THE DEVELOPMENT OF COST-EFFECTIVE PAVEMENT DESIGN APPROACHES USING MINEROLOGY TESTS WITH NEW NANO-TECHNOLOGY MODIFICATIONS OF MATERIALS

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ABSTRACT

The current official road pavement design manuals used in southern Africa dates back to the 1980s. In addition, materials classification is generally based on empirically derived test procedures, the majority of which was developed in the northern hemisphere more than 50 years ago. The use of these material criteria often leads to the exclusion of naturally available road building materials due to the possibility of “problem” materials that “may” lead to premature pavement failure. New technology developed for the accurate evaluation of the mineral composition of materials allows engineers to scientifically take these “problem” materials into account and adequately address the perceived risk during design procedures. New proven Nano-technologies developed over the last decade also allows engineers to adequately counter the presence of such problematic minerals. The introduction of these technologies in the road construction industry in southern Africa can considerable reduce the unit costs for the delivery of much needed road infrastructure and provide millions of citizens access to markets, schools, health facilities, etc. The Gauteng Province Department of Roads and Transport (GPDRT) recognised the potential impact of the fast-tracking of these technologies in the road sector. Not only are these technologies already being implemented in the province, but the GPDRT also undertook to fund road demonstration sections for the Accelerated Pavement Testing (ATP) using the Heavy Vehicle Simulator (HVS) of the department as operated by the CSIR. In co-operation with the University of Pretoria, recommendation with regard to the classification, testing and applicable material criteria of Nano-Modified Emulsions (NME) stabilising materials have been developed as a prerequisite to facilitate full scale implementation of these new technologies. A basic pavement design catalogue utilising NME stabilisation of naturally available materials for the HVS demonstration sections have been developed for comparison with typical road pavement structures currently in use.

1. INTRODUCTION

The road pavement design manuals currently in general use by the various road authorities in southern Africa are based on technologies dating back to the 1980s. In addition, materials classification is generally based on empirically derived test procedures, the majority of which dates back more than half a century. As a result of various problematic minerals present in natural road building materials (Weinert, 1980), road building practice in southern Africa has been based, to a large extent, on the avoidance of these materials resulting in the "normal" specification of freshly crushed (relatively expensive) stone from commercial sources in the upper layers of our pavement structures (Jordaan and Kilian, 2016). Initially, these relatively expensive crushed stone layers were mainly intended for use in higher order roads carrying high traffic loadings. However, in practice, the use and specifications on newly crushed stone layers from commercial sources have become the "norm" even for low-order roads in residential areas. These practices come at considerable costs to authorities resulting in unacceptable high unit costs for the provision of transportation infrastructure.

The Gauteng Provincial Department of Roads and Transport (GPDRT) is intensely aware of the problematic cost burden placed on the fiscus to provide road infrastructure using current design approaches. The availability of improved technologies (Nano-based) were identified by the GPDRT as a potential game-changer, enabling the use of naturally available materials even in the upper pavement layers. Over the last decade, Nano-technology based modifications of available natural materials have been developed, tested and implemented successfully in several countries throughout the world (CSIR-CRRI, 2010, 2015; NCAT 2009, 2011). The applicability and cost-effectiveness of the Nano-based technology was immediately recognised. In 2014 the GPDRT launched a programme to demonstrate the applicability and cost-effectiveness of these Nano-based technologies in the southern African environment.

The GPDRT involved design/research specialists from the University of the Pretoria to assist in the investigation of the use of Nano-based technology to lower the cost of the provision of road infrastructure., it was soon realised that historically used material classification tests were inadequate to fully understand and optimise material design aspects with regard to the chemical interaction of the Nano-based technologies with the various mineral components of naturally available road building materials. Advanced tests to identify the minerology of the materials were identified as a prerequisite to optimise the use of Nano-based technologies (Jordaan and Kilian, 2016).

The GPDRT has also identified specific roads to demonstrate the applicability of Nano-modified materials in practice (Jordaan et al, 2017). Through intensive investment in research the GPDRT committed to demonstrate the cost-saving implications of these technologies applicable to all categories of roads varying from low-capacity township roads to high-order dual-carriage roads carrying high traffic loadings. The province have committed to a number of demonstration sections to be evaluated using Accelerated Pavement Testing (APT) with the Heavy Vehicle Simulator (HVS) (Freeme, et al, 1982) of the GPDRT as operated by the CSIR, Built Environment, in South Africa.

This paper deals with recommendations towards the classification, testing and design of Nano-Modified Emulsions (NME) as a stabilising agent to be used with naturally available materials in all pavement layers of a pavement structure. In line with current practice, using available knowledge and numerous material minerology and laboratory tests over the last two years, recommendations towards material classification and testing procedures are made. Based on these tests and the experience gained using an array of different available Nano-Silanes and polymers, together with minerology tests and basic design approaches, a catalogue of designs are recommended for HVS evaluation for comparison with currently used designs. In addition, based on experience gained from the implementation of the technology on the first provincial roads in south Africa (Jordaan, et al, 2017), some recommendations are made towards the general use of NME with naturally available materials in practice.

