ADAPT OR ….? - A ROAD PAVEMENT ENGINEERING EPIPHANY: ACKNOWLEDGE PROBLEMS AND ACCEPT SCIENTIFICALLY BASED DISRUPTIVE TECHNOLOGIES

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ABSTRACT

Providing climate-resistant road infrastructure is a prerequisite for the development and economic growth of developing regions of the world. The unit costs of providing basic road infrastructure in these areas are currently unacceptably high – to such an extent that the available funds will never be able to address the current backlog in road network provision, maintenance and rehabilitation. Nano-scale silica-based technologies have been used in the built environment for over two centuries to protect buildings, monuments and statues. The same technologies can be used to improve naturally available granular materials for use in road load-bearing layers. Experience has shown that such practices could have a positive impact, while substantially reducing the unit costs of the provision of road infrastructure. This can be achieved without affecting the quality of the end product and improving the durability, resulting in more climate-resilient road infrastructure. The implementation of these technologies depends on understanding the fundamental challenges facing pavement engineers in practice and the basic concepts and impact that nano-scale silica-based technologies can have on addressing these challenges. This paper aims to identify these challenges and how these technologies can effectively address them to provide cost-effective, long-lasting, low-maintenance road infrastructure while facing imbedded resistance to change.

1. INTRODUCTION

The unit costs of providing basic climate-resistant road infrastructure can be dramatically influenced when naturally available materials can be effectively used in the upper pavement layers. The challenge is to prove the concept of the applicability of available nano-technology solutions currently used in the built environment in the macro-environment of road construction and material enhancement – to prove that naturally available materials can be modified to meet the demands of high traffic loadings in the upper pavement structures. It is acknowledged that this novel approach is disrupting and challenging existing codified knowledge based on historical best practices.

The successful application of proven and available nano-technology solutions in the field of pavement engineering is based on the understanding of the problems associated with the delivery of cost-effective road infrastructure, as well as the knowledge of the ability of these nano-technology solutions to successfully address these problems at a micro-level with a meaningful and lasting effect at a macro-level. It follows that the successful application of nano-technology solutions in pavement engineering is two-fold, e.g. (Jordaan & Steyn, 2019):

- First: understanding and accepting the major material quality and behaviour problems together with resource problems pavement engineers are faced with in designing long-lasting, climate resilient, cost-effective pavement structures (especially in a developing environment faced with enormous infrastructure delivery problems), and
- Second: understanding the micro-level solutions (basic chemistry and physics applicable to the macro-level environment) available of already proven nano-technology solutions that apply to pavement engineering, which could address existing identified problems at a macro-level to have a meaningful impact on the provision of cost-effective road pavement structures in a risk-managed environment.

2. RECOGNISING AND IDENTIFYING PAVEMENT ENGINEERING CHALLENGES

In practice, in a developing environment, pavement engineers are faced with a lack of maintenance ability within authorities and an abundance of naturally available materials that do not meet the generally accepted material criteria and standards for constructing the upper pavement layers. The upper pavement layers need to protect layers lower down in the pavement structure (of poorer quality) and need to be able to withstand the direct impact of high stresses imposed by heavy vehicles under conditions of poor or non-existing law enforcement in terms of traffic loading legislation (Jordaan, 2011(a)).

Due to the high cost of pavement structures containing thick asphalt layers (full-depth asphalt pavement structures), the developing world has developed technologies and pavement structures protected by relatively thin protective bituminous asphalt surfacings or seals which protect underlying layers consisting of high-quality crushed stone in combination with materials stabilised with cement, lime, bitumen and bitumen emulsions (Jordaan & Steyn, 2019) (see Figure 1). The adoption and implementation of the construction of roads using mainly high-quality crushed stone materials have significant cost advantages compared to full-depth asphalt pavement structures (Rust et al., 1998).

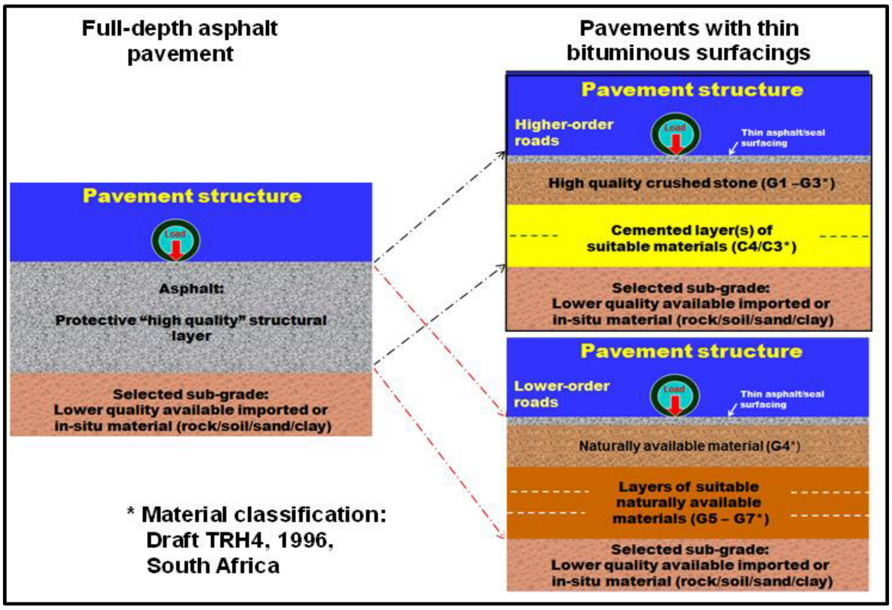

Figure 1: Typical example of full-depth asphalt pavement structure versus pavement structure containing thin surfacings (Jordaan & Steyn, 2019)

However, a thin seal or asphalt layer for optimal performance requires implementing a good Maintenance Management System (MMS). Thin bituminous surfacing layers must be kept intact to ensure that the granular sub-layers are protected against water ingress and damage to the structural bearing capacity of the upper pavement layers. In the face of a lack of maintenance ability, premature distress is usually inevitable (Horak et al., 2019).

