



STABILISATION OF BASE COURSE MATERIALS WITH NANOEMULSIONS

By

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DECLARATION 1

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ABSTRACT

The province of KwaZulu-Natal, like many geographical locations in South Africa and around the globe, lacks quality materials suitable for pavement construction. Pavement engineers are aware of the dangers of utilising substandard materials in building roadways due to their susceptibility to several forms of distress. Aside from the unrestrained emission of carbon compounds to the atmosphere and the high cost associated with hauling standard materials to the construction site, the continuous depletion of these natural materials results in distortion of the environment. Several techniques are employed to enhance substandard construction materials using traditional and non-traditional stabilisers; however, many researchers have proven the latter's effectiveness at improving marginal paving materials over the former.

The use of nanotechnological products, including nano polymers and nano-modified emulsions on South African pavements, is still at the experimental stage; however, numerous research studies using this technology are promising and could lead to the ultimate transformation of pavement structures that will satisfy the current environmental demands. Nanoemulsions can be formed using emulsifying agents to break down larger droplets of one liquid into smaller, more uniformly dispersed droplets throughout another liquid.

This study aims to improve the performance of a substandard base course material with nanoemulsions. The study also seeks to provide a long-lasting wearing course for unsurfaced roads in South Africa and across the globe. In this current study, two stabilisers designated as nano A and B were obtained from two manufacturers in South Africa. The stabilisers were mixed by mass at 0,7% - 1,5% with the soil sample, and the results indicate an optimum content at 1% and 1,2% for nano A and B, respectively. The impact of the stabilisers on the material was evaluated through California bearing ratio, unconfined compressive strength, and indirect tensile strength tests. Analysis of the experimental results reveals that nano A and B significantly improved the bearing strength of the material by as much as 53% and 92%. Significant improvements were also noted in the results of unconfined compressive strength and indirect tensile strength. Evaluation of the effect of rapid and 28-day curing conditions on the specimens yields similar results. Nano B also showed great potential by creating a hydrophobic effect in the soil matrix. These enhancements would prevent moisture damage in the stabilised layer and ensure the construction of quality roads.

Keywords: Nano polymer, Gravel materials, Rapid curing, Stabilisation, Soil

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LIST OF ACRONYMS

%	Percentage
AADT	Annual average daily traffic
DCP	Dynamic cone penetrometer
FT-IR	Fourier-Transform Infra-Red
Gm	Grading modulus
HLB	Hydrophilic-lipophilic balance
KPa	Kilopascal
ML	Machine learning
mm	Milimetre
MPa	Megapascal
NME	Nano-modified emulsions
nm	nanometre
o/w	Oil-in-water
RCS	Retained Compressive Strength
RTS	Retained Tensile Strength
SEM	Scanning Electron Microscopy
TEM	Transmission Electron Microscopy
TGA	Thermal gravimetric analysis
vpd	Vehicles per day
w/o	Water-in-oil
w/o/w	Water-in-oil-in-water
µm	Micrometre
°C	Degrees Celsius
AASHTO	American Association of State Highway and Transportation Officials
CBR	California bearing ratio
ESAL	Equivalent Standard Axle Load (80 kN)
G1- G10	Classification for granular materials as contained in TRH14
G _c	Grading coefficient

ITS	Indirect tensile strength
ITS _{dry}	Indirect tensile strength of specimen in dry condition
ITS _{wet} :	Indirect tensile strength of specimen after four hours soaking
km	Kilometre
km/hr	kilometre per hour
kN	Kilonewton
m ²	Metre square
m ³	Cubic metre
MDD	Maximum dry density
Mod.AASHTO	Modified AASHTO compaction
Nano A and B	Symbols used for the stabilisers
OMC	Optimum moisture content
PI	Plasticity index
UCS	Unconfined compressive strength
UCS _{dry}	Dry unconfined compressive strength
UCS _{wet}	Wet unconfined compressive strength
UTM	Universal testing machine

1 . INTRODUCTION

1.1 Background of the study

The global population is ever-increasing, and the demand for the expansion of road networks is also on the rise, but the non or limited availability of quality construction material in most parts of the world makes the construction process difficult. The most significant challenges occur when the available construction materials are substandard, hence the need for pavement engineers to seek alternative ways of improvement to ensure the useability of these materials in roadways. Several soil stabilisation processes have enhanced the properties of materials for paved and unpaved roads. Unpaved roads provide transportation of goods and forest products to dispersed settlements (Edvardsson, 2009). In the past, unpaved roadways offered people ease of locomotion, hunting, and other vital activities; these roads are associated with poor characteristics (Shtayat et al., 2020). Lateritic paving gravelly materials formed during weathering process constitute the higher percentage of materials for unpaved roads (Nwaiwu *et al.*, 2006).

The Roman military built their roads in four layers to a depth of 900 mm; however, over the years, numerous improvements were made, and the most significant is the macadam era which provided better strength and reduced the pavement layers to three and the thickness to 250 mm (Salleh et al., 2019). The preceding indicates that pavement structures are constructed in layers depending on the design, and each layer contributes to the performance in terms of providing support to the applied wheel loads and resisting the deterioration effect caused by environmental factors. When a pavement structure is substantially built, it will result in common distresses, including frost damage, corrugation, dust, potholes, and more (Alzubaidi and Magnusson, 2002).

It is essential to highlight the existence of several unplanned unpaved roads in South Africa built by the citizens, mainly in the rural setting that does not comply with the South African specification for road construction; such roads are informal roads (Thiede, 2020). In South Africa, a significant problem in unpaved roads has been reported by Paige-Green (1990) to arise from excessive road width ranging from 10 to 14 metres between shoulder breakpoints. This excessive road width results in loss of shape or flattening of the road's surface and often require surface maintenance. Furthermore, highly narrow roads lead to deep rutting and poor surface conditions, including high gravel loss and low performance.

Nowadays, unpaved roads are improved using various modifiers for better performance. Construction materials are modified using cement and lime in many sub-Saharan countries, these

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materials contain nanoscale particles, and their reactivity often results in cracks and distresses on the roads (Jordaan and Steyn, 2021b). Fly ash obtained from landfills has been used to stabilise materials for pavement as an alternative to cement stabilisation in South Africa (Heyns et al., 2018). Some construction materials are non-compactible with traditional stabilisers because of the presence of mica and smectite minerals and materials composed of organic and cohesionless sands; such materials are referred to as problem soil by Jordaan and Kilian (2016).

The construction of provincial roadways in South Africa using nano-modified emulsions (NME) has been in progress since 2015; many neighbouring African countries have also implemented this technology (Jordaan et al., 2017). The process involved in this technology is to ascertain the soil mineral composition through an X-ray diffraction test and formulate or purchase an appropriate nanotechnology-based product, such as silanes and polymers available in many countries to stabilise the soil (Jordaan et al., 2017). In Russia, unpaved roads are modified by residues from crude oil, which serves as a binder to the gravel constituent; this material is known as "oil-treated or oiled gravel". Oil-treated gravel contains a "low-viscosity oil binder with adhesive additives and crushed stone from rocks, " regarded as a loose-bound organic-mineral mixture (Vasilovskaya et al., 2019).

Another research in Southern Africa by Kidgell et al. (2019) highlights the effectiveness of nano silanes in improving the load-bearing and plasticity properties of dolomite and clays in pavement construction. Dolomite is a soil type with a high-water affinity and is unsuitable for pavement construction. The preceding indicates that materials with poor characteristics and considered unsuitable can be suitable for constructing the pavement's layers (i.e., subbase and base course) through the nano-modified emulsion. The pavement industry has a transformation chain as innovations evolve yearly, leading to better road performance (Salleh et al., 2019).

The three categories of emulsions are "water-in-oil (w/o), oil-in-water (o/w), and complex emulsions" (Nour 2018). Emulsion-stabilised aggregates serve as viable materials for pavement construction in Texas (Little et al., 1977). Several nano polymers with a size range of 70-80 nm have been used in modifying bitumen emulsions for pavement construction (Jordaan and Kilian, 2016). According to Naser et al. (2018), the asphalt industry continuously seeks innovative approaches to producing sustainable mixes that guarantee the excellent performance of the material.

The report on nanomaterial of sodium silicate-based admixture combined with lime and a vinyl acetate homopolymer coating used to stabilise expansive clay, artificial gravel, and selected soil in Andalusia, Spain, indicated a 50% increment in the California bearing ratio index of the expansive clay and sufficient enhancement of the strength of the soil (Rosales et al., 2020).

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Nanoscale materials have some advantageous properties; however, the outstanding benefits of nanotechnology are yet to be fully implemented in geotechnical engineering because the concept of nanotechnology is intertwined with numerous disciplines; therefore, a piece of comprehensive knowledge is necessary to obtain the best of this development (Arora et al., 2019). Nanotechnology is attractive, and the field is gaining popularity worldwide; however, the benefit of nanotechnology in pavement engineering has not been fully utilised due to many construction companies' non-acceptability of the technology (Jordaan and Steyn, 2021a). More research is required to ensure the acceptability of nanotechnology and general utilisation in improving substandard materials for quality pavement construction, hence the need for this study. This study focuses on contributing to existing knowledge on the application of nanotechnology to improve substandard paving materials. In this study, through a laboratory investigation, nanoemulsions were utilised to upgrade the substandard paving materials obtained from Pine town of KwaZulu-Natal.

1.2 Problem statement.

About 70% of the South African roads are unpaved, with a traffic capacity often below 400 vehicles per day (vpd); however, on the traditional standards, when the traffic volumes exceed about 400 vpd, upgrading such roads would be necessary as per standard (Van Zyl et al., 1995). Extreme road distress on the preceding roads often results in increased vehicle maintenance, safety hazards, dust pollution, and discomfort to road users (Carlesso et al., 2019). The limited availability of quality construction materials and high cost are the principal constraints confronting the pavement industries in upgrading these roads. Globally the longevity of road networks continues to be an intractable challenge that is worsened in some contexts by the impacts of climate change (Henning, 2017, Qiao et al., 2020, Matulla et al., 2018). A report by Bennett et al. (2002) indicates an abundance of substandard construction materials in several locations in the province of KwaZulu-Natal that are unsuitable for pavement construction. There is a need to investigate the potential of improving the performance of these non-standard construction materials to ensure their utilisation in building quality roadways that conform to the existing South African highway standards through nanoemulsions.

1.3 Research question

The pavement industry is increasingly demanding high-quality construction materials for pavement layers. High construction costs and depletion of the available natural materials are some of the implications of utilising quality materials in road construction. Hence, there is a need to seek an alternative in material selection for pavement construction. This research focuses on addressing the issue of whether sustainable pavement construction is possible with

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nanoemulsions. Nanoemulsions, in this context, refer to the state of the stabilisers at the nanoscale. A question also arises about whether some available procedures or methods can improve substandard materials with nanoemulsion and ensure their usage in the base layer of pavement instead of the traditional techniques or processes, which involve the use of quality construction materials at a high cost.

1.4 Aim of the study

This study's purpose was to evaluate the effect of nanoemulsions on the performance of base course materials.

1.5 Objectives

The following objectives will determine the above aim. These includes:

- I. Perform an elaborate literature review on various soil types and stabilisers used in building roadways in South Africa and across the globe
- II. Identify minerals that can undermine the material's usability in road construction
- III. Determine the optimum application rate for the nanoemulsions, which will provide the maximum effects or results for the stabilised specimens
- IV. Evaluate the impact of rapid and 28-day curing processes on the strength properties of substandard aggregate materials stabilised with nanoemulsions

1.6 Significance of the study

Modifying substandard materials using these nanoemulsions will minimise the burden of hauling quality materials to the construction site. In situ materials can also be utilised in building pavement through modification with nanotechnology, which will pave the way for sustainable pavement construction in South Africa. Furthermore, the study will add to the existing knowledge concerning upscaling a G6, i.e., substandard material for base layers, using this research stabiliser to build quality roadways. If adopted, the study's benefit will ensure roadways' durability, minimise government expenditure on road construction and maintenance, and ensure that road users have access to a quality road network.

1.7 Research methodology

The literature review provides the background of the methods for this investigation. The literature review also discusses the material characteristics and significance of the base course layer in the pavement structure.

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Furthermore, the literature review evaluates previous studies to improve substandard construction materials using nanotechnology-based stabilisers, including nano-modified emulsions and nano polymers for road construction. In conclusion, the preceding stabilisation methods indicate better performance and compatibility for substandard construction materials than traditional stabilisers.

The methodology approach involves sample collection and preparation for the various tests, including characterisation and strength tests. The optimum application rate for the nanoemulsions expected to provide the maximum effect on the strength property of the sample was determined. After preparing cylindrical samples for the strength test, the stabilised and unstabilised specimens were subjected to two curing conditions: rapid and 28 days of curing. Upon completing the curing process, three cylindrical samples each were tested for strength tests. Finally, the experimental results were analysed systematically to provide more details about nanoemulsions and their utilisation to improve the strength of substandard gravel materials.

In conclusion, based on the results of this study, recommendations were made to maximise the use of stabilisers in the form of nanoemulsions in building pavement, and proposals were made to advance this technology in the pavement industry. Figure 1 provides the methodology for this study.

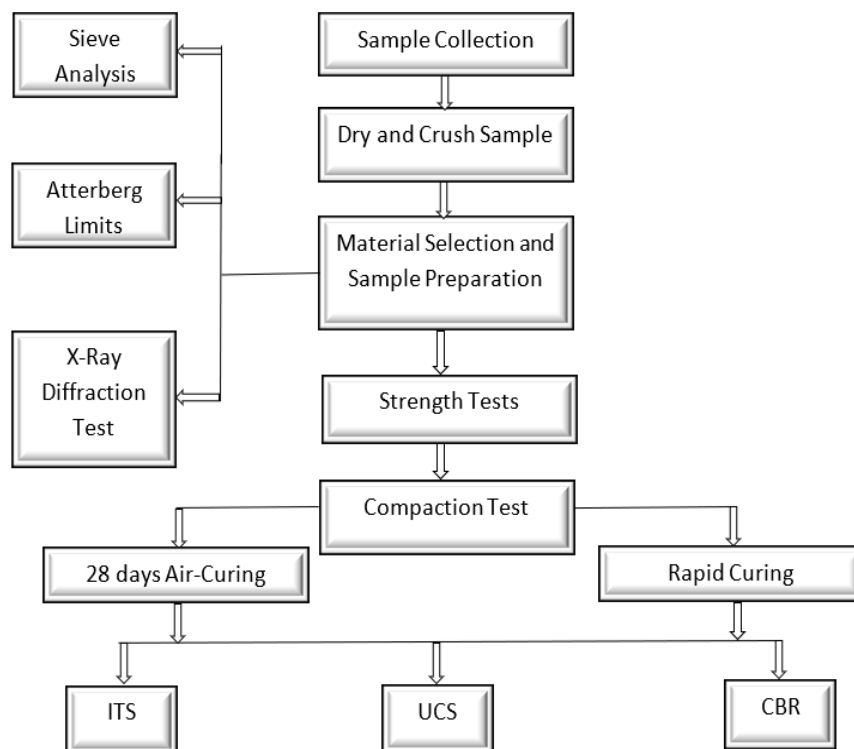


Figure 1-1: The research methodology flow chart.

