SIZE MATTERS – IMPORTANCE OF PARTICLE SIZE IN THE DESIGN OF EFFECTIVE NANO MODIFIED EMULSION (NME) STABILISING AGENTS FOR NATURALLY AVAILABLE GRANULAR ROAD MATERIALS

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ABSTRACT

The successful application of a Nano Modified Emulsion (NME) stabilising agent for Naturally Available Granular Materials (NAGM) for use in the load-bearing layers of a road pavement structure is mainly dependent on the mineralogy of the granular material determining the properties of the modifying agent to achieve strong chemical bonds and the particle sizes of all the different materials comprising the stabilised mix, i.e., the granular materials (grading), the modifying agent, e.g. nano-silane and the binder (bitumen emulsion or equivalent polymer). The importance of the mineralogy of granular materials for infrastructure has been covered in several publications since the 1800s. In addition to the mineralogy, the particle sizes of the NAGM, as well as that of the nano silane modifier and the binder, are crucial inputs to the design of an effective NME stabilising agent to optimise the potential of any NAGM through the use thereof. The chemical composition of the nano silane modifier is mainly a function of the available broken chemical bonds within an NAGM. The finer fractions of the NGAM determine the required particle sizes and the volume of the modifying agent and the binder to optimise the potential use of an NAGM. It follows that no single NME stabilising agent will be suitable for all available NAGMs. Each NAGM with different characteristics will require adjustments in the design of a Material Compatible (MC) NME stabilising agent (MC-NME). This paper discusses the importance of the particle sizes of all components comprising an NME-stabilised road pavement layer. The influence of the particle sizes of the material mix on the engineering properties (tensile strength and compressive strength) measured is demonstrated through the test results of materials tested in South Africa. Due to the scientific approach developed, the materials design method is universally applicable.

1. INTRODUCTION

The ability of Nano Modified Emulsion (NME) stabilising agents to effectively treat and or stabilise Naturally Available Granular Materials (NAGM) for use in the load-bearing layers of a road pavement structure relates to the following:

- Chemical composition of the NAGM, i.e., the primary and secondary minerals comprising the materials (Jordaan & Kilian, 2016; Jordaan et al., 2017; Jordaan & Steyn, 2019, 2021a);

- Ability of the NME stabilising agent to form strong chemical bonds with the NAGM as a function of the mineralogy (Jordaan & Steyn, 2019, 2021a);
- Ability of the NME stabilising agent to strongly bind with any binder to, with the NAGM, form a cohesive water-repellent material (climate resilient) (Jordaan & Steyn, 2019, 2021b);
- Ability of the NME stabilising agent to neutralise the possible negative impact of any secondary minerals that may form part of the NAGM as mainly determined by the finer fractions within the NAGM and most notably, the fractions passing the 0.075 mm sieve size and the percentage of the 0.075 mm fraction consisting of problematic materials such as clay (various types), mica (muscovite) and talc (Jordaan & Steyn, 2019, 2021c);
- Particle size of the nano silane modifier in the NME stabilising agent which must be able to form a three-dimensional coating around each NAGM particle to change the polarity thereof and render it hydrophobic. It is essential for the nano silane modifier to specifically be able to penetrate and neutralise the clay nano-layers formed within highly weathered NAGM to prevent any moisture influence, rendering these clay particles to be water-repellent (hydrophobic); and
- Particle size on any binder that is modified as part of the NME stabilising agent: the higher the percentage of the smaller fractions within the NAGM, the more difficult it becomes for big (micrometre size) particle size binders to bind the particles together, meeting the engineering specifications effectively. In such cases, an increase in the percentage of the modified binder will lead to a decrease in the measured compressive and tensile strengths.

The importance of the mineralogy in the design of a Material Compatible (MC) NME (MC-NME) stabilising agent has been discussed in numerous publications as refereed to, also in the built environment dating back to the 1800s (Von Hoffman, 1846; Von Ebelman, 1861; Wheeler, 2005). This paper concentrates on the influence of the particle sizes of the various components in the design of an effective MC-NME stabilising agent. Easy-to-follow design input guidelines are presented based on the NAGM characteristics, particularly the finer fractions of the NAGM. The influence of an MC-NME's design on the material's engineering properties is demonstrated using a practical example.

2. PARTICLE SIZE OF THE NATURALLY AVAILABLE GRANULAR MATERIALS (NAGM)

2.1 General

Any NME stabilising agent that needs to neutralise problematic and secondary minerals present in any granular material needs to:

- Cover the surface area of the granular material particles to effectively change the polarity of the particle surface and make it hydrophobic (water repellent), not enabling water to enter the particles, not allowing for the absorbent of water and resulting in:
  - Expansion of secondary minerals (e.g. various types of clays), causing expansion of the material, considerable reduction in shear resistance and an associated reduction in the bearing capacity of the material; and
  - Chemical weathering of primary minerals (as well as continuous weathering of secondary minerals) over time (even during the design period of a road) due to the access of water to the granular particles, resulting in the formation of secondary minerals which could negatively affect the bearing capacity of the granular material.

- Allow for the chemical bonding of the binder (bitumen or equivalent polymer) to the granular particles using a modifier (nano-silane), resulting in a cohesive material with an increase in bearing capacity. It should be noted that with normal bitumen emulsion or asphaltic mixes, no chemical bonding occurs between the bitumen and the aggregate (Weiner, 1980).