High-quality crushed stone have, over the years, together with the implementation of environmental and mining laws to control the opening of new borrow-pits, become a costly item. In many areas, especially areas subjected to higher temperatures or high rainfall (or both) where chemical weathering (chemical decomposition) (Weinert, 1980) is the norm, crushed stone meeting the high criteria to be used in the upper pavement layers is a scarce and relatively costly commodity. It follows that the pavement engineer is faced with two main material-related problems. Addressing these could substantially improve the provision of long-lasting, cost-effective pavement structures. These are improving the characteristics and durability of the:

- Surfacing layer, to provide long-lasting protection to the pavement layers below the surfacing and prevent premature distress due to cracking and water ingress; and
- Naturally available materials to enable their general use in the upper pavement structure at acceptable risk without exceeding allowable distress criteria applicable to a specific road category (Jordaan, 2013).

3. PAVEMENT SURFACE CHARACTERISTICS

3.1 General

The authorities' maintenance ability is usually severely limited or absent in the developing world. Hence, depending on several climatic, loading, quality, etc., factors (Jordaan, 2011(a)), the time before cracking of the bituminous surfacing is usually considerably shorter than that of the pavement design period. Consequently, the lack of a good maintenance programme which incorporates the ability to identify and immediately implement preventative crack sealing and/or re-sealing (re-surfacing) actions quickly results in water damage to the pavement sub-structure. Open cracks in the surfacing layer allow water to penetrate the pavement structure, and under loading, high pore pressures develop that damage even high-quality crushed stone granular and/or strongly cemented sub-layers.

Hence, in the absence of good sustainable maintenance programmes, pavement engineers are usually faced with premature distress due to the inability of the surfacing layer to provide the necessary protection to the pavement structure. This occurs due to the failure of the surfacing layer characteristics to give a long-lasting water-proof protective seal against climatic and load effects (Horak et al., 2022). Premature distress due to surfacing failures can be attributed to various factors, including (Jordaan & Steyn, 2019):

- Quality of the bitumen binder properties delivered in remote areas with little quality control during the placement of normal bituminous mixes under difficult conditions;
- Ageing of the bituminous binder due to high Ultraviolet (UV) radiation from the sun (resulting in oxidation of the binder) that rapidly leads to the escape of volatiles from bituminous binders, resulting in brittle materials that crack prematurely, and
- High-temperature variations in many developing regions due to day/night surface temperature changes cause high variations in stresses and strains, even in thin bituminous surfacings (Figure 2). Bitumen is a visco-elastic material, and the

stress/strain ratio is highly dependent on the temperature of the material. These continuous daily cyclic effects also contribute to the development of premature cracking of especially unmodified natural bituminous binders, even without the impact of traffic loading.

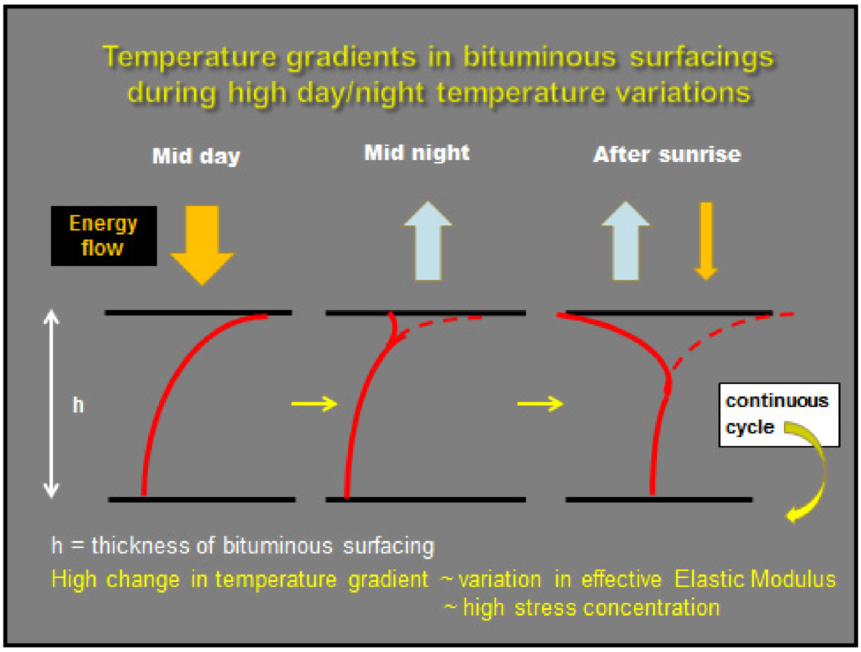

Figure 2: Changes in temperature variation in depth in bituminous surfacing resulting in relatively high-stress variations within the asphalt layer

These known behaviour trends of natural unmodified bituminous surfacings often lead to the manifestation of early distress and damage to high-cost structural pavement layers. This results in surfaced roads with crumbling surfacings full of pot-holes (Figures 3(a) and 3(b)). The resultant effect is a road network containing numerous roads exhibiting premature failures, not addressing the needs of the road user over the medium to longer term, i.e. not providing all weather accessibility and mobility at adequate speed, safety and comfort in a cost-effective way (COLTO draft TRH12, 1997).