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1.8 Scope and limitations of the study

This investigation examines the method for improving the strength properties of substandard paving materials with nanoemulsions. The study is limited to the stabilisation of G6 substandard (for a base course layer) gravel materials with nanoemulsions; hence, other categories of substandard paving materials were not investigated. The chemical constituents of the nanoemulsions were not examined due to copyright protection. Furthermore, the long-term effect of curing on the strength of the specimens was not considered; only rapid and 28 days curing duration was investigated. The 28 days curing procedure was performed using only one of the stabilisers due to the limited time frame for this study; however, rapid curing was performed using both stabilisers. Finally, this study does not present the cost analysis of using these nanoemulsions in pavement construction.

1.9 Research outline

The chapters' descriptions for this thesis are given below in Figure 1-2.

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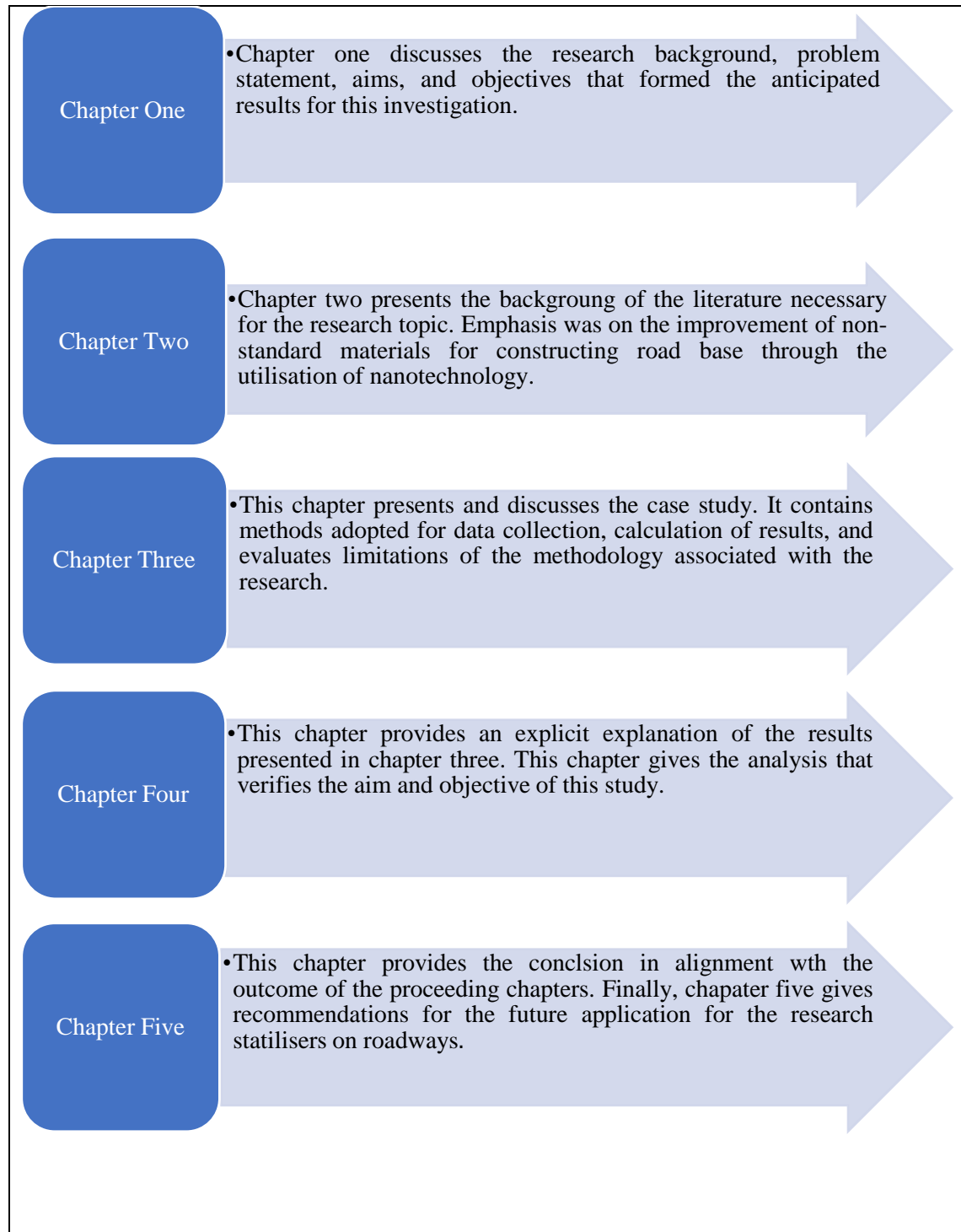


Figure 1-2: Organisation of the entire research structure.

2 . LITERATURE REVIEW

2.1 Introduction

Several conditions can lead to failure on paved and unpaved roadways, and the stability of each component of the pavement structure directly contributes to the pavement's performance. This research evaluates the suitability of nanoemulsion and how it can improve substandard-gravel materials for utilisation as a base course layer in pavement construction. This chapter provides an in-depth of substandard gravel materials for road construction. The chapter also explores the various methods of stabilising these materials and the significance of nanoemulsion technology in soil improvement for pavement construction.

2.1.1 Overview of pavement materials

The quality of the base and the subbase materials is crucial to the pavement structure; deformation in the base results in pavement failure. The preceding implies that the entire pavement system, including the different layers, supports the wheel loads (Sabita, 2020). It is necessary to use construction materials of satisfactory engineering when building roads; however, such materials are not readily available. The quality of the pavement materials, water interaction with the pavement, and traffic volume on the pavement determine road materials' performance in tropical and subtropical regions (Gourley and Greening, 1997). Pavement engineers claim that climate change has a more devastating effect than the impact of axle loading, especially on roads with lower traffic capacity (Mndawe et al., 2015).

Unpaved roads, for instance, are affected by a high level of deterioration, and the rate of this defect depends on indices such as the construction materials, temperature, traffic loads, maintenance, and drainage network (Vidas et al., 2021, Desai and Peerbhay, 2016). It is worth pointing out that about 14 million kilometres of global roadways are unpaved (Kunz et al., 2022). Unpaved roads hold sway in South African rural communities; they provide people with access and mobility, and their maintenance is far less expensive than surfaced roads (Van Zyl, 2011). Even though unpaved roadways provide a low-cost pavement infrastructure and require a little maintenance cost, the riding quality on these roads is less, resulting in increased transportation costs compared to surface roads. To ensure better performance of gravel materials in roadways, Mwaipungu and Allopi (2012) suggest that the material should have good cohesion, grading, and binding properties that ensure interlocking of the gravel constituent; these properties are critical to strength development and resistance to pavement deformation. The problem arises when there is a need to upgrade these unsurfaced roadways to surfaced roads using the available

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substandard materials; hence, this study focuses on adopting a modern stabilisation method to improve a G6 material to ensure their usage as base course material.

2.1.2 Classification of unpaved roads

A nation's road network is related to its economic well-being. A country's agricultural, mining, forestry, and tourism industries require an adequate network of all-weather roads to remain viable (Paige-Green, 1990). The preceding indicates the significance of having good road networks within a nation (paved or unpaved). The division of unpaved roads includes earth tracks, earth roads, and gravel roads (Paige-Green, 1990). According to Paige-Green (1990), earth tracks have vegetation at their centre and ruts on both sides, portraying a rural access route, and traffic flow on it is less than five vehicles per day, while earth roads have no foreign or borrowed materials, but the existing materials are free of shrubs and partially densified. Also, embankments are created through road surface modifications and built by a road authority or a regional development institution; finally, gravel roads have a designed layer of imported materials to a specified standard and width, and vertical and horizontal alignment on these roads is standard, providing an all-weather surface. These roads mainly connect viable cultivable land masses, promote trade and enhance ease of movement among local dwellers where most of the population lives (Gourley, 2002).

2.1.3 Conditions of the South African unpaved roads

Research by October (2016) shows that the unpaved road network in the Western Cape only carries 4% of the total provincial Traffic, namely 330 million vehicle kilometres per year. About one per cent of these unpaved roads within the Western Cape carry more than 500 vehicles per day, while 93 per cent carry less than 250 vpd. High traffic flow on unpaved roads often results in rapid surface distress, which worsens by poor construction. When operating a vehicle on roadways, sufficient energy is required in terms of fuel consumption by the engine to overcome frictional forces due to the vehicle's moving parts, air resistance, and changes in the slope along the travel path (Bester, 1984). Yearly, the fuel cost continues to sore high; hence roadways with considerable distress consume more fuel than roadways with little or no distress. An investigation by Paige-Green (1999) attributes rutting and general deterioration of the base layer to low densities, which permits water ingress. Table 2-1 compares the South African roadways with some selected countries.

Globally, approximately 1,2 billion people lack the means to all weathered roadways, while 40%-60% are about 8 km away from the health sector (Greening and O'Neill, 2010). The World

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Bank acknowledges the significance of the road sector in the economy, which is why it allocates 26% of its loan to boost the transportation sector (Greening and O'Neill, 2010).

Table 2-1: An approximation of road network composition (Greening and O'Neill, 2010).

Countries	Total road network (km)	Length Unpaved (km)	Percentage unpaved (%)
Ethiopia	46 000	39 000	85
Tanzania	87 000	81 000	93
South Africa	900 000	600 000	67
USA	6 400 000	2 100 000	33

2.1.4 Road pavement categories in South Africa

It is noteworthy to highlight the classes of the road network that are available in South Africa. Table 2-2 provides details of the categories A - D of roads. South Africa's roads have different categories, and each has some characteristics which differentiate it from others. According to SAPEM (2013), the methods of categorising roads depend on the importance and level of service. Category A requires a fundamental duration of 25 years, with a proposed duration of 15 to 30 years. In this case, the road has stable alignment for an extended period and with good precision, and the importance of a shorter design period becomes insignificance compared to the high maintenance cost for high-traffic roads; also, rehabilitation of new roads is generally unacceptable as it inconveniences the road users (SAPEM (2013)). Category B, according to SAPEM, necessitates a fundamental design duration of 20 years, with an ideal range of 15 to 25 years. Traffic flow, lack of funds, and confidence in design procedures could reduce the design period.

Furthermore, a lack of sufficient funds could result in selecting a 10-year structural project lifetime for category C, but if structural reconstruction is complicated, a period of 20 years may be suitable. Finally, category D requires a road design specification and a certainty level of 50%, implying that half of its surface will be distressed at the expiration of the project's lifetime. Category D is associated with low traffic volume, while the evaluation of its traffic growth is relatively complex.

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Table 2-2: Definition of the categories of the road (A-D) (TRH4, 1996).

Categories	A	B	C	D
Description	Major interurban roadways and major rural roads	Interurban collectors and rural roads	Lightly trafficked strategic roads	Rural access roads
Significance	Very important	Important	Less important	Less important
Level of service	Very high	High	Moderate	Moderate
Typical Pavement Characteristics				
Risk	Very low	Low	Medium	High
Approximate design reliability (%)	95	90	80	50
Total equivalent traffic loading (E80/lane)	3– 100 x 10 ⁶ over 20 years	3 – 10 x 10 ⁶ Depending on the design strategy	<3 x 10 ⁶ Depending on the design strategy	< 1 x 10 ⁶ Depending on the design strategy
Typical Pavement Class	ES10 – ES100	ES1 – ES10	< ES0.03 – ES3	ES0.003 – ES1
Daily Traffic: (e.v.u)	> 4000	600 – 10 000	< 600	< 500
Constructed Riding Quality:				
PSI	3,5 - 4,5	3,0 - 4,5	2,5 - 3,5	2,0 - 3,5
HRI (mm/m or m/km)	1,5 - 1,0	2,0 - 1,0	2,7 - 1,5	3,5 - 1,5
Terminal Riding Quality:				
PSI	2,5	2,0	1,8	1,5
HRI (mm/m or m/km)	2,7	3,5	3,9	4,5
Warning Run level	10	10	10	10
Terminal Rut Level (mm)	20	20	20	20
Area/length of road exceeding terminal conditions (%)	5	10	20	50

Where: ES Equivalent Standard Axle (80 kN) Class. Approximate daily Traffic in e.v.u: Equivalent vehicle unit (1,25 vehicle = 1 e.v.u), PSI = Present Serviceability index, scale 0 to 5,

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HRI = Half-car Roughness Index of a single averaged longitudinal profile (left & right wheel track) in mm/m or dm

2.1.5 The functional classification of roads in South Africa

Both urban and rural roads have the six functional classification systems; however, rural roads have a high degree of mobility due to their more expansive range of connectivity compared to urban roads (TRH26, 2012). The administrative classification of roads is the study of road networks (national, provincial, and municipal roads) and the associated authority that manages their operations (TRH26, 2012). Veramoothea et al. (2015) have utilised TRH26 (2012) to perform a functional classification for the Gauteng Provincial roads to provide a detailed understanding of the status of the roads to enhance upgrading and implementation of safety measures. Roads are built for different purposes or uses; the functional classification of rural roads according to TRH26 (2012) is as follows.

- I. Rural principal arterial (R1) refers to roads with high mobility. They are common in urban settings or regions. The reach of connectivity of this type of road is usually greater than 50 km, while the annual daily traffic flow ranges from 1000 to 100, 000+
- II. Rural major arterial (R2) are road networks in smaller cities and towns having high mobility. The reach of connectivity of this type of road is greater than 25 km with an AADT of 500 – 25 000 and above.
- III. Rural minor arterials (R3) roads exist in small towns, villages, and larger rural areas. The reach of connectivity of this type of road is greater than 10 km with an AADT of 100 – 2 000 and above.
- IV. Rural collector road (R4) refers to roads that provide access to parks, mines, recreational centres, and smaller rural settlements. This road's connectivity reach is less than 10 km with an AADT of less than 1000.
- V. Rural local roads (R5) provide access to private properties in rural areas, such as farms. It has an AADT of less than 500, and the connectivity reach is less than 5 km.
- VI. Rural walkways (R6) link settlements, farms, transport nodes, and water points. They are developed through constant use and hence serve as non-standard routes.

