Article

Evaluation of cost-effective thin modified binder seals on Nano-Modified Emulsion (NME) stabilised base layers using Accelerated Pavement Testing (APT)

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Featured Application: The surfacing layer on roads plays as essential role in the future performance of the road structure. In many traditional design approaches, the surfacing is also the most expensive part of the road pavement structure. It is directly exposed to the traffic loading as well as to harsh environmental conditions. The performance of the surfacing is highly dependent on the characteristics of the binder used and the interaction of the surfacing with the environment and the rest of the pavement structure. New-age nanotechnologies enables engineers to use modify binders to substantially improve the performance of surfacings and reduce the thicknesses thereof without compromising the integrity of the road structure as a whole. The optimisation of binder characteristics, using applicable thin (chip seal) surfacing can contribute substantially to the reduction of road unit costs.

Abstract: Emulsion stabilisation of base layers surfaced with chip seals often proves problematic with chips punching into the base and early distress. This can be aggravated by the use of modified binders that restricts the evaporation of moisture from pavement layers. The introduction of New-age (Nano) Modified Emulsion (NME) stabilisation has the advantage that water is chemically repelled from the stabilised layer resulting in an accelerated development of strength. A need was identified to evaluate the early life performance of selected chip seals, together with identified binders. Three different chip seal surfacings with unconventional modified binders were constructed and evaluated using Accelerated Pavement Testing (APT) with the MMLS3. The objectives of the experimental design and testing were to evaluate binder performance, early loss of chips before chip orientation at low temperatures, punching of the chips into the NME stabilised base, deformation characteristics of a Cape seal and the effect of the use of a standard normal modified binder. This paper contains details of the NME base layer, the binder and seal selection and the test results. It is shown that a cost-effective thin chip seal in combination with a suitable binder can be used on a NME stabilised base with confidence.

Keywords: nanotechnology in pavement engineering; thin surfacings for New-age (Nano) Modified Emulsion stabilised base layers; applicable modified binders for chip seals; Cape seals using anionic New-age Modified Emulsion slurries; Sasobit-M® modified binders for chip **seals.**

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1. Introduction

Investment in a surfaced road network creating accessibility to markets and reducing transportation costs has been shown previously to be a major stimulus for economic growth. Sub-Saharan Africa compares poorly when comparing the surfaced road network to that of the developing world [1]. The general lack of adequate funding for upgrading of gravel roads and maintenance of surfaced roads, together with relatively high unit costs associated with the provision of all-weather roads using traditional design and construction procedures, make it almost impossible to provide the road network required to stimulate economic growth [2].

The adoption and implementation of available technologies that has been used in the built environment to protect stone buildings can find direct application in the road construction industry. Material compatible New-age (Nano) Modified Emulsions (NME) stabilising agents using naturally available materials in the base / sub-base layers of pavement structures have been tested, evaluated and validated through numerous laboratory tests [3] and Accelerated Pavement Tests (APT) with the Heavy Vehicle Simulator (HVS) [4, 5]. The use of naturally available materials stabilised with material compatible (NME) has been shown to be able to reduce road unit costs considerably [3, 4, 5, 6].

In order to optimise cost savings, the NME stabilised naturally available materials in the base / sub-base layers must be used in combination with cost-effective thin all-weather surfacings (e.g., chip seals). This provides a relatively low-maintenance surfacing, resulting in a relatively low (compared to traditional material and design approaches) life-cycle cost. However, the traditional use of emulsion stabilisation in base layers together with thin chip seal surfacings has often proved problematic with punching of the stone into the base. This leads to early distress in terms of severe bleeding of the binder, associated rut deformation and a weak interlayer near the top of the pavement structure. With normal emulsion stabilisation, moisture is only relieved from the layer through evaporation. The general specification and use of some modified binders known to restrict the evaporation of moisture from base / sub-base layers [7], entraps moisture and further aggravate the problem at the top of the base layer.

The introduction of material compatible NME stabilisation has the advantage that water is effectively repelled from the stabilised layer through a chemical reaction between the minerals of the materials and the modifier applied to the emulsion. This results in an accelerated drying of the layer with an associated accelerated development of compressive and tensile strengths [8]. It follows that the use of thin chip seal surfacings may be a cost-effective low-risk option when used in combination of a material compatible NME stabilising agent.

Hence, a need was identified to evaluate the early life performance of selected chip seals, in combination with appropriate binders on a NME stabilised base layer using APT with the MMLS3 [9]. Three different chip seal surfacings were constructed on a base and sub-base using naturally available materials stabilised with a material compatible NME. The naturally available materials used in the base and sub-base layers were severely weathered material considered "unsuitable" for use in the upper pavement layers according to traditionally used material classifications (e.g., [10, 11, 12]).

Three different chip seal types with unconventional as well as conventional modified binder types were constructed. The surfacings and binders were carefully selected in order to meet the objectives of the testing and the evaluation of:

- Binder performance:

     o Sensitivity of an unconventional modified binder as a tack coat placed outside normal specified temperature ranges on stone adherence (work done in remote areas using small contractors make strict adherence to temperature limitations difficult);

     o Effect of the use of normally specified modified binders on the restriction of the evaporation of moisture (also applicable to base layers constructed with crushed stone and / or cement stabilisation);

- Punching of the stone into the newly constructed NME stabilised base layer constructed using "sub-standard" naturally available materials with a high percentage of fines in the base-layer;
- Stone loss during testing at low temperatures before reorientation of the stone has taken place, and
- Deformation characteristics (using a full-scale MMLS3 test) of a Cape seal constructed with a NME slurry, no cement additive and mixed and placed by hand on site.

High accuracy, 3-D scanning techniques based on Visual Simultaneous Localization And Mapping (VSLAM) were used to quantify and evaluate possible aggregate loss, reorientation of the stone and punching of the stone during the APT testing. The initial testing was done at low temperatures normally expected to result in high stone loss due to a brittle binder. These digitised twin samples allowed for accurate objective calculations and analyses of the effect of the APT loading on each of the different surfacings.

The test results showed the versatility of the unconventional tack coat with no stone loss during placement, as well as the APT testing done under adverse conditions during which reorientation of the stone took place. It follows that the specific binder modification could be suitable for application in remote and / or developing areas where temperature control and strict adherence to specifications can be challenging. No measurable punching of the stone into the NME stabilised base could be detected. The MMLS3 test done on the Cape seal using a NME modified slurry showed deformation characteristics comparable to the requirements of asphalt surfacing specified for highways [13]. Over and above the pavement structural performance, the NME stabilised base has shown the ability to develop the early compressive strengths required to prevent punching of stone into the top of the layer. The APT results gave confidence to the use of cost-effective thin chip seal surfacings on NME stabilised naturally available materials to construct cost-effective road pavement structures at an acceptable risk.

Visual evaluation of the seals two years after construction (the last 14 months without any traffic) showed the development of multiple scattered holes visible on the surface of the double seal where a conventional modified binder was used for the placement of the second seal. This indicates that the binder prevented any evaporation of moisture from the base to take place, resulting in formation of clearly visible holes, allowing for the moisture to escape from the pavement. In practice, a binder that inhibits the evaporation of moisture under trafficking could lead to the stripping of the seal from the base layer and/or bunching of the chips (stone) into the top of a saturated base and resultant failures.

2. Background

2.1. Materials used in the base and sub-base layers of the pavement structure

It is not the objective of this paper to give a detailed description of the testing, evaluation and analysis done of the pavement design and evaluation thereof in terms of the bearing capacity of the pavement structure. Of importance is an understanding of the materials used in the construction of the base (200 mm thick) directly on top of a sub-grade with a CBR < 3 at 93 per cent mod AASHTO, to form a highly flexible pavement structure. The base was stabilised using 1.5 per cent material compatible anionic NME. The properties of the naturally available materials used for the construction of the base layer, mineralogy tests as well as the stabilised Unconfined Compressive Strengths (UCS) and Indirect

Tensile Strengths (ITS) (test procedures described in reference [6]) are summarised in Figure 1.

Base and Sub-base material for Accelerated Pavement Testing (APT) (MMLS3) of thin (chip seal) surfacing

Material grading
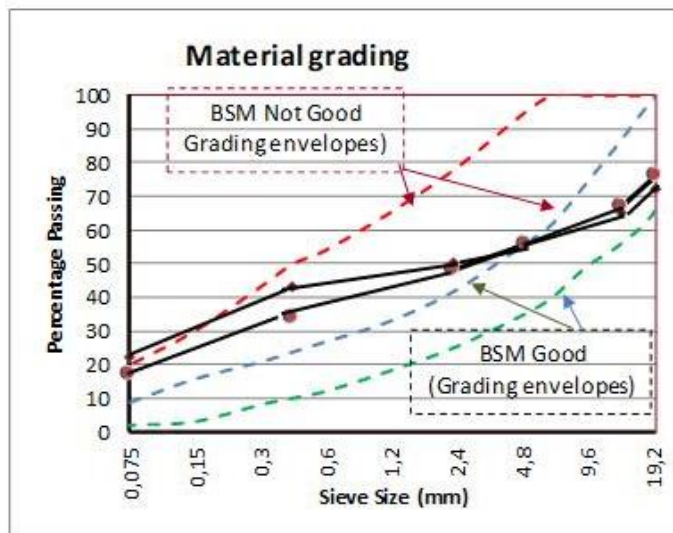
Material Test results	
Fraction	%
Coarse Sand (CS)	29 - 33
Fine Sand (FS)	28 - 35
Coarse Fine Sand (CFS)	10 - 11
Medium Fine Sand (MFS)	11 - 17
Fine Fine Sand (FFS)	6 - 8
Silt and Clay (S & C)	35 - 39
OMC (%)	11,4
MDD (kg/cub m)	2030
GM	1,85
Atterberg Limits	
Liquid Limit (LL)	28 - 30
Plasticity Index (PI)	8 - 14
PI (0.075)	
Linear Shrinkage (LS)	4 - 7

Mineral Percentages present in Material Sample

Minerology	Total sample %		0.075 mm Fraction %	
Mineral Groups	Individual	Combined	Individual	Combined
Quartz	43,2	43,2	23,0	23,0
Plagioclase	14,8		6,6	
Augite	2,4		1,3	
Enstratite	0,0		0,5	
Actinolite	3,8		1,4	
Microcline	6,5		4,2	
		27,5		14,0
Mica: Muscovite	12,2	12,2	36,2	36,2
Clay: Kaolinite	6,1		15,0	
Clay: Smectite	7,5		3,0	
Calcite	0,5	14,1	6,5	24,5
Talc	3,1	3,1	2,3	2,3

CBR (mod AASHTO)	
95%	10 - 17
93%	9 - 14
Classification	
H.R.B.	A-2-6
COLTO	G8
TRH14	G8

Mineral Groups:
(Weathering = chemical decomposition)
Primary (Not subject to Weatering)
Primary (Subject to Weathering)
Mica
Secondary minerals
(Nano-scale crystals/molecules)

Results: Stabilisation

Agent	New-age Modified Emulsion (NME)				Conventonal Emulsion stabilisation			Unit
%	0,7	1,0	1,2		!.5% SS60 Emulsion + 1% Cement			
UCS(dry)	3395	4807	4859		3277			kPa
UCS(wet)	1745	1830	1671		656			kPa
UCSw/d %	51	38	34		20			%
ITS(dry)	254	420	268		167			kPa
ITS(wet)	61	321	221		61			kPa
ITSw/d %	24	76	82		37			%

UCS = Unconfined Compressive Strength; ITS = Indirect Tensile Strength;
BSM = Bituminous Stabilised Materials

Figure 1: Material test results, mineralogy and NME stabilisation results of the Base material

The variation shown is of several samples of the materials tested along the 250 m length of a 3.7 m wide lane constructed next to the road. Similar materials stabilised with NME were used in a pavement structure to evaluate the bearing capacity of the pavement with different layer thicknesses (150 mm base and 150 mm sub-base) as reported elsewhere [4, 5].

