LABORATORY EVALUATION OF ALTERNATIVE COST-EFFECTIVE PAVEMENT MATERIALS

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ABSTRACT

The South African road network is severely impacted by the high costs associated with upgrading, maintaining and constructing road infrastructure in conjunction with the shortage of good quality construction materials. The Council for Scientific and Industrial Research (CSIR) has conducted extensive research on an innovative, cost-effective bituminous stabilising agent known as Nano-Organosilane Modified Emulsions (NMEs). These emulsions allow road engineers to design stabilised base and subbase layers using marginal materials which are normally considered unusable for road construction. For the purpose of determining the potential performance of NMEs, extensive advanced laboratory evaluations have since been conducted, most recently in the form of triaxial testing.

This paper outlines the results and findings from both monotonic and dynamic triaxial testing conducted on NME materials, and draws correlations with Heavy Vehicle Simulator (HVS) test results. Compared to standard materials and designs, the initial results on the use of NMEs as a stabilising agent in road bases and subbases has since showed excellent performance and cost savings.

The key results in this paper conclude that NME materials:

- Exhibit strong-cohesion as observed from monotonic triaxial testing as well as from test-pit samples cored from HVS test-sections at Provincial Road D1884;
- Have significant potential for improved long-term pavement performance, based on laboratory measured resilient moduli in conjunction with back-calculated field-moduli on NME test-sections;
- Display very low susceptibility to Permanent Deformation (PD) including rutting; and
- Justify being considered as a sustainable and environmentally friendly alternative to traditional pavement materials and designs.

Keywords: Nanotechnology, Nano-Organosilanes, Nano-Organosilane Modified Emulsions (NMEs), Bitumen-Emulsions, Stabilisation, Monotonic Triaxial-Testing, Dynamic Triaxial Testing.

1. INTRODUCTION

The economic and social wellbeing of South Africa is highly dependent on the functionality of a good all-weather road network. However, poor economic growth coupled with everincreasing road infrastructure costs have recently hampered the ability of many local road agencies to keep up with maintenance schedules, thus leading to huge backlogs nationwide. These circumstances have thus necessitated the need for further investigations into alternative road building materials such as Nano-Organosilane Modified Emulsions (NMEs) that have huge cost-saving potential.

NMEs claim to offer hydrophobic properties and improve marginal materials at a nanoscale, making them directly suitable for road construction. Standard granular road building materials can be moisture susceptible lowering their applicability, whilst NME modified materials claim to provide better performance in terms of moisture resistance. The implementation of NMEs therefore has the potential to improve the long-term quality and cost efficiency of South African road infrastructure. However, there remains a significant gap in scientifically proving this claim since the majority of publications show only basic laboratory results obtained from Unconfined Compressive Strength (UCS) and Indirect Tensile Strength (ITS) tests on NME materials. Therefore, there is a significant need for advanced specialised laboratory testing procedures such as triaxial testing of materials enhanced with NMEs in order to assess comprehensively their practical applications in South African road infrastructure.

Additionally, several South African pavement engineers (Jordaan & Kilian, 2016) are of the opinion that nanotechnologies such as NMEs have not been effectively utilised by the South African road industry even though their benefits have been quantified and scientifically proven in various other parts of the world. Furthermore, many local engineers persist with using traditional approaches and tested technologies rather than relying on newly developed nanotechnologies for pavement engineering applications. Engineers often resist change and new technologies if unproven. It is therefore necessary to provide material and pavement engineers with more fundamental tests and associated proof as presented in this paper. These tests could include for example tri-axial testing.

The CSIR has therefore decided to evaluate NME materials more extensively by means of a multi-disciplinary research programme comprising a desktop study, a long-term laboratory evaluation as well as a series of HVS tests on NME roads. The primary aim of this paper is therefore to present NME performance results as obtained from monotonic and dynamic triaxial testing and correlate behavioural trends with data obtained from HVS tests on NME material treated roads.