(a) Rural road

(b) Urban road

Figure 3: Typical failures due to inadequate surfacing characteristics and a lack of maintenance ability

The surface characteristics of natural unmodified bituminous products can considerably be improved through the introduction of proven nano-technology solutions to resist and/or improve the material characteristics in terms of improvements in:

- Resistance against the harmful effect of UV radiation that leads to the ageing of the binder (similar to UV-resistant polymers or ZnO_2 commonly used in suntan lotions as protection against harmful UV radiation);
- Fatigue properties (that leads to cracking) of the binder (seals and asphalt mixes);
- Deformation properties of the binder (high temperatures often lead to excessive deformation or bleeding even when seal or asphalt design criteria are met), due to the thermoplastic nature of; and
- Adhesion properties between the binder and the aggregate - applicable both to seals and asphalt.

3.2 Generally Available Bitumen Modifications for Surfacing Materials

Most roads requiring upgrading or rehabilitation in the developing world can be considered low-traffic-volume roads with design traffic loadings of less than 3 million E80 or 3 million equivalent standard axles (3 MESAs). Design engineers often design pavement structures that contain high-quality crushed stone materials with surfacings using unmodified natural bitumen binders. Little cognisance is taken of the vast improvement achieved through modifying bituminous binders. In contrast, known enhancements to surfacing behaviour characteristics that can be achieved by using a number of these modifications that have been used and proven in practice are not contained into official documents and hence, ignored.

Numerous bitumen modifications have been developed (especially since the 1970s) using various technologies to improve bituminous binders' deformation and fatigue characteristics (Qin et al., 2014). These modified bituminous binders have successfully been implemented internationally to provide longer, distress-free protective surfacings ideally suited for use in a developing environment. Although the industry has produced numerous guideline documents on modifying and improving bituminous binders (e.g. various manuals funded and produced by SABITA in South Africa), these available technologies have largely not been incorporated into official design documents, many of which still date back to the previous century. Consequently, many of these proven technologies are currently not implemented by practitioners who rely heavily on official documents, such as the draft TRH4 (COLTO, 1996), which is widely used throughout the SADC region of Africa. In other parts of Africa, there may even be reliance on outdated design guidelines originating in the USA or Europe, adding to a basic design environment misfit.

The earliest of these modifications to bitumen for use in roads dates back to the 1940s (Anderson & Nelson, 1940), with considerable progress shown since the 1980s (Zhu et al., 2014). These proven modifications usually refer to the modification of the bitumen binders using various polymers, such as elastomers (rubbers or elastics) and plastomers (plastics) (Walker, 2014). These polymer modifiers are usually applied to increase rut (deformation) resistance or fatigue resistance (cracking). However, modifications to the bitumen binder can also include products such as chemical modifiers, extenders, oxidants and antioxidants, anti-stripping additives and commercial Fischer-Tropsch (FT) Paraffin Waxes (Jordaan et al., 2015; Walker, 2015). As previously discussed, these modifiers can enhance several binder properties, such as rut and/or crack resistance and UV radiation, resulting in resistance to the “ageing” effect. The addition of a suitable applicable modification of the bitumen binder could have a meaningful increase in the expected durability of the surfacing, resulting in a maintenance-free, long-life, cost-effective protective layer (Zhu et al., 2014; Hossein et al., 2015).

Applicable and proven nano-technology solutions have been shown to improve the behaviour of surfacing materials to provide a protective layer by enhancing the bituminous binder characteristics (deformation, cracking and UV-resistant characteristics) and improving the constructability and workability of surfacing layers (Jordaan et al., 2015). It is not the purpose of this paper to discuss technologies that have been proven and implemented successfully (e.g. elastomers, plastomers, Fischer-Tropsch (F-T) Waxes, etc.) over many years or decades, but to improve understanding of applicable nano-technology solutions and the fundamental properties of available products that can be used to enhance binders further to meet the considerable challenges facing the pavement engineer in practice.

It is also not the objective to discuss the impact of these proven modifications. However, the knowledge base of pavement engineers must be expanded to include general awareness of these products. At a minimum, official design documents must be updated regularly (at least every decade) to ensure that the latest proven, cost-effective technologies are implemented as part of generally accepted practice. Most of these modifiers have been used in practice for at least two decades. They cannot be considered nano-materials, as most are of micro-dimensions (similar to bitumen molecules – 1 000 to 5 000 nm in size).

Over and above improvement of the indicated binder properties, the behaviour and durability of the surfacing layer can be improved by using applicable proven nano-technology solutions through the addition of, among other things, silicon-based stone consolidants (chemically bound permanent surface protection layer to resist environmental destructive influences). These proven nano-technology solutions based on nano-silanes/silanols/siloxanes can, among other things, be applied in pavement engineering as water-proofing agents, aggregate adhesives, stone strengtheners and stone preservatives (Wheeler, 2005).

In terms of surfacing characteristics, applying available nano-technology solutions to improve the adhesion properties of the aggregate to the bituminous binder can considerably impact the layer's durability and behaviour. Relatively new developments in asphalt technology show several advantages to be achieved through a combination of technologies, such as F-T wax in combination with nano-silanes, as well as in combination with pure nano-silica products mixed and used together with traditionally graded bitumen (not to mention various available polymers (Hossein et al., 2015; Ashad et al., 2016).