2.2. *Specifications of chip seal and Cape-seal surfacings*

The general specifications for the placement of chip seals applicable to South Africa [14] contains strict limitations with regard to temperature of placement and binder temperatures in order to limit failures. These recommendations are largely in line with current recommendations for use in South Africa [15].

Over and above additional considerations, only the relevant data in terms of this paper are repeated in terms of road surface temperature requirements. Binder application may only be placed under the following temperature conditions:

- Hot binders with 0% solvents: 25°C and rising, and
- Emulsions: 10°C and rising.

The surface temperature can be reduced by 1°C for each percentage point of a Low Flash-point Solvent (LFS) (e.g., paraffin) added. For single and double seals with a elastomer modified binder (S-E1; S-E2) [7], a maximum of 4 per cent LFS is recommended, while for a bitumen-rubber (S-R1) binder a maximum of 8 per cent High Flash-point Solvent (HFS) is recommended.

Lower temperatures will normally lead to a rapid drop in binder temperatures, an increase in binder stiffness and a resultant increase in risk of adhesion failure [7]. Adhesion failure is the most common problem experienced with chip seals with an associated risk during winter periods or under challenging conditions, resulting in a drop of binder temperature before spreading of the stone. Trafficking of newly laid chip seals before orientation of the stone has taken place at temperatures below 20ºC, will often also result an increase in stone loss.

With the construction of the test sections on the anionic NME stabilised base, binder options were considered with the specific intention to limit risks associated with construction and temperature related aspects that could be challenging to meet under difficult construction and environmental conditions. The APT test programme was designed to test at temperatures below 20ºC to evaluate stone loss during early trafficking, while orientation of the stones took place.

2.3. *Binder selection: Tack coat for the chip seals and Cape seal*

In order to meet the objectives of the project, the selected binder must adhere to the following criteria in terms of practical requirements, allowing for the:

- Continued evaporation of moisture from the NME stabilised release in terms of vapor from the anionic NME stabilised base layer;
- Leniency in terms of temperature specifications, allowing stone to be applied at lower temperatures without an increase of risk of stone loss, and
- Reorientation of the stone to take place under the action of trafficking at temperature below 20ºC without an increase in stone loss (risk reduction).

These requirements in terms of the successful placement of the chip seal need to be met before the resilience of the anionic NME base to the penetration of the chips into the top of the base layer can be assessed. Conventional modified binders commonly used in the construction of chip seals do not meet these requirements. Hence, the use of novel solutions using available proven modified binders available in the industry was investigated.

SASOBIT® - FT wax modification [16] to bituminous binders was developed more than 25 years ago and has been successfully applied and proven throughout the world in the placement of asphalt layers (e.g., [17, 18, 19]). The benefits of the SASOBIT® modification for use in asphalt mixes, inter alia, includes [19]:

- Increased resistance to cracking due to the formation of an interlocking "tree-branch" structure within the binder;
  Increased resistance to deformation (after crystallisation of the FT-wax molecule the melting point is increased from about 70ºC to 100ºC which increases the viscosity and hence, the deformation characteristics of the binder between these temperatures), and
- Benefits in terms of construction – allowing asphalt compaction to continue down to temperatures as low as 80°C at which point crystallisation of the wax molecule occurs. In 2016, an improved modifier SASOBIT-M® was introduced into the market. The

SASOBIT-M® modifier (FT-wax-M) consists of FT-wax with a crude oil additive that does not influence the main characteristics of the bitumen and is classified as non-hazardous in terms of European standards. Several trail sections using typically 1.5 per cent SASOBIT-M® in the binder has shown a further decrease in the compaction window to asphalt to about 60°C [20]. This modification effectively allowed for the use of a warm-mix asphalt instead of a traditional hot-mix asphalt in practice. The comparison between "standard" bitumen, 3 per cent SASOBIT® modified bitumen and a 1.5 per cent SASOBIT-M® modified bitumen is demonstrated in Figure 2.

It was reasoned that the characteristics of the SASOBIT® modified binder and proven history and use thereof in asphalt mixes should apply to the use thereof in the placement as a tack coat for chip seals. If proven successful, this modified binder could considerably reduce the risks to contractors in the placement of chip-seals in practice, allowing for the application of stone at lower binder temperatures without an increase in stone loss. Hence, a SASOBIT-M® modified binder (1.5 per cent) to a 60 / 70 pen binder was selected as a tack coat for the adhesion of the stone.

2.3. Binder selection: Second binder application for the double chip seal

In order to assess the performance of commonly used modified binders for chip seal applications, a test section was constructed using a second application with an elastomer modification, using a SBS polymer (S-E2) [7]. This modified binder is often specified without considering the noted disadvantage that it "can restrict evaporation of entrapped moisture" [7].

2.3. Binder selection: Slurry for the construction of the Cape seal

Cape seals [21] are normally constructed using a slurry consisting of a bitumen emulsion, crusher dust, sand and a cement filler. The slurry provides additional protection and acts as an adhesive, keeping the stone in place where the turning movement of vehicle tires can potentially result in stone loss. Practical experience has shown that a well-constructed Cape seal can be expected to have an advantage in terms of maintenance-free surfaced life [22].

The use of a cement or lime filler as part of the slurry mix may result in a brittle mix, reducing the crack-free life of the slurry seal on a highly flexible pavement structure. In this case it was decided to test a slurry using an anionic nano-modified emulsion without a cement or lime filler. The influence of nano-silane modifications has been covered in detail by several publications (e.g., [2, 6, 23]). The main advantages of anionic nano-silane modifications of bitumen emulsions in terms of this paper are in that it:

- acts effectively as an aggregate adhesive which "permanently" bind the bitumen to the aggregate;
- renders the aggregate to become hydrophobic and repels the water from the mix, and
- assists in the stability and better distribution of the bitumen particles, effectively reducing the percentage of binder required to achieve the same engineering properties in terms of tensile and compressive strengths.
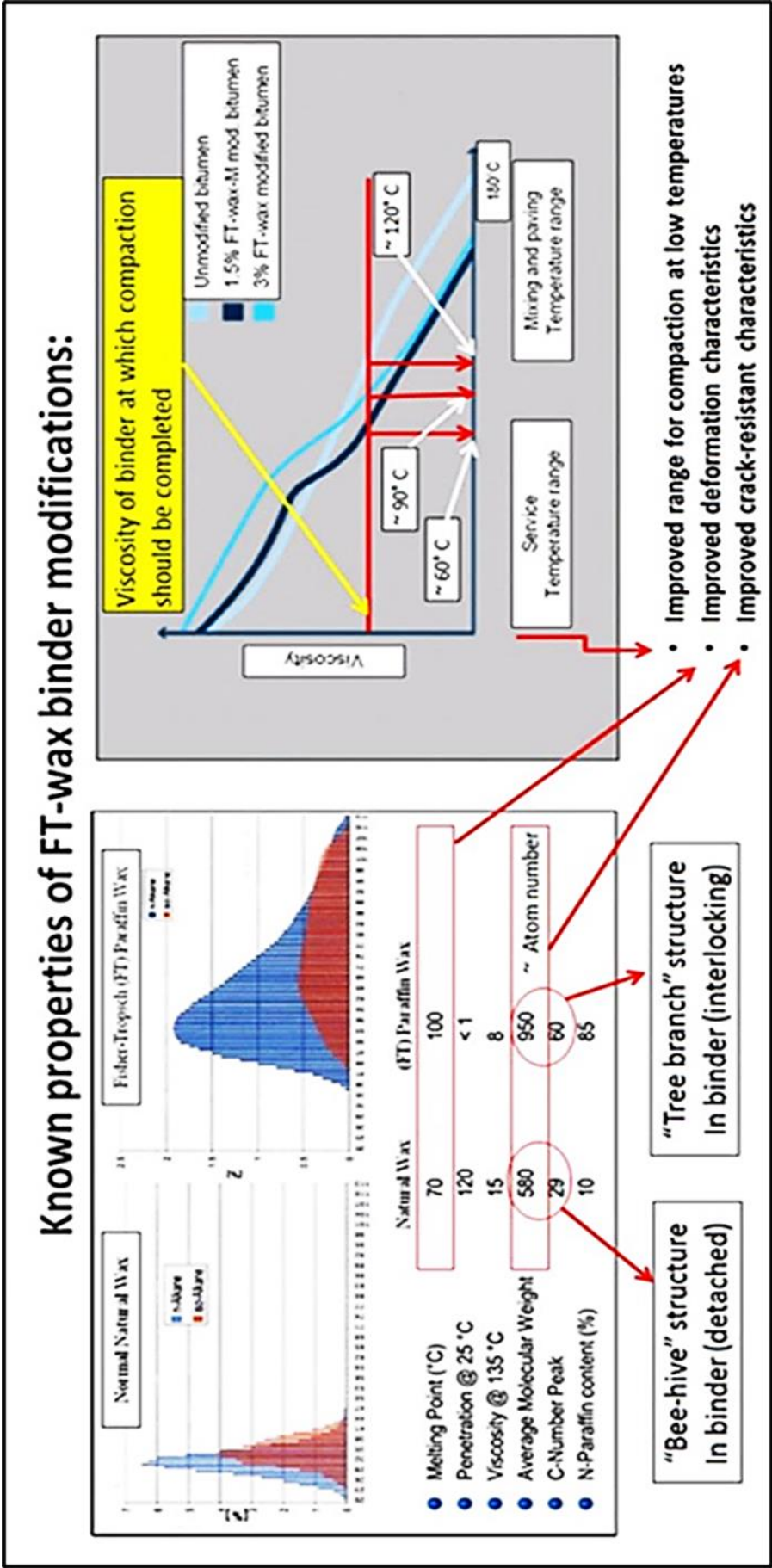
Figure 2: Working principles as applicable to a standard pen bitumen, 3% SASOBIT® (FT-Wax) modified bitumen and 1.5% SASOBIT-M® modified bitumen binder

2.4. *Novel use of APT test equipment*

In order to test the adhesive properties of the seals using the modified binders, the different experimental seal sections were subjected to APT testing using the MMLS3 scaled APT equipment [9] that is typically used for the testing of the deformation characteristics of asphalt mixtures for highways [13]. The tire pressures of the MMLS3 is equivalent to that of heavy vehicles commonly found on southern African roads (690 kPa to 850 kPa) and loads are applied on the 300 mm diameter tire at 2.9 kN at a rate of 7 200 repetitions per hour [13].