Adequate mobility and access are critical to the functionality of urban roadways. The functional classification of urban roads is summarised as follows (TRH26, 2012).

- I. Class U1 (urban principal arterials) are freeways providing mobility to cities and are used as essential routes for imports and exports of goods for economic activities. Being the longest stretch of the road network in the urban that links other cities or R1 routes, their length is usually 20 km or more and average daily traffic (ADT) of 40 000 to 120

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000. Regarding land development density, the required space between parallel roads ranges from 5 to 10 km.
- II. Class U2 (urban major arterials) cater to the traffic needs of cities, medium towns, and other economic activities which U1 does not cover. The reach of connectivity for U2 is greater than 10 km and carries a traffic volume ranging from 20 000 to 60 000 vpd, while the space between parallel roads is 1,5 to 5 km.
 - III. Class U3 (urban minor arterials) provide traffic services to urban regions, small towns, and economic activities that U1 and U2 do not cover. The reach of connectivity for U3 is 2 km or more, and the expected range of ADT is between 10 000 to 40 000. Regarding land development density, the required space between parallel roads ranges from 0,8 to 2,0 km.
 - IV. Class U4 (urban collector) streets provide the channel for receiving and distributing Traffic between the district streets and the arterial network. The access function for U4 is characterised by restricted traffic volume and mobility. Collectors are classified as 4a (class 4a commercial collector street) and 4b (class 4b residential collector street). The reach of connectivity for class 4a is about 2 to 3 km and has a traffic volume below 25 000, while class 4b is restricted to 10 000 vpd and a maximum length of 2 km.
 - V. Class U5 (urban local streets) provides an exclusive access function to private properties. This class of street carries only Traffic, which begins and ends on the same street. Class U5 is classified into two, namely, class 5b (residential local street) and class 5b (residential local street). Class 5a streets provide access to industrial, commercial, and residential regions with a traffic volume limited to 5 000 vpd and a road length limited to one km. Class 5b provides access mainly to the residential apartment and sometimes to public transport, refuse, and small trucks. The traffic volume on class 5b should not exceed 1000 VPD with a reach of connectivity from 0,5 to 1 km.
 - VI. Class (U6) urban walkways consider pedestrians to be of great significance; hence, road signs and markings are not considered. Class U6 is subdivided into class 6a (pedestrian-priority street or area) and class 6b (pedestrian-only street or area).

2.2 The performance attribute of the base and subbase

In a typical flexible pavement structure, the base layer is above other layers, and the surfacing is constructed on the base while the subbase is found below the base (COLTO, 1998). According to Adlinge and Gupta (2013), high-stiffness materials are utilised at the top of the pavement structure, where wheel loads are applied to a small pavement surface area, while those with weaker stiffnesses are found at the bottom. The preceding is further explained in Figure 2-1. Rust et al. (2019) recommend that the design of the sub-base should accommodate the peak

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tensile strain below the stabilised layer, and the base should have sufficient support to resist the development of peak compressional stress above the base. The improvement will ensure adequate strength in the base material to resist compressive forces, and a sufficient unconfined compressive strength UCS will minimise the water infiltration capacity and ensure durability.

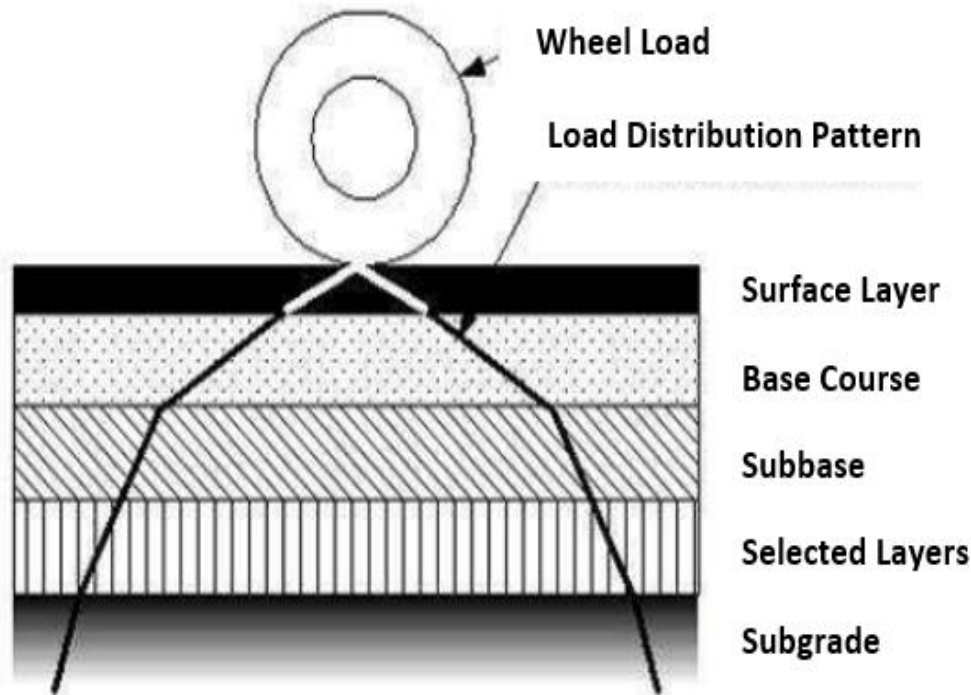


Figure 2-1: Load distribution of flexible pavement (Adlinge and Gupta, 2013).

2.2.1 Non-standard construction materials in developing countries

There is abundant laterite in Sub-Saharan Africa that are used for the construction of roads, and the laterites are composed of gravel, clay, and shales (Kamtchueng et al., 2015). These materials often need modification and improvement before being utilised on the road. Interestingly, research conducted in the late 1960s in several countries, including Angola, Mozambique, Nigeria, Australia, and Brazil, on the performance properties of laterites in road construction results in better strength for laterite in many cases (Netterberg, 2014). The accessibility and convenience of using these substandard materials in pavement construction are crucial to providing cost-effective roadways. According to Jordaan and Steyn (2021b), there is a pressing need to address the lack of scientific guidance on using and applying these substandard resources in pavement building. The presence of standards for these substandard materials will remove doubts and give pavement engineers more confidence in their decision to utilise them in road construction. The laboratory experiments conducted in this study using nanoemulsions to stabilise substandard material will provide important information about the degree of enhancement

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attained and will contribute to existing studies regarding the application of nanotechnology in the pavement industry.

In South Africa, granular construction materials are classified as G1 to G10, referring to high-standard to substandard materials (Van Zyl et al., 1995, TRH4, 1996). The classification provides guidelines for selecting and utilising construction materials in the layers of the pavement structure, i.e., base, subbase, selected layers, and subgrade (TRH4, 1996). Sometimes, these construction materials are blended or stabilised to enhance the desired engineering properties and ensure their utilisation as construction materials. TRH14 (DoT 1985) recommends G1-G4 as base material, G5 - G6 as subbase material, and G7 - G10 as suitable for subgrade material. TRH14 (DoT 1985) guidelines also recommend G6 – G9 for selected layers in the pavement structure.

Netterberg (2014) states that the formation of laterite results from weathering activities. Furthermore, the weathering process on the material causes a reduction of silica content; the clay mineral component is mainly kaolinitic, while the parent material contains iron and aluminium oxides and hydroxides (sesquioxides). Netterberg (2014) concludes that the above processes yield "yellow, brown, red, or purple materials, with red" as the most prevalent. It is not always possible to use standard materials for pavement construction due to their scarcity and high cost in developing countries; hence the need to use available local materials, but these materials are termed sub-standard. The introduction of proven nanotechnology, such as organofunctional silane technologies, has enabled the use of these substandard materials, even for heavy load-bearing pavements (Jordaan and Wynand, 2021). The preceding should be an eye-opener for pavement engineers to embrace the innovation, allowing them to build standard roads at a meagre construction cost.

The properties of soil vary with its type and the surrounding condition. A fast way to obtain the strength and layer thickness of construction material is by the dynamic cone penetrometer, DCP, test (Paige-Green and Du Plessis, 2009). Al-Refeai and Al-Suhaibani, (1997) and Sabita (2020) provide the description and operation of the DCP equipment. Van Zyl et al. (1995) suggest a minimum of two samples to evaluate the moisture content; Atterberg limit and soaked CBR. The classification and strength tests are crucial and should be performed for all materials utilised in pavement construction works.

2.2.2 Traffic classes of pavement and material characteristics for road base

There are ten primary categories for pavements, ranging from extremely light Traffic to exceedingly high Traffic, equal standard axle (80kN) ES0,003 to ES100. The very light to extremely light Traffic is typically accommodated by pavement categories ES0,003 to ES0,3, which could also comprise pavements in the evolution from dirt to surfaced roadways (TRH4,

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1996). The characteristic of a pavement component relating to its strength to support environmental load is a function of the quality of the design, construction procedures, and types of materials utilised.

The base is a critical pavement component, and its material selection is vital to effective load-bearing characteristics. Table 2-3 provides recommendations for construction materials to ensure their utilisation as base materials in pavement construction. The attributes of gravel materials utilised in South African roads are contained in Table 2-4.

Table 2-3: Fundamental roadbase material selection factors (Gourley, 2002).

Key Engineering Factor	Material Requirements
Strength	Aggregate particles need to be load resistant to any loads imposed during construction and the pavement's design life
Mechanical Stability	The aggregate as a placed layer must have a mass mechanical interlocking stability sufficient to resist loads imposed during construction and the pavement's design life.
Haul Distance	Reserves must be within physically and economically feasible haulage distance.
Durability	Aggregate particles need to resist mineralogical change and physical breakdown due to any wetting and drying cycles imposed during construction or pavement design life
Placeability	The material must be capable of being placed and compacted by the available plant.
Environmental Impact	Material reserves must be capable of being won and hauled within any governing environmental impact regulations.

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Table 2-4: South African unsealed road materials specification (Mwaipungu and Allopi, 2012).

Maximum size (mm)	37,5
Oversize index (I_o) ^a	< 5 %
Shrinkage product (S_p) ^b	100 – 365
Grading coefficient (G_c) ^c	16 – 34
CBR (at 95% AASHTO T180)	> 15%
Tetron Impact Value	20 – 65

Where: (I_o)^a – Percent on sieve 37,5 mm s and lower than 75 mm, (S_p)^b - Linear Shrinkage x Percent obtained from sieve 0,425 mm, (G_c)^c - (Percent passing 26,5 mm sieve – Percent passing 2,0 mm sieve) x (Percent passing 4,75 mm sieve)/ 100

2.2.3 Lateritic gravel characteristics

The geotechnical properties of reconstituted lateritic soils and their response to various stabilising agents are better understood using index properties. Furthermore, factors such as mineralogical composition, grading characteristics, plasticity, and clay size content in fine-grained lateritic soil affect the optimal dry density, the ideal amount of moisture, and the permeability of the laterite (Osinubi et al., 2012). Lateritic soil composition and properties vary depending on the geographical location. The properties of available lateritic materials in the Western Cape are shown below in Table 2-5.

Table 2-5: Properties of laterite material soil (Bondietti et al., 2004).

Liquid limit	19
Plasticity Index	4
Linear Shrinkage (%)	2.0
Grading Modulus	2.51
Maximum Dry Density (kg/m^3)	2141
Optimum Moisture Content (%)	4.2
CBR at 98 % Mod AASHTO	114
TRH14 Classification	G4

2.3 Formation of clay mineral

Several clay minerals form when rocks encounter water, air, or steam in various environments, the clay formed during the process depends on the rock's mineralogy, textural composition, the nature of the fluid flow, and the aqueous solution composition (Mwaipungu and Allopi, 2016). Feldspar, a common mineral in many granitic rocks such as pegmatite, is a significant antecedent

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of clay deposits (Akinola and Obasi, 2014). Determination of the minerals present in the clay sample is necessary for selecting the suitable stabiliser for the stabilisation process (Jordaan and Steyn, 2021b). The preceding indicates that an inadequate investigation into the mineral constituents of paving materials can result in poor construction and a waste of resources.

2.3.1 Methods for mineral identification in a soil sample

Application of advanced analytical techniques has made the identification and characterisation of clay minerals easier; they include “Nitrogen Adsorption Isotherm, X-ray diffraction, Fourier-Transform Infra-Red (FT-IR), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Zeta potential, and thermal gravimetric analysis (TGA)” (Kumari and Mohan, 2021). Although X-ray diffraction is essential for examining a single crystal in a sample, this method is time-consuming. The goal of the X-ray diffraction scans, as explained by Jordaan and Steyn (2019), is to evaluate the mineral composition of the soil sample and recognise secondary minerals received from the 0.075 mm sieve, which can provide a guide when selecting stabilising materials; some of these minerals include clay, mica, sulfide, and iron minerals, and organic materials including pulverised reef. According to Ermrich and Oppen (2013), "the wavelength of X-rays ranges from 0.01nm to 10 nm," which equals an energy range from 0.0125 kiloelectronvolt. Ermrich and Oppen (2013) further state that the wavelength λ of an X-ray is inversely proportional to its energy E, in equation (1).

$$E = hv = h \frac{c}{\lambda} \quad (1)$$

Where h is the Planck's constant, v is the frequency, and c is the velocity of light.

To observe the mineral constituent of lateritic soil through an X-ray diffraction test, Millogo et al. (2008) explained that the diffractogram of the powder mix reveals the presence of minerals shown in Figure 2-2 while a diffractogram greater than 2 μm fraction shows the existence of kaolinite, rankinite, and quartz as explained in Figures 2-3 below.