Work to improve the characteristics of bituminous binders is ongoing. Improved evaluation and test methods and “new-age” nano-technology solutions are continuously being developed. Hence, the practical implementation of these technologies should remain an ongoing concern for road authorities. These authorities are entrusted with public funds to ensure that service delivery in general, and the delivery of road infrastructure projects in particular, are done in the most cost-effective way, incorporating the best applicable methods and proven technologies to benefit the public in general. **To “not know” or to “ignore” should not be acceptable as the norm, especially considering the tremendous backlog in the world's developing regions. Accountability should also include the essence and ability to procure services that will allow for the**

incorporation and implementation of the best cost-effective technologies, thereby ensuring the best application of scarce resources.

4. PAVEMENT LAYER MATERIALS

4.1 General

Constructing pavement structures using the concept of full-depth asphalt pavement structures is costly. It has resulted in developing pavement structures consisting of high-quality crushed stone and materials stabilised with cement, lime, and bitumen (see Figure 1). Materials used in the upper layers of a pavement structure must meet the minimum load-bearing criteria to carry the design traffic loading without exceeding the distress criteria applicable to the road category at the required level of confidence (Jordaan, 2013).

Consequently, material classification systems and specifications have been developed to classify materials in terms of their applicable use in various pavement layers at minimum risk (e.g. the South African Materials Classifications System). High-quality crushed stone (G1/G2/G3) is about three times the cost of naturally available materials (G4/G5/G6) from commercial sources. G6 to G8 quality materials are generally available in situ at little cost in most areas. The material specifications developed for use in these pavement structures mainly aim to eliminate the risk associated with secondary minerals that could adversely affect the behaviour of any of the layers in the pavement structure (Jordaan and Kilian, 2016). Material specifications for general use are mostly based on empirically derived material tests developed in the northern hemisphere over a century ago (Jordaan et al., 2017).

Most official design documents based on material classification systems, such as the draft TRH14 (COLTO, 1985), would exclude the use of any material with a lesser classification than a G4 quality (only allowed in roads with a relatively low design traffic loading) in the base layer of a pavement structure. Materials not meeting the required criteria can be improved by applying a suitable stabilising agent and creating a bound layer with improved load-bearing and durability characteristics. Many of the official documents in the developing world date back decades and only cover traditional stabilising agents such as cement, lime and neat bitumen (e.g. COLTO draft TRH4, 1996). Viable existing alternative and cost-effective stabilising agents, such as bitumen emulsions which have been developed more than a century ago, are often excluded from these official design documents.

The recommended stabilising agents often contained in official design documents contain severe limitations in terms of unwanted characteristics and applicability of the minerals contained in the materials to be stabilised, such as those associated with reactive agents such as cement and lime (Jordaan & Kilian, 2016). The associated cost implications of neat (unmodified) bitumen stabilisation also only make it a cost-effective option for high-order roads (high design traffic loading) in association with high-quality crushed stone materials, very similar to that of asphalt (Jordaan & Kilian, 2016).

The common use of reactive stabilising agents such as cement and lime, using general empirically derived indicator testing to determine the suitability of using the stabilising agent, often leads to pre-mature distress. These distresses are often blamed on poor construction techniques without any other plausible explanation. Examples of such premature distress are shown in Figures 4(a) and 4(b). In both examples, carbonation was excluded as a possible cause of distress.

(a) (b)

Figure 4: Premature distress of pavements containing cement-treated materials in the base layer in the Limpopo province of South Africa

The current practice of not considering the mineralogy during design in pavement engineering is of concern. Work done at the University of Pretoria, South Africa, shows the effect of free mica (muscovite) on the behaviour of cement-treated materials. Figure 5 (Mshali & Visser, 2013) shows the impact of free mica (muscovite) on the Unconfined Compressive Strength (UCS) of a good quality G5 granite with an increase in the percentage of free mica (muscovite). The UCS of the cemented material was done as per the standard test method for cemented materials after seven days.