In this case the standard test (100 000 repetitions at a controlled surfaced temperature of 50ºC), was only applied to the Cape seal containing various novel modifications in terms of the tack coat and the slurry mix. In addition, the MMLS3 was used on the three thin surfacings, applying 18 000 repetitions to each of the test sections at temperatures below 20ºC to evaluate:

- Adhesion of the stone to the binders placed at temperatures below the normal specifications;
- Early loss of stone during trafficking at temperatures below 20ºC when reorientation of the stone take place (resulting in stone loss using normal modified binders), and
- Penetration of the stone into the newly constructed NME stabilised base constructed using naturally available materials containing a high percentage of fines, not meeting the general specifications for materials recommended for use in base layers (Table 1). A typical description of the setup of the MMLS3 on site is shown in Figure 3.

2.5. *3-D Scanning to determine seal surface characteristics*

The surface characteristics of the different seals before and after APT testing were determined and compared using 3-D scanning using handheld EinScan equipment [24]. After scanning each of the samples using a handheld EinScan Pro, the digitised mesh was stored in an STL (stereolithography) file format. The mesh is processed using Blender (an open-source animation and rendering software suite)   to obtain representative samples with the correct orientation. Thereafter CloudCompare (an open-source point-cloud processing tool) is used for point-cloud generation and statistical analysis.

Due to optical limitations, the EinScan is best suited for scanning lightly coloured, opaque materials. Dark coloured geometry is not captured during the scan. Hence, a thin layer of evenly distributed white spray paint was applied to the area of interest. The spray paint was applied at an angle of 45° relative to the horizon, from all cardinal directions, to ensure that the crevices and cracks are coated adequately. The minimum suitable sample size was determined as 100 x 100 mm. This sample size mitigates the effects of small, hollow voids caused by the reflective tracking markers. Calibration prior to scanning was conducted, with the reported calibration accuracy falling within a range of 10 – 15 μm.

Reference markers were designed, printed with a 3D printer and used for sample orientation in the environment as part of the mesh itself and as a scale reference for visual clarity. Each geometric feature of the arrow measures either 10 mm or multiples thereof (with the exception of the diagonals). These arrows were coated with two layers of white spray paint to provide easy tracking for the scanner. Each arrow is provided with a reflective marker on the surface as an additional tracking target. The arrows delineate the edges of the scanning area, the line separating APT and non-APT sections and indicating the direction of traffic loading (Figure 4).
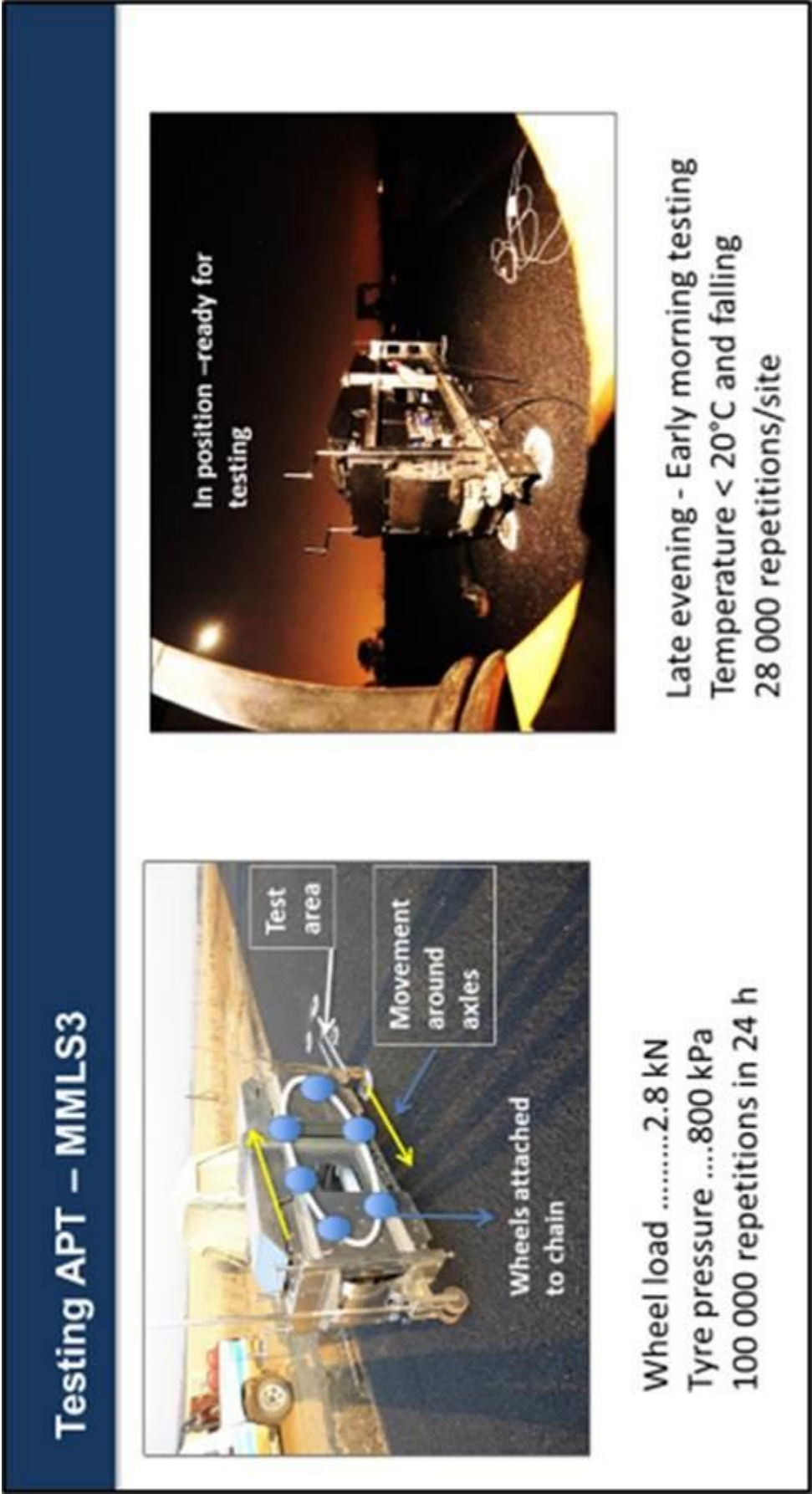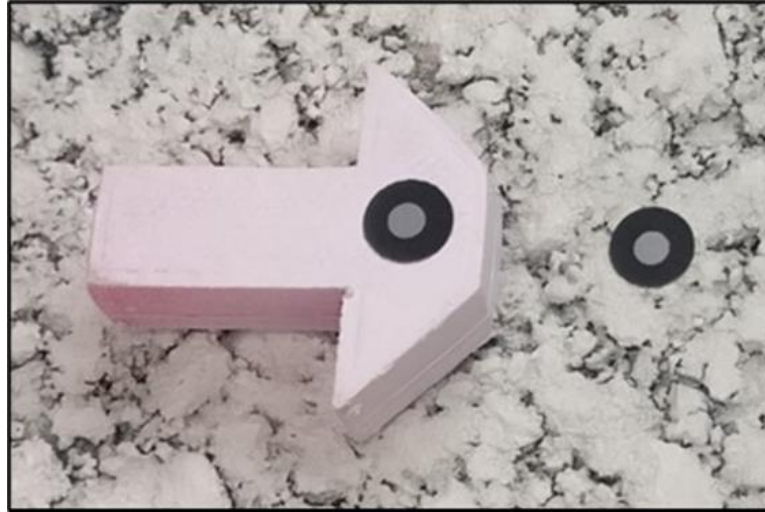
Figure 3: Graphical illustration of the setup and working of the MMLS3 on site

**Figure 4:** Example of 3-D reference arrows placed on the surfacings

For larger, aggregate geometries (>10 mm), handheld scanning provides superior angles to cover a larger percentage of the exposed surface area, compared to the fixed scanning method. A wider range of rotation of the scanner is required to cover all areas and angles. For the "Handheld HD Scan" setting, an accuracy of 0.1 mm and a point-distance of 0.2 to 2.0 mm is obtainable. For adequate coverage, approximately 16 scans were required around the circumference of the sample with 2 to 3 different pitch angles for 32 to 48 scans. Typically, a cloud-point composed of more than 5 million points was found to be indicative of a complete scan. The scanning process takes approximately 20 minutes per sample. The scans are scaled in the appropriate unit of measurement (millimetres). The final mesh was exported as an industry standard STL file. Using the 3D Toolbox add-on of CloudCompare, the surface area was calculated. For samples selected at random locations, the surface area varied by less than 2 per cent.

Analysis of the digitised samples was performed using CloudCompare. Distributions of roughness, curvature and point-densities can be performed and compared for different samples and specimens with the built-in functionality. All calculations were performed on a point-cloud instead of the original mesh, as only individual points are required for the analysis. Considering the resolution of the scanner and the sample size, a point-cloud density of 100 points/mm^2 was found to have sufficient resolution and repeatability. This equates to 1 000 000 points for a 100 mm x 100 mm sample. A typical example of an imported mesh of the 20 mm stone prior to APT loading is shown in Figure 5.