2. ROAD PAVEMENT BUILDING MATERIALS AND DESIGN

2.1 Background

The road pavement design manuals currently in general use by the various road authorities in southern Africa are based on technologies dating back to the 1980s (e.g. draft TRH14, 1985; draft TRH4, 1996: draft TRH12, 1997, etc.). In addition, material classifications generally used are based on empirically derived test procedures, many of which date back more than half a decade. These include tests like the California Bearing Ratio (CBR) developed by the California Division of Highways in ±1930, material grading envelopes in the1930's (McLeod, 1937) and Atterberg limits defined by a Swedish agriculturist, Albert Atterberg, in the 1960's (Seed, 1967). Among others, these tests form the foundation of material classification used throughout the sub-continent as contained in the draft Technical Recommendations for Highways (TRH)14 (COLTO, 1985) as detailed in in the document: Test Methods for Highways - TMH1 (COLTO, 1986).

These test methods have been proven and refined over many years through practical experience and laboratory testing and observations by numerous material engineers. The main aim of these tests are to ensure that materials used in road pavement structures constructed with a high degree of quality monitoring (COLTO, 1998) will, with a high degree of confidence, usually result in a low risk of pavement failure under conditions with adequate maintenance policies in place. The testing of materials using these tests (TMH1, COLTO, 1986) and adherence to criteria developed based on these tests (draft TRH14, COLTO, 1985) enables "problematic materials" (Jordaan and Kilian, 2016) to be identified and normally excluded from use in the upper layers of road pavement structures. However, most of these tests and material criteria originate in the northern "cold" regions of the world. Table 1 (Netterberg, 1985: SATCC, 2001) gives a comparison of materials naturally found under different climatic regions with important differences highlighted. From Table 1, it is apparent that considerable differences exist between naturally available materials normally found under different climatic conditions. Hence, quote: "Unfortunately, many of the naturally occurring roads building materials in the SADC region are disparagingly described as being "non-standard", "marginal", "low-cost", or even "sub-standard"! This is because such materials are often unable to meet the required specifications, which are usually based on European or North American practice that did not always make provision for local conditions." unquote (SATCC, 2003).

Table 1; Differences between Basic Rock and Weathered Materials (Netterberg, 1985: SATCC, 2003)

Climatic conditions	Cold regions (little weathering)	Warm regions (considerable weathering)
Property	Conventional (crushed rock base, river gravels, glacial outwash)	Pedogenic (laterites, calcretes, ferricretes, silcretes)
Climate	Temperate to cold	Arid, tropical, warm temperate ←
Composition	Natural or crushed	Varies from rock to clay ←
Aggregate	Solid, strong rock	Sometimes porous, weakly cemented fines
Clay minerals	Mostly illite or montmorillonite	Wide variety, e.g. halloysite, attapulgite
Cement/bonding agent	None (usually)	Iron oxides, aluminium hydroxide, calcium carbonate, etc
Chemical reactivity	Inert	Reactive ←
Grading	Stable	Sensitivity to drying and working
Solubility	Insoluble	May be soluble
Weathering	Weathering or stable	Forming or weathering
Consistency limits	Stable	Sensitive to drying and mixing
Salinity	Non-saline	May be saline
Self-stabilisation	Non-self-stabilising	May be self-stabilising
Variability	Homogeneous	Extremely variable ←

The development of the technology and use of high quality freshly crushed materials in the base layers of roads in the 1980s in South Africa, was a unique development in pavement technology (Maree, 1982). This technology enabled high capacity roads to be cost-effectively designed and constructed, meeting all material criteria and replacing very costly thick asphaltic layers (the norm in most developed countries in the northern hemisphere) (Rust, et al. 1998). The use of freshly crushed stone material considerable reduced the presence of “problematic” minerals due to the weathering process. The fast tracking of the use of these materials and pavement design technologies were achieved through ATP using a fleet of HVSs (Freeme, et al, 1982) and a unique close corporation between client bodies (road authorities), researchers at the then National Institute of Transport and Road Research (NITRR) at the CSIR and practitioners (consultants and contractors). This technology was primarily developed for use in the design of higher order roads carrying high traffic loadings. However, in practice, the use and specifications on newly crushed stone layers from commercial sources have become the “norm” even for low-order roads in residential areas. These practices come at considerable costs to authorities resulting in unacceptable high unit costs for the provision of transportation infrastructure.

The intention is not to question the importance of these material tests as a sound basis for the characterisation of basic material properties. The strict testing and adherence to criteria using traditional material test procedures have a proven track record of the cost-effective use of road building materials, especially in the northern regions of the developed world. However, new technologies, to accurately identify the mineral composition of materials have been developed over the last three decades. Some of these relatively new test methods have become generally available and price competitive and can supplement traditionally used tests to tremendously improve decision taking and enables the cost-effective use of naturally available materials that are normally available in regions subject to high weathering climatic conditions (Weinert, 1980). The implementation of advanced mineral tests becomes even more relevant when considering the cost-effective use of Nano-technologies together with naturally available materials. These Nano-technologies have the ability to neutralise the harmful effect in “problematic” minerals present in “problem” materials. In addition, the physical/chemical interaction of Nano-products with material surface minerals can, to a large extent curtails (if not prevents), the weathering cycle caused by high water contents in combination with seasonal high temperatures.