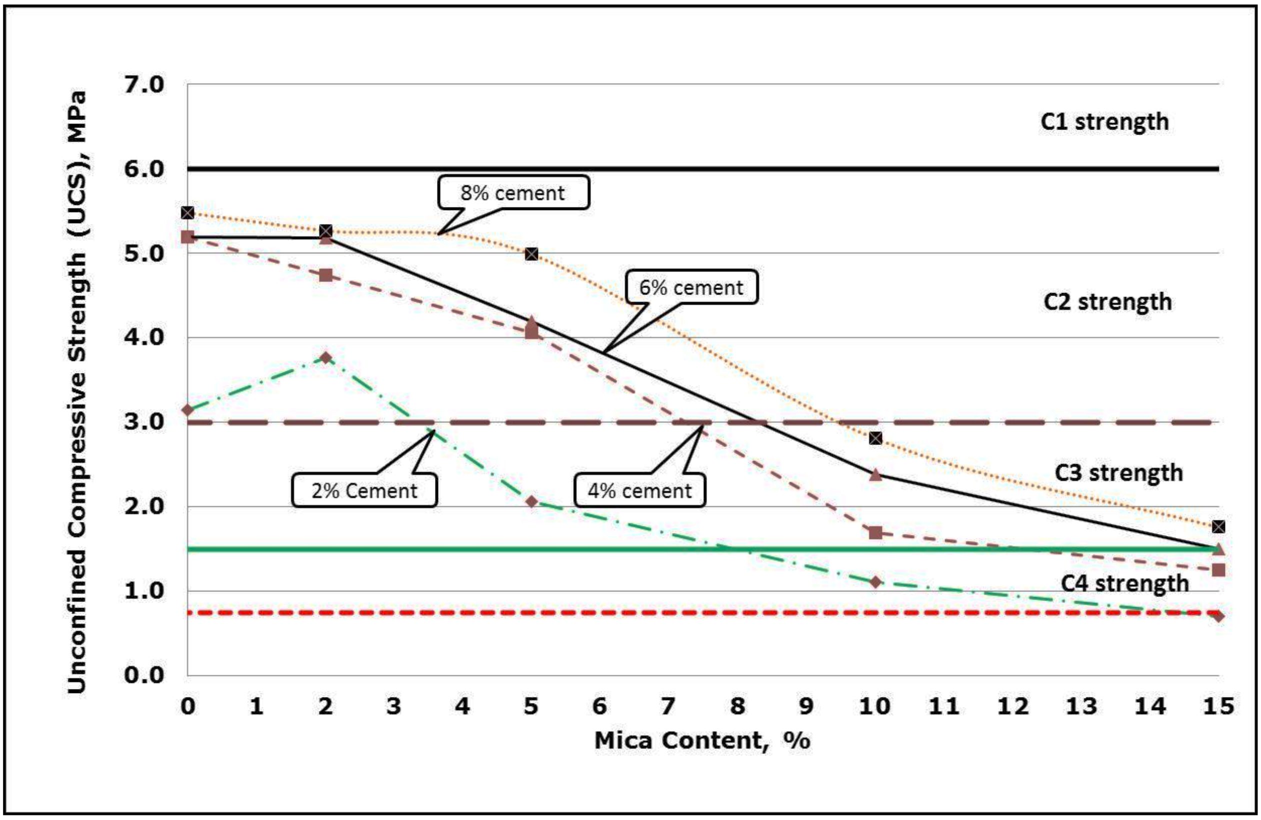

Figure 5: Influence of Mica in weathered granite on the UCS using cement as a stabilising agent (Mshali & Visser, 2013)

As per normal accepted practice, the 7-day test is assumed to be approximately equal to 2/3 of the results after 28 days of curing of cemented materials. In the same study, the UCS tests were repeated after 28 days, using the same material stabilised with 6 per cent cement and mica (muscovite) percentages varying between 2 and 10 per cent. The 2 per cent mica samples showed a decrease in UCS strength from 5.2 MPa to 2.4 MPa, while the samples with 10 per cent mica decreased from 3.1 MPa (7 days) to 1.2 MPa (28 days) (Mshali & Visser, 2013). This work demonstrates the inadequacy of regular indicator tests in identifying the expected behaviour of reactive stabilising agents. It also indicates the inadequacy of normal 7-day tests to predict the behaviour of materials typically used in pavement layers using relatively low percentages of a stabilising agent. During the design stage, with adequate time available, UCS tests should, as an absolute minimum, also be tested after 28 days to ensure that the required and specified strengths will be met.

Due to the high risk of cracking, carbonation and material-related problems with cement stabilisation of base layers, together with the general scarcity of natural G4 quality materials, practitioners more often than not resort to commercial crushers for high-quality crushed stone pavement structures with a stabilised sub-base, even for low volume roads. The main reason for stabilising the sub-base is to construct a layer against which the base layer can be compacted (often referred to as an anvil) to achieve the requirements in terms of e.g. density specifications, of a high-quality crushed stone base-layer.

The generally applied practice of using high-quality crushed stone materials in combination with stabilised layers is considered a “safe” design option but comes at a high cost and hidden risks not fully understood by practitioners. The consequence of this practice is that even low-volume two-lane roads in South Africa cost, on average, about US$ 700 000/km (2018). Further North in the SADC region, the costs of a two-lane low-volume road can reach upward of US$ 1.5 million/km (2018) to US$ 5 million in war-torn regions and more than US$ 10 million/km in some developing regions (e.g., South-East Asia). This high unit cost of the provision of surfaced roads and a general lack of funds for infrastructure construction and maintenance makes it impossible for the developing world ever to develop the transportation infrastructure required to compete economically with the developed world. The comparative situation of surfaced road networks in the world (Figure 6) has little chance of any significant change in the foreseeable future if current trends in the use of materials, material specifications and material classification tests remain unchanged.

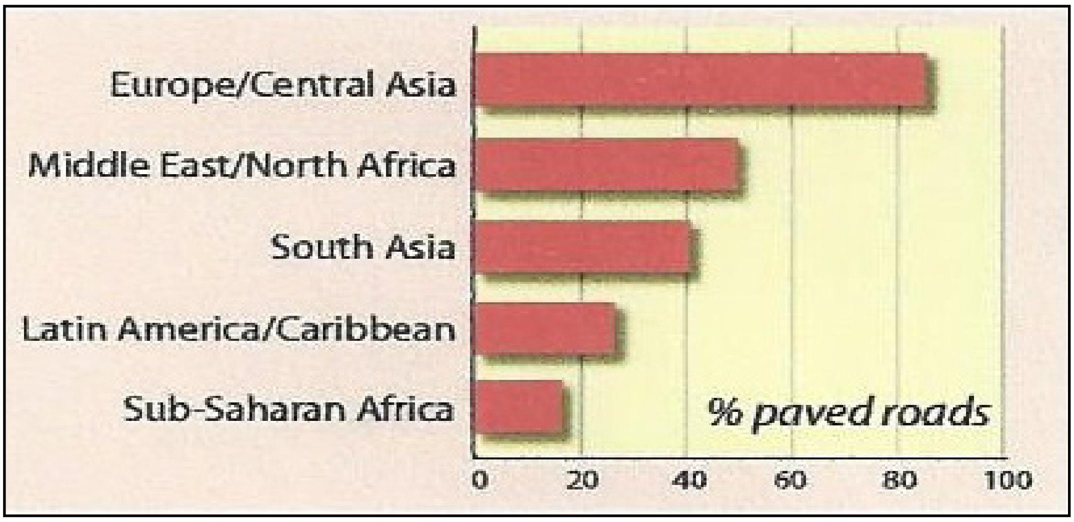

Figure 6: Sub-Saharan Africa compared with the rest of the world in terms of paved road infrastructure (SATCC, 2003)

It follows that the incorporation and implementation of available and proven nano-technology solutions to enable the "improved use of naturally available granular materials and the processing of these materials to enable them to fulfil the required specifications of perpetual pavement structures" (Steyn, 2009) could have a dramatic impact on the provision of cost-effective roads throughout the world (Jordaan & Kilian, 2016).