The surface area of the granular material increases exponentially with a decrease in particle size. The finer fractions within the granular materials mainly determine the surface area to be protected by any nano-size protective modifying agent as part of any "alternative and innovative" product. The fractions that are of main interest are the fractions passing the 0.075 mm sieve size (in terms of normal material sieve analysis) and the fraction passing the 0.002 mm, which can be determined in soil laboratories. However, the fraction smaller than 0.002 mm, as determined using the hydrometer test (ASTM 422, 2002), will not indicate the type of problematic minerals (e.g., muscovite, type of clay, talc) present within this fraction.

2.2 Granular Material Fraction Passing the 0.075 mm Sieve Size

The fraction of the material passing through the 0.075 mm sieve contains the "dust" particles in the granular material that are present both as a result of mechanical weathering (crushing) and chemical weathering (change in chemical composition in the presence of water). This fraction of the material does not necessarily indicate potential problematic material performance within a pavement structure. Without an abundance of problematic minerals, this fraction will ensure that granular material can be used to achieve good interlocking and a good surface finishing of a pavement layer.

2.3 Granular Material Fraction Smaller Than 0.002 mm

The fraction of the material smaller than 0.002 mm will contain the secondary minerals (e.g. various types of clays) as well as some problematic primary minerals (e.g. muscovite) within the NAGM. Any NME stabilising agent needs to neutralise these minerals to improve the bearing capacity and durability of the naturally available materials. The absence of such ability within the stabilising agent will immediately be detected by a considerable reduction in the "wet" Unconfined Compressive Strength (UCS) and "wet" Indirect Tensile Strength (ITS) measurements of the mix as per recommended specifications (Jordaan and Steyn, 2019; COTO draft TRH24, 2024). The neutralisation of this fraction of the NAGM is crucial to the durability and long-term performance of any pavement layer using NAGM stabilised with MC-NME.

Traditional material classification systems for use in pavement structures aimed at avoiding or limiting the presence of secondary minerals within the upper pavement structure by specifying new crushed stone materials. However, this practice is expensive (Jordaan & Steyn, 2019a). With the implementation of NME technologies, not only can the problematic minerals be neutralised, but durability can be increased by limiting or even preventing future weathering.

However, not all secondary minerals can be considered equal. The "clay problem" is a subject that requires extensive discussion and will not be covered in any detail in this paper. To appreciate the considerable challenges offered by materials containing a high percentage of clay, the properties of some of the most commonly found clays are summarised in Table 1 (Based on Kumari & Chandra, 1960).

Table 1: Illustration of the variation in important characteristics of a selection of clay particles (based on Kumari & Chandra, 1960)

Property	Type of Clay				
	Smectite (Montmorillonite)	Vermiculite	Illite	Chlorite	Kaolinite
Specific Area (m^2/g)	700–800	500–700	50–200	25–40	5–30
External surface	Very High	Very High	Medium	Medium/low	Low
Basal spacing (Å)*	9.6–20	10 -15	10	14	7.2
Internal surface	Very High	High	Medium	Medium	None
Expanding	Yes	Slightly	No	No	No
Swelling capacity	High	Medium High	Medium	Low	Low
Cationic exchange capacity (CEC) (meq/100g)	80–100	100–150+	10–40	10–40	3–15
Similar clays and problematic minerals	Beidellite Nontronite Saponite Bentonite		Mica FeO_2** Fe_2O_3*** $Al(OH)_3$		Halloysite Anauxite Dickite Nacrite

*10 Angstrom (Å).= 1 nm; **FeO2 = Red Iron based clay; Fe2O3 = "Black cotton Soil"

The specific surface area of the different clays (in m2/g) shown in Table 1 is critical when stabilising materials containing high percentages of clay using a nano-silane modification and selecting an applicable stabilising agent. To achieve a high level of hydrophobicity, the total area of all the particles in the material needs to be covered. It is seen that the specific surface area of clay could vary from about 700 to 800 m^2/g (Smectite) to 7 to 30 m^2/g (Kaolinite), a considerable difference that will determine the percentage of a nano-silane of appropriate size to be required to achieve a durable hydrophobic effect that will be lasting under the impact of loading. It follows that the smaller the particle size of the nano-silane, the less volume will be required to penetrate the clay matrix to achieve the necessary hydrophobic effect and vice-versa.

However, simultaneously, the specific clay's Cationic Exchange Capacity (CEC) is just as important. The higher the CEC, the more suspectable to chemical interaction the clay will be. Smectite, for example, has a comparatively high specific area in combination with a high CEC. Hence, Smectite is much more susceptible to chemical alteration than, for instance, Kaolinite, which has a relatively low specific area but a similarly low CEC (7 to 15 meg/100g). In combination with relatively small particle sizes, a low CEC may prove challenging to alter chemically and firmly bind together through any modification. In all definitions, Kaolinite can be considered as a "dead" clay with little attraction to nutrients and water for agricultural purposes. Similarly, materials containing relatively high percentages of Kaolinite present considerable challenges towards the effective strong formation of chemical bonds during stabilisation. The challenge is to penetrate the clay matrix, activate the clay surface with an applicable modification to the nano silane (Hydroxy Conversion Treatment (HCT)) and create the chemical bonds that will enable the material to be stable and durable under loading conditions.