2.2 Minerology tests

Technologies developed over the last three decades allow engineers to accurately, on a routine basis, identify the metrological (chemical) composition of natural road building materials (Steyn, 2007; Zang, 2008). These include testing methods based on:

- Microscopic analyses: “Microscopy is a category of characterization techniques which probe and map the surface and sub-surface structure of a material. These techniques can use photons , electrons , ions or physical cantilever probes to gather data about a sample's structure on a range of length scales” (Wikipedia, the free encyclopaedia). Examples of microscopic analyses tools vary considerably in complexity and include instruments such as Optical Microscopes (quite common) to Atomic Force Microscopes (AFM) (relatively scarce). Most of the advanced instruments in this group are currently still confined to specialists research and development institutes,
- Spectroscopy analyses techniques: “This group of techniques use a range of principles to reveal the chemical composition, composition variation, crystal structure and photoelectric properties of materials”. (Wikipedia, the free encyclopaedia). These instruments include X-Ray Diffraction (XRD) scanning equipment that is now generally available and affordable for everyday application.
- Macroscopic testing: A huge range of techniques are used to characterise various macroscopic properties of materials. This group include mechanical test equipment that is currently done routinely on road building materials, such as compressive tests (e.g. UCS) tensile tests, etc. Other tests included in this group of tests are however, not used on a routine basis, these include, Differential Scanning Calorimetry (DSC) and Ultrasound techniques.

Of all the above, Spectroscopy analysis techniques, and more specific XRD scans, are generally available and cost-effective (Ermrich and Opper, 2011) for road building material testing to identify the mineral composition of the road building materials, identification of problematic minerals, identification of weathering patterns in different climatic regions, etc. This information is of critical importance not only for the selection and matching of appropriate new Nano-modifiers (eg. Silanes and polymers) but, also in the prevention of premature failures that are all too common on roads throughout southern Africa, using traditional stabilising agents (Jordaan and Kilian, 2016).

XRD scan equipment is currently the only laboratory technique commonly available to the material scientist/engineer that reveals structural information, such as chemical composition (and hence, minerology), crystal structure, crystallite size, strain, preferred orientation and layer thickness (Ermrich and Opper, 2011). Materials researchers therefore use X-ray diffraction to analyse a wide range of materials, from powders and thin films to Nano-materials and solid objects. Small-angle XRD equipment and pair distribution function (PDF) analysis are specifically suited for the analyses of the structural properties of Nano-materials and can play a role in the further development of appropriate Nano-materials to further improve the use of naturally available road building materials and hence, the cost-effective provision of road infrastructure..

2.3 Nano-Modified Stabilising agents

The importance of the identification, testing and implementation of appropriate Nano-technologies in the road sector in South Africa has been discussed and motivated (Jordaan and Kilian, 2016). Since 2015 Nano-Modified Emulsions (NME) have been implemented and used in practice on provincial roads in South Africa and neighbouring countries (Jordaan et al, 2017), and test protocols were developed using XRD-scans specifically for the analysis and interpretation of naturally available road building materials to be used by materials/pavement engineers. These XRD protocols aim to provide the mineral information to allow engineers to assess the impact and applicability of new Nano-based as well as traditionally used stabilising agents when used with naturally available materials. It should be emphasised that numerous different Nano-products such as different Silanes and Polymers are available in the market from various countries. These products have different chemical compositions and react differently when in contact with different minerals and quantities of these minerals. Care and experience in the use of these Nano-materials (testing!) are emphasised in order to select appropriate and cost-effective Nano-additives.

Engineers need to assess the mineral composition of materials together with available applicable stabilising agents to design cost-effective road pavement structures. This information is also crucial to design Nano-modifications to specifically arrest weathering patterns associated with a specific climatic region. Not all Nano-modifiers will give the same benefits to chemically reduce the negative impact of “problematic” minerals by attaching to the “free energy” surrounding mineral molecules (which generally attracts and binds to water molecules). The correct type of Nano-modifier will attach to the surface of these naturally available materials (gravels) to become hydrophobic and thereby arrest future weathering of the material by preventing water/temperature interactions on the minerals comprising the specific materials. (This paper does not allow explaining in detail the different mineral composition of materials and the differences in weathering patterns that can be possible due to variations in temperature, seasonal rainfall as well as the free ions that may be available in a specific area.) However, Nano-technologies have been proven to provide cost-effective (Jordaan, et al, 2017) and scientifically sound solutions to the road sector, resulting in durable materials for use in roads in various countries throughout the world (CSIR-CRRI, 2010, 2015; NCAT 2009, 2011).