4.2 Improving Naturally Available Materials for Use in the Upper Pavement Layers

Most tests used to classify available materials have been empirically developed, some more than a century ago. These tests do not determine the mineralogy present in the material and, because of built-in empirical limitations, can have severe and costly consequences in terms of unforeseen failures due to risks not been identified through the use of these tests. Many of these tests are highly subjective (Jordaan and Kilian, 2016). They must be reviewed in terms of applicability and usefulness when considering the general implementation of scientifically based nano-technology solutions. The objective and need to incorporate these nano-technology solutions are primarily identified to neutralise the impact of secondary (e.g. clays) and problematic primary minerals (e.g. mica (muscovite)) in naturally available granular materials. These minerals are considered to have a detrimental impact on the long-term behaviour and durability of the granular materials when used in the upper pavement layers. Any successful implementation of nano-technology solutions in pavement engineering will require a basic understanding of the chemical interaction needed with available natural materials. Hence, mineralogy tests will be a pre-requisite to cost-effectively design and select applicable nano-technology solutions compatible with the available natural materials in a specific area (Jordaan et al., 2017(a)).

Considerable evidence (Jordaan et al., 2017(a)) exists that available and proven nano-technology solutions can be applied in pavement engineering that would allow for the use of naturally available materials (currently being classified as being "non-standard", "marginal", "low-cost", or even "sub-standard" in terms of the standard material indicator tests (Atterberg, 1911) and bearing capacity tests (CBR, ca 1930)). These technologies can be used together with current stabilising agents such as bitumen emulsions and cement to:

- Neutralise potentially harmful primary and secondary minerals present in materials that would contribute to the classification of naturally available granular materials as "non-standard", "marginal", "low-cost", or even "sub-standard", and improve the quality of the granular material using an appropriate nano-modified stabilising agent to enable the use of these materials in the upper pavement layers;
- Render materials water-repellent and prevent further decomposition of the materials when used in the various pavement layers. The specific area aspect of nano-silane implies clay particles (also on the nano-scale) can, in effect, be encapsulated and protected against water intrusion into the particles. Even high-quality crushed stone or cemented materials are subject to water ingress and weathering within a pavement structure. Test results during the rehabilitation of the N14 in Gauteng, South Africa (2018) showed that the constructed G1 layer decomposed to an effective G4/G6 within 22 years. The results of a rehabilitation investigation of a secondary road in Gauteng, South Africa (2014) showed that the constructed cement-treated C4 base-layer weathered in-situ to an effective G7/G8 quality layer within 25 years;

- Achieve strength criteria in terms of Unconfined Compressive Strengths (UCS) and Indirect Tensile Strengths (ITS) for use in the upper layers of the pavement layers; and
- Achieve long-term durability of the pavement layers through improved permanent adhesion of the stabilising agent with the material (soil/stone) and the covering of each granular particle with a water-repellent nano-silane surfacing that inhibits assess to water and hence, limits potential chemical weathering.

Laboratory test results and practically proven implementation of naturally available materials with available, proven and applicable design nano-technology solutions will require a re-thinking of traditional material classification systems classifying materials as “acceptable “or “unsuitable“ for use in specific pavement layers. Applicable material classification systems are essential to implementing nano-technology solutions in pavement engineering. The application of proven nano-technology solutions will render some of the more pronounced differences in materials characteristics due to variations in climatic conditions, such as those provided in Table 1, irrelevant in terms of the use of the materials with the introduction of mineral-specific, designer Nano Modified Emulsion (NME) stabilisation agents using applicable and appropriate nano-technology solutions.

Table 1: Differences between Basic Rock and Weathered decomposed materials (adapted from Netterberg, 1985: SATCC, 2003)

Climatic Conditions	**Cold Regions (little decomposition)**	**Warm Regions (considerable decomposition)**
Property	**Materials: Conventional (Crushed rock base, river gravels, glacier outwash)**	**Materials: Pedogenic (laterites, calcretes, ferricretes, silcretes, etc.)**
Climate	Temperate to cold	Arid, tropical, warm temperate
Material Composition	Natural or crushed	Varies from rock to clay
Material Chemical reactivity	Inert	Reactive
Material Variability	Homogeneous	Extremely variable

The significant effects of weathering through chemical decomposition found in the warmer regions of the planet can effectively be countered and prevented. At the same time, problematic materials in terms of empirically derived criteria, such as poorly graded materials, water-degradable materials and even materials containing high silica-depraved minerals such as calcretes, dolomites and calcites, can be adequately modified and stabilised with the basic proper identifications of the mineral composition of the material as a basic pre-requisite.

