mm G1 base (a high-quality crushed aggregate base), a 150 mm C3/C4 stabilised subbase and a 150 mm selected layer with a cost in the order of R7 million (US$ 407.000) per km. Therefore, the alternative NME design was very cost effective in terms of construction costs with a 40% cost reduction. In addition, there was about 50% saving in construction time (Jordaan 2020).

At road K46 the conventional design was costed at R354 million and the alternative NME design at R254 million, indicating a 28% cost reduction (Jordaan 2020).

Life cycle cost analysis data in this study is not available yet, since the roads have recently been built and no maintenance data is available yet. The use of a flexible bitumen-rubber seal and the resistance of the NME to water ingress indicate that the incidence of pothole forming (which is usually associated with crushed stone pavements that are not well maintained) will be lower. The water- resistant nature of the NME material could lead to further savings in periodic maintenance costs.

Summary and conclusion

The objective of the work was to, through laboratory testing and accelerated pavement testing with the HVS, determine the performance of NME materials in base and subbase layers when used to upgrade sub-standard materials. From the analysis of the results from two roads the following can be noted:

- Laboratory testing of the D1884 modified material indicated dry UCS of 2,620 kPa; wet UCS of 1,865 kPa; dry ITS of 232 kPa; and wet ITS of 184 kPa;
- Laboratory testing of the K46 modified material indicated dry UCS of 2,430 kPA; wet UCS of 1,923 kPa; dry ITS of 179 kPa; and wet ITS of 158 kPA;
- The K46 material indicated significant increases in strength over a standard emulsion modified material with no NME additive in the wet state (up to 338%);
- The initial (N10 readings) MDD back-calculated moduli for the base and subbase of K46 were about double those of D1884;
- The repetitions to failure (life) predicted for D1884 was between 3 and 5 million 40 kN standard axles (for 12 mm rut depth) – which correlated very well with the actual HVS test results that showed 3.5 million standard axles for an 8 mm rut at the end of the test;
- The life prediction for K46 indicated a minimum of 22 million standard axles to a rut depth of 12 mm;
- The life prediction result on K46 is double that of the standard design life of 10 million standard axles for this category of road, and
- Cost savings between 28% and 40% were realised using the NME technology instead of conventional high quality crushed aggregate bases supported by cement stabilised subbases.

The above analysis indicated that both the roads investigated should perform better than their respective design lives. In addition, significant cost savings were achieved and there is also an environmental impact in significantly less use of quarried crushed aggregate. This technology has specific application and benefit where high mica concentrations are present in the available in-situ road building materials that would make cement stabilisation less effective. The technology can, *inter alia*, be very beneficial for the upgrading of urban neighbourhood roads at significant cost savings and construction time savings. The inherent benefit of the NME dispelling water ingress could also minimize maintenance on these roads.

Acknowledgement

This work was funded by the Gauteng Department of Roads and Transport and is published with approval from the department.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was funded by the Gauteng Department of Roads and Transport and is published with approval from the department.

References

Akhalwaya, I. and Rust, F. C., 2018. Laboratory evaluation of road construction materials enhanced with nano-modified emulsions (NMEs). Proceedings of the South African Transport Convention. Pretoria, South Africa.

Bala, N., and Napiah, M, 2018. Fatigue life and rutting performance modelling of nanosilica/polymer composite modified asphalt mixtures using Weibull distribution. *International Journal of Pavement Engineering*, 21 (4), 497–506.

COLTO, 1985. Committee of land transport officials (COLTO) TRH14 - guidelines for road construction materials, Pretoria, South Africa.

De Beer, M., Horak, E., and Visser A., 1989. The multidepth deflectometer (MDD) system for determining the effective elastic moduli of pavement layers. In: G. Baladi and A. Bush, eds. Nondestructive testing of pavements and backcalculation of moduli. West Conshohocken, PA: ASTM International, 70–89.

Du Plessis, L., Rust, C., and Horak, E., 2008. Impact of the CSIR heavy vehicle simulator (HVS) on the performance of the SA road network. Science Real and Relevant: 2nd CSIR Biennial Conference.

Ezzat, HI, *et al*., 2018. Predicted performance of hot mix asphalt modified with nano-montmorillonite and nanosilicon dioxide based on Egyptian conditions. *International Journal of Pavement Engineering*, 21 (5), 642–652.

Ganjei, M. A., and Aflaki, E, 2019. Application of nano-silica and styrene-butadienestyrene to improve asphalt mixture self healing. *International Journal of Pavement Engineering*, 20 (1), 89–99.

Gutiérrez, J. M., *et al*., 2008. Nano-emulsions: New applications and optimization of their preparation. *Current Opinion in Colloid & Interface Science*, 13 (4), 245–251.