3. Design and construction of the thin surfacings on the anionic NME stabilised base

In June 2018, a 250 m long bypass along a road to the South-East of Johannesburg, South Africa was constructed and used to test different thin surfacings on a newly constructed anionic NME base-layer. The bypass was constructed using in-situ equivalent G8 (Figure 1) [10] shoulder material to construct a 200 mm thick base-layer using a material compatible [8] stabilising agent consisting of 1.5 per cent anionic NME on an in-situ subgrade with a CBR < 3 at 93 per cent mod AASHTO. The base was primed using anionic nano-silane modified bitumen emulsion diluted at a 1:2 ratio with water. The bypass was designed for a design traffic loading of 1.0 million standard 80kN dual wheel single axles (E80s), a cost-effective alternative to traditional pavement designs. Although the bypass was intended to be used for only four months, it also provided an opportunity for a possible future full-scale APT to evaluate the road pavement structure without the

interference of normal traffic. Similar APT tests have already been performed in South Africa for a 3 million E80 and a 10 million E80 traffic loading [4, 5].
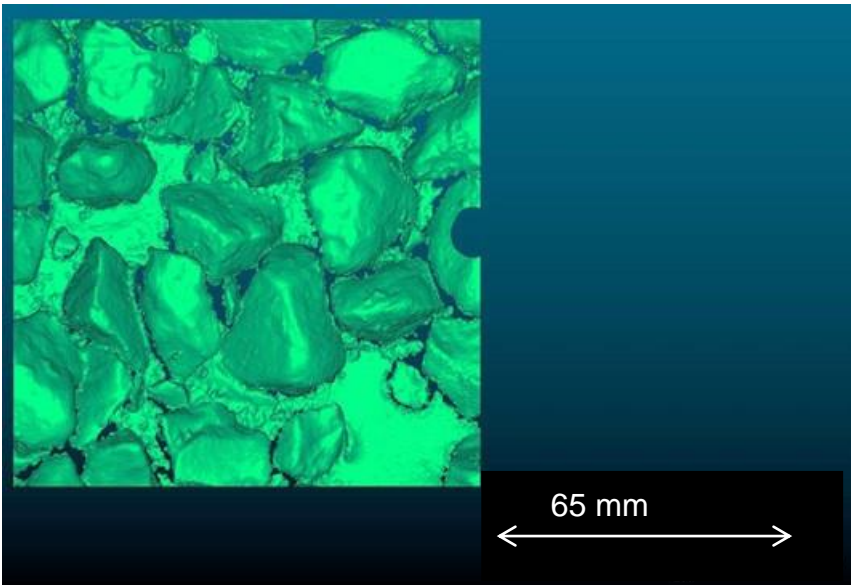
Figure 5: Typical example of an imported mesh of the 20 mm single seal

As discussed, adhesion of the stone is of major importance in the long-term performance of cost-effective thin surfacings. The compliance to strict temperature specifications to achieve adhesion is a major challenge when working in remote areas with small contractors. Hence, it is important to evaluate the use of modified binders that allow for leniency in terms of stone application without compromising future performance and maintenance needs. The successful application and evaluation of the selected binders could also contribute to the development of small contractors in developing economies with the emphasis on labour intensive construction. The layout of the test sections is shown in Figure 6.
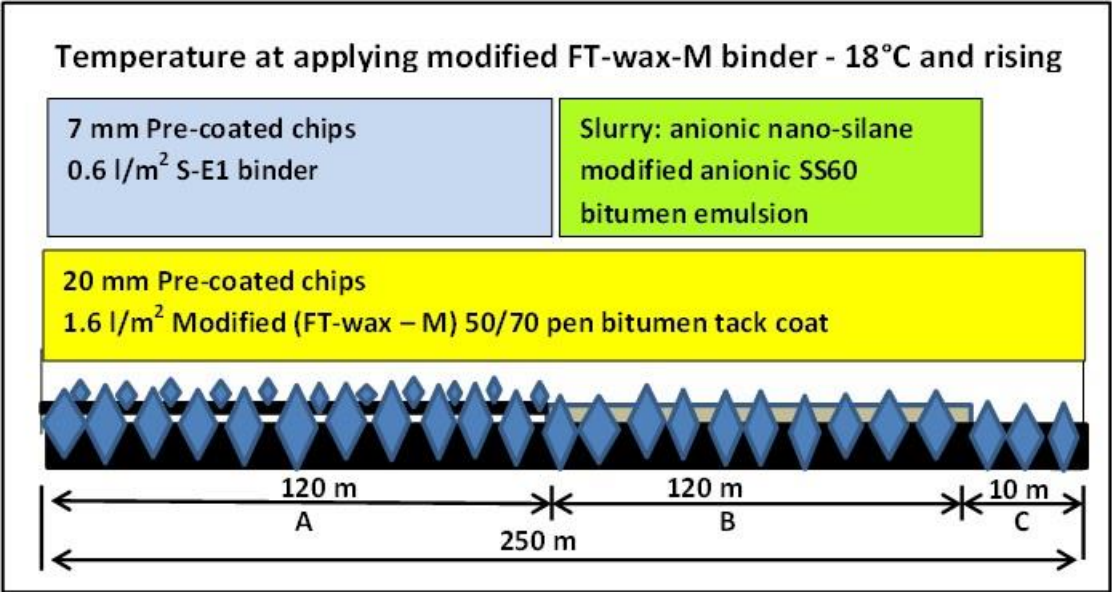
Figure 6: Experimental layout of three different chip seal types for APT testing

The 20 mm single seal was specifically placed in order to evaluate stone loss during loading at temperatures below 20ºC (during reorientation of the stone and possible early

punching of the stone into the NME stabilised base layer (a general problem associated with normal emulsion stabilisation of base layers)). The SASOBIT-M® tack-coat was placed at an application rate of 1.6 l/m^2 at 18ºC. The hypothesis was that the same properties that made the compaction of asphalt at lower temperatures possible through the SASOBIT-M® modification, should apply to the construction of seals at temperatures lower than the minimum specifications currently applied.

The Cape seal (20 mm stone with hand mixed and placed slurry) was constructed using a combination of previously untested binders (SASOBIT-M® tack and an anionic NME slurry with no cement or lime filler). The deformation characteristics of this thin surfacing was considered of particular interest in terms of the deformation characteristics thereof on the anionic NME base as compared to that of an asphalt surfacing on highways [13}. The APT test on the Cape seal was included as a good indication of possible punching of the large stone size into the anionic NME stabilised base layer, resulting in associated flow of the slurry and severe bleeding visible on the surfacing.

The second seal of the double seal (20 mm stone first layer and 7 mm stone second layer) was placed using a normal SBS elastomer binder (S-E2) [7], at an application rate of 0.6 l / m^2. The binder used for the second layer was chosen specifically to assess the effect of possible entrapment of moisture evaporating from the anionic NME stabilised base.

The placement of the SASOBIT-M® tack-coat for the 20 mm stone, done on 25 July 2018, is shown in Figure 7. With the consideration of possible future labour-intensive construction, the slurry part of the Cape seal (Section B in Figure 6) was mixed on site using a standard concrete mixer and applied to the surfacing by hand in one application, using squeegees (Figures 8(a) and 8(b)). In order to achieve a working window of 6 hours to allow the workers with enough time to properly fill all voids and to achieve a smooth surfacing, the normal NME binder was diluted with water at a 1:2 ratio during mixing with the aggregate.

Figure 7: Placement of the SASOBIT-M® tack-coat for the 20 mm stone

(a)   (b)
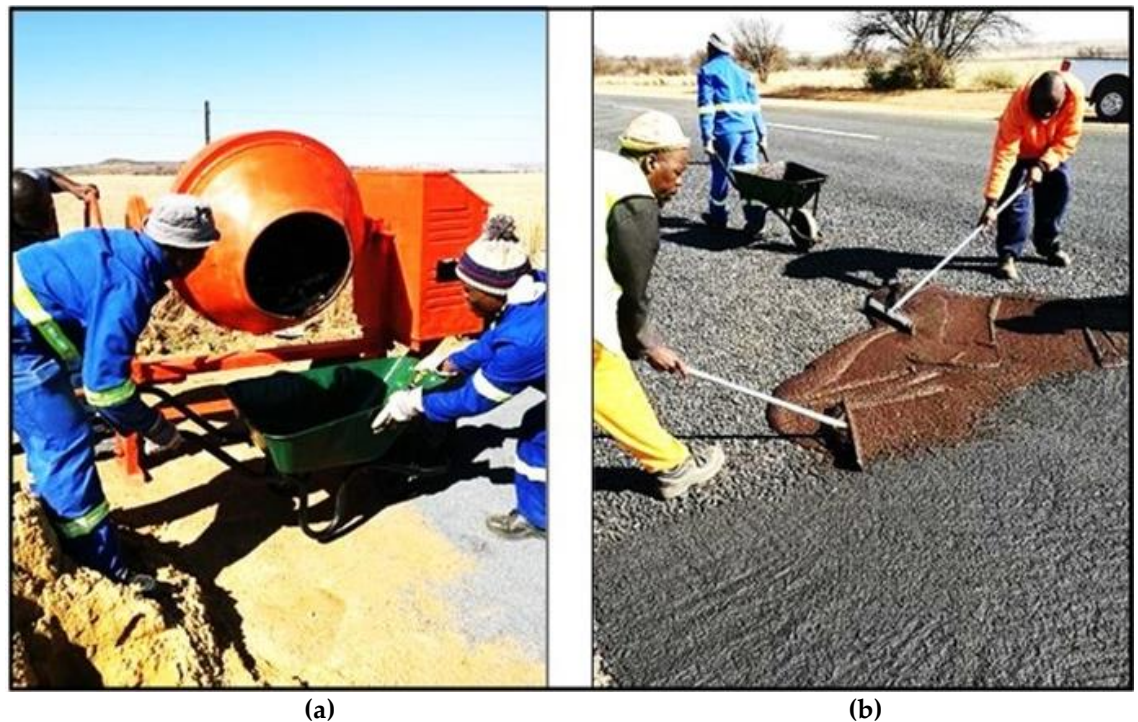
Figure 8: On site mixing (a) and placement (b) of the anionic NME modified slurry mix

After construction, the bypass was closed to traffic to allow for the evaluation of the early stone orientation using APT loading with the MMLS3 on each of these sections at temperatures lower than 20°C.

4. APT loading and evaluation of the 3 different seals using the MMLS3

4.1. General – APT loading

The MMLS3 [9] was used to test the early performance of the three seals under loading at temperatures below 20°C during August 2018. In order to test possible embedment into the NME stabilised base and stone loss during reorientation of the stone at temperatures less than 20ºC, more than 18 000-wheel loads were placed on each of the different seal types using a wheel with a 300 mm diameter at a wheel load of 2.9 kN and tire pressure of 6 900 kPa. In addition, a full MMLS3 test was done according to the prescribed test protocol [13] to evaluate deformation characteristics during a 24 h test with 100 000 repetitions at a controlled temperature of 50ºC on the Cape seal section.

The APT loading to evaluate early performance was done at temperatures that varied between 12ºC and 19ºC while applying 18 000 repetitions to each of the three different thin surfacings. It was expected that the single 20 mm test would most clearly illustrate any stone loss during orientation at loadings below 20ºC, while also clearly illustrating penetration of the stone into the NME treated base layer using naturally available materials. Similarly, the Cape seal and double seal were expected to show signs of bleeding if the 20 mm stone is to penetrate into the NME base layer.

4.2. *3-D Scans and analysis of the three thin surfacings*

The Mean Profile Depth (MPD) and Mean Texture Depth (MTD) calculations were done using data obtained through handheld 3-D scanning equipment. The surface characteristics of the different seals before and after APT loading were determined and compared using 3-D scans. The MPD is calculated as the average profile depth of two sections (using the highest peak on each section) over a 100 mm long baseline [25].

The sand patch test [26] uses a volumetric approach of measuring pavement macrotexture. The MTD [15] can be expressed as the ratio of the volume of material that is required to fill the surface, divided by the area that is covered by the volume of material. Unlike the ASTM method, the surface area of the sample remains fixed when using 3-D scanning technology, with the volume of material filling the surface texture serving as the variable quantity. The benefit of this calculation is that an equivalent sand patch value can be calculated directly using the software. The volume of both the cuboid surrounding the sample (area multiplied by the greatest difference in height) and the volume of the aggregate are known. The difference in the volume is occupied by the virtual sand particles that would fill the surface until the entire surface is covered uniformly.