Clay crystals are usually 1 to 3 nm in size (Figure 1, Moore, 1960). These crystals form nano-plates that (depending on the type of clay) are susceptible to water “capturing”, resulting in the considerable swelling of the material (e.g., the Smectite group of clays as shown in Table 1). To utilise materials with a high clay content effectively, specialised technologies are required to achieve the hydrophobic nature, expel the water and achieve the strengths required through stabilisation. Clay in a dry state has a high bearing strength. The problem is that clay in nature is usually associated with water “capturing”, and to make it hydrophobic, water is required as a carrier fluid for the nano-silane modifier to reach the clay particles. The nano-silane have to replace the “captured” water particles in the clay matrix to renter it hydrophobic. The clay particles will release and repel the water molecules only after the characteristics of the clay particles have been changed. High percentages of clay within a NAGM presents construction problems in the presence of water. Hence, such stabilisation treatments should be done at a moisture content as low as possible. It is recommended that the nano-silane modified binder be diluted with water to a 50:50 ration and applied to the NAGM at an Optimum Moisture Content (OMC) of the NAGM not exceeding 50 per cent to avoid constructability problems. The process of the effective utilisation of materials containing a high clay content presents technological as well as practical challenges.

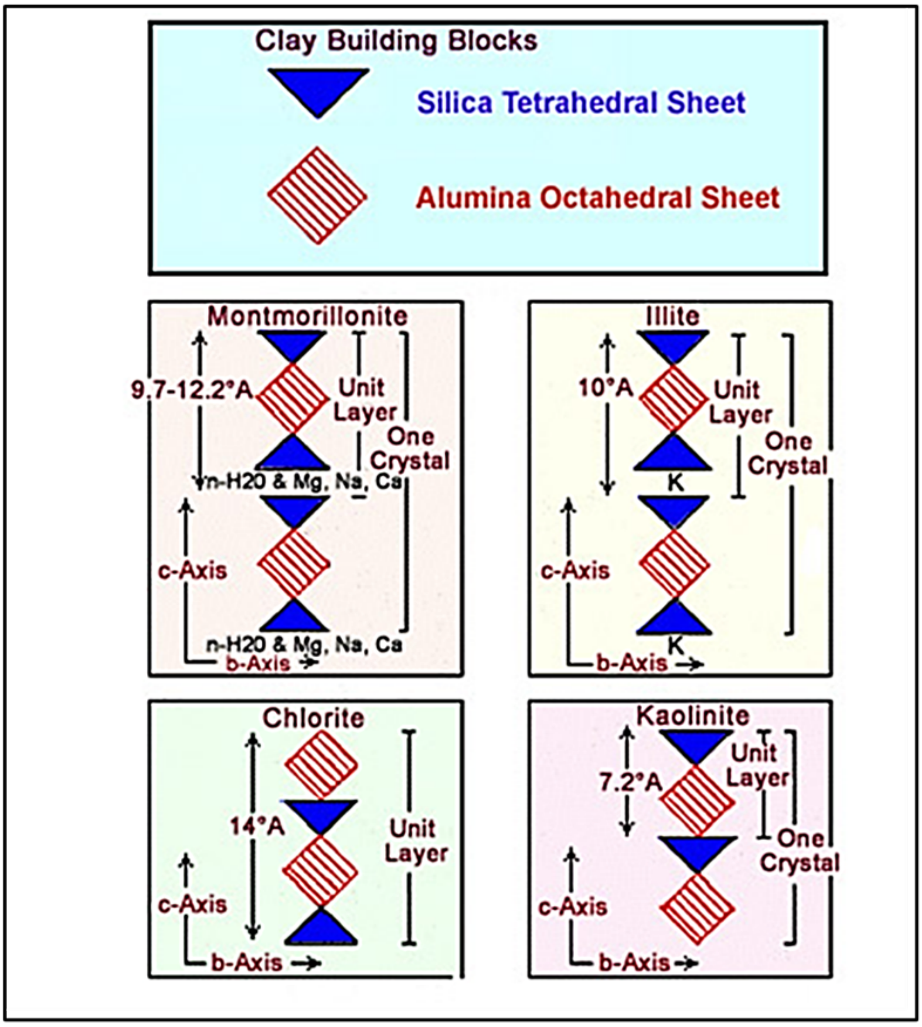

Figure 1: Some typical sizes of clay crystals as measured in Angstrom (where 1 Angstrom (Å) = 0.1 nm), (Moore, 1960)

3. PARTICLE SIZE OF THE NANO SILANE AND THE BINDER IN THE NME

3.1 Particle Size of the Nano Silane

Generally, available nano-silane particles are often in the order of 2 to 5 nm in size and will not be ineffective in penetrating the clay matrix (refer to the Basal Spacing in Table 1 and Figure 2) and render clay particles hydrophobic. The treatment of several clay nano-layers is easily achievable using technologies based on relatively large nano-silane particle sizes. However, any stress/strain on these samples causes slip-planes and breakage within the nano-clay layers, allowing water access to the clay nano-layers that have not been effectively accessed and have not been chemically changed to become hydrophobic. The result is that the material becomes hydrophilic, absorbs water, swells, and breaks any bonds an applied stabilising agent creates. The "good" anionic nano-silanes available in the market are less than 1 nm in size and are effective in treating clay materials.

Ideally, the area of the particles to be bound together should be matched by the area the stabilising agent can cover. With materials containing a grading with a high percentage of clay (<0.002 mm in size), the stabilising agent should have a grading to match the increase in the area to be covered, creating a stable environment within the material. This concept is illustrated in Figure 2 (Jordaan & Steyn, 2019, 2021c), the practical implementation of which is discussed in the following recommended detailed material design method.