2. DESKTOP STUDY

2.1 Comparison Between NMEs and Traditional Bitumen-Emulsions

NMEs comprise of a similar chemical composition to traditional bitumen-emulsions with the exception of nano-additives present within the emulsion. These emulsions are usually formulated by adding nano-particles such as nano-organosilanes and/or nano-polymers to a standard anionic or cationic bitumen-emulsion (Akhalwaya, 2018). The nano-organosilanes present within a NME therefore serve as a coupling agent by chemically altering the surface of virtually any silica-based material and rendering it hydrophobic, whilst the nano-polymers are used to protect, stabilise and functionalise the emulsion against heat and Ultra-Violet (UV) radiation. The NME is then likewise applied to a mineral soil or aggregate during construction with the water molecules similarly evaporating during curing. However, the nano-particles present within a NME cause the emulsion to react significantly differently to a traditional bitumen-emulsion when applied to a mineral soil or aggregate. This is mainly characterised by the formulation of a siloxane surface on each soil or aggregate particle as shown in Figure 1.

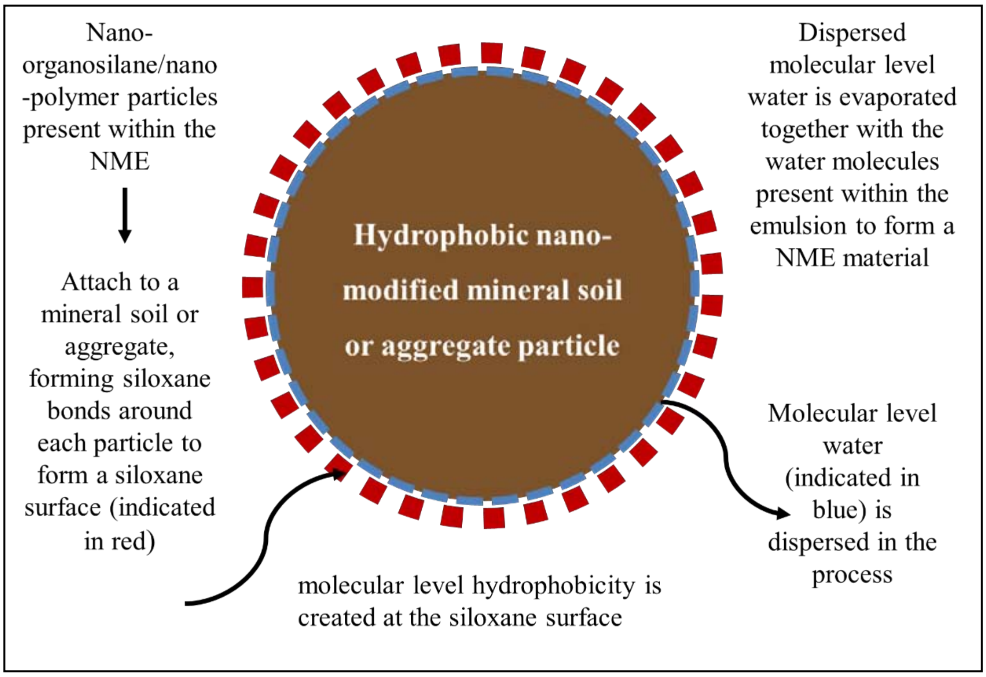

Figure 1: Summary of the formulation of a siloxane surface on a NME stabilised mineral soil or aggregate (Akhalwaya, 2018)

2.2 Performance of NME Materials Under HVS Traffic

2.2.1 Multi-Depth Deflectometer (MDD) Back-Calculated NME Pavement Layer Moduli

Typical MDD back-calculated pavement layer moduli for NME materials under HVS traffic and HVS loads have been computed by Rust *et al*. (2019) for Provincial Road D1884 as shown in Table 1. The authors indicate that although the MDD moduli data did not deteriorate significantly under HVS traffic, the NME base layer stiffened slightly in the early stages of testing due to post-construction compaction. However, this stiffness was later observed to decrease slightly as the base layer began to fatigue under heavy traffic loads.

Table 1: Final MDD back-calculated moduli for NME materials under HVS traffic

NME Pavement Layer	MDD 4 Average moduli (MPa)	MDD 4 moduli range (MPa)*	MDD 12 Average moduli (MPa)	MDD 12 moduli range (MPa)
Base (NME3 Classification)	173	69 - 797	127	71 - 214
Sub-base (NME4 Classification)	93	40 - 142	98	71 - 134

Note: The singular measurement of 797 MPa at MDD4 was an unexpected outlier. Variation in moduli is due to the inherent variation in deflection measurements as well as the stage during the HVS test when the moduli were calculated. Moduli tend to decrease as the pavement layer fatigues under HVS traffic or when moisture is introduced into the pavement during the test.