Two quantitative metrics are used for describing the relevant surfacing characteristics. For each sample, the kernel size is configured to be between 25 per cent and 100 per cent of the nominal aggregate dimension. Smaller kernel sizes provided improved representative statistics of the samples. The two metrics that were found to provide good results are curvature and roughness.

The built-in curvature tool provides an assessment of the extrinsic mean curvature that is derived from differential geometry. The curvature of each point is estimated by best fitting a quadratic around that particular point. A histogram provides the distribution of the metric. The roughness distribution is based on a best fitting plane of the surrounding points within the kernel. The roughness will thus be highly dependent on the volume and shape of the aggregate protruding from the seal or binder surface. The statistical data can be expressed using either a Weibull distribution with a- and b-parameters describing the scale and shape respectively, or an exponential distribution. The goodness-of-fit is highly dependent on the aggregate dimensions and shape for each test.

4.3. Comparing the 3-D Scans of the three different thin surfacings subjected to APT loading with ajecent areas subjected to no loading

4.3.1. General

The two-chip seal and the Cape seal APT sections were evaluated using the 3-D scanning technology and the statistical evaluation tools described. The main objectives of these tests were to evaluate the performance of thin cost-effective surfacings on an anionic NME stabilised base using naturally available materials. Simultaneously, the opportunity was used to test the use of unconventional binders that would provide contractors with more leniency with regard to the strict specifications applicable to the successful placement of chip seals at no increase in risk.

4.3.2. Single 20 mm chip seal with 1.5 per cent SASOBIT-M® modified 60 /70 pen bitumen

Visual assessment: The demarcated area for the APT loading done on the 20 mm single seal with the area for the 3-D scans painted in white is shown in Figure 9. The stone reorientation that occurred on the 20 mm single seal after 18 000 repetitions is clearly visible. No stone loss could visibly be detected on the test section and no stone penetration into the anionic NME stabilised base (using G8 materials) could be detected.

3-D scan of the surfacing with and without loading: The height maps of the 20 mm seal produced from the 3-D scans are shown in Figure 10 (APT loading on the left and no loading on the right). The blue to red 3-D generated pictures show the relative differences in height within the scanned areas. The less red in the scan after the APT loading is an indication of the reorientation of the stone that has taken place and the filling of the vacant blue areas. The statistical evaluations of the data of the two scanned areas are given in Table 3.

Figure 9: Condition of the 20 mm single chip seal in and outside the APT test area
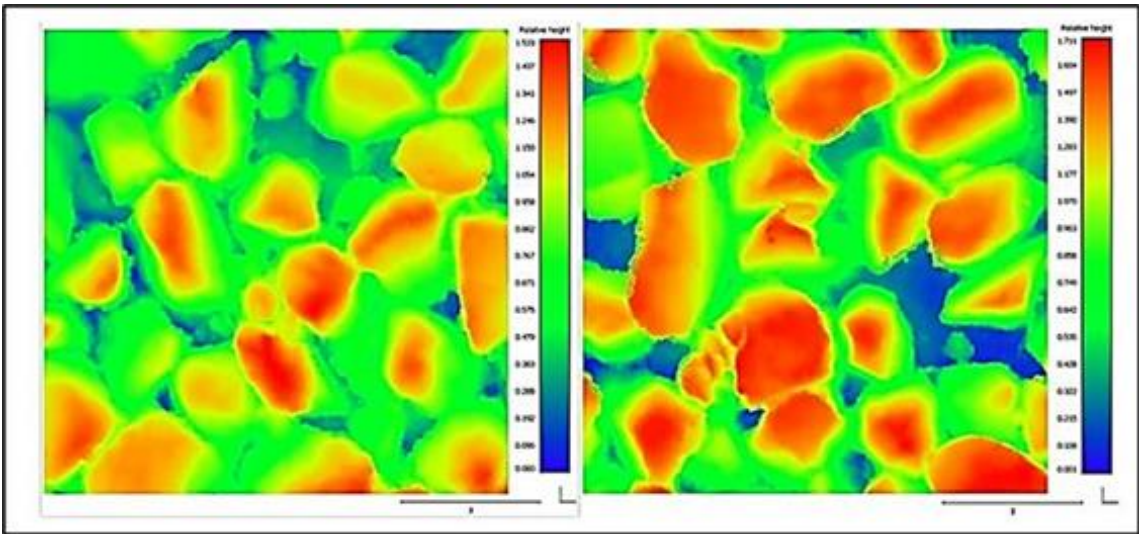

Figure 10: 3-D scan of the 20 mm single seal: Left: APT loading, Right: no loading

. **Table 3:** Volume and Void ratios calculated from a statistical analysis of the 3-D scans of the single 20 mm seal shown in Figure 14

Parameter	APT loading	No-loading
Solid volume (V_T) [cm³]	156.22	178.88
Sample area [cm²]	100.2	100.2
Largest height difference [mm]	15.622	17.888
Aggregate volume (V_s) [cm³]	84.83	110.40
Void volume (V_v) [cm³]	71.39	68.48
Void ratio (V_v/V_s)	0.8416	0.6203
Void ratio (V_v/V_T)	0.4570	0.3828
MTD [mm]	7.14	6.85
MPD [mm]	6.34	5.76

4.3.3. 20/7 mm double seal with a SASOBIT-M® tack-coat and an elastomer modified (S-E2) second application followed by a fog spray

Visual assessment: Figure 11 shows the surfacing of the double seal with and without the testing with more than 18 000 repetitions applied at temperatures between 12ºC and 19 ºC with the MMLS3. No visible difference between the test area and untested surfacing was detected. No sign of an access of binder could be detected on any of the test sections section with no sign of bleeding of the binder

3-D scan of the double chip seal surfacing with and without loading: The 3-D scan images generated on the double seal are shown in Figure 12. Although no visual differ-ence could be detected by eye, the 3-D scanned images show a clear difference between the surfaces with and without loading. The height maps generated from the image are shown in Figure 13. The areas subjected to the APT loading (left in Figures 12 and 13), clearly show a denser matrix when compared to the adjacent area where no loading was applied (right in Figures 12 and 13). It follows that the smaller 7 mm stone were packed closer into the first 20 mm seal under loading, leaving fewer gaps and moving towards a uniform surface.

The volume and void ratios calculated from the scan data sets are given in Table 4.
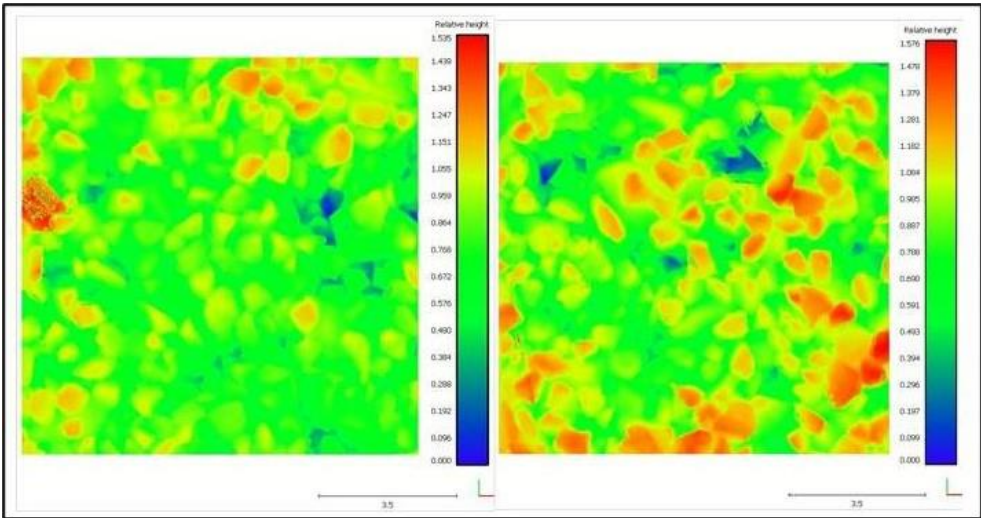

Figure 11: Condition of the 20/7 double seal after the APT done at < 20°C
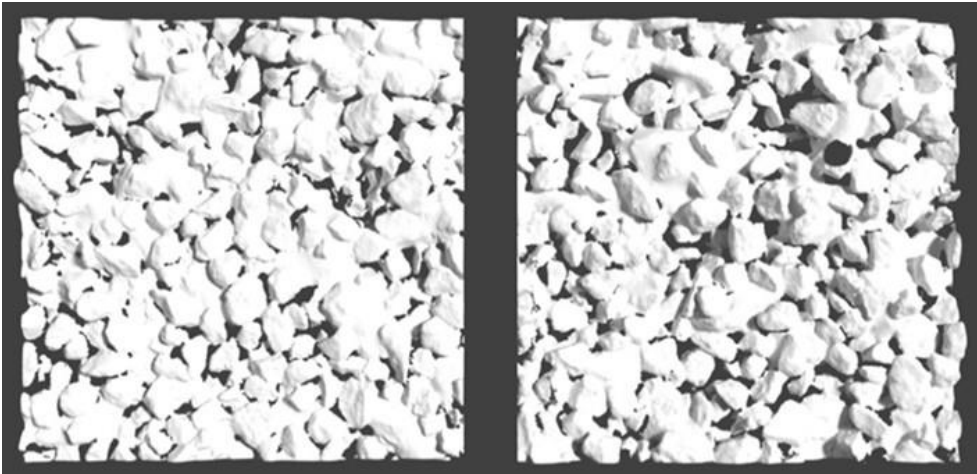
Figure 12: 3-D scan image of the area subjected to APT loading (left) and the adjacent area (right) that received no loading

Figure 13: Height maps obtained from the 3-D scans of the area subjected to APT loading (left) and the adjacent section that received no loading**.**

Table 4: Volume and voids ratios calculated from a statistical analysis of the 3-D data sets on the double seal and shown in Figures 16 and 17

Parameter	APT loading	No loading
Solid volume (V_T) [cm^3]	81.504	93.158
Sample area [cm^2]	100.2	100.2
Largest height difference [mm]	15.37	15.76
Aggregate volume (V_S) [cm^3]	21.668	28.010
Void volume (V_V) [cm^3]	59.836	65.248
Void ratio (V_V/V_S)	2.761	2.326
Void ratio (V_V/V_T)	0.734	0.669
MTD [mm]	5.97	6.50
MPD [mm]	3.81	3.57

The area subjected to APT loading (left in Figure 13) illustrates the reorientation of the particles with less protruding features above the surface. The distribution of curvature shifts correspondingly toward lower values, i.e., uniformity. The roughness distribution indicates roughness values between 0.6 mm and 1.0 mm that is likely a representation of surface roughness of the aggregates rather than the macroscopic dimensions.

4.3.4. 20 mm Cape seal with 1.5 per cent SASOBIT-M® modified tack-coat and an anionic nano-silane modified bitumen emulsion slurry without any cement / lime filler – First test: 18 000 repetitions applied with the MMLS3 at temperatures between 12ºC and 19ºC

Visual Assessment: Figure 14 shows the surfacings of the Cape seal subjected to loading. A slightly rougher surface could be detected in the test area, indicating that the 20 mm stone did not penetrate into the base, but that the slurry actually filled any voids that was not properly filled during the placement of the slurry by hand.