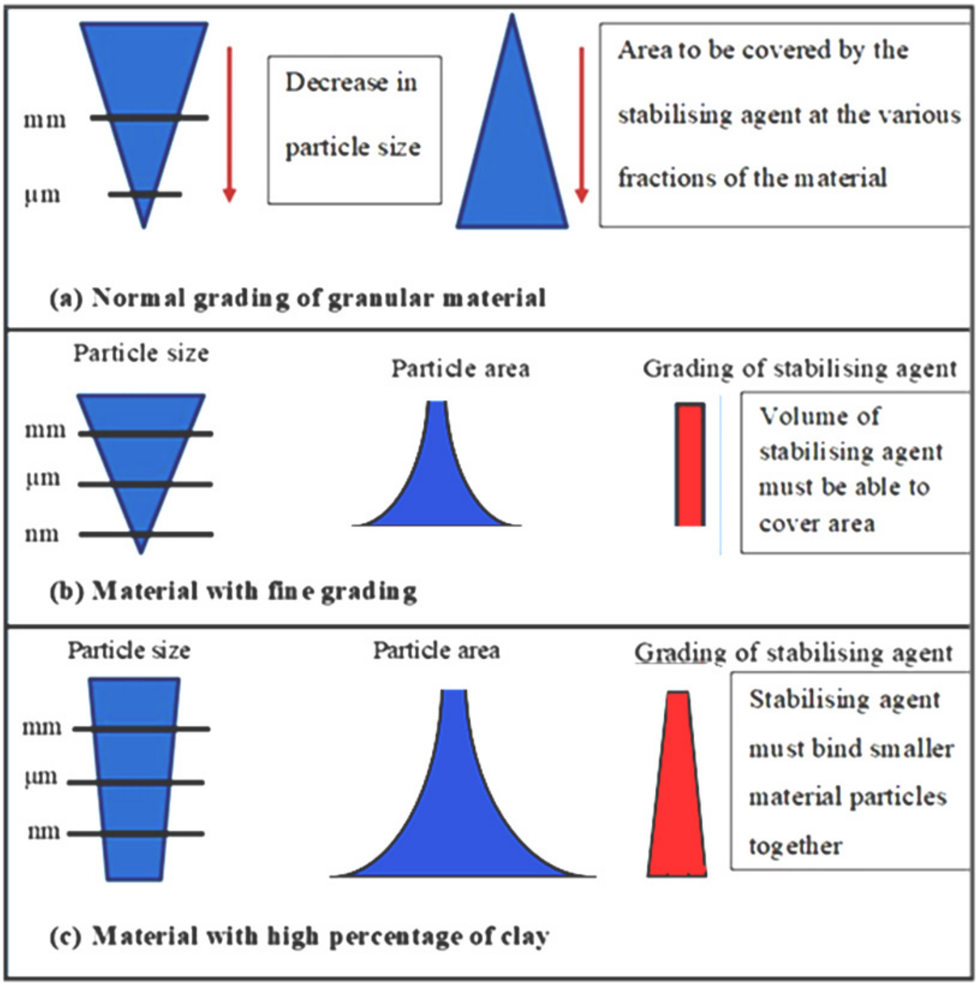

Figure 2: Illustration of grading of material (particle size) versus area to be covered by an applicable stabilising agent and required particle size of the stabilising agent (Jordaan & Steyn, 2019, 2021c)

Hence, to effectively treat materials containing high percentages of clay, the nano-silane particle must have the highest quality and purity of a sub-nano (Pico) size to penetrate the clay nano-matrix. Only nano-silane particles exhibiting these characteristics can replace the captured water molecules by binding with free cations present in the clay particles. The pico-size silane can render each clay nano-layer hydrophobic by penetrating the clay matrix, repelling the captured water molecules and preventing any water from penetrating the clay nano-layers. No shearing of the clay nano-layers under loading will expose the clay matrix to allow water ingress, creating a durable, stable layer. This process will result in a considerable reduction in volume when the water is repelled from the clay nano-layers, which will normally (in the case of high-swelling clays) be associated with considerable shrinkage, as shown in Figure 3.

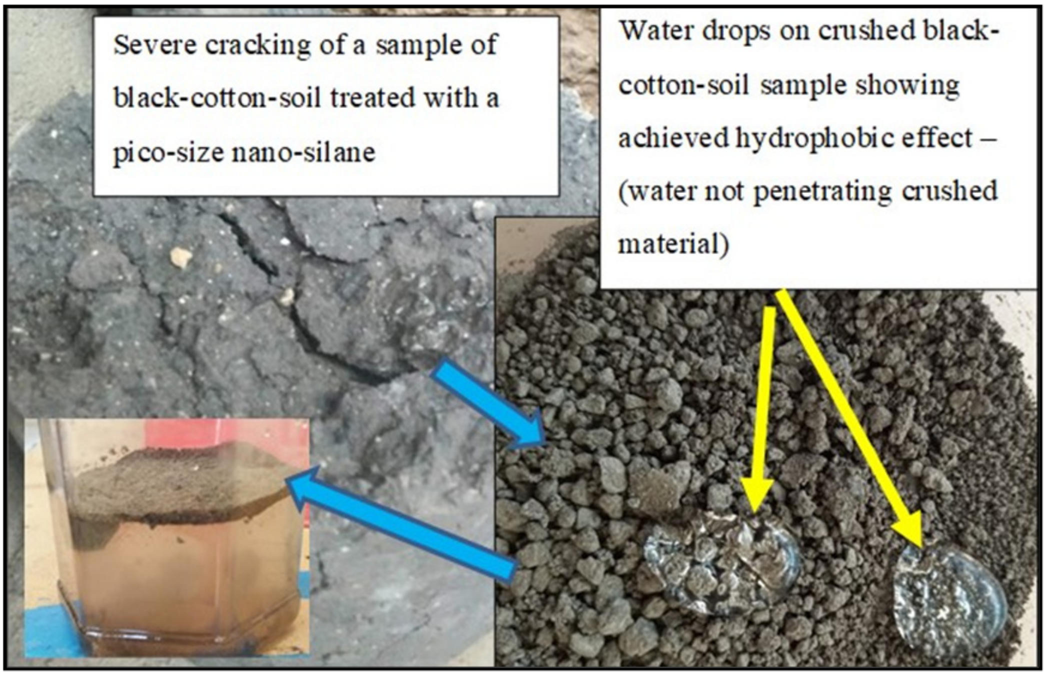

Figure 3: Treatment of black-cotton soil to obtain hydrophobicity with crushed clay particles floating on water (Jordaan & Steyn, 2019, 2021c)