The GPDRT realised that the impact of Nano-Modified stabilising agents needs to be demonstrated, proof-tested and rolled-out as soon as possible in order to address the considerable back-lock that exists in the provision of required road infrastructure in the face of dwindling funds, New technologies, where found applicable, could enable not only the province, but the whole of the sub-continent with the ability to fast-track road infrastructure development and provide millions of citizens with the ability of improved living standard and enable countries to become competitive in the global market. The GPDRT has the ability to demonstrate and verify the use of any cost-effective “new technology” in road construction through Accelerated Pavement Testing (ATP) using the Heavy Vehicle Simulator (HVS) of the department, as operated by the CSIR, Built Environment, in South Africa. HVS evaluation and verification can lead to the fast-tracking of the implementation of cost-effective technologies for the provision of road infrastructure in the province, similar to the process with the development of crushed-stone materials in the 1980s, previously referred to.

The GPDRT considered the immediate improvement of current practice to be of high priority and involved design specialists from the University of Pretoria and the CSIR to prepare a proposal for the design, construction and evaluation of pavement demonstration sections using relatively small quantities of Nano-Modified Emulsions (NME) together with naturally available materials in all pavement layers together with an appropriate cost-effective surfacing.

3. HVS EVALUATION OF PAVEMENT SECTIONS INCORPORATING NANO-TECHNOLOGIES

The main objective of the HVS testing is to provide the GPDRT with alternative cost-saving design options based on the use of naturally available materials modified with small quantities of Nano-based products (Nano-Modified Emulsions (NME). These alternative designs should cover the various categories of roads from township roads to the higher order roads carrying high traffic loadings. The aim is to provide such guidelines for general practical use and implantation by the end of 2018.

In order to achieve the overall objectives the following sub-objectives have been identified:

- Development of recommendations towards a material classification system for Nano-Modified Emulsions (NME) in line with current practice contained in existing Technical Recommendation of Highways (TRH) documents, i.e. draft TRH14 (COLTO, 1985);
- Development of recommendations towards material test criteria for the testing and quality control of NME materials to be generally applicable for future implementation;
- Development of first recommendations towards a design catalogue based on the use of NME stabilised naturally available materials for comparison with currently used the currently used design catalogue contained in the draft TRH4 (COLTO, 1996).

These sub-objectives are addressed in this paper. Following the HVS testing and evaluation of results, the GPDRT is committed to the effective transfer of new design technologies through the organisation of workshops and symposia.

4. NANO-MODIFIED EMULSION (NME) MATERIAL CLASSIFICATION AND SPECIFICATIONS

4.1 Recommended Material Classification

The recommended approach is based on the same principles followed in the Nationally approved recommendations for the classification of road building materials, draft TRH14 "Guidelines for Road Construction Materials", (COLTO, 1985). In this document materials such as Crushed stone (G1 – G3), Naturally Available Material (G4 – G10), Cemented materials (C1 to C4) and Bituminous Stabilised Materials (BT1 to BT3) are specified in terms of "strength"/bearing capacity potential for use in pavement structures. The draft TRH14 classification denotes a Class "1" material as the best quality material with the highest potential bearing capacity. The potential bearing capacity of any specific material is, off course, a function of the quality of all the layers in the pavement structure and the pavement structure balance as a whole, given the assumption that quality control during construction is done in such a way to ensure that the required criteria for the construction of each pavement layer is fully met (COLTO, 1998). Taking these basic concepts into account, the following material classification is recommended as used in Table 2:

- NME1- Highest quality stabilised naturally available materials - stabilised with a mineral compatible Nano-Modified Emulsion (can be compared to that of a typical G1 or C1 equivalent material), suitable for upper layers of pavement structures capable of withstanding high axle loadings under conditions of high tyre pressures. The base material to be stabilised must be tested to ensure that the durability of the material will be able to withstand high tyre pressures;
- NME2 – High quality stabilised naturally available materials - stabilised with a mineral compatible Nano-modified Emulsion (can be compared to a typical G2 or C2 equivalent material), suitable of withstanding relatively high traffic loadings and tyre pressures without durability problems;
- NME3 – Medium quality stabilised naturally available materials - stabilised with a mineral compatible Nano-modified Emulsion (can be compared to a typical G3 of C3 equivalent material) suitable of withstanding of material loadings of medium impact, and
- NME4 – Suitably quality stabilised naturally available materials - stabilised with a mineral compatible Nano-modified Emulsion using relatively poor quality naturally available materials (normally rejected for use in pavement layers using current criteria) (can be compared to a typical G4 or C4 equivalent material). The Nano-Modified Emulsion stabilisation of the normally unsuitable material (according to "traditionally" used criteria), will enable these materials to be to be utilised successfully within the pavement structure, and
- NEG5 – Material of a quality less than that of a G5 material modified with a suitable Nano-Modification to become water repellent (not subject to failure modes associated with a "wet" condition. With relatively small percentages of Nano-Modified Emulsions, Lower quality material (G6/G7) can be modified to become Equivalent G5 material (NEG5) which are chemically enhanced to be water repellent.