Figure 14: Condition of the Cape seal after the APT done at < 20°C

3-D scan of the surfacing with and without loading: The height maps of the 20 mm Cape seal produced from the 3-D scans are shown in Figure 15. The statistical evaluations of the data of the two data sets are given in Table 5. Of interest is that visually little differences could be observed between areas with and without loading. However, the 3-D scan data and the corresponding statistics of the data sets clearly show that some changes did occur during APT loading.
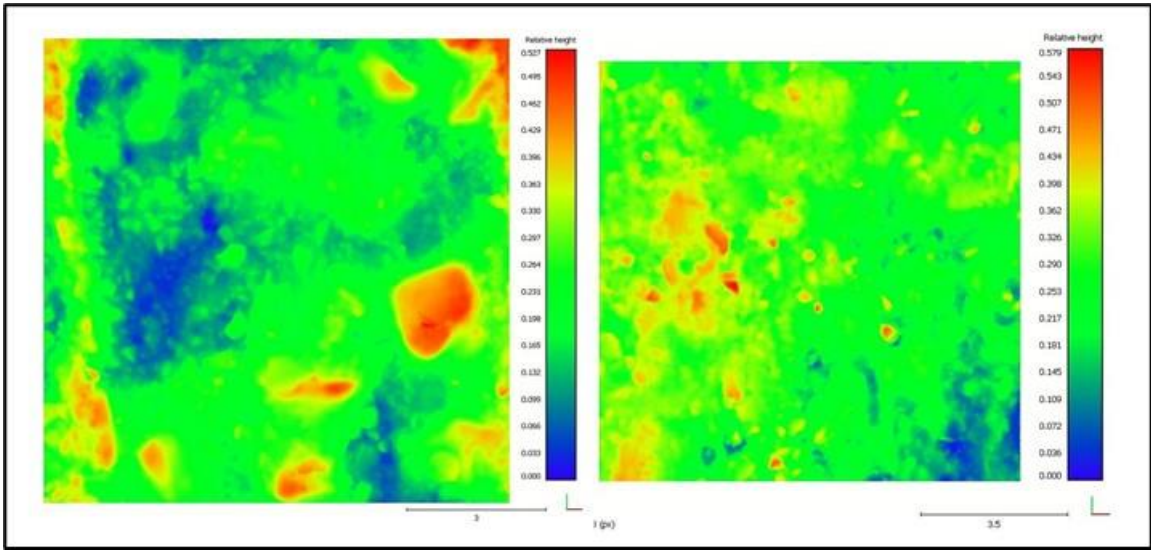
Figure 15: 3-D scan of the 20 mm Cape seal: Left: APT loading, Right: no loading

The APT-loading sample (left) illustrates more pronounced visibility of the 20 mm aggregate from below the slurry mix. This is likely due to the reorientation of the smaller particle sizes in the slurry mix moving toward the most stable state. From the roughness analysis, it is shown that the APT area (left) illustrates the loss in micro texture and the exposure (appearance) of the larger 20 mm aggregate. This could be an indication that not all voids were filled during the hand placement of the slurry mix.

In order to compare the three tests done under similar conditions on the three different chip seal surfacings, the visual conditions and 3-D scan are shown together in Figure 16.
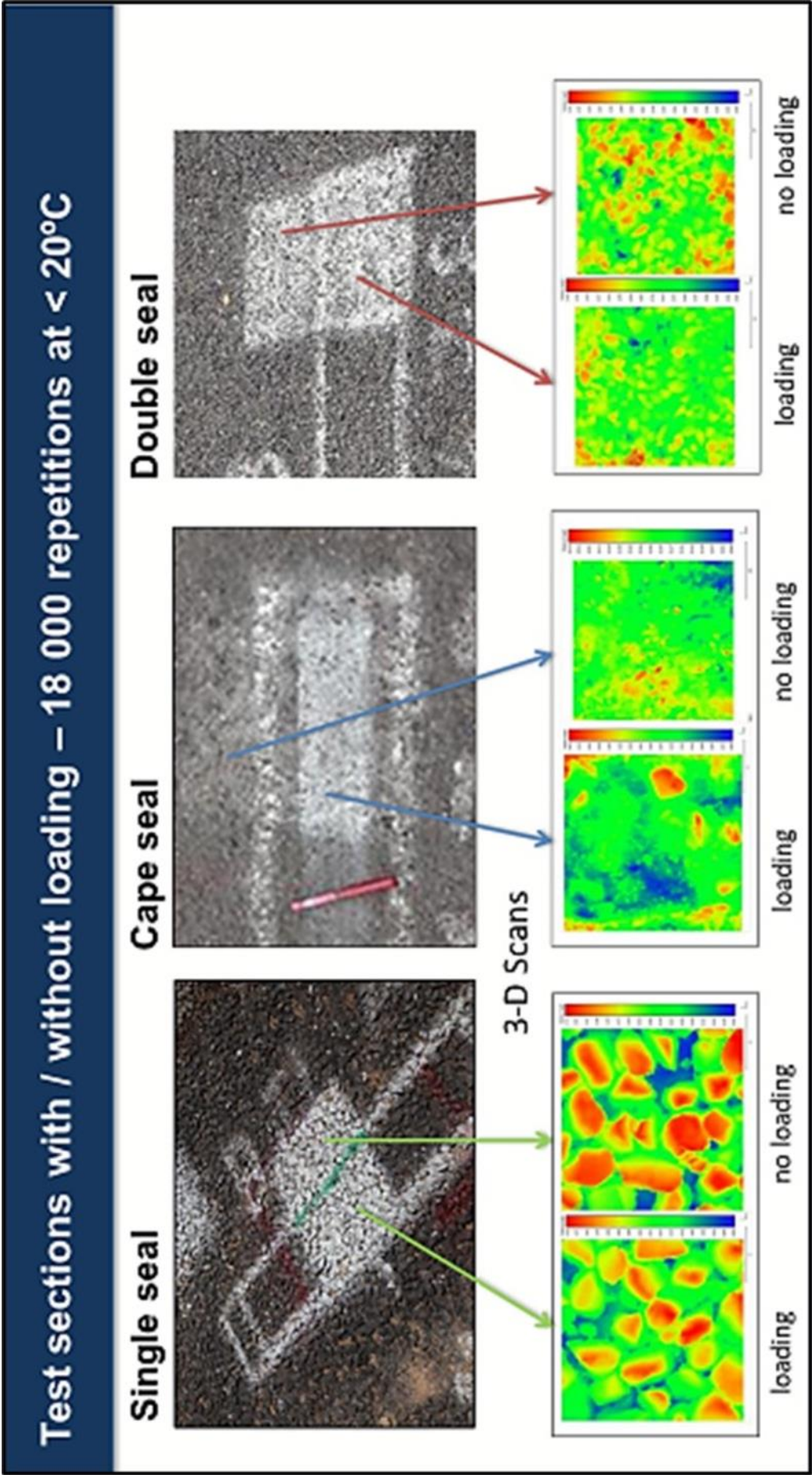
Figure 16: Test sections on the three thin surfacings tested using the MMLS3 at temperatures below 20ºC with associated 3-D scan maps measuring 100 mm x 100 mm.

Table 5: Volume and Void ratios calculated from a statistical analysis of 3-D scans of the Cape seal

Parameter	APT loading	No- loading
Solid volume (V_T) [cm^3]	52.805	58.918
Sample area [cm^2]	100.2	100.2
Largest height difference [mm]	5.27	5.88
Aggregate volume (V_S) [cm^3]	21.668	28.010
Void volume (V_V) [cm^3]	31.137	30.908
Void ratio (V_V/V_S)	1.437	1.103
Void ratio (V_V/V_T)	0.590	0.525
MTD [mm]	3.11	3.08
MPD [mm]	1.83	1.59

4.3.5. 20 mm Cape seal with – Second test: Full APT loading - standard 100 000 repetitions applied within 24 hours with the MMLS3 at a controlled temperature of 50ºC

Visual and measured assessment: The comparative surfacings of the full MMLS3 24h, 100 000 repetitions at 50ºC is shown in Figure 17 with the test area enhanced to emphasize the differences in appearance.
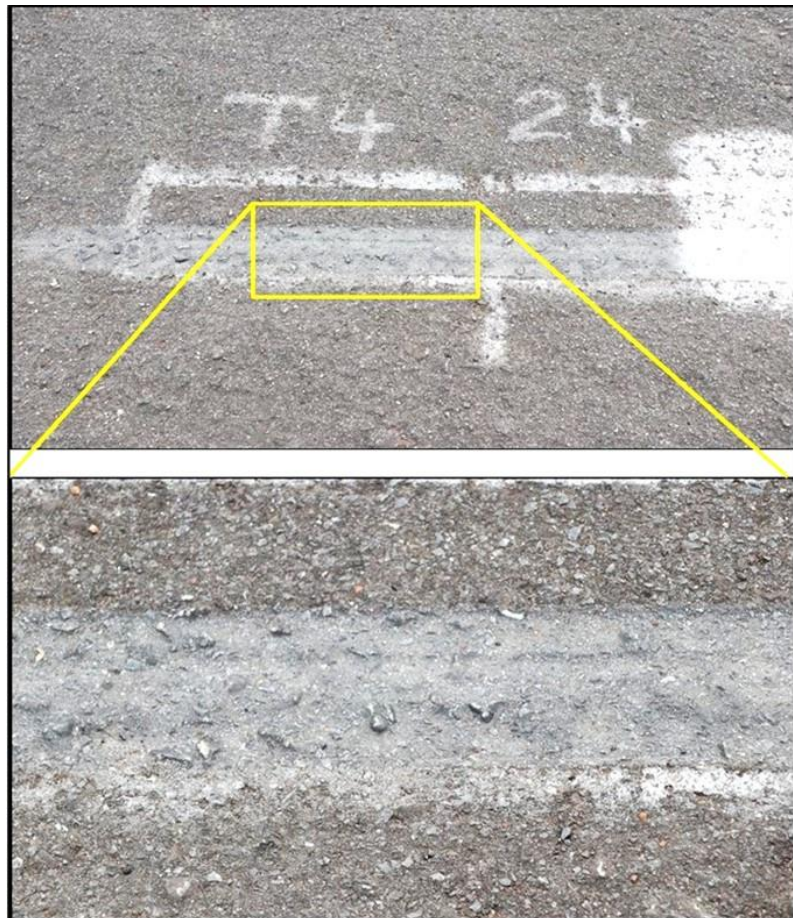

Figure 17: Condition of the Cape seal after a full-scale 24 h MMLS3 (APT) test at 50°C applying 100 000 load repetitions

The results of the full standard APT using the MMLS3 on the Cape seal as given in Table 6, and summarized in Figures 18 and 19 , were obtained following the protocols

for the evaluation of the deformation performance of asphalt surfacings for highways [13]. A test result of a rut depth measurement of less than 3 mm is considered adequate for the future expected deformation behaviour over the design period of the asphalt surfacing on highways. The measured rut depth on the Cape seal after the test was less than 4 mm. Considering the test results in the context of the design traffic loading (1 million E80s) and the material used, the rut depth performance of the Cape seal with the novel modified binders can be considered as more than satisfactory.