3.2 Particle Size of the Binder in an NME

In relation to the particle sizes within the granular materials to be stabilised, the particle size of the binder will determine whether the minimum engineering properties will be met. The particle sizes of the bitumen binder in a NME vary between 1 µm and 5 µm. Most equivalent polymers are of a similar size. However, with an increase in the percentage of the problematic minerals within the 0.075 mm fraction measured in nm (refer to Figure 2) and an increase in the 0.075 mm fraction, these binder sizes (>1000 times larger) will be too large to act effectively as a binder agent. Hence, an appropriate binder should have a particle size much smaller as a function of the percentages of the .075 mm fraction and the percentage of the secondary and problematic minerals within the 0.075 mm fraction. A grading in the binder comparable to the grading of the finer fractions of the NAGM will result in a stable and effective mix. A decrease in particle size of the binder (and nano silane modifier) will exponentially increase the coverage area, decreasing the dosage percentage needed to achieve the minimum required engineering properties. Too large a percentage of the binder will cause the “pushing out” of the binder during sample compaction for testing. Excellent nano polymers (40 to 80 nm in size) are available to form an excellent Nano Polymer Nano Silane (NPNS) modified binder as a NME stabilising agent.

4. GUIDELINES FOR THE DESIGN OF AN MC-NME STABILISING AGENT

Numerous tests performed in laboratories on various materials available in South Africa since 2015 have been used to establish general guidelines for optimising a MC-NME mix design (Jordaan & Steyn, 2019a, 2021c). Over and above the previously discussed requirements of the modifier and the binder, the optimisation is defined in terms of the particle sizes of the various components comprising the MC-NME mix. The finer fractions of the NAGM to be stabilised mainly determine the surface area to be addressed by the MC-NME. The fraction of the NAGM passing the 0.075 mm sieve size and the percentage of the problematic minerals within the 0.075 mm sieve size smaller than 0.002 mm have been identified as the main inputs to determine and design an MC-NME stabilising agent. The combination of these two NAGM fractions will indicate the relative percentage and particle size of an effective nano-silane and the particle size of an applicable binder, as presented in Figure 4 (Jordaan & Steyn, 2019a, 2021c). In the blue area (Zone 3A) shown in Figure 4, the particle size of the nano-silane and that of the binder is significant. The engineering properties will only be met with a nano-silane of a size able to penetrate the clay matrix. At the same time, the binder particle sizes should preferably vary between 40 and 100 nm to enable the stabilised NAGM to meet its full potential (with an MC-NME consisting of an NPNS).

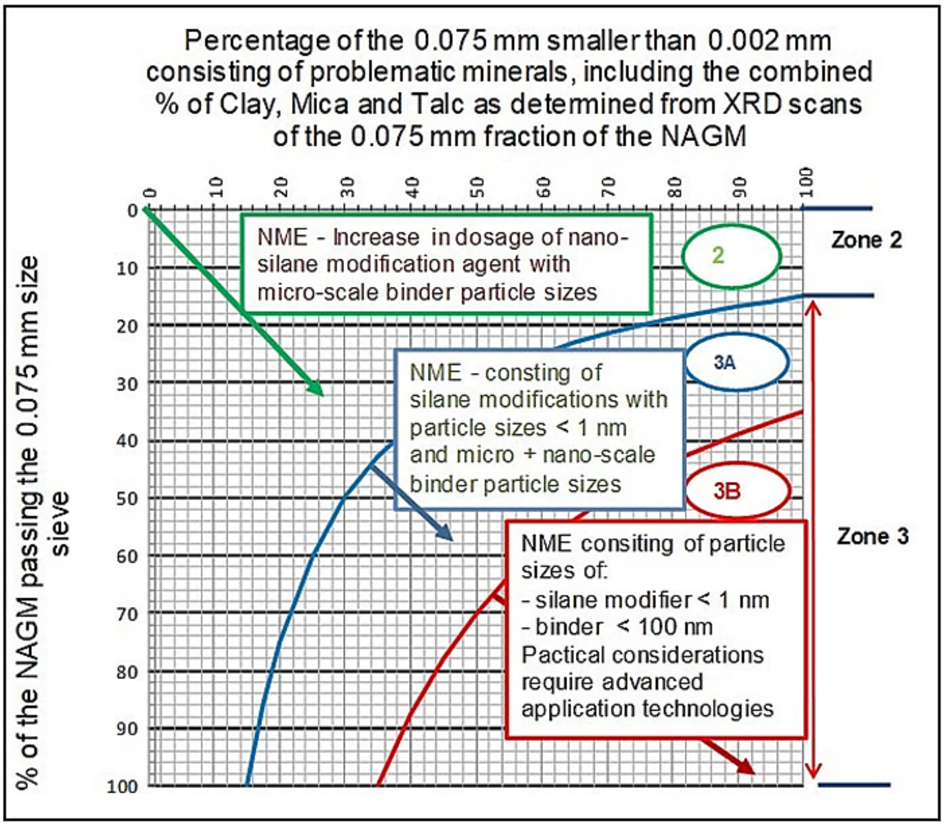

Figure 4: Influences of the NAGM particle sizes in the design of an MC-NME stabilising agent with applicable nano silane and binder particle sizes (Jordaan & Steyn, 2019, 2021c)