Table 2: Recommended material specifications for naturally available materials stabilised with Nano-Modified Emulsion (NME)

Test or Indicator	Material[1]	Material classification			
		NME1	NME2	NME3	NME4
Material spec. Soaked CBR (%) (Unstabilised material)	CS (98%)	> 80	> 45	> 25	>15
	NG	> 45 or > 25 and ACV < 30% or 10%FACT>110 kN	> 45 or > 25 and ACV < 30% or 10%FACT>110 kN	> 25	> 15
Plasticity Index (PI)	CS	< 10	< 10		
	NG	< 12	< 12	< 16	< 16
	GS		< 12	< 16	< 16
	SSSC				< 16
P0.075 (%) (test when OMC >8% and % passing 0.075 mm sieve >10%)	CS	< 15	< 15	< 25	< 40
	NG	< 20	< 20	< 25	< 40
	GS	< 20	< 20	< 25	< 40
	SSSC	< 20	< 20	< 25	< 40
MOD AASHTO density		> 100%	> 100%	> 97%	> 95 %
DCP DN (mm/blow) Material compacted to spec. (before stabilisation)		< 3.0	< 3.6	< 9.0	< 13.5
DCP DN (mm/blow) Material compacted to spec. (after stabilisation)		< 1.5	< 1.8	< 3.7	< 5.5
Friction Angle (°)		> 40	> 40	> 30	> 30
Grading modulus	NG	> 1.9	> 1.8	> 1.2	> 0.45
	GS			> 1.2	> 0.75
Typical Effective Elastic Moduli for pavement design (MPa)*		650 - 450	500 - 400	350 - 250	220 - 180
ITS** (dry) (kPa)	150mm Specimen	> 180	> 140	> 100	> 70
ITS** (wet) (kPa)	150mm Specimen	> 140	> 100	> 70	> 50
UCS (rapid curing method 24h at ambient temp + 48h at 40°C -45° C + 4h water cooling) (kPa)	All	> 3 000	1 500 to 6 000	750 to 4 000	450 To 3000
Retained Cohesion ITS Wet/Dry (%)	All	> 80	> 70	> 60	> 50

* These recommended values could vary considerably and are dependent of various influences including, appropriate mix design, pavement balance, quality control during construction, etc.
**ITS repeatability is questionable (TG2, 2009) and may be replaced in future with more reputable test procedures (e.g. Mbaraga, Jenkins and Van der Ven, 2014)
[1]CS – crushed stone; NG – natural gravel; GS – gravel soil, and SSSC – sand, silty sand, silt, clay

The pavement layer in which the various stabilised naturally available materials (as identified above) will be suitable to be used in, will be determined by the required traffic loading and an analysis of the pavement structure bearing capacity and the requirements of the specific layer.

4.2 Recommendations Towards Material Specifications

4.2.1 General

The material specifications recommended in Table 2 borrows heavily from the specifications contained in TG2 for Bituminous Stabilised Materials (BSM) (Asphalt Academy, 2009) and draft TRH14 (COLTO, 1985) for Cement Treated Materials with input from various experts familiar with the use of NME stabilising agents. In comparing the differences in the various specifications, it should be remembered that in both the THG2 and TRH14 specifications materials are specified which contains cement as an active ingredient. With an active cement ingredient it is imperative to have an upper limit in the specifications (with relation to compressive as well as tensile properties) to prevent excessive cracking from occurring within any layer that could progress to the top of the pavement, resulting in premature failure through water ingress into the pavement structure. It follows that the “upper limits” specified for cement-treated materials does not necessarily also apply (at least not to the same extend) to Nano-Modified Emulsions (NME) stabilisation additives (or at least, should be much more lenient than the criteria specified for materials containing cement). This point is illustrated through the comparison of strain/repetition fatigue lines for cement and fully cured Emulsion-Treated Materials shown in Figure 1. It is seen that Emulsion-Treated Materials will, under similar strain conditions, give at least a 4 to 6 times increase in the expected strain behaviour when compared using previously published data (Otte, 1976/8: Jordaan, 1988; De Beer, 1990; Jordaan, 2011).