Harvey, J., *et al*., 1999. Caltrans accelerated pavement test (Cal/APT) program-results from tests on asphalt pavements 1994–1998. *Proceedings, 7th conf. on asphalt pavements for Southern Africa (CAPSA '99)*, Victoria Falls, Zimbabwe.

Jahromi, S. G, 2019. Introduction of a simple method for prediction of the rutting resistance factor of nanoclay-modified bitumen. *International Journal of Pavement Engineering*, 20 (2), 216–221.

Jordaan, G. J, 1994. The South African mechanistic pavement rehabilitation design methods. Research Report RR91/242, Council fort Scientific and Industrial Research, Pretoria, South Africa.

Jordaan, G. J., 2011. Behaviour of an emulsion treated base layer (ETB) as determined from Heavy Vehicle Simulator (HVS) testing. *10th Conference on Asphalt Pavements from Southern Africa (CAPSA 2011)*, Drakensberg, South Africa.

Jordaan, G. J., *et al*., 2017a. Practical application of nano-technology in roads in southern Africa. *Proceedings of the 8th transportation technology transfer conference*, Lusaka, 2017.

Jordaan, G. J., *et al*., 2017b. The development of cost-effective pavement design approaches using minerology tests with new nano-technology modifications of materials. *Proceedings of the 2017 Southern Africa transportation conference (SATC'17)*, Pretoria.

Jordaan, G. J., 2020. Design engineer, roadD1884 and K46. Personal discuission.

Jordaan, G. J., and Steyn, W. J. vdM., 2015. Processing of structural and functional pavement properties during the initial assessment of project level rehabilitation design projects. *11th conference on asphalt pavements for Southern Africa (CAPSA 2015)*, Sun City, South Africa.

Jordaan, G J., and Steyn, W. J vdM., 2019. Testing of granular/soil characteristics for the optimisation of pavement designs using reactive stabilising agents including "new-age" nano-technologies. *Paper presented at the 12th conference on asphalt pavements for Southern Africa (CAPSA),* Sun City, South Africa, 13-16 October 2019.

Kekwick, S. V., 1985. Derivation of pavement relative damage coefficients from heavy vehicle simulator testing: Methods and accuracy. CSIR technical Report RP/17, 1985.

Maree, J H, van Zyl, N J W, and Freeme, C R., 1982. Effective moduli and stress dependence of pavement materials as measured in some heavy vehicle simulator tests. Transportation Research Record 852, Transportation Research Board, Washington D.C., pp. 5260.

Mittal, A, Sharma, G, and Kumar, G, 2010. Laboraotry evaluation fo Zycosoil (nano technology based) for subgrade soils, aggregates and sand. CRRI, 2010.

Nejad, F. M., *et al*., 2014. Investigating the effect of nanoparticles on the rutting behaviour of hot-mix asphalt. *International Journal of Pavement Engineering*, 17 (4), 353–362.

Nokes, W. A., *et al*., 1996. Establishing the California department of transportation accelerated pavement testing program. *Transportation Research Record*, 1540 (1), 91–96.

Partl, M. N., Gubler, R., and Hugener, M, 2004. Nano-science and-technology for asphalt pavements. *Nanotechnology in Construction*, 343–355.

Rooholamini, H., Imaninasab, R., and Vamegh, M, 2017. Experimental analysis of the influence of SBS/nanoclay addition on asphalt fatigue and thermal performance. *International Journal of Pavement Engineering*, 20 (6), 628–637.

Rust, F.C., *et al*., 1997. The impact of the heavy vehicle simulator (HVS) test programme on road pavement technology and management. *8th international conference on asphalt pavements*, Seattle.

Rust, F.C., *et al*., 2019. Evaluation of a nano-silane-modified emulsion stabilised base and subbase under HVS traffic. *Paper presented at the 12th conference on asphalt pavements for Southern Africa (CAPSA)*, Sun City, South Africa, 13-16 October 2019.

Steyn, W. J. vdM., 2009. Potential applications of nanotechnology in pavement engineering. *Journal of Transportation Engineering*, 135 (10), 764–772.

Taylor, AJ, and Willis, JR, 2011. Effects of nanotac additive on bond strength and moisture resistance of tack coats. Final Report. National Centre for Asphalt Technology (NCAT). USA.

TG2, 2009. Technical guideline 2: Bitumen stabilised materials. Asphalt Acadamy, South Africa.

Theyse, HL, 2002. Stiffness, Strength, and Performance of Unbound Aggregate Material: Application of South African HVS and Laboratory Results to California Flexible Pavements. Research Report, University of California Pavement Research Centre.