2.2.2 MDD Plastic (Permanent) Deformation Measurements for NME Pavement Layers

Results similarly published by Rust *et al.* (2019) for NME pavement layers under HVS traffic observed plastic (permanent) deformation on both the NME base and subbase layers at Provincial Road D1884. However, these deformations were considered to be extremely low in terms of South African pavement design standards, with the total pavement structure showing a final rut measurement of only 8mm after an application of 3.5 Million Equivalent 80 kN Standard Axles (MESA). Note that the MDD anchor did not move during the test.

3. METHODOLOGY

3.1 Test Methods and Protocols

The test methods used in this investigation have been selected in line with the procedures followed by Jordaan *et al.* (2017a) as well as the 'Technical Guideline for Bitumen Stabilised Materials (TG2)' by Asphalt Academy (2009). Furthermore, all advanced specialised triaxial testing methods for NME materials have been prepared and tested according to the "Protocols for Triaxial Testing" as recommended by CSIR Transportek (2002). It should be noted that all sample preparation requirements adhered to the curing protocols specified by Jordaan *et al.* (2017b), regardless of the type of test being conducted.

3.2 Triaxial Testing Rationale

Triaxial testing with representative conditions of material moisture, compaction and a range of stress conditions were used to characterise the i) shear; ii) resilient; and iii) plastic deformation properties of NME pavement materials.

Three different triaxial tests were performed during the advanced laboratory evaluation:

- Monotonic triaxial tests in order to determine shear parameters such as cohesion and friction angle;
- Dynamic triaxial tests in order to obtain the resilient modulus; and
- Dynamic triaxial tests in order to obtain the plastic (permanent) deformation (PD).

The following rationale was applied to analyse triaxial test data:

- Fundamental shear parameters as determined from monotonic triaxial testing may be used to define the failure state of NME materials. These may also be used as a point of reference to analyse relative damage resulting from repeated loading at lower stress states (Jenkins *et al.*, 2007).
- Stress Ratios may be used to express the deviator stress applied during repeated load triaxial testing, relative to the maximum deviator stress as determined during monotonic triaxial testing (Jenkins *et al.*, 2007; Venkatesh *et al.*, 2018).
- The resilient modulus and PD parameters may be used to characterise NME stabilised materials during mechanistic-empirical pavement design procedures (Venkatesh *et al.*, 2018; Alnedawi & Al-ameri, 2019).
- The resilient modulus may also be used as an indication of tolerance (Alnedawi & Al-ameri, 2019), while PD may be used to give an indication of failure or for rutting predictions (Alnedawi & Al-ameri, 2019).
- During resilient modulus triaxial testing, the material is tested over a range of confining and vertical stress levels. This enables the determination of the resilient modulus as a function of the stress condition, making it possible to fit models in order to predict the resilient modulus at any imposed stress condition within the range of stress conditions tested (Jenkins *et al.*, 2007).

4. EXPERIMENTAL RESULTS AND ANALYSIS

4.1 Classification

The selected raw materials used in this laboratory evaluation have been obtained from the alternative pavement design structure built at the K46 HVS site in Diepsloot. These materials consist of G5 (COLTO, 1985) NME-stabilised base and subbase materials. The reason for selecting these raw materials is to correlate and supplement laboratory performance results for NMEs with HVS performance results in other studies.

X-Ray Diffraction (XRD) scans of the available K46 G5 materials (COLTO, 1985) conducted by the CSIR (Akhalwaya & Rust, 2018; Jordaan *et al.,* 2017a) indicate that these materials may be classified as marginal materials as they contain minerals consisting of approximately 17-20% Mica (Muscovite) and 7-43% clay minerals (Smectite/Kaolinite). Further descriptions and properties on the various stabilised samples used in the laboratory evaluation are provided in Table 2 and Table 3 respectively.