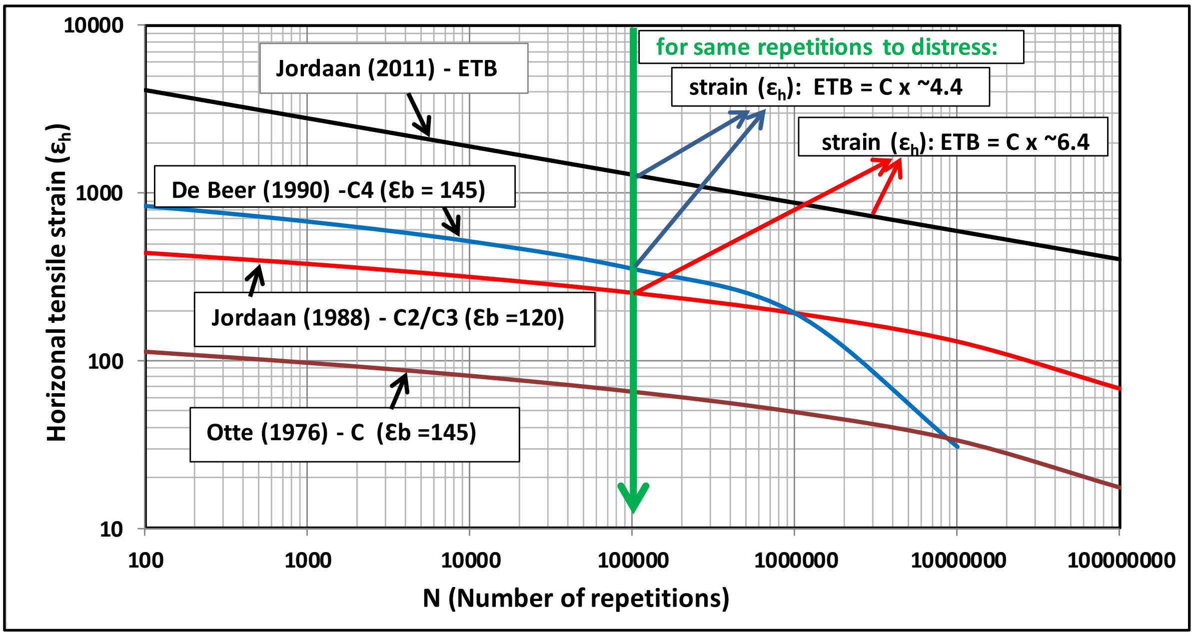

FIGURE 1
Comparison of Cement-Treated and Emulsion-Treated materials strain behaviour as found under Heavy Vehicle Simulator (HVS) Testing

Nano-Modified Emulsion (NME) materials are considerable more flexible than cement-treated materials and may continue to cure (gain in bearing capacity) for periods in excess of a year, in a similar pattern than Emulsion-Treated Materials (Jordaan, 2011) as shown in Figure 2 with the comparison of the strain behaviour of ETB materials obtained with HVS testing on a newly constructed road (ETB not fully cured) (De Beer and Grobler,2003), laboratory tests (Santucci, 1989) and HVS testing on an 8 year old road with the ETB layer fully cured (Jordaan, 2011). During the curing process the material is moulded through traffic to become in balance with the pavement structure before being subjected to the established behaviour of the layer. However, visual observations on roads already constructed using NME technologies may point to an accelerated curing process, which could be explained through the water repellent properties of Nano-Modification using various appropriate Nano-Silanes that is introduced into the emulsion. It is expected that the assumed behaviour of NME stabilised materials will be verified during the HVS testing programme. (Verification of the strength gain with time can be achieved through the repetition of the HVS test programme after a period of two years.) It is expected that the HVS determined behaviour of the NME materials will show an improvement over that determined for pavements containing normally Emulsion-Stabilised layers, mainly due to:

- Absence of cement additives that result into more brittle behaviour trends;
- Improved adherence of the bituminous additives to the aggregates facilitated by the Nano-modifications of the aggregate surfaces to make it water repellent and oil (bitumen) attractive (Jordaan and Kilian, 2016), and
- Accelerated curing of the stabilised layer due to the introduction of hydrophobic Nano-modifications.