Table 6: Summary of the rut depth measurements of the standard MMLS3 test (SANS 3001-DP1) done on the Cape seal with an anionic NME slurry mix placed on an anionic NME stabilised base constructed with naturally available materials (Table 1 - G8 / A-2-6 quality)

| Measured rut (mm) at different Axle load repetitions at different positions in the test areas							
Position	**0**	**2 500**	**5 000**	**10 000**	**25 000**	**50 000**	**100 000**
0100	0	1.69	2.05	2.38	2.57	2.84	3.03
0200	0	1.86	2.04	2.34	2.56	2.83	2.98
0300	0	3.04	3.24	3.54	3.87	4.10	4.22
0400	0	2.80	3.06	3.40	3.99	4.35	4.69
0500	0	2.63	2.91	3.29	3.60	3.90	4.13
0600	0	2.56	2.65	2.86	3.15	3.37	3.82
0700	0	2.56	2.65	2.86	3.15	3.37	3.62
0800	0	2.94	3.03	3.42	3.71	4.05	4.25
0900	0	2.59	2.67	2.86	3.00	3.13	3.46
Average	0	2.58	2.76	3.07	3.38	3.65	3.87
Std. Dev.	0.00	0.50	0.45	0.48	0.57	0.61	0.63
COV %	0	19.4	16.3	15.6	16.9	16.7	16.3
Average rutting @ 100 000 repetitions = 3.87 mm							
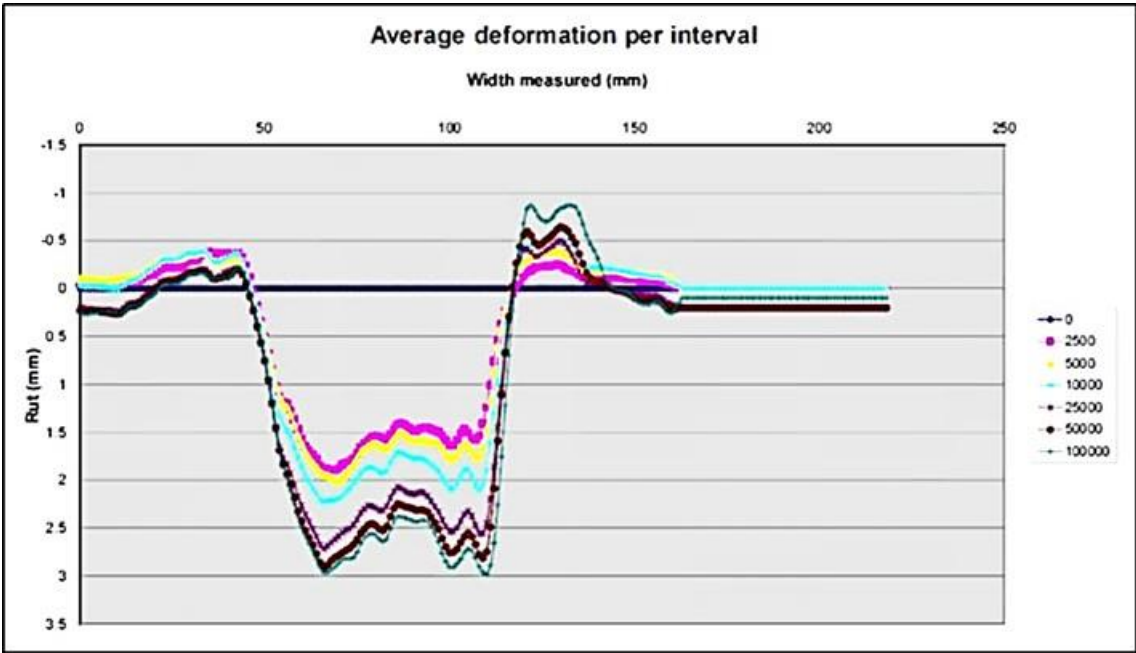
Figure 18: Profile measurements taken at various repetitions during the full MMLS3 test (APT) done on the Cape seal
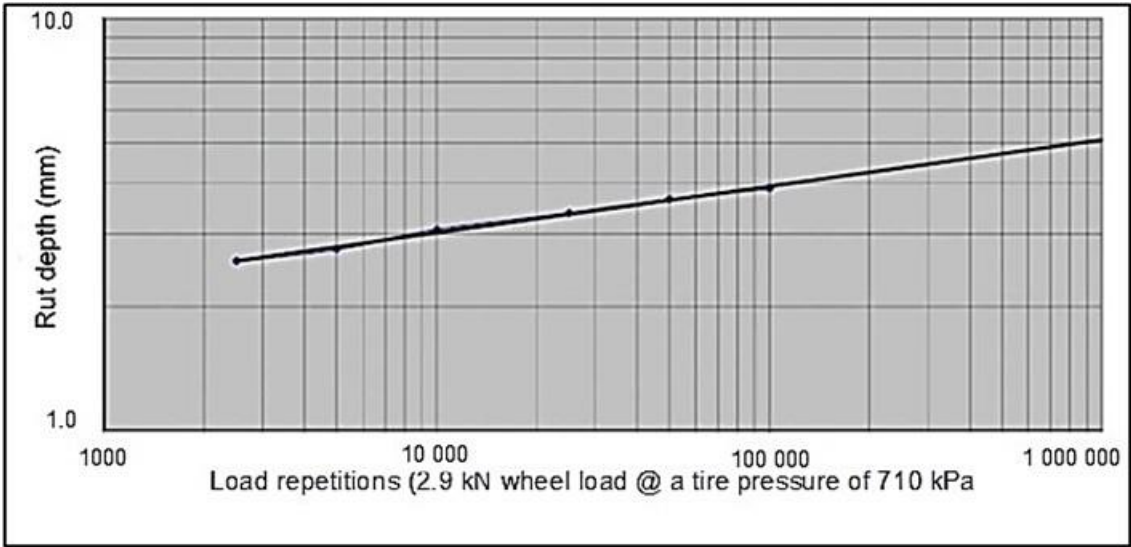
Figure 19: Plot of and extrapolation of the average measured rut depth during the MMLS3 24h, 100 000 repetitions test done on the Cape seal constructed using unconventional binders

3-D scan of the surfacing with and without loading: The height maps generated from the 3-D scans are shown in Fig.20. The volume and void ratios calculated from the data sets are shown in Table 7. Similar to the cold test section subjected to APT loading (left) again shows the protruding of the 20 mm aggregate between the slurry. This result confirms the conclusion that not all voids were filled during the application of the slurry mix.
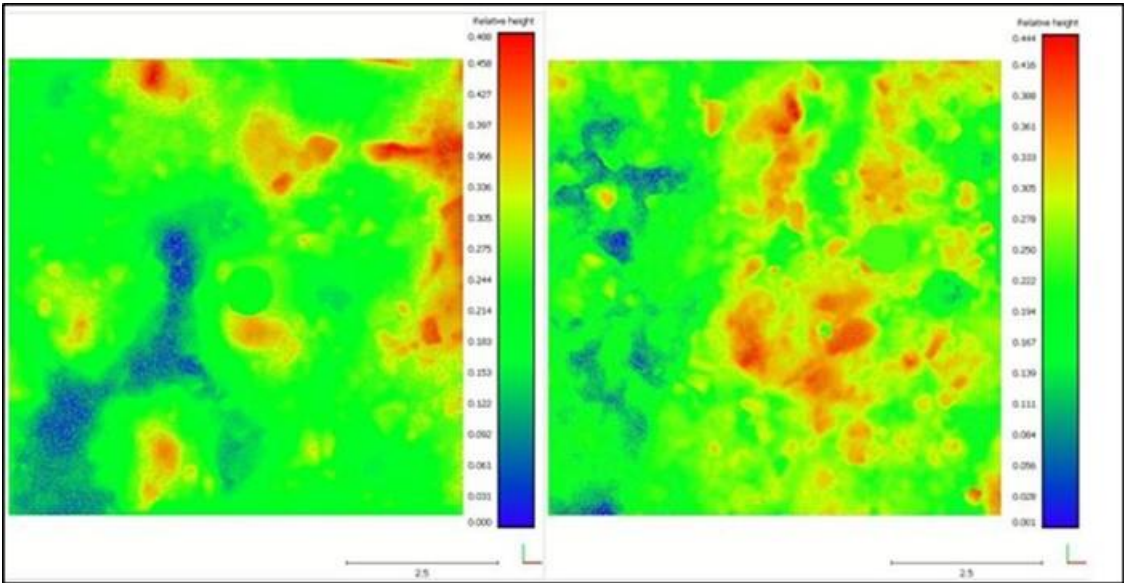
Figure 20: Height maps generated from the 3-D scan of the area subjected to a standard APT loading in order to assess the rut of the Cape seal

Table 7: Volume and Voids ratios calculated from a statistical analysis of the 3-D data stets of the 24h test done on the Cape seal

Parameter	APT loading	No loading
Solid volume (V_T) [cm^3]	27.523	24.985
Sample area [cm^2]	56.4	56.4
Largest height difference [mm]	4.88	4.48
Aggregate volume (V_S) [cm^3]	13.305	13.619
Void volume (V_V) [cm^3]	14.218	11.366
Void ratio (V_V/V_S)	1.069	0.835
Void ratio (V_V/V_T)	0.517	0.455
MTD [mm]	2.52	2.02
MPD [mm]	1.43	1.40

4.4. Visual inspection: 19 March 2020

The test section was visually inspected on 19 March 2020. No traffic has used the test section for 14 months since January 2019**.** The single seal and Cape seal showed no difference. However, closely spaced (about 100 mm apart) small holes were now clearly visible all over the double seal section (double seal - Figure 21, Cape seal Figure 22). A close-up of one of the holes is shown in Figure 22 with excess binder from the hole visible on the top of the surfacing. The size of the holes can be compared to the lens-cap of the camera, partially shown in Figure 21. The Cape seal was still in a perfect condition (Figure 22).

Figure 21: March 2020 - Condition of the Cape seal

Figure 22: March 2020 - Condition of the double seal showing multiple holes all over the test section

In terms of binder application, the first tack coat on both sections is the same, i.e. a SASOBIT-M® modified binders. The only difference in binder application that could lead to this observed performance on the double seal is in the binders used in applying the second (7 mm) seal on the double seal and the anionic NME modified binder used in the slurry mix. The second application on the double seal and the slurry mix are different between the two sections. From these observations it is clear that the modified binder

used on the second seal of the double seal – a elastomer modified binder (S-E2) [7], did not allow for the evaporation of moisture from the anionic NME base to continue – a disadvantaged that is clearly noted in the TG1 document. The vapor manages to escape from the pavement by "popping" through the binder.