Table 2: Summary of classification results for K46 G5 untreated materials

Sample Description, Information and Properties		**Atterberg Limits (TMH1, 1986: Methods A2&A3)**	
Sample Name	K46 Diepsloot	Liquid Limit %	19.37
Material Classification	G5 (COLTO, 1985)	Plasticity Limit %	16.11
Stabilising Agent	Untreated	Plasticity Index%	3.26
pH Value	8.07	Electrical Conductivity	0.01
Sieve Analysis - % of material passing sieves (TMH1, 1986: Method A1a)		**Compactions (TMH1, 1986: Method A7)**	
Sieve Size (mm)	**%** passing each sieve		
75.0 mm	100.00	MOD AASHTO: Max Dry Density (MDD) (kg/m^3)	2096
53.0mm	100.00	Optimum Moisture Content (OMC) (%)	7.4
37.5 mm	100.00	Dry Density achieved (kg/m^3)	2099
26.5 mm	97.5	% of Max Dry Density (MDD)	100
19.0 mm	92.2	Moulding Moisture Cont. (%)	7.8
13.2 mm	86.1	% Swell	0.20
9.5 mm	79.2	**Soaked California Bearing Ratio (CBR) (TMH1, 1986: Method A8)**	
6.7 mm	71.4		
4.75 mm	69.4	100 % Mod AASHTO	102
2.00 mm	49.4	98 % Mod AASHTO	82
0.850 mm	31.1	95 % Mod AASHTO	65
0.425 mm	20.1	93 % Mod AASHTO	39
0.250 mm	14.0		
0.150 mm	9.9		
0.075 mm	6.6		

Table 3: K46 G5 materials NME classification (Akhalwaya & Rust, 2018)

Sample Description, Information and Properties				
Sample Name	K46 Diepsloot			
Material Classification	G5 (COLTO, 1985)			
Stabilising Agent	**SS60 anionic nano-modified emulsion (NME) with organo-silane and nano-polymer additives**			
% of stabilising agent added	0.7% per mass			
% of cement content	None			
Optimum Moisture Content (OMC) %	6.0			
Triaxial Sample Height (mm)	305 mm Sample			
Triaxial/UCS/ITS Sample Diameter (mm)	150mm Φ Sample			
Classification Test Performed	UCS (Dry)	UCS (Wet)	ITS (Dry)	ITS (Wet)
Test Method and curing Protocol used for UCS/ITS and Triaxial Testing	Jordaan et al., 2017b	Jordaan et al., 2017b	Jordaan et al., 2017b	Jordaan et al., 2017b
Average (kPa)	**2430**	**1923**	**179**	**158**
NME Equivalent Classification (Jordaan *et al*. 2017b)	**NME2**			
BSM Equivalent Classification (TG2, 2009)	**BSM2**			

4.2 Monotonic Triaxial Testing

Based on the shear parameters shown in Table 4, the untreated K46 G5 granular materials demonstrated very low cohesion in partially saturated samples. It can also be seen that the saturation level for the NME-treated materials did not differ significantly from the untreated samples. Thus, the increase in cohesion after stabilisation may be seen as a direct result of the addition of NMEs.

Table 4: Shear parameters measured from monotonic triaxial testing

Monotonic Triaxial Test Results				
	Cohesion C (kPa)	Friction angle ϕ (º)	Saturation (%)	Relative dry density (%)
Untreated	31.3	49.7	71%	81%
NME-Treated	181.0	50.9	74%	82%

A similar trend of NME materials having good cohesion was also observed at the HVS test-section at Provincial Road D1884 (Rust *et al*., 2019). This interpretation was made based on the ability of field-technicians to obtain full test-pit blocks directly from the NME base layer. It is worthwhile to note that these blocks did not disintegrate at all after coring, even though the materials had no added cement to assist with cohesion. These cored blocks are shown in Figure 2 below.

Figure 2: Test-pit blocks cored directly from the NME base layer at Provincial Road D1884

The maximum deviator stresses for both NME-treated and untreated samples at different confining pressures are shown in Figure 3. It can observed that the deviator stress of the treated samples increased significantly. An increase in maximum deviator stress of approximately 35-55% was observed between the untreated and NME-treated samples.