The development of bitumen emulsions represents an early use of nano-technology solutions in constructing road pavement structures (James, 2006). Although the use of bitumen emulsions in road design and construction is covered in some official documents, it is primarily addressed in numerous design documents produced by industry and not included in main design documents, generally used throughout regions such as southern Africa, i.e. the draft TRH4 “Structural Design of Flexible Pavements for Interurban and Rural Roads “(COLTO, 1996). Although more recent documents have been produced by industry and road agencies (e.g. SANRAL, 2013), these are largely ignored in everyday practice. The exclusion of bitumen emulsions and the various modifications thereof developed over the last few decades (James, 2016) as an option for the stabilisation of available materials in official design documents, in practice, also leads to the exclusion of the consideration of such possibilities in the design of road infrastructure in numerous cases. The same dilemma must be addressed by introducing any applicable and proven new nano-technology solutions that could dramatically change the cost-effective delivery of much-needed road infrastructure by considerably reducing input costs and providing long-lasting, maintenance-free roads using naturally available materials.

Bitumen emulsion stabilisation provides a flexible layer with a low risk of cracking, which does not react with unknown minerals in the materials that are being stabilised and gives improved characteristics in terms of resistance to water damage (Jordaan and Kilian, 2016). The considerable advantages of bitumen emulsion stabilisation in terms of crack resistance are shown in Figure 7. In Figure 7, the number of strain repetitions to fatigue cracking of a fully cured bitumen emulsion-treated layer (Jordaan, 2011(b)) is compared to the strain repetitions to fatigue cracking for a cement-treated layer as determined by various researchers (Otte, 1976; Jordaan, 1988; De Beer, 1990). In this comparison, it is seen that bitumen emulsion-treated materials can, under similar load repetitions, tolerate strain levels of approximately 4 to 6 times higher than that of cement-treated materials without the considerable disadvantages associated with alternative stabilising agents as previously discussed. This comparison is of note when discussing and comparing the use and influence of available and applicable nano-technology solutions with naturally available materials in the upper layers of a pavement structure.

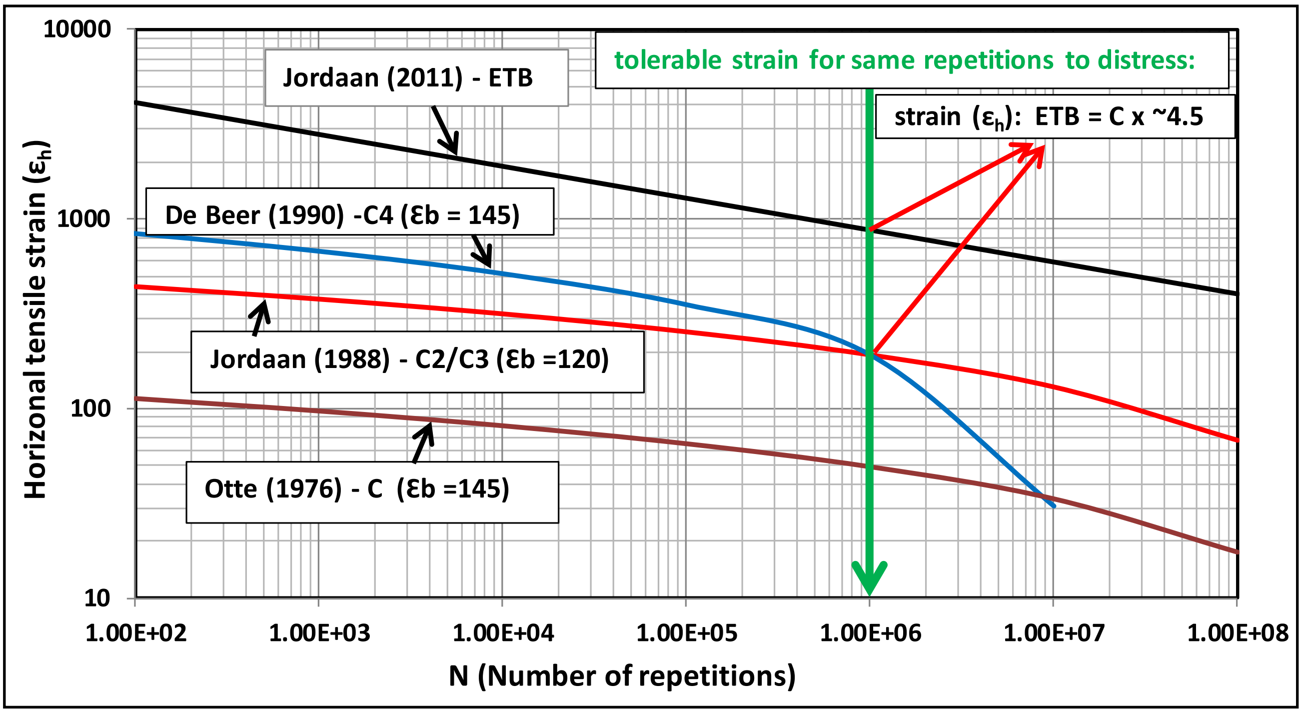

Figure 7: Comparison of Cement-Treated and Emulsion-Treated materials strain behaviour as found under Heavy Vehicle Simulator (HVS) Testing (Jordaan et al., 2017)

Bitumen emulsion stabilisation has proven very cost-effective when using relatively small quantities (less than < 2 per cent) with residual bitumen less than 1.2 per cent per mass together with some cement (around 1 per cent) (to mainly assist with the breaking of the emulsion (SABITA, 1999)) and a small percentage of lime in the presence of material with a PI over 6. This stabilisation recipe has been utilised for the in-situ reworking of many roads during rehabilitation throughout South Africa. HVS testing (Jordaan, 2011(b)) has also shown that this stabilisation recipe can be utilised cost-effectively on roads with relatively high traffic loading, providing a flexible pavement structure compatible with the rest of the pavement layers. The successful use of this emulsion stabilisation recipe lies in the fact that the bitumen emulsion, to some extent, covers the clay particles (encapsulates) and prevents the interaction with the cement and water that may lead to the breaking up of the pavement layer. Bitumen emulsion is also suitable for stabilising cohesion-less sand, providing the smaller particle fractions bind the material together.