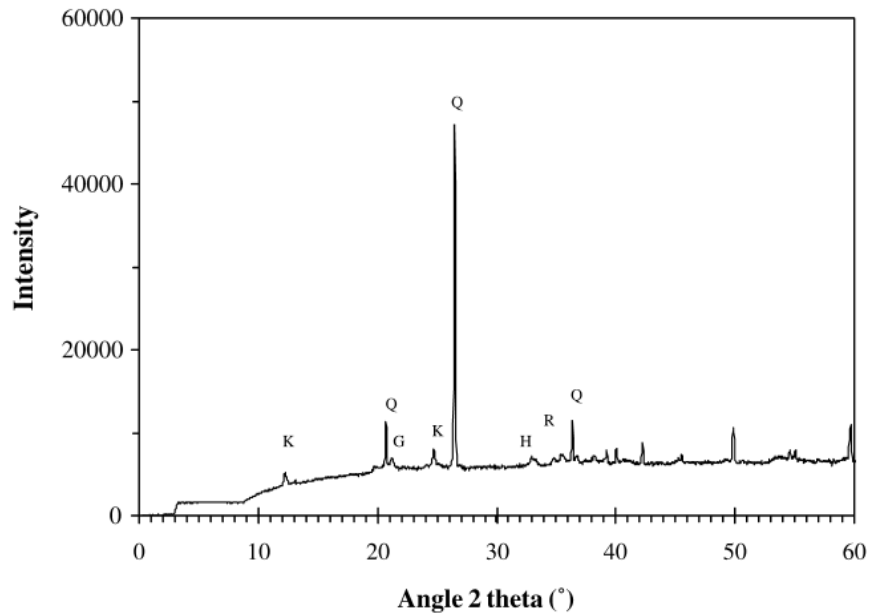


Figure 2-2: X-ray spectrum of the total sample: K = kaolinite, Q = quartz, H = hematite, G = goethite, R = rankinite (Millogo et al., 2008).

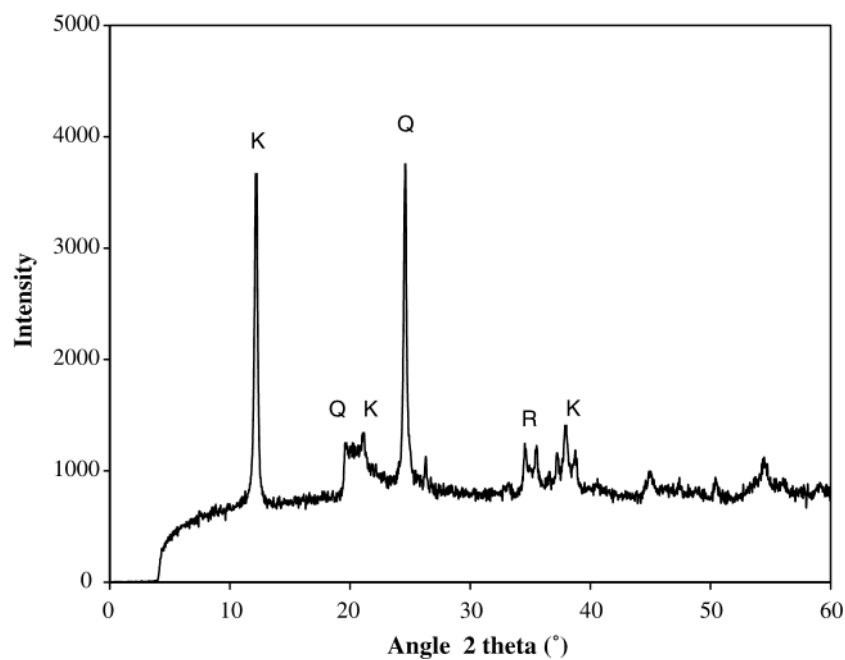


Figure 2-3: X-ray spectrum of the < 2 μm sample fraction: K = kaolinite, Q = quartz, R = rankinite (Millogo et al., 2008).

The term kaolinite originates from Kaolin in China, referring to materials obtained from the disintegration process of feldspars (Al-Ani and Sarapää, 2008). The analysis by Millogo et al. (2008) also indicates that the test sample contains no smectite, a clay composition known for its swelling properties once it contacts water. The reason for increased water absorption by smectite material is that its particles exist at a nanoscale with a high specific surface area resulting in an

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increment in water absorption capacity (Srivastava and Singh, 2011). One crucial enhancement criterion for construction material is to minimise water ingress by carefully selecting a suitable stabilising agent to modify the engineering properties of the soil. The smaller the particle size of the stabilising agent, the smaller the quantity of the stabiliser that will be required to coat the soil's matrix (Jordaan and Steyn, 2021b). Table 2-6 below depicts a few essential characteristics of clay minerals and their applications.

Table 2-6: Properties of clay minerals that can be related to their applications (Al-Ani and Sarapää, 2008).

Kaolin	Smectite	Palygorskite
1:1 layer	2:1 layer	2:1 layer inverted
White or near white	Tan, olive green, white	Light tan
Little substitution	Octahedral and tetrahedral Substitution	Octahedral substitution
Minimal layer charge	High layer charge	Moderate layer charge
Low base exchange capacity	High BEC	Moderate BEC
Pseudo-hexagonal flakes	Thin flakes and laths	Elongate
Low surface area	Very high surface area	High surface area
Very low absorption capacity	High absorption capacity	High absorption capacity
Low viscosity	Very high viscosity	High viscosity

2.4 Soil stabilisation

Soil is an important material that consists of air, solids, and water (Balasubramanian, 2017). Soil is classified into the following categories of "gravel (4.75 mm to 75 mm), sand (0.075 mm to 4.75 mm), silt" (2 μ m to 75 μ m), clay (1 μ m to 2 μ m), and nanosol (1 nm to 100 nm) (Arora et al., 2019). The strength and performance of soil materials often vary depending on the preceding soil's categories; however, improvement can be obtained through stabilisation processes. The concept of soil stabilisation is 5000 years old (Firoozi et al., 2017). Applying the chemical or mechanical method to enhance a specific characteristic in soil and ensure its use in construction

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is known as stabilisation (Jones et al., 2011). Soil stabilisation aims to reinforce the soil constituents with adequate support to increase bearing capacity and prevent undue soil settlement. An appropriate roller is necessary for compacting soil mass to improve density and durability (Mwaipungu and Allopi, 2012).

2.4.1 Soil stabilisers

Using chemical or mechanical stabilisation processes enhances the performance of soils with poor properties. Cement, fly ash, bituminous materials, and lime are utilised as traditional stabilisers, while non-traditional stabilisers are chlorides, clay additives, synthetic polymer emulsions, and tree resin emulsions (Kestler, 2009). Traditional stabilisers become less suitable when dealing with highly active soils; therefore, non-traditional stabilisers are utilised to overcome these shortcomings (Taher et al., 2020). Figure 2-4 shows the utilisation of non-traditional stabilisers in constructing roads.



Figure 2-4: (a) Application of dry chlorides to construction materials (Kestler, 2009). (b) Placement of 150 mm base anionic nano-modified emulsions NME mix using the paving machine (Jordaan and Wynand, 2021).

Chlorides and lignosulfonates were the chemical stabilisers used for the improvement of non-standard materials for road construction some years back; however, the latest advancements use synthetic polymer emulsions, "organic nonpetroleum, organic petroleum" and synthetic fluid, clay additives, and concentrated liquid stabilisers, including sulfonated oils and petroleum products, or a combination of these additives (Jones and Surdahl, 2014).

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According to Wilmot (1994), a key factor to consider when using polymeric stabilisers is to ensure proper mixing of the product with the soil's matrix; this enables the polymer to bind itself to the fines of the soil, and the result of this combination is an increase in soaked CBR and strength, resistance to water ingress and reduction in permeability and capillarity rise.

The structure and mineral composition of construction materials across the globe vary; these indices form the basis for selecting and utilising the different stabilising processes in pavement construction. The selection of the required stabiliser is a function of the soil type, the reason for the stabilisation, the financial implication, the strength, and the impact of the stabilisation process on the environment; these factors are crucial and should be evaluated (Guyer, 2018).

2.4.2 Stabiliser mixing and application equipment

It is essential to use the appropriate equipment for the application and mixing of stabilisers with construction materials to ensure ease of the construction process. During stabilisation with asphalt, Jones et al. (2011) recommend a rotary mixer or recycler, alongside an asphalt emulsion tanker and a water tanker, if required, i.e., the asphalt stabiliser and compaction water, if needed, are sprayed onto the soil in the mixing chamber of the rotary mixer or recycler. For powder stabilisation, Jones et al. (2011) also recommend spreading the stabiliser evenly on the surface before mixing and levelling overlapped windrows and other areas of excess or under application before mixing. Finally, Jones et al. (2011) proposed a rotary mixer or recycler with a water tanker to mix in-situ soils and blend materials during mechanical stabilisation activities.

2.5 Soil compaction

It is crucial to check the material thicknesses for various compacting equipment to ensure it complies with the recommendation for static rollers in Table 2-7, resulting in the maximum dry density during compaction. During the compaction procedures, the properties of the material and the required thickness determine the type and number of roller passes or compaction equipment for the process (Sabita, 2020).

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Table 2-7: Recommended static mass of the primary roller (Sabita, 2020).

Layer thickness (mm)	Static mass (ton)
<150	12
150-200	15
200-300	20
300-350	25

2.6 Nanotechnology

Nanotechnology is not a new science or technology, but science and technology have been developing long ago, enabling the manipulation of materials at the nano-scale (Ganesh, 2012). Nanotechnology was made known by Norio Taniguchi in a paper entitled “On the Basic Concept of Nanotechnology” in 1974, which he presented at the international conference on production engineering hosted in Tokyo, Japan; he explained that the required limit size of fineness is in the range of 1nm (Rogers et al., 2007). People in different fields and professions around the globe began to use and apply the term "nanotechnology" after the presentation in Tokyo by Norio. "Nano" originated from Nanos, a Greek word meaning dwarf, and nano is a prefix denoting 10^{-9} (Rogers et al., 2007). Technology advances forward and backwards, i.e., from science and knowledge to applications and problems to technology for solutions (Whitesides and Lipomi, 2009). Advances in nanoscience and nanotechnologies have made it possible to use nanoparticles in soil stabilisation (Bahari et al., 2013). These advances also extend to applying nanotechnology in the lower and upper layers of pavement to enhance better performance (Rogers et al., 2007).

2.6.1 Formation of an emulsion

Emulsion formation is by dispersing one liquid into another liquid in which both are immiscible, i.e., water in oil (Meleson et al., 2004). Force is needed to spread one phase into another during the production of an emulsion, and by adding a surfactant, i.e., emulsifying agent, stable emulsions are formed, but without the addition of surface materials, the emulsions formed will be unstable (Nour, 2018). Emulsion produced by mechanically mixing two immiscible substances will remain unstable, hence the need to add a third substance to attain stability of the solution (Finkle et al., 1923). Non-ionic surfactants are the most effective for emulsifying oil-in-water or water-in-oil (Safaya and Rotliwala, 2020).

2.6.2 Types of emulsion

As earlier stated, the three basic types of emulsions, according to Nour (2018), include water-in-oil (w/o), oil-in-water (o/w), and complex emulsions known as water-in-oil-in-water (w/o/w). Some people consider double emulsions to consist of three liquid phases in which one of the liquids serves as the boundary between the other two liquids, and several technical terms are used when referring to mixes of this category, such as complex mixes (Benichou et al., 2002). A dispersion of bitumen in water in the presence of an emulsifier is an example of an emulsion.

2.6.3 Nanoemulsions

One significant attribute of nanoemulsions is their small droplet size, although numerous studies on this substance indicate varying sizes range. According to Gadhave (2014), nanoemulsions have particle sizes ranging from 20 – 200 nm, and like microemulsions, nanoemulsions are transparent or translucent due to their small size (Jintapattanakit, 2018). McClements (2012) explains that nanoemulsions consisting of o/w in which one is in the dispersed phase have a size range below 100 nm. There is a significant variation in the sized properties between nanoemulsions, microemulsions, and macroemulsions (Gupta et al., 2016). Nanoemulsion and microemulsion are formed using oil and water combined with a surfactant, and sometime co-surfactants are added to the mix (McClements, 2012). A surfactant, in this case, refers to a detergent that enables the stability of the solution. One significant attribute of the surfactant during emulsion creation is to avoid fusing the mix and reduce the interfacial tension and droplet size (Maali and Mosavian, 2013). McClements (2012) explains that thermodynamic stabilities differentiate nanoemulsions from microemulsions, and in this state, microemulsions are stable, unlike nanoemulsions. Nanoemulsions are kinetically stable at rest or stable at a peak energy level. In research to explore the properties, formation and utilisation of o/w nanoemulsion, Pal et al. (2019) discovered that the repulsion of oil droplets due to electrical reduction is the reason for the gradual decrease with elapse of time in the system's stability. Table 2-8 below compares macroemulsion, nanoemulsion, and microemulsions.

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Table 2-8: Comparison between macroemulsions, nanoemulsions, and microemulsions.

Emulsion class	Macroemulsion	Nanoemulsion	Microemulsion	Reference
Size	0,1-10 μm	20-100 nm	5-100 nm	(Gadhav, 2014)
Polydispersity	Often high - (>40%)	(Typically, low (<10-20%))	Typically, low (<10%)	(Gupta et al., 2016)
Stability	Thermodynamically unstable	Thermodynamically unstable	Thermodynamically stable	(Gadhav, 2014)
Surface-to-mass ratio (m^2g)	0.07-70	70-330	330-1300	(Gadhav, 2014)
Appearance	Turbid	Transparent	Transparent	(Gadhav, 2014)

Note: μm = micro metre, nm = nanometre.

2.6.3.1 Preparation of nanoemulsions

Gadhav (2014) explained that high or low-energy approaches follow the production of nanoemulsions. Nanoemulsion formation relies on the device used during the process; however, the mechanical methods of producing this substance are grouped into high-pressure homogenisers, ultrasonication processes, and high-speed devices (Gadhav 2014). The low-energy approach method employs phase transition to make a nanoemulsion at a constant temperature with a change in composition or a stable composition and change in temperature (Gadhav 2014). Furthermore, the low-approach procedures are "phase inversion temperature, spontaneous emulsification", membrane emulsification, and emulsion inversion point; however, industries' most widely adopted method for producing nanoemulsions is the phase inversion temperature (Gadhav 2014).

Safaya and Rotliwala (2020) explain that a phase inversion temperature is an advanced version of the spontaneous emulsification procedure for producing nanoemulsions, which uses non-energy-intensive equipment to make nanoemulsions at room temperature. Figure 2-5 demonstrates the formation of the w/o emulsion as water is fed drop-wise into the system.

Production of the emulsion through spontaneous emulsification involves the migration of water-miscible constituents from one face, which is organic, to another that is liquid, and the process

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consists of mixing the organic phase with the liquid phase (Safaya and Rotliwala, 2020). Finally, the emulsion inversion point process consists in maintaining the temperature and varying the composition of water or oil, resulting in nanoemulsions formation by this method (Gadhav, 2014).