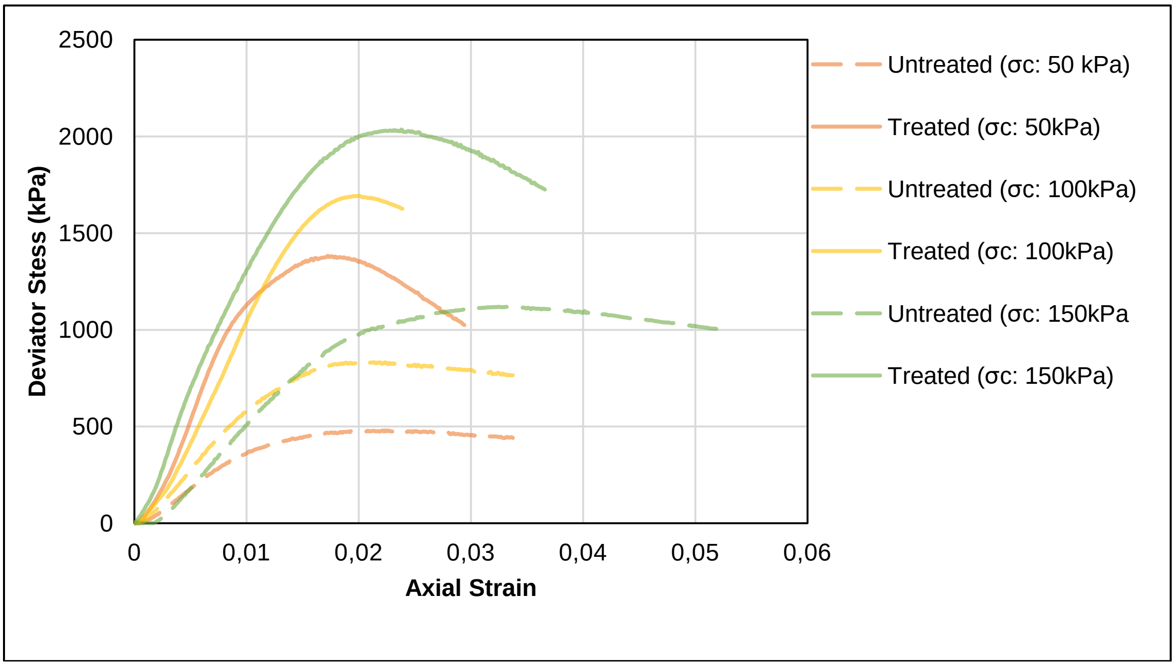

Figure 3: Summary of NME-treated and untreated sample deviator stresses (kPa) at different axial strains and different confinement pressures (σc)

4.3 Resilient Moduli (Dynamic) Triaxial Testing

Results for resilient moduli as determined from dynamic triaxial testing for the untreated and NME-treated samples are shown in Figure 4 and Figure 5 respectively. Based on these results, it can be seen that both the NME-treated and untreated samples show an increase in resilient modulus as the confinement pressure is increased. This trend is in line with previous findings by other researchers (Cameron, 2013; Fedrigo *et al.*, 2018; Venkatesh *et al.*, 2018), with the only expectation seen in the untreated sample at low deviator stress and confining pressure. This increase in resilient modulus may be due to an increase in density with increasing confining stress, thus resulting in higher stiffness's.