Within each of the identified areas within Figure 4, the percentage of the nano-silane as a fraction of the NME stabilising agent should increase as a function of the percentage passing the 0.075 mm sieve and the percentage of the problematic minerals within the 0.075 mm fraction as shown in Figure 5 (Jordaan & Steyn, 2019, 2021c). Similarly, the binder particle's size and the binder's percentage per mass need to be adjusted, as shown in Figure 6 (Jordaan & Steyn, 2019, 2021c).

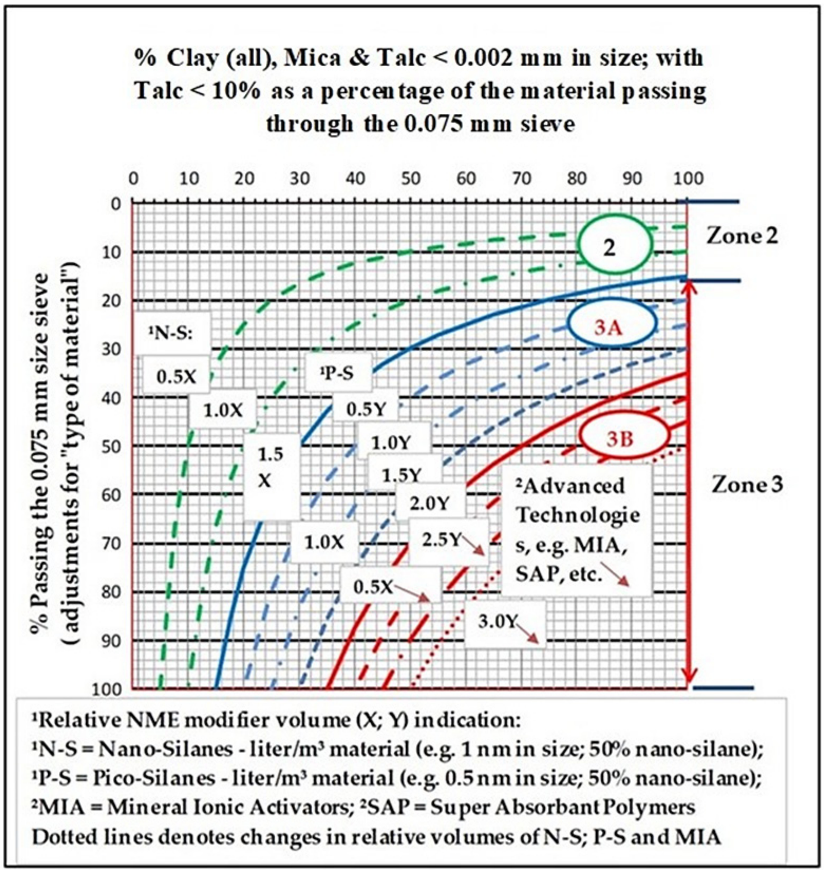

Figure 5: Relative volumes of nano-silane modifications as part of an MC-NME stabilising agent to achieve hydrophobicity within an NAGM (Jordaan & Steyn, 2019, 2021c)

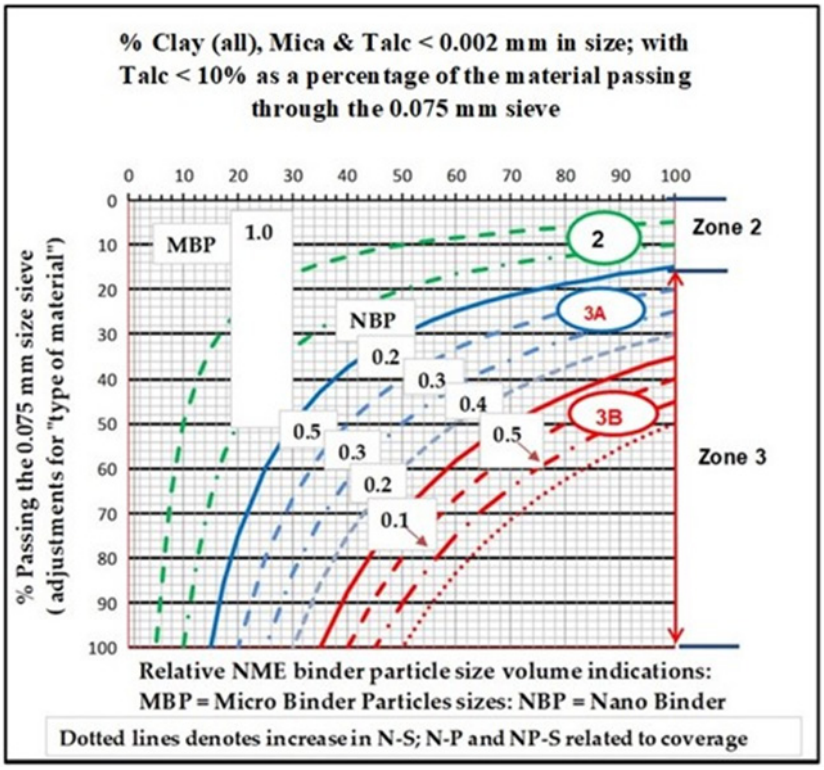

Figure 6: Relative size and percentage per mass of an applicable binder as part of an MC-NME stabilising agent to achieve the full potential of the NAGM (Jordaan & Steyn, 2019, 2021c)