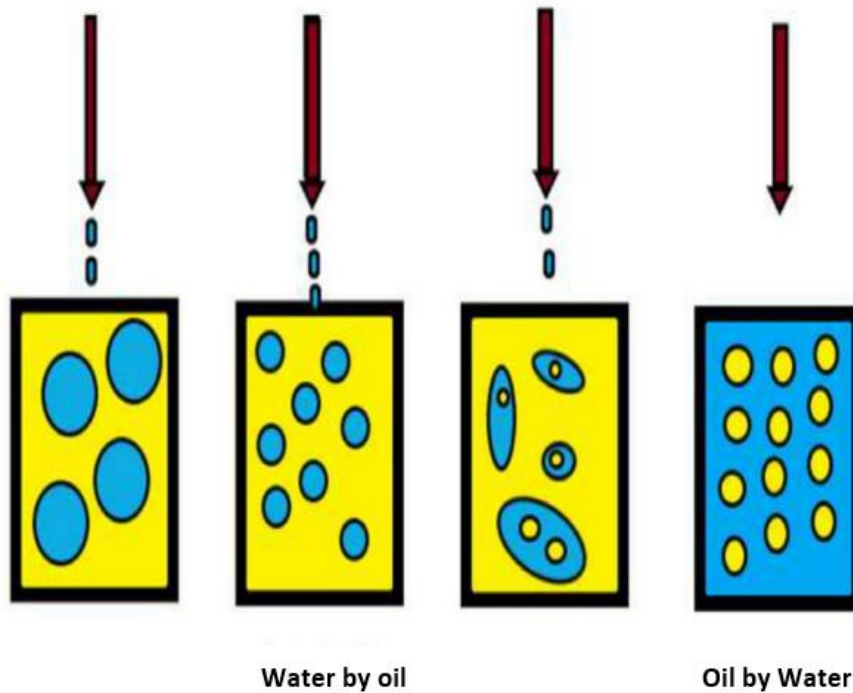


Figure 2-5: Phase inversion composition method of producing nanoemulsion (Safaya and Rotliwala, 2020).

Nanoparticles are also an essential category in nanotechnology. An example of nanoparticles is nano clay which has been used to improve construction materials due to their low cost (Papadimitropoulos et al., 2018). Furthermore, many researchers are currently exploring the field of nanotechnology to develop cost-effective nano-construction materials. The preparation of nanoparticles is done by bottom-up and top-down methods (Eswaramoorthi et al., 2017). The top-down approach uses mechanical grinding processes to break substances into smaller pieces, while the bottom-top approach assembles atoms into a nano size. The preceding is further explained as shrinking from the top down or growing from the bottom up (Ganesh, 2012).

2.6.3.2 Characteristics of nanoemulsions

The three factors that affect changes in free energy of forming or preparing a possible, stable mechanism for micro and nanoemulsions include variations in interfacial free energy, the force of exchange within the droplets, and the degree of disorderliness of the dispersion (Amani et al., 2010; cited Ruckenstein et al. (1975). The various characterisation of nanoemulsion includes

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viscosity, particle size distribution, thermodynamic stability, interfacial tension, surface characteristics, and conductivity (Bainun et al., 2015). The essence of the viscosity test is to determine the system's state of o/w or w/o emulsion (Gurpreet and Singh, 2018). High viscosity shows that the system is w/o, while low viscosity indicates that the system is o/w. The ratio of particle size after thirty (30) days to the particle size after thirty minutes (30) is indicative of the stability of the samples (Amani et al., 2010). The term o/w nanoemulsion refers to an unstable state of a thermodynamic in which one liquid (oil) is being distributed as tiny droplets in another liquid (water) (McClements, 2012).

2.6.3.3 Hydrophilic–lipophilic balance (HLB)

Surfactants are classified based on hydrophilic-lipophilic balance (HLB) (Safaya and Rotliwala, 2020). Al-Sabagh (2002) reported that HLB systems were used to select the most appropriate emulsifiers for stabilising emulsions for the last five decades. This method determines surfactants' hydrophilic and hydrophobic content. As shown in Figure 2-6 below, the hydrophilic and hydrophobic property of any given material is a function of its contact angle, i.e., when the contact angle of the material lies between 90 °C - 180 °C, the material is hydrophobic (beading effect), but a contact angle below 90 °C, indicates a hydrophilic substance (Jordaan and Steyn, 2021b).

It is pertinent to obtain the required HLB balance in the system because high HLB represents excess hydrophilic surfactant content and vice versa (Ngan et al., 2014). Surfactants whose HLB is greater than seven result in o/w emulsions, while those with an HLB lower than seven are w/o emulsions (Maali and Mosavian, 2013). Ibrahim et al. (2015) present an expression for evaluating the average number of HLB in equation (2).

$$\text{Hydrophilic-lipophilic balance (HLB)} = x_1 \text{HLB}_1 + x_2 \text{HLB}_2 \quad (2)$$

x_1 and x_2 are the mass fractions of the two surfactants with HLB1 and HLB2, respectively.

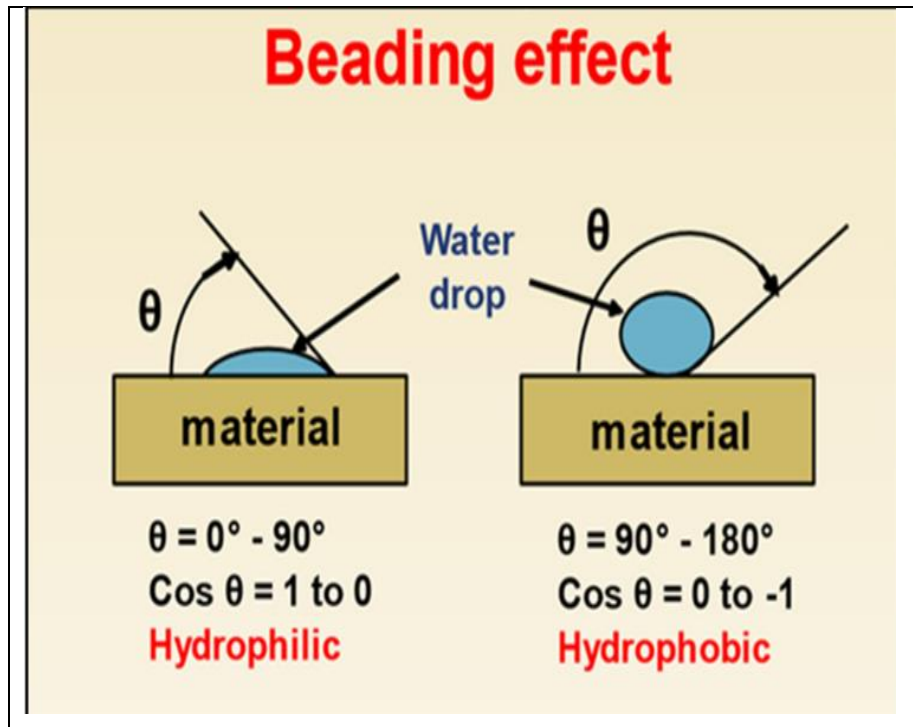


Figure 2-6: The demonstration of hydrophilic and hydrophobic properties for materials (Jordaan and Steyn, 2021b).

2.6.3.4 Stability of nanoemulsions

One significant nanoemulsion parameter is stability due to its small size (Gadhav, 2014). In practice, an anionic nano-modified emulsion will remain stable in a storage tank for more than four months in unfavourable weather with a daily temperature exceeding 35 °C (Jordaan and Wynand, 2021). Furthermore, using a circulating pump to agitate the emulsion in the storage tank once a week will ensure the stability of the emulsion for one year. The preceding agrees with the statement of Gupta et al. (2016) that nanoemulsions can be modified or improved to have an extended life span varying in months or years. A mixture of surfactants can be used to improve an emulsion's stability in situations where the desired stability is not achieved with a single emulsion (Maali and Mosavian, 2013). Figure 2-7 below explains the stability characteristics of nanoemulsions. Hong et al. (2018) stated that a Laser light diffraction instrument possessing a dual-wavelength detection system could measure the particle size distribution of emulsions, and an optical microscope at a magnification of 400x is applied to observe emulsions morphology. Nanoemulsions can be modified or improved to have an extended life span varying in months or years (Gupta et al., 2016). Equation (3) below shows the detachment energy, ΔE , for a model spherical particle in a liquid interface to a bulk layer or interface (Saha, 2015).

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$$\Delta E = \pi R^2 \gamma_{ow} (1 - |\cos \theta|)^2 \quad (3)$$

R represents the particle radius, γ_{ow} represents the surface tension of oil-water interfacial, and θ denotes the contact angle within the preceding phases.

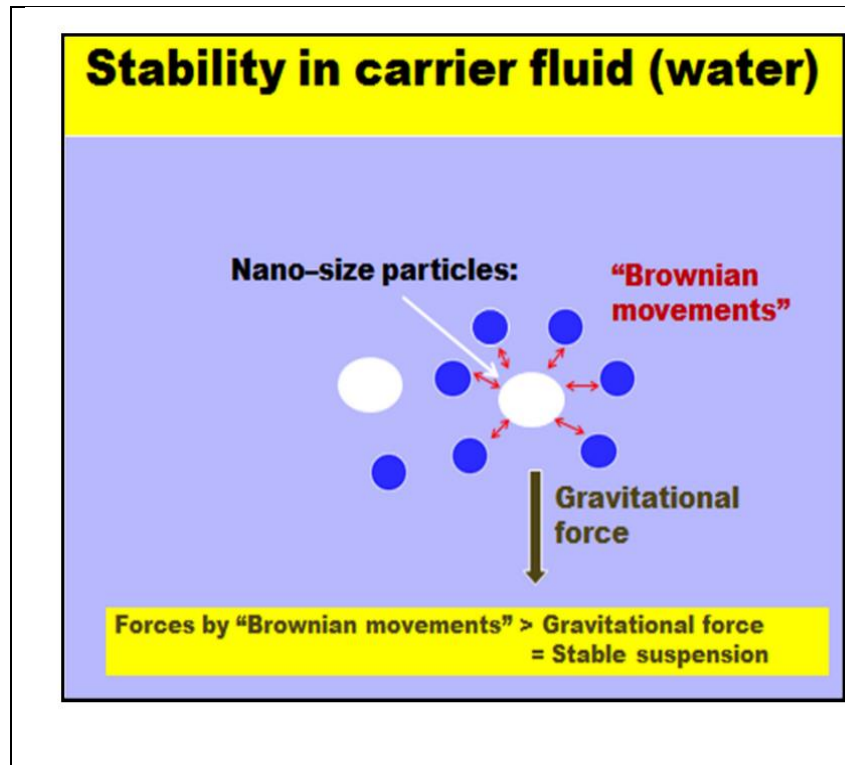


Figure 2-7: Demonstration of the stability of nano-scale technologies in a water carrier fluid (Jordaan and Steyn, 2021a).

2.6.3.5 Application of nanotechnology in pavement engineering

Innovation is the driving force required by all professionals seeking growth and relevance within the 21st century. Nanotechnology is the study and manipulation of material within the nano-scale; it is more than just a technology that deals with materials in tiny dimensions; it is a science that exploits the unique physical, optical, mechanical, and chemical properties of materials at this scale (Papadimitropoulos et al., 2018). The interfacial layer of the nano-scale matter consists of ions inorganic and organic molecules (Sarver and Jassal, 2020). Construction materials with undesirable mineral compositions can become durable and resistant to adverse environmental conditions through nanotechnologies (Jordaan et al., 2017). As a result of climatic change and weathering activities that resulted in soil or rock formation, the characteristics of construction materials vary significantly around the globe; however, the prediction of the features and properties of these materials becomes possible through the use and application of nanotechnology (Arora et al., 2019). The variation in soil properties directly impacts how these

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materials are utilised for pavement construction. Some regions worldwide have suitable construction materials, while poor materials abound in other areas.

Applying nanotechnology to construction soils improves soil engineering properties and minimises underground and surface water ingress into pavement layers (Ugwu, 2013). A few trial sections (roads) have recently been built with nano-modified emulsions (NME) in the Province of Gauteng and the Limpopo of South Africa to ensure the use of substandard materials in road construction (Jordaan and Kilian, 2016). Many countries (including India and the United States of America) have successfully used these nanotechnology-based products to construct numerous roadways using substandard materials (Jordaan and Kilian, 2016, Rust et al., 2020).

In December 2003, the US government approved large funds to conduct research in nanotechnology (Rogers et al., 2007). The stipulated amount includes careful planning and consideration for the environment and the public such that the emergence of disaster through the use and application of nanotechnology could be avoided. Nanotechnology-related industries will require more than two million workers to expand this innovation (Ganesh, 2012).

Modifying bitumen products through nanotechnology improves the material's tensile strength and provides better resistance to rutting driveways than un-modified bitumen materials (Papadimitropoulos et al., 2018). In an experiment on the impact of polyvinyl alcohol and "1,2,3,4-Butanetetracarboxylic acid" on the compressive strength of clay soil, Mirzababaei et al. (2017) recorded a significant increase in the unconfined compressive strength (UCS) for the tested specimens while the 14-day curing procedure increases the peak strain energy in the stabilised specimens. A study conducted by Parsana et al. (2021) using terrenoseal to stabilise expansive soil samples resulted in high UCS of 25,45% and 22,00% and dry density up to 14,10% and 14,35% for soils found in Bhavnagar and Nakhtran respectively. According to Parsana et al. (2021), a small quantity of terrenoseal improves the maximum dry density (MDD), swell-shrinkage characteristics, and reduction in the optimum moisture content (OMC). Kumar et al. (2020) noticed about five times increment in the CBR results and 7,25% for MDD when 0,5 to 1 kg per cubic metre of organosilane and nano acrylic copolymer were blended with 2% lime to stabilise black cotton soil, i.e., expansive soil. Kumar et al. (2020) also report a 60% and 34,30% reduction in the specimen's free swell index and OMC.

Murphy et al. (2019) investigated the strength properties of a granite G5 material using eight anionic bitumen emulsions from five suppliers in South Africa, with all the products conforming to the national standards. The G5 materials were stabilised using 1,2% anionic nano-modified emulsions. The results of the preceding experiment indicated that five of the eight specimens gave results above 80% increase for retained compressive strength (RCS), while six of the eight

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specimens gave results above 85% increase for retained tensile strength (RTS). Figure 2-8 shows that the modification of G5 materials using nanotechnology causes a significant reduction in the layer thickness requirement. Figure 2-9 also shows that the use of NMEs in pavement construction indicates a significant reduction in project cost and layer thickness compared to traditional construction methods. This transformation is an alternative to conventional design methods that utilises high-quality materials (Rust et al., 2020).