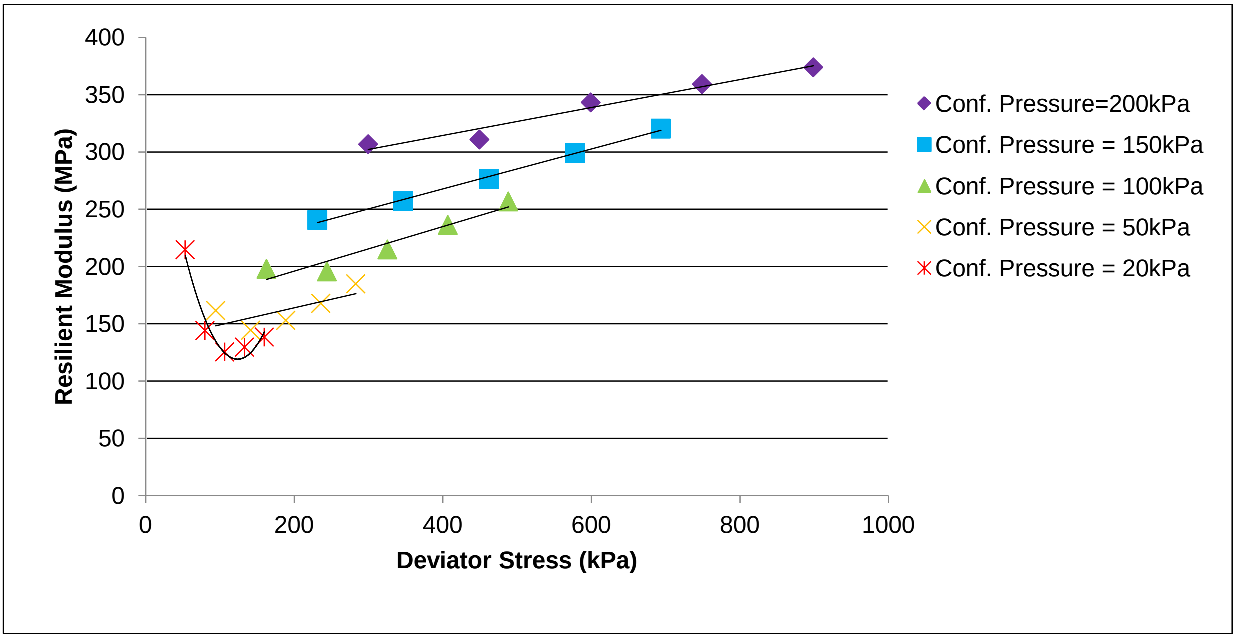

Figure 4: Resilient modulus plotted against deviator stress at different confinement pressures for untreated specimens

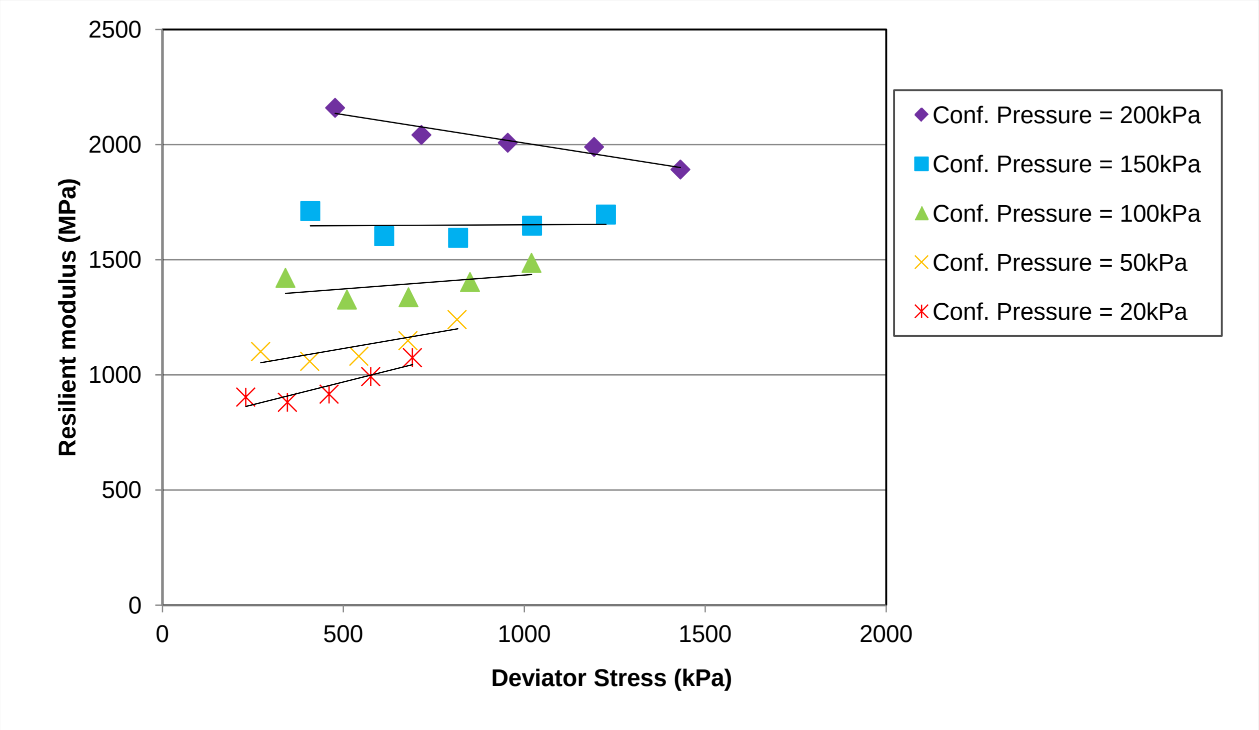

Figure 5: Resilient modulus plotted against deviator stress at different confinement pressures for NME-treated specimens

The resilient modulus showed an increasing trend with increased deviator stress. This may possibly be due to strain hardening, a trend previously observed by other researchers (Cameron, 2013; Fedrigo *et al.*, 2018). The only exception was observed with the NME-treated material at 200kPa confining pressure as shown in Figure 4. It is also worthwhile to note that there seems to be a change in the slope of the regression lines as the confining pressure increases. This effect in the NME-treated material may be worth investigating further.