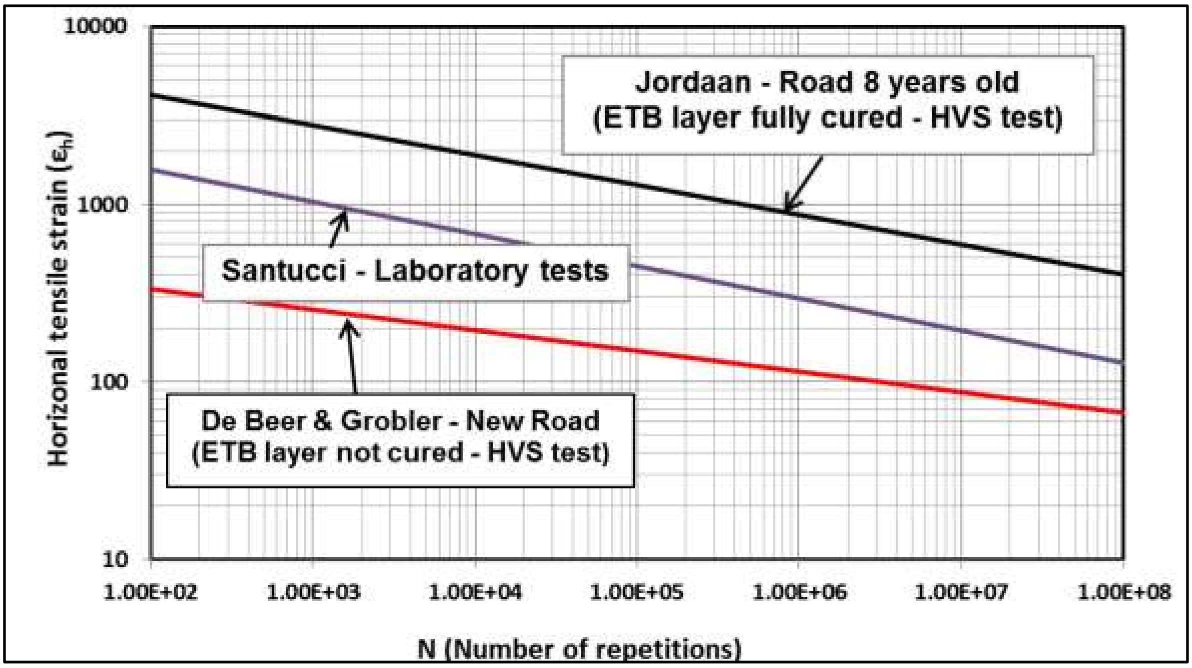

FIGURE 2
Comparison of the strain behaviour of a newly constructed, Laboratory tested and fully cured Emulsion Stabilised layer

4.2.2 Curing of samples for laboratory testing

As concluded from the previous discussions, NME materials cannot be considered to be similar to other existing materials and need to be defined separately. These are mainly due to:

- The naturally available materials (before stabilised using NME products) normally do not conform to the current specifications considered applicable for use in the upper layers of pavements, with material classification properties totally different from historically accepted practice (refer Section 2.1);
- The Nano-silanes and Nano-polymers contain chemical components that require different approaches in terms of material protocol for the preparing of samples for laboratory testing (e.g. during rapid curing processes temperatures should not exceed 50°C due to the potential harm to certain polymers). However, at the same time, protocols recommended for use are kept as close as practically possible to existing test protocols followed for other stabilising agents currently used. (However, even current guidelines for the testing of Bituminous Stabilised Materials (BSM) (Asphalt Academy, 2009) and Emulsion Stabilised Materials (SABITA, 1999) show some variation from those recommended in the original TMH1 (COLTO, 1986)), and
- NME products are relatively new and contrary to existing documents referred to for test protocols, contain no cement additives. Hence, some variations to recommended test methods are required taking into account the unique characteristics of the stabilising agents. Similar to Emulsion-Treated Materials (with small percentages of cement additives), the material gains strength as a result of curing and testing is normally done using a “rapid curing” process where the laboratory samples are prepared and cured in an oven before testing.

The following laboratory aspects with relevance to preparation of samples for NME stabilising agents for laboratory testing are currently recommended:

- Briquettes are prepared as per TMH1 specification, but since no cement is used, briquettes are NOT to be wrapped in plastic bags;
- OMC for briquette preparation for laboratory testing is done as per TG2 (Asphalt Academy, 2009);
- Samples are cured for 24 hours in sunlight (or cured for 24 hours in an oven at 30°C) before being subjected to a “rapid curing” process in an oven (for 48 hours at 40 - 45°C) (temperatures in the oven should NOT exceed 50°C);
- Samples are allowed to reach ambient temperatures before testing is done (24 hours in sunlight) (24 hours at 30°C in oven), and
- Testing is done according to the normal specification for UCS and ITS. “Before CBR and UCS testing the cured samples should be cooled, weighed and submerged in water at ambient temperature (20 - 23°C) for 4 days (SABITA, 1999) and 4 hours respectively (TMH1, Method A14, 1986)”.

5. FIRST STEP TOWARDS A DESIGN CATALOGUE USING NME MATERIALS

5.1 Development of typical pavement design structures

Recommendations for typical pavement structures to be tested and compared with existing pavement structures are given in Figure 3 in a typical “Catalogue of Designs”, similar to that found in the draft TR4 (COLTO, 1996). Typical examples taken from the draft TRH4 (COLTO, 1996) are incorporated into Figure 3 for easy comparison.

The materials specifications for the NME material classes are as per Table 2. The design recommendations for typical pavement structures using NME materials in the various layers are the result of the following:

- Considerable number of material testing using naturally available materials found in the vicinity of the K46 (William Nicol) road close the N14 (the naturally available materials vary from G5 to G7 quality), (where the HVS demonstration sections are intended to be constructed);
- Several XRD- scans of the material in the area has shown relatively high percentages of Mica to be present in the naturally available material. The presence of Mica make the use of cement as a stabilising agent a high risk option (Mshali and Visser, 2013) with a high probability of early deterioration – the use of NME stabilising agents eliminates these known risks;
- The naturally available materials have been tested using an array of different Nano-products at various rates of applications. The required specifications could be achieved (without problems) with NME stabilisation with a maximum application of 1.2 per cent per weight of the material used (residual bitumen less than 0.72 per cent). (Percentages as 0.4 per cent residual bitumen using NME stabilisation have been effectively mixed into pavement layers using conventional construction equipment);

  Numerous pavement behaviour analyses using recommended design procedures as per draft TRH12 (COLTO, 1997) for the different road categories and different design traffic loadings, considering tyre pressures varying from 700 kPa (for the lower category roads) to 800 kPa (for the higher category roads. Designs were tested and verified using a holistic approach, with both Mechanistic-Empirical models and recommended Empirically-derived design methods. The NME stabilised layers were evaluated using available models derived for Emulsion-Stabilised materials (Jordaan, 2011) – it is expected that these models will be found to be conservative for the reasons previously discussed.