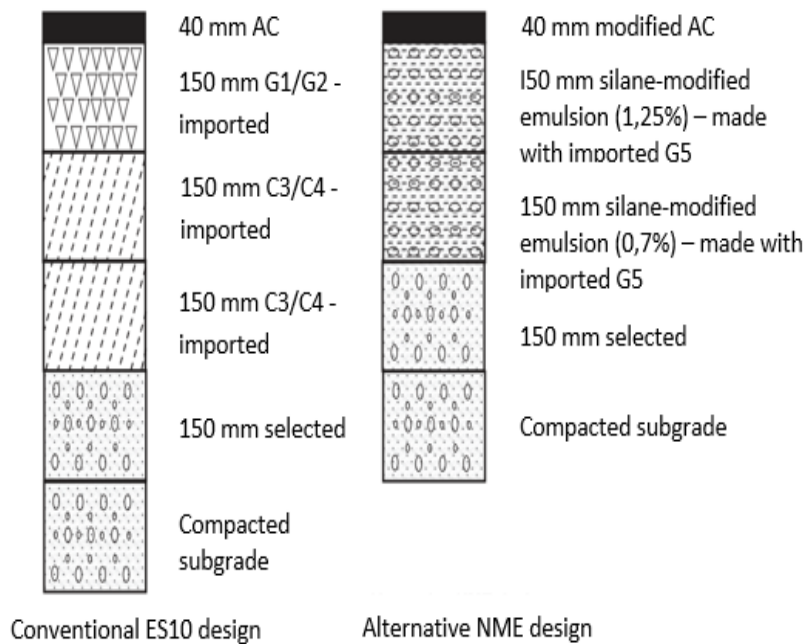


Figure 2-8: Conventional vs NME design (10 million ESALs) for Road K46 (Modified from Rust et al., 2020).

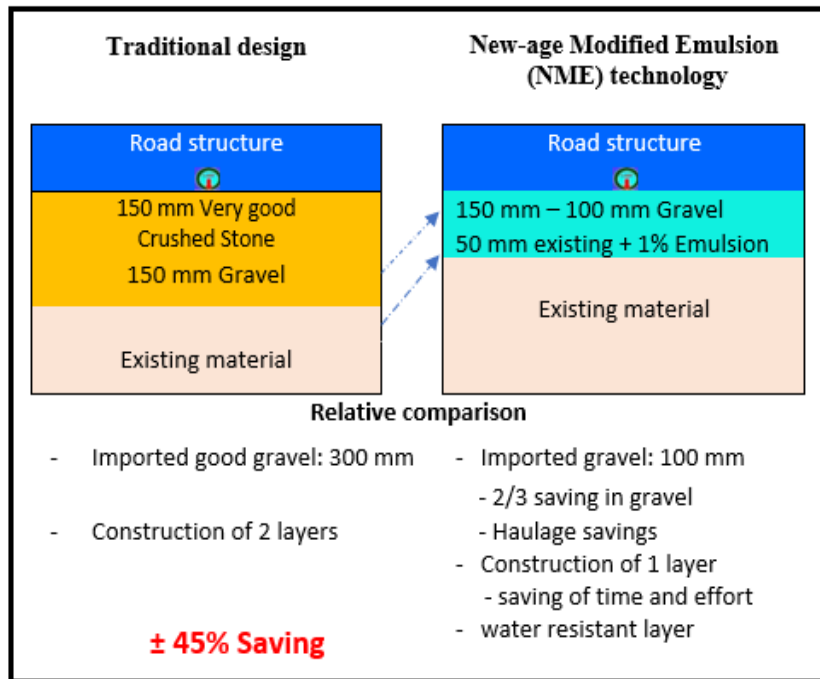


Figure 2-9: Sample of soil stabilisation using conventional design methods vs NME utilisation for low traffic loading (Jordaan and Steyn, 2021a).

In an attempt to utilise substandard materials in the upper layer (base course) of pavement, an independent laboratory performed an experiment following the recommendation of Jordaan and Steyn (2021b) to stabilise a 200 mm thick base material using NME; stabilisers were received from three manufacturers; however, the results prove that two of the manufacturer's products met the requirements for the test. Although nano technological-based stabilisers have numerous advantages in enhancing the performance of construction materials, the reader should know that standard laboratory tests are necessary to confirm their suitability in pavement construction.

2.7 Accelerated curing procedure for nanotechnology stabilisers

Air drying is the most frequent method for curing polymer-stabilised materials (Santoni et al., 2002). It becomes expedient to highlight that any curing period can be indicated for testing; however, 7, 28, and 90 days of curing are widely applied (ASTMD5102-09, 2009). Naeini et al. (2012) subjected a polymer-stabilised soil sample to 2, 4, 6, 8, and 14 days of curing and observed a significant increase in the UCS within eight days of curing as results became stable up to 14 days. Naeini et al. (2012) suggest eight days as the optimum curing period for this polymer.

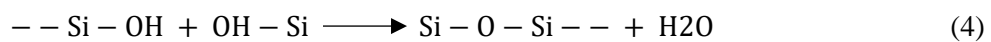
Rezaeimalek (2016) explains that another way of curing polymer-stabilised materials in the laboratory is by subjecting them to an elevated temperature; however, extreme temperature could degrade the polymer of the product; hence, crucial to select the appropriate curing methods

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(water, air, and heat) when dealing with the curing procedures for these products. To investigate the curing methods for stabilised material, Rezaeimalek (2016) subjected soil samples stabilised with styrene acrylic-based liquid polymer to two days of curing at 100 °C, and the specimen showed similar UCS results to samples cured for 28 days in the air. A significant reduction in the experimental time was achieved by applying high temperatures to expel moisture from the test sample. The preceding agrees with the recommendations (except the temperature for rapid curing) by Jordaan and Steyn (2021b) that the results of UCS and indirect tensile strength (ITS) tested in wet and dry conditions after 28 days of curing in the air for NME treated materials should differ by not more than 5% for rapidly cured samples at 40 – 45 °C. Standardising rapid curing procedures will eliminate the long curing period for these stabilisers during laboratory testing, thus facilitating the construction process. The maximum variation of 5% in ITS and UCS results for NME stabilised materials, as recommended by Jordaan and Steyn (2021b), will be evaluated in this study for specimens subjected to rapid and 28 days of curing.

2.7.1 Nano silane in pavement construction

Silane is the foundation for silicon material, implying that the substance's size is smaller than 100 nm, and the application of reactive nano polymer in combination with organosilane allows for stronger particle-to-particle bonding than the other polymers (Shil, 2017). Nanosilane is utilised as a modifier to bitumen and polymers, ideal for stabilising construction materials (Jordaan and Steyn, 2021b). Sarver and Jassal (2020) opine that “organic molecule coating inorganic nano-particles are stabilisers, capping, and passive agents”. According to Jordaan and Steyn (2021a), treating aggregate or soil material with “an alkoxy-silane or alkoxy-silane modified binder” activates a hydrophobic effect in the material, which occurs when the contact angle is between 90° to 180°. Shil (2017) states that the four valence electrons in silicon atoms can form four bonds. Furthermore, Shil (2017) highlights that the alkoxy group would dissolve in water to create Silanol (Si-OH) compound; away from the alkoxy (X-OH) unit, the hydrolyzed Silane would form a Si-O-Si bond upon interaction with the soil constituents, as shown in equation (4) below. The below process makes the substance hydrophobic or water-repellant.



Organosilane is a synthetic polymer suitable for stabilising coarse-graded unbound road materials (Barbieri et al., 2021). The local authorities of Vichada Columbia have used organosilane to improve laterite for road construction due to the region's lack of quality construction materials (Jerez et al., 2018). Jerez et al. (2018) explained that the organosilane enhanced the CBR of the laterite material and minimised the soil sample's permeability coefficient (k) by 41%.

2.8 Advantages and disadvantages of using nanotechnology in the pavement

We live in a dynamic world where new ideas and innovation are essential for our well-being, and to this end, the pavement industry is not an exemption. The continuous climate change and its catastrophic impact on roadways in terms of deformation and reoccurring maintenance have become a global challenge. The pavement industry is constantly seeking alternative methods of constructing sustainable pavement that can withstand the current environmental needs, hence the emergence of nanotechnology, which could solve these pressing needs regarding the demand for durable pavement. Table 2-10 provides the advantages and disadvantages of nanotechnology in pavement construction.

Table 2-9: Advantages and disadvantages of nanotechnology in pavement construction.

Advantages	Reference
It enhances the flexibility of construction materials	(Jordaan and Kilian, 2016)
Help in obtaining the desired bearing capacity with minimal use of stabilising materials	
It reduces cracks	
It enhances the proper utilisation of local materials at a reduced risk	
Provide a waterproof layer and ensure flexibility of construction	
Save energy and cost	(Das et al., 2019)
It ensures long-term stability for polymer-modified asphalt	
Disadvantages	Reference
It reduces the fatigue resistance of bitumen treated with nanomaterials	(Das et al., 2019)
Causes delays in curing construction materials	(Jordaan and Wynand, 2021)

2.9 Summary

The literature highlights that due to the high demand for roadways in South Africa and globally, the pavement industries can effectively modify and employ non-standard materials with nanotechnology for sustainable pavement construction. The literature review reveals that researchers have utilised varieties of non-traditional stabilisers available to enhance the

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engineering properties of weak construction material to become distress-resistant and strength-sufficient to support high-load bearing pavement compared to traditional stabilisers.

Improving soil with nanotechnology has enabled the efficient use of substandard materials within the pavement layers; the innovation is evident in some South African roadways, including the Gauteng and the Limpopo province having Weinert n value of < 5 (Jordaan and Kilian, 2016). Through this technology, the search for quality materials associated with long haul distances and high construction costs is, thus, eliminated. The technology also helps to prevent the distortion of land masses and depletion of natural resources, implying that construction industries can obtain materials from multiple locations, thereby minimising the impact of construction on the environment. There are numerous non-traditional stabilisers in the market, and their reaction with soils varies due to their composition and the heterogeneous nature of the construction material, hence the need to evaluate the properties of both the stabilisers and construction materials to avoid design failure.

TRH14 (1985) recommends G5 and G6 materials for sub-layer; however, this research focused on performing a laboratory experiment using two nanoemulsions to stabilise a G6 material and determining whether these stabilisers can enhance the performance attributes of the material in the base layer of a pavement. Furthermore, the study will evaluate the relationship between rapid and 28 day of curing conditions and how it affects the strength properties of the stabilised and unstabilised material. The literature review has indicated the need to explore the field of nanotechnology to ensure its wide application in the pavement industry. This investigation will be crucial in providing relevant information on the use and application of nanotechnology in improving substandard paving materials with nanoemulsions.

The subsequent chapters build upon the current background in the literature review by providing the systematic procedures or the laboratory methods for achieving the goal of this research. Furthermore, the chapter explains the properties of the nanoemulsions used for this investigation and the development of the required mix design and material selection for the stabilisation activities.

3 . MATERIALS AND METHODS

3.1 Introduction

Numerous nanotechnology-based stabilisers have been used to improve engineering characteristics, including the strength and permeability of pavement materials. The use of these non-traditional stabilisers has proven to be effective. In this study, two nanoemulsions from two manufacturers were utilised as stabilisers to evaluate their effectiveness in stabilising a G6 construction material through laboratory investigation. This chapter also analyses the properties of the construction materials, the stabilisers, and the procedure for executing the study. The experiment was performed on gravel samples obtained from Stockville Quarries in Pine town of KwaZulu-Natal, South Africa.

3.2 Materials

3.2.1 Soil sample collection

The test material for this investigation was obtained from (latitude 29°49'24.79"S and longitude 30°46'42.98"E) Giba Gorge in Pine town of KwaZulu-Natal, South Africa. The gravel material for this research has constantly been used to re-gravel the Umgeni Road in Pine town to improve its surface condition. The soil sample was collected from Stockville Quarries to investigate the suitability of the research stabilisers in upgrading and ensuring the usability of this substandard material in building pavement. Adequate representation of the test samples was collected in air-tight bags from the Stockville Quarries. The collected samples were spread evenly in the shade to dry; after the drying procedure, the samples were stored in suitable air-tight bags for laboratory tests.

3.2.2 Soil stabiliser

The nanoemulsions used for this study are designated nano A and B to avoid unintentionally endorsing these products. Forty litres of nano A were purchased from a manufacturer in Johannesburg, while another manufacturer in Durban supplied forty litres of nano B for this research. Both nano A and B were received from the manufacturers in air-tight containers. Based on the product's datasheet, nano A is a nontraditional water-based modified bitumen emulsion with nano polymer, and the stabilising polymer of this product has elastomers that require sufficient compaction to bind them to the soil matrix, enabling it to gain strength once cured. The manufacturer of nano A also claimed that it is suitable for improving base and subbases and is also used as dust suppressers. Furthermore, nano A requires ultraviolet rays to improve the strength characteristics of the stabilised specimens. One property of this product is

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its ability to remain stable and resist brittleness once cured. According to the product's datasheet, nano B is a modified bitumen emulsion with nanosilane that ensures the construction of an effective pavement structure by preventing cracks, providing better performance, and ensuring the durability of the stabilised layers by creating a hydrophobic effect within the soil matrix. Unlike nano A, the polymers of B do not depend on ultraviolet rays for strength gain due to the existence of nano silane in its composition; however, the radiation aids in expelling moisture from the stabilised material. Table 3-1 provides further details about the nano A and B used in this research. The presence of surfactant in nano A and B causes a decrease in the surface tension of these products, thereby causing them to easily mix with water and ensure proper lubrication of the soil's particles or constituents.

Table 3-1: Properties of the research stabilisers

Name	Nano A	Nano B
Colour/Appearance	Dark grey	Thick milky brown liquid
Flammability	None	None
Odour	Slightly	Slightly
Solubility in water	Yes	Yes
Toxicity	None	None
Boiling point	Same as water	Same as water
pH	8-9	10-11

3.2.3 Water

Water suitable for drinking was utilised during the sample mixing processes to avoid contamination of the stabilising agent, i.e., tap water (SANS 241-1 (2011); SANS 241-2 (2011)). Table 3-2 provides the requirements for water utilisation for the earthworks and pavement layers construction process.