Figure 6 shows the results for the resilient modulus plotted against the stress ratio of the NME-treated and untreated specimens at different confinement pressures. A significant increase in the resilient modulus between the NME-untreated and treated specimens was observed at all confinement pressures. In the case of the untreated material, the stress ratio increase caused an increase of about 22% in the modulus. For the NME treated material this increase was only 12%. This indicates that the untreated material behaved like a standard granular material and the treated material less so.

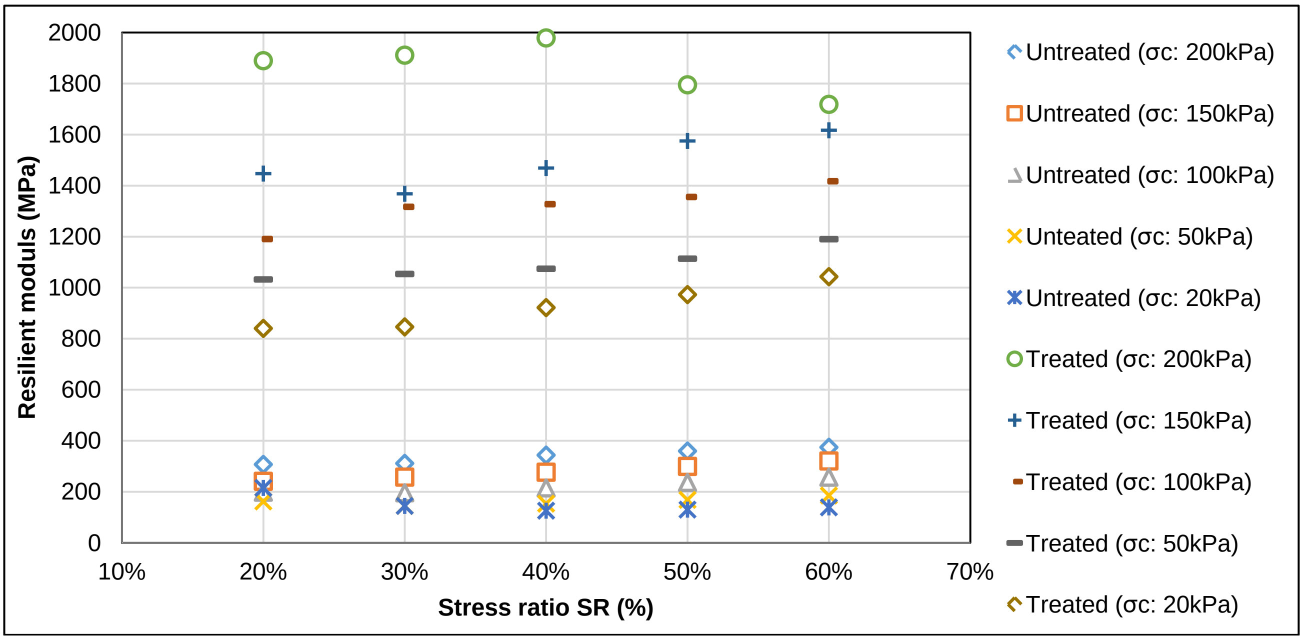

Figure 6: Resilient modulus plotted against stress ratio for untreated and NME-treated specimens at different confinement pressures

4.4 Plastic Deformation (Dynamic) Triaxial Test

Plastic deformation was measured at 80kPa at different stress ratios. Figure 7 shows the results for the permanent strain plotted against the number of load cycles for a stress ratio of 0.7. It can be observed that the NME-treated samples had a significantly lower plastic strain compared to the untreated samples. Actual density achieved was 2142 kg/m^3 and 2185 kg/m^3 for the NME treated and untreated samples respectively. It can be noted that the treated material performed better in spite of a slightly lower density.