5. Discussion of results

The test results confirmed that the application of the stone using a SASOBIT-M® modified binder at temperatures considerably lower than current recommendations can be done at low risk. In addition, reorientation of the stone took place under APT loading applied at temperatures less than 20°C (12ºC to 19ºC) without any apparent stone loss. These observations were confirmed both visually and using 3-D scans of the surfacings on the 20 mm single seal areas. The tack-coat on all the various test sections was applied at a road surface temperature of approximately 18°C, i.e., 7°C less than the minimum recommended best practice of 25ºC and rising [15], with no apparent stone loss. No stone embedment into the newly constructed NME stabilised base layer could be observed (constructed with naturally available materials classified as "unsuitable" for use in the base and sub-base layers of a pavement structure).

No obvious differences between the areas subjected to APT loading during cold conditions and the adjacent areas could visually be observed on the double seal, and very little difference on the Cape seal test sections. However, the 3-D scans clearly indicated that reorientation of the stone occurred on both the Cape seal (protrusion of the bigger 20 mm stone) and on the double seal (closer matrix due to compaction under loading and stone reorientation). No stone loss could be detected on any of the three experimental seal sections subjected to APT loading at temperatures below 20°C.

The 3-D scans done to compare areas subjected to loading with the adjacent areas gave an objective and quantitively measurement of the effect of the load applications through the generated 3-D surface maps and the statistical analyses of the data sets. Much of these differences could not be detected visually. The resulting point clouds from the 3-D scans also made it visually obvious what happened with regard to stone reorientation and change in surface characteristics under the effect of the ATP loading.

The full-scale APT test on the Cape seal gave remarkably good results, especially considering the thickness of the surfacing and the materials used in the base layer (less than 4 mm deformation). The protrusion of the larger 20 mm stone is also more pronounced compared to the scans done during the initial 18 000 repetition test (MPD and MTD data in Figures 23 and 24). These results confirm that little (if any) punching of the 20 mm stone into the surfacing of the base was observed under the standard 100 000 repetition test at a controlled temperature of 50ºC.

The visual inspection done 14 months after the last traffic on the test sections was significant in terms of findings regarding binder selection on newly constructed layers where evaporation of moisture is expected to continue. The formation of numerous holes on the double seal clearly shows that the applicability of a binder that allows for the evaporation of moisture to continue is an important criterion to be considered when binders are specified.

6. Conclusions and recommendations

The cost-effective combination of thin chip seal surfacings for use on a highly flexible pavement containing a base layer consisting of "sub-standard" naturally available materials stabilised with a material compatible New-age (Nano) Modified Emulsion (NME), was successfully tested and evaluated using APT equipment and 3-D scanning technologies. The design of the thin chip seal surfacings was done to specifically address possible early life failure at the top of the base layer with punching of the stone into the newly stabilised base layer.
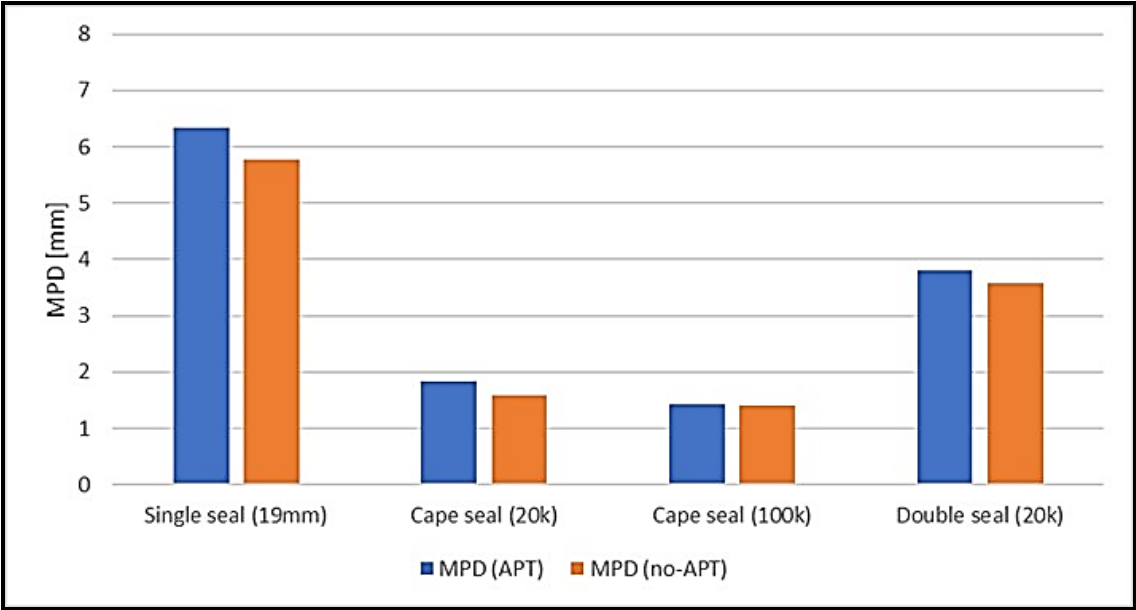
Figure 23: Comparative Mean Profile Depth between the various chip seal surfacings both with and without APT loading
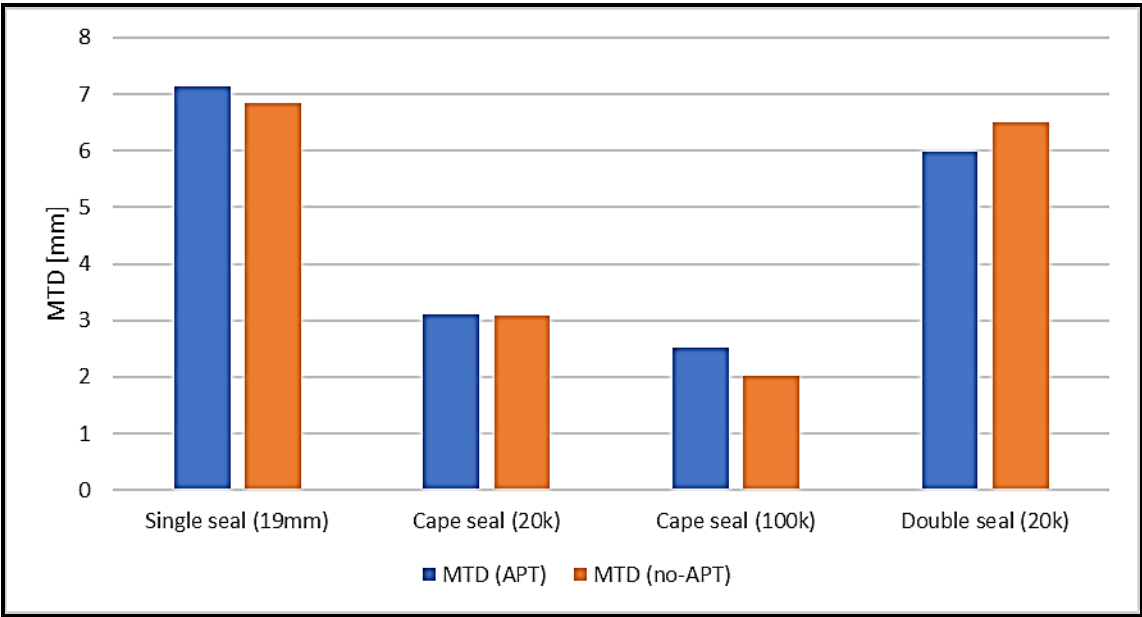
Figure 24: Comparative Mean Texture Depth (MTD) between the various chip seal surfacings both with and without APT loading

In addition, the three test sections were designed with novel modified binders to address risks associated with the construction of chip seals. These risks are specifically associated with the minimum binder temperatures required to minimise stone loss as well as the early life performance under loading (during the orientation of the stone) at temperatures below 20ºC (also associated with stone loss and seal failures).

The APT MMLS3 equipment was originally designed to evaluate the deformation (rut potential) of asphalt surfacings for highways. On these test sections, it was also used to evaluate the early life performance of the different seals during critical temperature conditions as well as possible penetration of the stone into the base layer of the thin chip seal surfacings. Evaluation of the results was done visually and analysed using 3-D hand scanning technology to generate 3-D point-clouds from which accurate statistical models

of the surfacings with and without APT loading could be generated. Hence, surfacing characteristics could be determined with a high degree of accuracy and repeatability.

A SASOBIT-M® tack-coat with a 20 mm seal was successfully applied over the whole test area at a road surface temperature of 18°C (7°C less than the recommended minimum of 25ºC) with no visible stone loss. In addition, to a single seal section, part of 20 mm chip seal was turned into a Cape seal using a slurry mix done with a NME binder and no cement or lime filler. The slurry mix was prepared next to the road and placed by hand. A third test section was done on the 20 mm first seal as a double seal with elastomer modified binder and a 7 mm stone.

All three test sections were tested with the MMLS3 at temperatures between 12ºC and 19ºC with no apparent stone loss and no penetration of the stone into the newly constructed NME stabilised base layer. The selection of the specific modified binders proved successful to reduce construction risks normally associated with chip seal surfacings. The NME stabilised base constructed using "sub-standard" materials developed the early strengths required to prevent stone penetration into the top of the base that often results in associated bleeding of the binder and failure at the top of the base layer. All results were confirmed using the handheld 3-D scanner and the accurate statistical analysis of the 3-D point-clouds developed with the scans on all APT sections.

In addition to the "cold" testing, the Cape seal section was also subjected to a standard 24 hour, 100 000 repetitions MMLS3 test, at a controlled temperature of 50ºC. For asphalt layers used on highways the deformation specified should be less than 3 mm using the standard MMLS3 test. The maximum deformation measured on the Cape seal was less 4 mm, a remarkable result considering the thickness of the surfacing and the quality of the materials used in the NME stabilised base layer.

The visual inspection done on the test areas after 14 months of no trafficking showed multiple small clearly visible holes over the whole of the double seal section. No such problems were observed on the single seal or the Cape seal sections. The use of an elastomer modification of the binder on the second seal, which is known to "restrict evaporation of entrapped moisture", is the only difference in terms of binder usage compared to the other chip seal sections. In order to escape, the evaporated moisture forced through the binder, leaving excess binder on the top of the surfacing with a resultant hole in the surfacing. It follows that limitations with regard to the "breathability" in the selection of an applicable modified binder for use on any base layer is an important factor, requiring careful consideration.

All three thin surfacings was also subjected to normal traffic loading during a heatwave in December 2018 with no visible signs of bleeding. The application of the tack coat with a binder modified with 1.5 per cent SASOBIT-M® applied with a 20 mm first chip seal tested under "abnormal" temperature conditions is considered to be a success warranting further investigation in terms of limits of application. This modified binder may well reduce the risk of failure associated with construction limitations.

It has been shown that the stabilisation of naturally available materials for use in base layers can successfully be combined with thin chip seal surfacings, without an increase in the risk of early life failure. Considering the relatively poor quality of material used in the construction of the NME stabilised base, a considerable margin of error was built into these test sections. The positive results obtained from the tests done using these novel binder modifications with thin chip seal surfacings, warrant further investigation in terms of possible inclusion in future specifications.

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