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Table 3-2: Construction water for earthworks and pavement layers (COLTO, 1998)

Purpose	Electric Conductivity (EC) at 25°C (maximum)	Total dissolved solids (TDS) (maximum)	pH range at 25°C	Sulfate as SO ₄ (maximum)
Crushed stone base layer compaction and slush- compaction	170 ms/m	1200 mg/l	5,0 – 9,7	-
Chemical stabilisation compaction and curing	170 ms/m	1200 mg/l	5,0 – 9,7	450 mg/l
Bituminous stabilisation	170 ms/m	1200 mg/l	5,0 – 9,7	-
Other layers and materials	370 ms/m	2400 mg/l	4,0 - 10,0	–

Note: Siemens per metre (S/m) is the standard SI unit. Water salinity can also be expressed in milligram per litre (mg/ℓ) or percentage (%). The relationships between the units are: 1 000 mg/ℓ = 0,1 % = 150 mS/m.

3.3 Methods of the research

The methodology for determining the properties of the gravel material for this investigation is shown below in Table 3-3.

Table 3-3: Test procedures for the gravel material.

Name of Test	Aims	Test Specification	Test Condition
Sieve analysis	To classify the construction material	TMH1, 1986: Method A1(b)	% < 0,075 mm, < 50%
Atterberg limits		TMH1, 1986: Method A2, A3	PI < 16%
MDD/OMC	Strength determination	TMH1, 1986: Method A7	MDD/OMC
CBR	Strength determination	TMH1, 1986: Method A8	CBR > 7% at (93%)

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Table 3-3: Continued			
X-ray diffraction scan	To determine the presence of non-compatible minerals in the soil	Malvern Panalytical Aeris diffractometer and X'Pert Highscore plus software.	$P_{0.002} > 35\%$
Indirect tensile strength	Strength determination	TMH1, 1986: Method A8	
Unconfined compressive strength	Strength determination	TMH1, 1986: Method A14	

3.3.1 Particle size analysis

Hillel (2013) explains that it is possible to separate soil particles into groups and characterise the soil in terms of the relative proportions of its particle-size groups, which may differ in mineral composition and particle size. The sieve analysis aims to provide the characteristics of the research gravel material following TMH1, Method A1_(b) (1986). The grading of the material was presented on a semi-logarithmic graph, as recommended by Das (2021). TRH14 (1985) provides the expression in equation (5) that was utilised to evaluate the grading modulus (GM) for the material.

$$GM = \frac{(P_{2,00} + P_{0,425} + P_{0,075}) \text{ mm}}{100} \quad (5)$$

Where,

$P_{2,00}$ mm, $P_{0,425}$ mm, and $P_{0,075}$ mm represent the percentage of materials retained on the corresponding sieves.

3.3.2 Atterberg limits determination

This section evaluates the Atterberg limit states, which comprise the liquid and plastic limits of the test sample. The liquid limit (LL) represents the transformation from plastic to a liquid form, while the plastic limit PL indicates the change from crumbling to the plastic state of a given soil sample, as demonstrated in Figure 3-1 below. The change in moisture between the liquid and plastic limits is known as the plasticity index of the sample (PI). The shear features of soil are low at the liquid limit, such that when a groove is made on the sample in the Casagrande device, and its handle is rotated at two blows per second, the total blows that close the 10 mm cut is the liquid limit for the test sample at that moisture content.

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The Atterberg limits test is a necessary classification test that indicates soil's phase transition due to moisture interactions with the soil. Determination of the liquid limit of the soil sample is vital when selecting material for pavement construction as it enables the forecast of consolidation of construction materials and provides pavement and geotechnical engineers with the relevant information regarding the consistency of the soil. Soil with a high plasticity index indicates poor soil, associated with smectites and montmorillonite, which will undergo excessive volume change and are usually unsuitable for construction except improved through stabilisation processes (COLTO, 1998).

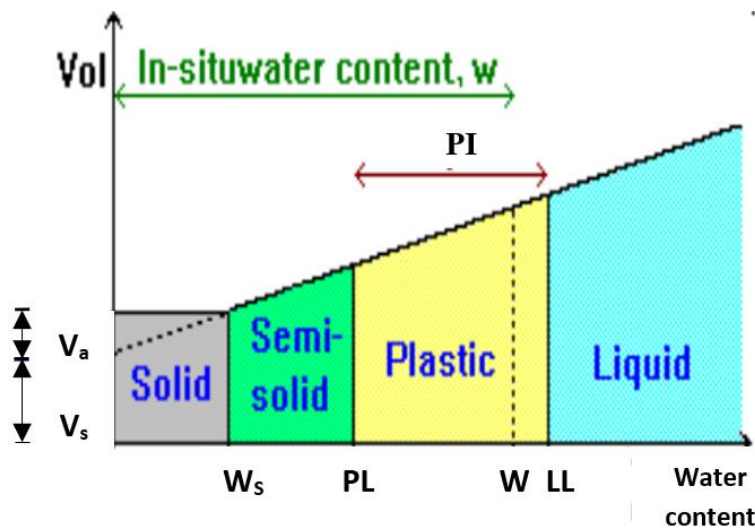


Figure 3-1: The consistency limits and plasticity graph (Modified from Sen et al., 2016).

The liquid limit experiment was conducted using the one-point method. Figure 3-1 above demonstrates the Atterberg limits for a given soil sample. TMH1 (1986) presents the expression for calculating the liquid limit in equation (6) below.

$$LL = W_N \times (N \div 25)^{0.12} \quad (6)$$

Where N = number of taps to close the groove within the moisture content, W_N .

3.3.3 X-ray diffraction test

The purpose of the X-ray diffraction test is to examine the crystal structures of a substance (Ogundalu and Oyekan, 2014). Applying heat to the filament that lies within a cathode ray tube would result in the formation of electrons, and the displacement of the electrons of the material under investigation by the electrons created in the tube would result in the formation of X-ray bands (Bunaciu et al., 2015). Bunaciu et al. (2015) further explained that the reaction of the

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incoming light beams and the specimen would create a diffraction pattern of rays if the available situation conforms to Bragg's law in equation (7).

$$n\lambda = 2d\sin\theta \quad (7)$$

where n = integer, λ = wavelength of the X-rays, d = interplanar spacing creating the diffraction, and θ = diffraction angle.

By subjecting the sample to a variety of scanning at 2θ s, because of the particles' unpredictable orientation, all feasible lattice diffraction axes were obtained. Figure 3-2 below shows a diagram of a diffractometer system. When the data for 2θ is less than 30 degrees, not all the X-ray beams strike the sample; hence, such data was ignored (Post and Bish, 1989).

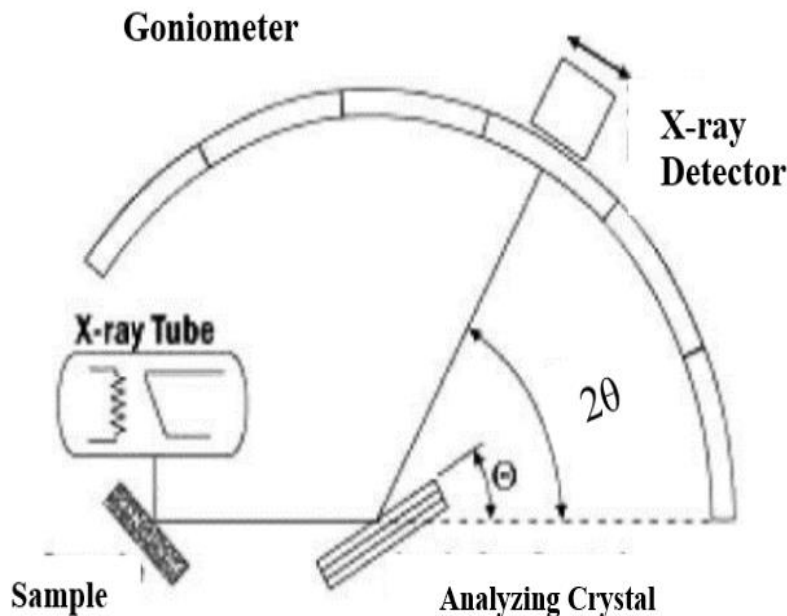


Figure 3-2: Schematic diagram of a diffractometer system (Bunaciu et al., 2015).

3.3.3.1 Test procedures

The sample for the X-ray diffraction test was prepared following the guideline of Pernechele et al. (2021) by grinding with a swing mill to ensure particle size of less than 60 μm , thereby enhancing mineral quantification by X-ray diffraction and minimising preferential orientation; the sample was prepared in a 27 mm backloading sample holder. The Aeris Malvern Panalyticals, which has a user-friendly interface or benchtop, was used for this analysis; the linear PIXcel1D Medipix3 detector in the equipment enables a quick scan that creates instant results in the Minerals Edition of Aeris. The first group of the specimen was sieved for a 0,075 mm fraction,

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while the second group was milled for seven minutes within a chrome steel milling pot. The specimen would spin along a circular route due to the orientation of the X-ray diffraction compartment. The sensor on the X-ray diffraction arm keeps track of the diffracted rays at every 2θ , while a goniometer helps to keep the angle at the desired orientation and also spins the specimen during the experiment (Bunaciu et al., 2015).

Rocks are a composition of minerals. Some rock minerals are very hard, making them desirable as construction materials, while the presence of minerals such as micas and clays (in high content) in construction materials makes the construction process difficult due to low hardness properties of these minerals. The hardness properties of the rock are a function of its mineral constituent, as evident in Table 3-4 below.

Table 3-4: Hardness of rock-forming minerals (TRH14, 1985).

Minerals	Hardness
Quartz	7,0
Olivine	6,5-7,0
Pyroxenes	6,0-6,5
Feldspars	6,0
Opal	5,5-6,5
Amphibole	5,5-6,0
Dolomite	3,5
Calcite	3,0
Micas	2,5-3,0
Chlorite	2,0-2,5
Clay minerals	1-2

3.4 Formulation of the mix for stabilisation

The appropriate application rate for the nano A and B was based on the results from the X-ray diffraction scans to identify the "problem minerals", CBR of the unstabilised material and the percentage of soil samples that passed the sieve 0,075 mm was utilised to select the required content of the stabiliser for this research (Jordaan and Steyn, 2021b). Figure 3-3 indicates that NME ranges from NME1 to NME4, which represent different types of stabilised materials with NME. Each classification of NME has a minimum requirement of soaked CBR (at 93% or 95%, Mod AASHTO) for unstabilised construction materials. The UCS and ITS results of the stabilised materials were also compared with the minimum requirements in Figure 3-3 to determine the type of classification of NME that has been attained through the stabilisation process. Based on the

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preceding information, the needed application rate for stabilisation processes ranges from 0,7% to 1,5%. The benefit of determining the application rate for the stabiliser is establishing the range at which the stabiliser will have an optimum impact on the construction material. Therefore, nano A was admixed with the sample at 0,75%, 1%, and 1,5%, while the application range for nano B is 0,7%, 1%, 1,2%, and 1,5%. Section 4.5.3 of chapter four demonstrates how the required application rate for the stabiliser was determined.

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Test or indicator	Material ¹	Material classification			
		NME1	NME2	NME3	NME4
Minimum materials requirements before stabilisation and/or treatment (natural materials)					
Material spec (minimum) Unstabilised material Soaked CBR (%) (Mod AASHTO)	NG/(CS)	>4 5 (95%)	> 25 ²	> 10 ²	> 7 ²
		ACV< 30%	(95%)	(93%)	(93%)
Grading Modulus (GM)	NG	> 1,8	> 1,5	-	-
	GS	NA	> 1,5	-	-
Sieve analysis % < 0,075 mm (P _{0,075})	ALL	< 20 %	< 25 %	<35 %	< 50 %
XRD scans: -Total sample -0,075 mm fraction (P _{0,075})	ALL	√	√	√	√
	ALL	√	√	√	√
% Material passing 2 µm (P _{0,075}) (e.g Clay & Mica & Talc) as a % of Material (with Talc < 10%) (XRD-scans of the material passing the 0,075 mm sieve is used to determine the % clay, mica (muscovite) and talc in the material.- In this case P _{0,002} = P _{0,075} X (P _{clay} , etc In P _{0,075})	NME stabilisation with micro-meter (um) emulsion particle sizes				
	ALL	< 15%	< 15%	< 15%	< 15%
	NME stabilisation with emulsion containing micro-scale as well as nano-scale particles (adjusted according to material grading)				
	ALL	NA	< 35 %	< 35 %	< 35 %
NME stabilised with emulsion containing nan-scale and pico-scale particles (grading adjustment) together with technologies addressing the workability of materials on site					
Materials specifications after stabilisation and/or treatment					
In-situ density to be required after stabilisation and compaction (Mod AASHTO) (%) (minimum)	Base	> 100 %	> 100 %	> 98 %	> 97 %
	Sub-base	NA	> 98 %	> 97 %	> 95%
DCP(DN mm/blow)(Quality control) (stabilised and compacted)	-	NA	NA	> 26	> 35
Mod AASHTO density (%) (for laboratory testing)	-	> 100%	> 100%	> 100%	> 100%
*UCS _{wet} (kPa) (150 mm ϕ Sample)	Design ³	> 2 500	> 1 500	> 1000	> 750
	Construction ₄	> 2 200	> 1 200 ⁵	> 700 ⁵	> 450 ⁵
Retained compressive strength (RCS): (UCS _{wet} /UCS _{dry}) (%)		> 85	> 75	> 70	> 65
RCS in relation to minimum UCS _{wet(criteria)} = RCS _{effective} = (RCS X (UCS _{wet} /UCS _{wet(criteria)}))	-	> 100	> 100	> 100	> 100
*ITS _{wet} (kPa) (150 mm ϕ Sample)	Design ³	> 240	> 200	> 160	> 120
	Construction ⁴	> 220	> 180 ⁵	> 140 ⁵	> 100 ⁵
Retained tensile strength (ITS): (ITS _{wet} /ITS _{dry}) (%)		> 85	> 75	> 70	> 65
ITS in relation to minimum ITS _{wet(criteria)} =ITS _{effective} = (ITS X (ITS _{wet} /ITS _{wet(criteria)}))	-	> 100	> 100	> 100	> 100

¹CS – crushed stone: NG – natural gravel GS – gravel soil, and SSSC – sand, silty sand, silt, clay,

²CBR only used as reference to traditionally used test procedures as a broad first indicator

*Definitions: UCS = Unconfined Compressive Strength; ITS = Indirect Tensile Strength;
UCS_{dry}; ITS_{dry} = testing after rapid curing; UCS_{wet}; ITS_{wet} = testing after rapid curing and 4 hours in water (as per test
procedure specified for the testing of cementitious stabilising agents (SANS 3001-GR32:2010));
Design³ Minimum criteria to be met in the laboratory during the design phase
Construction⁴ = Minimum criteria to be met during construction as part of quality control
⁵Criteria based on reference TG2 (ASPHALT Academy, 2009)

Figure 3-3: Minimum recommended standard specifications for Nano Modified (NME) stabilised materials, addressing four different classifications in terms of engineering requirements (Jordaan and Steyn, 2021b).