6. PRACTICAL CONSIDERATIONS DURING CONSTRUCTION OF THE HVS DEMONSTRATION SECTIONS

Construction of NME pavement layers can be constructed similar to that of Emulsion-stabilised layers as described in detail in TG2 (asphalt Academy, 2009), using either:

- Conventional equipment (graders and water-bowsers);
- Recyclers, or
- Mixing in a centralised plant and the layer put down with a paver.

Depending on the equipment used and climatic conditions, the design quantity of the stabilising agent should be adjusted. The use of conventional equipment will unavoidably result in some variation in the mixing of the stabilising agent. The following adjustments are recommended, depending on the construction process used:

- Conventional equipment – increase the laboratory design percentage of the NME stabilising agent by 0.2 per cent;
- Recyclers – increase the laboratory design percentages of the NME stabilising agent by 0.1 per cent, and

Design traffic Loading Equivalent Standard Axles	Typical road Category	Recommended Pavement structure (Material classification - draft TRG14 (1987) - Layer thicknesses in mm) (draft TRH4)* Granular Base (Dry)	(draft TRH4)* Granular Base (Wet)	(draft TRH4)* Hot-Mix Asphalt	(draft TRH4)* Cemented Base	RECOMMENDED Pavement structure with naturally available materials stabilised with Nano-modified silanes and/or polymer	HVS Demonstration Section
ES30	A	40 A 150 G1 125 C3 125 C3	50 A 150 G1 200 C3 200 C3	40 A 120 BC 200 C3 200C3		30 FT Wax A 150 NME1 200 NME3 150 G5 / (125 NEG5 Hydrophobic)	3
ES10	A	40 A 150 G2 125 C3 125 C3	40 A 150 G1 150 C3 150 C3	40 A 90 BC 150 C3 150 C3		30 FT Wax A 150 NME2 150 NME4 150 G5 / (125 NEG5 Hydrophobic)	1
ES3.0	B	S*/30 A 150 G3 150 C4	S/30 A 150 G1 150 C3	30 A 80 BC 200 C4	S (40 A) 125 C3 200 C4	** S/10CS¹/30 FT Wax A 150 NME3 200 NEG5 Hydrophobic	2
ES1.0	C	S (40 A) 125 G4 125 C4	S (40 A) 125 G2 150 C4		S (40 A) 125 C3 125 C4	** S/(7CS¹/30 FT Wax A) 150 ME4 200 NEG5 Hydrophobic	

*typical examples of recommended pavement structures taken from the draft TRH4 (1996)

** Appropriate Seal according to requirements(Urban/Rural/Required surfacing life/etc); ¹ Cape Seal with a 7 mm stone or 10 mm stone; ² No Cement added

Figure 3

Comparative Design catalogue developed for the construction of demonstration pavemen through APT using the HVS of GPDRT

- Mixing in a centralised plant – no adjustment of the laboratory design percentages of the NME stabilising agent.

Ideally NME stabilised pavement layers should be compacted at Optimum Moisture Content (OMC) + 0.5 per cent (SABITA, 1999). The type of material testing as mentioned above, the climatic conditions and the in-situ moisture of the material to be stabilised are all important factors to be considered when the amount of water is calculated to be added with the NME materials. Some moisture loss during the processing of the material is unavoidable during mixing and provision should be made for this loss to ensure that the material moisture content is not below OMC when compaction is commenced. Under NO circumstances should clean water be added during construction to increase the moisture content of the layer.

7. CONCLUSIONS

The Gauteng Province Department of Roads and Transport (GPDRT) in South Africa identified the use of Nano-Modified stabilising agents as a potential game-changer to provide cost-effective road infrastructure in a developing environment. Nano-modified materials enables the use of naturally available materials also in the upper pavement layers of roads varying from residential to high order roads carrying heavy traffic loadings, with considerable cost, environmental and energy savings. In order to fast-track these technologies in a traditionally conservative environment such as that of road design and construction, the buy-in of all roll players, as led by a major road authority, is a pre-requisite.

The GPDRT took the initiative and has been the driving force in the testing and implementation of Nano-Modified naturally available materials for roads in the province since 2014. The province has also committed to the testing of demonstration sections built using Nano-Modified Emulsions (NME) through ATP using the HVS owned by the GPDRT as operated by the CSIR. In preparation of the construction and evaluation of these demonstration pavement sections, this paper recommends a material classification system and material criteria using NME materials, In addition, a catalogue of designs is presented for comparison with conventional pavement structures traditionally used in South Africa since the 1980s. This catalogue of designs is based on design principles and material testing presented in the paper.

Full-scale HVS testing of a road rehabilitation using small quantities of NME and naturally available materials are planned for 2017/18, involving the GPDRT, the CSIR and the University of Pretoria. The HVS testing on the pavement demonstration sections is expected to provide the impetus for the provision of affordable road infrastructure throughout the province.

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