It is seen that, for example, within the green area (Figure 5 (Zone 2)), an increase in the percentage of fines will result in an increase in the area to be covered by the nano-silane and, hence, an increase in the volume of the nano-silane to fully cover the particles within the NAGM stabilised material. Very fine material particle sizes with high percentages of problematic materials may present challenges in terms of workability, requiring advanced application technologies, as shown in Figure 7 (Jordaan & Steyn, 2019, 2021c) with the NAGM fraction sizes shown on a log-log scale.

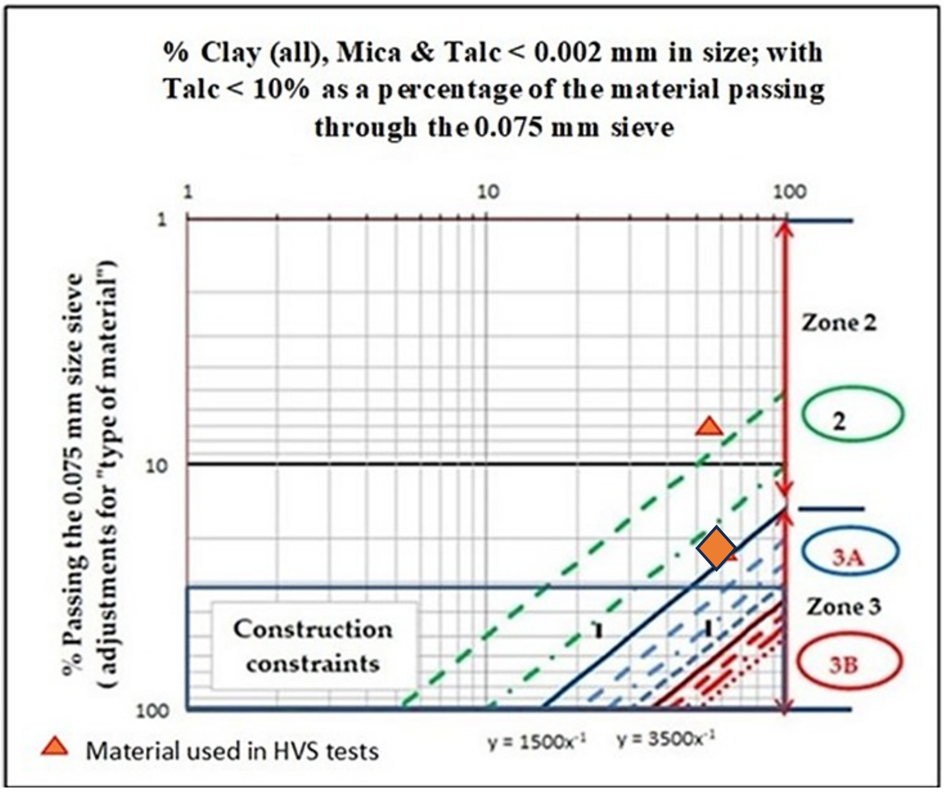

Figure 7: Figures 5 and 6 in a log-log scale showing material fractions with possible practical problems in terms of traditional construction techniques requiring special designs (Jordaan & Steyn, 2019, 2021c)

5. DEMONSTRATION OF THE INFLUENCE OF PARTICLE SIZES

Detailed materials testing was done on materials taken from a site representative of the red highlighted "diamond" in Figure 7. The percentage of the NAGM on this site passing the 0.075 mm sieve size was measured as between 20 and 25 per cent. Of the 0.075 mm fraction, more than 63 per cent can be considered problematic and secondary minerals. The XRD scans and analyses of this material are shown in Table 2 (Jordaan & Steyn, 2019b).

From Figure 7, it is seen that the material characteristics from the red highlighted diamond are on the borderline between Zones 2 (Green) and 3A (Blue), in line with the dotted green lines and recommendations contained in Figure 5, three (3) times the percentage of anionic nano-silane had to be added compared to the materials in the red triangle to achieve the required hydrophobicity.

The results of UCS and ITS rests are shown for 1, 1.2 and 1.5 per cent of the MC-NME stabilising agent with the NAGM. The results from the mineralogy scans are shown in Table 2. In this case, a bitumen emulsion binder was used in the MC-NME stabilising agent with 1.5 litres per m^3 of a nano-silane as a modifier to the binder in the MC-NME.

Table 2: XRD scans and analyses of the total sample and the fraction passing the 0.075 mm sieve size of the NAGM materials highlighted in Figure 7

APT - HVS 1						
Mineralogy of materials stabilised with an anionic MC-NME						
Mineral Groups	Total sample %			0.075 mm fraction %		
		Mineral groups combined			Mineral groups combined	
Primary Minerals						
Quartz	48.7	48.7		21.1	21.1	
Plagioclase	14.4			7.4		
Augite	3.2			0.5		
Enstatite	1.4			1.1		
Actinolite	1.9			1.8		
Microcline	4.3	25.2	73.9	4.9	15.7	36.8
Problematic Minerals						
Mica-Muscovite	13.7	13.7		36.1	36.1	
Secondary Minerals						
Clay Kaolinite	6.4			16.5		
Clay - Smectite	4.6			4.4		
Calcite	1.4	12.4	26.1	6.2	27.1	63.2