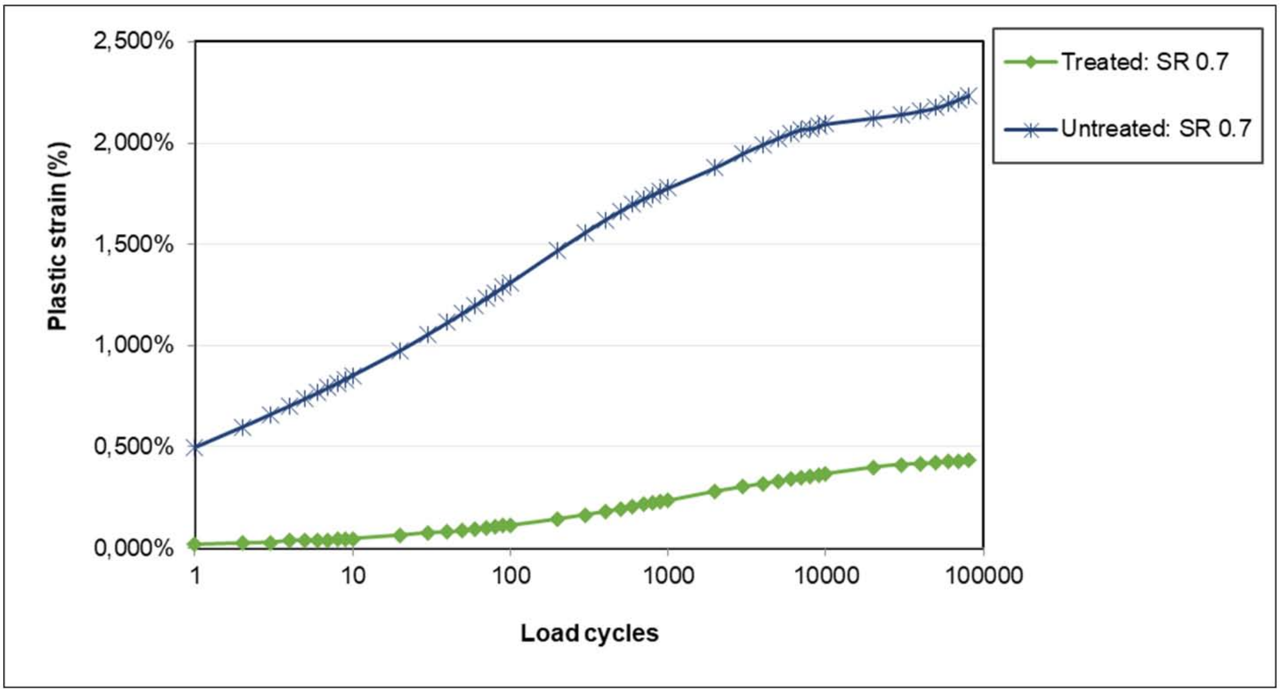

Figure 7: Plastic strain plotted against the number of load cycles for NME-treated and untreated samples

5. CONCLUSIONS AND RECOMMENDATIONS

Based on the above-mentioned results and discussions, the following conclusions and recommendations are made regarding NME materials:

- During the monotonic triaxial test, an increase in the friction angle can be observed between the untreated and NME-treated samples. The NME-treated granular material additionally showed significantly higher cohesion which is in-line with test-pit samples cored from the HVS test-section at Provincial Road D1884. Additionally, the NME-treated samples had a maximum deviator stress of approximately 35-55% higher than that of the untreated samples.
- Resilient moduli (dynamic) triaxial tests further showed that both untreated and NME-treated samples exhibit an increase in resilient modulus with increased confinement pressure. This increase in resilient modulus may be due to an increase in density due to increasing confining stress, thus resulting in higher stiffness's. The resilient modulus also showed an increasing trend with increased deviator stress which may be due to strain hardening. A significant increase in the resilient moduli between the untreated and NME-treated specimens was also observed at all confinement pressures.
- Based on the observed MDD back-calculated moduli for NME pavement layers under HVS testing and the computed resilient moduli using dynamic triaxial testing, it can be concluded that NME materials exhibit significantly high elastic moduli. This thereby indicates that pavement layers constructed with NME materials may potentially have improved long-term performance qualities. However, it is recommended that further testing still be done in order to draw direct correlations between MDD back-calculated moduli and laboratory calculated resilient moduli (e.g. developing indirect diametrical tests for NME materials).
- The observed MDD plastic permanent deformations for NME pavement layers under HVS testing and the computed permanent strains using dynamic triaxial testing

conclude that NME materials exhibit extremely low plastic strains. Further testing is however still required for comparisons between NME and standard bitumen-emulsion materials.

- Based on the consolidation of correlated behavioural trends with data obtained from the laboratory, it can be concluded that NMEs have significant potential in terms of making a practical impact on South Africa’s road infrastructure. Further specialised studies involving the environmental risks and associated life-cycle costs of NME materials are, however still recommended in order to assess comprehensively their practical application for South African road infrastructure.

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