Incorporating nano-technology solutions in the manufacturing of bitumen emulsions is important in the investigation of proven and applicable nano-technology solutions in road pavement engineering. Understanding the fundamental concepts contained in the manufacturing of bitumen emulsions will considerably improve the understanding and explanation of nano-technology solutions used to improve the delivery of road infrastructure at reduced costs. The nano-technology solutions applicable to the manufacturing of bitumen emulsion also form the basis for identifying and understanding relevant, available and proven nano-technology solutions for application in pavement engineering (Jordaan et al., 2017(b)). These technologies can improve the characteristics of both the surfacing as well as enhance existing or provide alternatives to the stabilisation of “marginal”, low-cost” or even “sub-standard” naturally available materials in the upper layers of pavement structures of roads designed for traffic loadings exceeding 30 million E80s. Hence, the manufacturing and the role of the emulsifying agent and their properties in terms of quality, stability, etc., need to be well appreciated.

Significant improvement in emulsifying bitumen compatible with the nano-silane in terms of size had also improved the production of Nano Modified Emulsions (NME). NME-treated materials must be designed to meet end-use specifications, as has also been incorporated in the recent publication of the draft draftTRH24 (2024).

5. RESISTANCE TO CHANGE

On a more philosophical note, it is virtually inevitable that innovations such as nano-silane will challenge existing norms, specifications, understanding, and treatment of naturally available granular materials. The fact that nano-silane can improve the aforementioned marginal natural granular materials (e.g., G6 down to G10) to be used as a base layer implies actual technology disruption characteristics. As explained previously, material testing and standards are not only old or dated but rather empirical in several cases.

Roberts (2008) states that products, services, processes, guidelines, and policies are defined as codification practices. He states, “S*uch knowledge codification practices, by their very nature, lead to ignorance since they involve the reduction of often complex rich knowledge to those components that are central for the task at hand”.* As described, using new technologies, such as nano-silanes, requires new knowledge or even a more fundamental knowledge of the minerals in the soil or granular materials. Wehling (2021) refers to “blind spots” developing in scientific research related to the groupthink created by the codification that guidelines tend to create.

Humans often cling to their codified knowledge as if it is the only truth that ignores the larger field of non-knowledge. This phenomenon has been described by Kuhn (1962) as paradigms where information is often in plain sight but treated as mere outliers that do not fit the thinking or understanding framework. Even at a more specialised level of forensic investigations (Horak, 2019), it is true to human nature to resist change or new technology for various reasons. Over and above an unknown new disruptor technology, the existing codified knowledge has limitations in thinking and personal predisposed ness, as well as confirmation and hindsight biases (Davis, 2009; Pinto, 2019).

Overcoming such resistance to change and, in effect, new knowledge cannot be fought on an emotional level. Factual information, i.e. peer-reviewed publications, demonstration projects and, in general, scientific reasoning, should be applied. Therefore, using nanotechnology requires a more fundamental understanding of the chemistry, physics and minerals of soil and gravel, which aligns with such a paradigm change. The fact that end-product specifications have also recently been incorporated into the codified knowledge of the draft TRH 24 (COTO, 2024) implies that the logic of this more fundamental knowledge requirement will win over engineers with current paradigm blinds.

6. CONCLUSIONS

Two critical aspects influencing the performance and cost of road transportation infrastructure in the developing world, i.e.:

- Premature surfacing cracking that, under low or no maintenance conditions, allows water to penetrate the road pavement structure. This results in the quick development of secondary distress in the upper pavement layers under the effect of traffic loading, forming pot-holes and severely influencing the reliability and safety of the road user, and
- Relatively high cost of high-quality materials specified for use in the upper road pavement structures to prevent failure due to the influence of weathering and the possible adverse effect of problematic primary and secondary minerals on the behaviour of granular materials. Compared to the abundance of naturally available granular materials that are considered “non-standard”, “marginal”, “low-cost”, or even “sub-standard” in terms of the standard material indicator tests, which were developed more than a century ago.

In these cases, using available nano-technology solutions proven and used in the built environment, can considerably contribute to delivering long-lasting, low-maintenance and cost-effective road transportation infrastructure. Many of the nanotechnologies required for improving the characteristics of granular materials are already in use in many built-environment products throughout the world, positively influencing the various items now considered part of daily living.

In the case of the improvement of the expected crack-free performance of the road surfacings, numerous modifications have been implemented for decades. However, due to the slow updating of official documents, many of these modifications (although thoroughly addressed in industry documents) are not used in practice. Even in the case of improved and enhanced surfacing materials, available nano-technology solutions can prove to further contribute to the concept of long-lasting, durable and climate-resistant surfacings currently used in practice.

The recognition that nano-silane has technology disruptor characteristics implies there will be a natural or human reaction to such a change in the paradigm of thinking and understanding of road-building materials. Biases strengthened by codified knowledge in specifications, guidelines and thinking of material behaviour clearly may provide resistance to this technology disruptor application. The fact that nano-silane is grounded in a more fundamental understanding of the chemistry, minerals and their interaction on a nano-scale implies the scientific proof thus provided will help to change paradigms and thinking to accept such new innovative technologies.

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