Table 3: UCS and ITS results of materials stabilised with an MC-NME stabilising agent

Project name :	D1884 - APT - HVS 1								
MDD :	$2072 kg/m^3$								
OMC :	6.50%								
Material classification - TRH14 - G8 [16]									
Anionic MC-NME stabilisation								Traditional design	
UCS				ITS				UCS	ITS
Percentage Anionic MC-NME	1.00%	1.20%	1.50%		1.00%	1.20%	1.50%	1.5 SS60 + 1.0% Cement	
UCS(dry) (kPa)	4807	4859	2620	ITS(dry) (kPa)	420	268	232	3277	167
UCS(wet) (MPa)	1830	1671	1865	ITS(wet) (kPa)	321	221	184	656	61
RCS (%)	38%	34%	71%	RTS (%)	76%	82%	79%	20%	37%
$RCS_{effective}$ - NME1	28%	23%	53%	$RTS_{effective}$ - NME1	102%	76%	61%	5%	9%
$RCS_{effective}$ - NME2	46%	38%	89%	$RTS_{effective}$ - NME2	123%	91%	73%	2%	11%
$RCS_{effective}$ - NME3	70%	57%	133%	$RTS_{effective}$ - NME3	153%	114%	91%	2%	14%
$RCS_{effective}$ - NME4	93%	77%	177%	$RTS_{effective}$ - NME4	204%	152%	122%	1%	19%
NME classification	NME4		NME3		NME1	NME2	NME3		
Class Per									
Specifications	UCS				ITS				
NME1 (wet)	2500	kPa			240	kPa			
NME2 (wet)	1500	kPa			200	kPa			
NME3 (wet)	1000	kPa			160	kPa			
NME4 (wet)	750	kPa			120	kPa			

Without discussing the results in detail (Jordaan & Steyn, 2019a, 2019b), it is noted that an increase in the percentage of the MC-NME to the NAGM leads to a considerable decrease in the test results, especially in the ITS results. This aspect demonstrates the importance of the various particle sizes. The material characteristics are on the border, where a binder with a smaller particle size is recommended. The particle size of the bitumen emulsion binder is more than 1000 times bigger than the nano-size clay particles. Hence, an increase in the stabilising agent results in granular particles being separated and "swimming" within the binder. In such cases, an increase in the MC-NME stabilising agent will not necessarily result in better results.

6. PRINCIPLES FOR THE IDENTIFICATION OF THE POTENTIAL EFFECTIVENESS OF STABILISING AGENTS BASED ON BASIC INFORMATION

Many proprietary "soil" stabilisers available on the market do not adjust their products according to the characteristics of the NAGM. However, the same basic principles discussed in this paper can also be applied to pre-evaluate any "standard" (not designed) NME stabilising agent's ability in terms of the potential effectiveness for use with any NAGM. This can be done with some basic information about the components and particle sizes of the NME without infringing on intellectual properties as incorporated into any specific proprietary product. Such general basic information could be limited to information such as:

- Particle size of the binder agent used or type of binder that will give an indication of the particle size, which will indicate the limitations of the NME in terms of NAGM properties (for example, it is often stated that it is bitumen-based (particle size 1 to 5 µm) or contained a unique polymer of a size between 100 and 200 nm);
- Presence and type of a modifying agent within the NME stabilising agent (e.g. anionic nano-silane) that will indicate the ability of the stabilising agent to be able to change the polarity of every particle within the NAGM to become water-repellent (hydrophobic);
- Size of the modifying agent particle (e.g. anionic nano-silane), which will indicate the ability and potential effectiveness of the modifying agent in the presence of high percentages of problematic minerals within the 0.075 mm fraction of the NAGM; and
- Recommendations for the adjustment of the formula of the NME stabilising agent as a function of the mineralogy (primary and secondary) and grading of the NAGM.

Using the concepts discussed in this paper with reference to Figures 4 to 7, this basic information will give a good indication of any specific NME product's limitations and ability to achieve the required engineering results when used with a specific NAGM.

7. CONCLUSIONS

It is well established that the successful design and application of a Nano Modified Emulsion (NME) stabilising agent is a function of the primary as well as the secondary minerals of the naturally Available Granular Materials (NAGM) to be used in the construction of load-bearing layers within a road pavement structure. What is less emphasised is the important role of the particle sizes of the various components of the NME stabilised pavement layer. This paper identifies the various components of the NME stabilised layer and the importance of the particle sizes of each of these components, i.e., the:

- Fractions of the NAGM that will influence the design of an effective MC-NME stabilising agent to fully realise the potential of the NAGM, i.e., the:
    - Fraction passing the 0.075 mm sieve size; and
    - Percentage of problematic and secondary minerals within the 0.075 mm fraction;
- Particle size of the nano-silane modifying agent and the influence of the NAGM on the volume of the nano-silane required to render each particle size hydrophobic; and
- Particle size of the binder in the MC-NME stabilising agent applicable given the particle size fractions of the NAGM.

Based on the proven interaction between the components of a MC-NME stabilising agent, a simplistic recommendation is given for designing an effective MC-NME stabilising agent for any given material. With basic mineralogy tests and gradings of the NAGM available, the method allows for the adjustments for the required particle size and volume of the nano-silane modifying agent and the particle size of a binder that should achieve the optimum results in terms of engineering properties. Arguably, the procedure can also be used to evaluate the potential success of any proprietary stabilising agent with basic knowledge of the particle sizes of the various components comprising the stabilising agent, together with a recommended design method from the supplier.

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