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3.5 Soil strength tests

The strength of a particular soil mass or sample refers to its ability to support its weight and any applied load. Several conditions, including loads, and moisture interaction with pavement materials, are the causes of the failure of the pavement. The strength capacity and characteristics of the construction materials in this research were done through laboratory investigations; these tests include the ITS, UCS, and CBR.

3.5.1 Optimum moisture content and maximum dry density

The correct quantity of moisture is necessary to ensure proper compaction of the soil material (Kidgell et al., 2019). Compaction enables the densification of soil constituents by applying force on the soil's surface. BS1377-1 (1990) defines compaction as the packing or compression of soil particles through mechanical means to improve their dry density. Soil specimen would have their theoretical maximum unit weight when compacted to zero air void at a certain moisture content (Das, 2021). The specimen was compacted in five layers, and each of the five layers in the cylindrical mould was tamped 55 blows using the 4,536 kg rammer; the compaction process was carried out automatically. The mould height is 127 mm, and the width is 152,4 mm. The OMC for the soil sample is the water content that yields the maximum dry density. Five specimens were prepared corresponding to the required five points on the moisture density curve, while a representative fraction was placed in the oven for moisture content evaluation. The moisture content for each point was determined by oven-drying a representative portion of the specimen. The OMC obtained from the compaction process was used to prepare samples stabilised with nano A and B. The optimum stabiliser content is the quantity of nano A and B that yields the maximum strength for this investigation. The impact of nano A and B on the OMC and MDD of the specimen was also examined at various application rates. Equation (8) below provides an expression for calculating the moisture content of the specimens (TMH1, 1986).

$$d = \frac{a - b}{b - c} \times 100 \quad (8)$$

d = moisture content expressed as a percentage of the dry soil, a = mass of the container and wet material, b = mass of the dry container and material, and c = mass of the container only.

Furthermore, the dry density for each point is expressed as follows.

$$D = \frac{w}{d + 100} \times \frac{100}{v} \times 1000 \quad (9)$$

Where:

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D = dry density in kg/m^3 , w = mass of wet material in grams, and v = volume of mould in milligrams.

3.5.2 Sample for strength tests

Cylindrical specimens were prepared for the UCS, ITS, and CBR tests using the OMC as discussed in session 3.5.1, resulting in a total of 213 cylindrical specimens for the investigation. The samples were prepared at 0% and stabilised with 0,75%, 1%, and 1,5% for nano A and 0,7%, 1%, 1,2%, and 1,5% for nano B. Post-treatment of the specimens or treatment of the compaction mould to aid the de-moulding process was avoided as it may affect the results (Jordaan and Steyn, 2021b). Figure 3-4 shows the sample preparation for the tests.

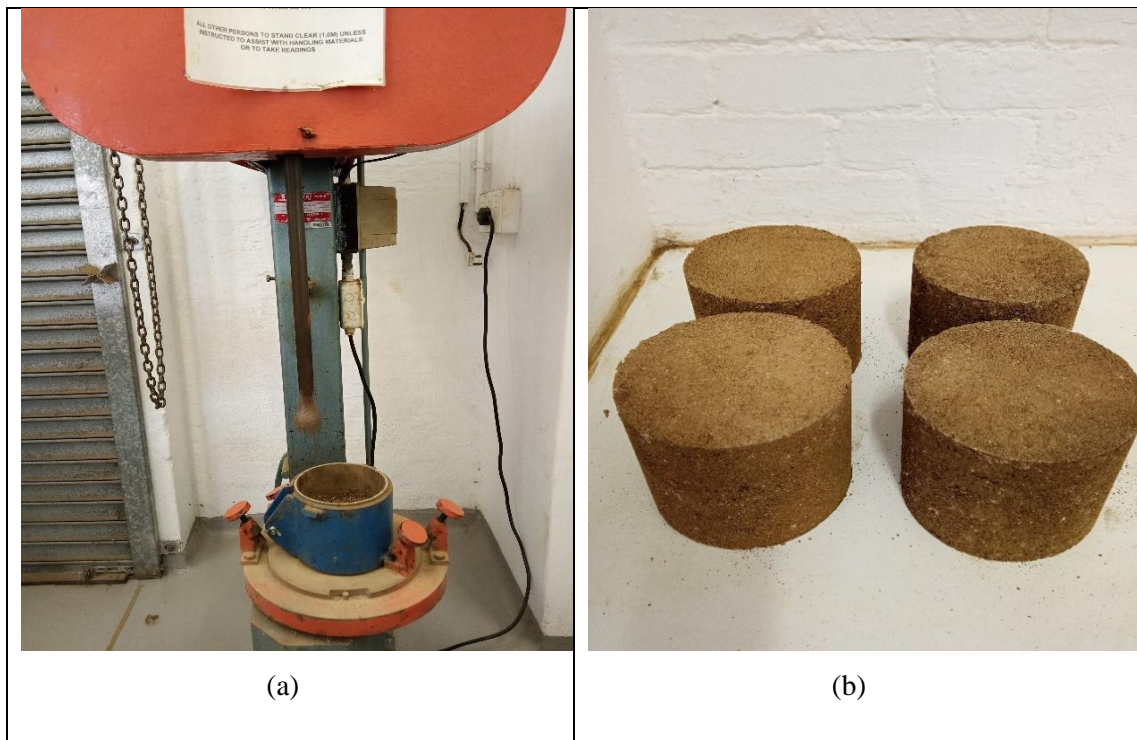


Figure 3-4: (a) Preparation of the cylindrical specimens (b) Prepared specimens

3.5.3 Curing of samples

The specimens were cured in two conditions, namely: rapid and 28-day curing conditions. The use of rapid curing in this investigation aims to obtain a strength equivalent to 28 days of curing in air. Before rapid curing, the specimens were cured for 24 hours at $30\text{ }^{\circ}\text{C}$, then cured at $45\text{ }^{\circ}\text{C}$ for 48 hours, and finally cured at $30\text{ }^{\circ}\text{C}$ for 24 hours (Jordaan and Steyn, 2021b). The second condition deals with curing the specimens in the air for 28 days. Analyses or the measure of the influence of curing conditions on the strength and performance of the specimen were done

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through the strength tests (ASTMD5102-09, 2009, Jordaan and Steyn, 2021b, Rezaeimalek, 2016, Taher et al., 2020). Jordaan and Steyn (2021b) further explained that specimens subjected to the rapid curing process should not be wrapped with plastic bags to minimise moisture loss, unlike bituminous stabilised materials mixed with cement, as moisture loss from the specimen is crucial to strength gain. The preceding indicates that moisture evaporation from nanotechnology-based stabilisers is essential to ensuring a stronger particle bond resulting in high strength of the stabilised material.

Specimens for the ITS and UCS test were also submerged in water to determine their strength characteristics in the wet condition (SAN 30001-GR50, 2013; SAN 30001-GR53, 2010). The purpose is to replicate a wet pavement layer for nano A and B stabilised materials, and this condition is similar to ordinary Portland cement (OPC)-treated materials that are submerged in water to cure (Jordaan and Steyn, 2021b). Three samples obtained from both curing conditions for the stabilised and unstabilised specimens were tested in the dry and (UCS_{dry} and ITS_{dry}) wet conditions (UCS_{wet} and ITS_{wet}). The wet test is aimed at determining the resistance to water absorption by the specimen. The effect of curing conditions on the UCS and ITS cylindrical specimens was evaluated by comparing the mass of freshly prepared specimens to the mass of the specimens after the curing process. Also, the increase in mass for the specimens subjected to four hours of soaking was measured to determine the resistance to water absorption in the stabilised and unstabilised specimens. Finally, only nano A stabilised specimens were subjected to both curing methods, while nano B stabilised specimens were subjected to rapid curing only due to the limited time frame for this study.

3.5.4 California bearing ratio (CBR)

The CBR test is a frequent strength test suitable for measuring soil and sub-grade quality and appropriateness for pavement's sub-base and base courses (Franco and Lee, 1987). The CBR refers to the proportion of standard loads (13,344 kN, 20,016 kN, and 25,345 kN) for a compacted soil specimen to be penetrated by a circular piston of 1935 mm² at 1,27 mm/min to 2,54 mm, 5,08 mm, and 7,62 mm depth (TMH1, 1998). The compaction requirements for the CBR samples were done at 93%, 95%, and 98% Mod AASHTO compaction. Stabilisation of the CBR samples was performed at the optimum content of nano A and B. Curing of the stabilised specimens to expel moisture is necessary for strength gain; hence, the specimens were subjected to rapid curing, as discussed in session 3.5.3. The CBR specimens were immersed in water for four days before testing. The outcome of the CBR tests on the stabilised, and unstabilised soil samples was obtained for analysis and comparison. This test focuses on determining the impact of nano A and B on the CBR specimens. Appendix A shows the setup for the strength tests.

3.5.5 Indirect tensile strength (ITS) test

This section determines the ITS for dry and wet (ITS_{dry} and ITS_{wet}) cylindrical samples. The ITS test was carried out by subjecting the specimen to a compressive force, as shown in Figure 3-5 (Hudson and Kennedy, 1968). The effect of the load creates reasonably tensile stress at a right angle to the specimen. Typically, the failure occurs by fracturing along this loaded plane. Hudson and Kennedy (1968) further highlight some of the characteristics that affect the test; thus, the testing temperature and rate of loading, composition and dimensions of loading strips, dimension and size of the specimen, and the load-deformation characteristics of the material. The ITS test was performed by 40 kN/min on the stabilised and unstabilised (0% - 1,5%) specimen using the universal testing machine UTM until it failed. The rate of water absorption by the ITS specimens was investigated through the retained tensile strength (RTS) and its relation to the minimum ITS_{wet} condition ($RTS_{effective}$) (Jordaan and Steyn, 2021b). Sabita (2020) presents an expression for calculating the indirect tensile strength of samples in equation (10).

$$ITS = \frac{2 \times G}{\pi \times d \times h} \times 10^6 \quad (10)$$

Where:

ITS = indirect tensile strength, in kilopascals, (kPa), G = force at cracking point (kN), d = specimen diameter, (mm), and h = specimen height, in (mm).

Jordaan and Steyn (2021b) provide the expression for calculating the RTS in equation (11) below.

$$RTS = \frac{ITS_{wet}}{ITS_{dry}} (\%) \quad (11)$$

Where: RTS = retained tensile strength (%), ITS_{wet} , and ITS_{dry} = indirect tensile strength for the wet and dry sample (kPa).

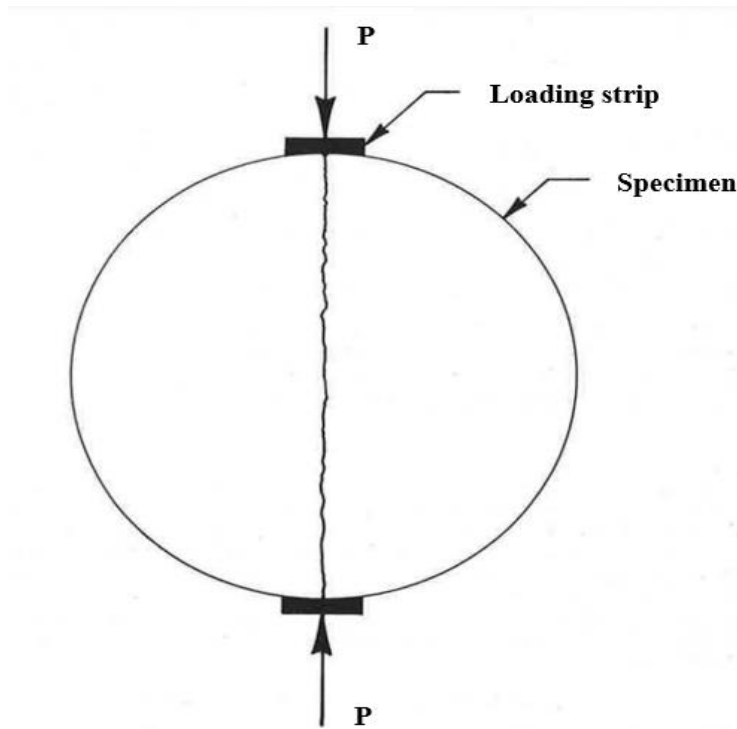


Figure 3-5: Indirect tensile strength test (Hudson and Kennedy, 1968).

3.5.6 Unconfined compressive strength (UCS) test

This test aims to evaluate the UCS of fine-grain soil or rock with sufficient cohesion to evaluate the unconfined compressive strength of specimens containing varying amounts of nano A and B. In this section, the UCS of the cylindrical specimens in the dry (UCS_{dry}) and wet (UCS_{wet}) conditions were tested. The resistance of the UCS specimens to water ingress was investigated through the retained compressive strength (RCS) and its relation to the minimum UCS_{wet} ($RTS_{effective}$) (Jordaan and Steyn, 2021b). The test procedure involves subjecting a cylindrical specimen to axial stress and monitoring the stresses causing the axial strains in the specimen (Das, 2021). UCS tests were performed on the unstabilised and stabilised specimens (0% and 0,7%, to 1,5%) using nano A and B. The curing procedure for the UCS specimens has already been discussed in section 3.5.3. The test procedure involves applying a compressive force to the specimen in the UTM compartment at 140 kPa/s until failure. Also, a personal computer (PC) attached to the UTM automatically records the UCS test. SANS 3001-GR53 (2010) provides an expression for calculating the UCS test as thus;

$$UCS = \frac{1000F}{(\pi \times r^2)} \quad (12)$$

Where;

UCS = unconfined compressive strength (MPa);

F represents the force required to crush the specimen (kN), while r is the radius of the specimen face (mm).

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Since 152,4 mm diameter specimens were used for the experiment, the above expression in (12) becomes (13).

$$UCS = \frac{F}{18,15} \quad (13)$$

Jordaan and Steyn (2021b) provide the expression for calculating the RTS in equation (14) below.

$$RCS = \frac{UCS_{wet}}{UCS_{dry}} (\%) \quad (14)$$

Where: RCS = retained tensile strength (%), UCS_{wet} , and UCS_{dry} = unconfined compressive strength for the wet and dry sample (MPa).

4 . RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter discusses the experimental results. The analysis of the results provides the characteristics of the soil material utilised for the study and the degree of improvement attained through stabilisation using nano A and B at various contents (0%, and 0,7% - 1,5%). The analysis also indicates the optimum content (%) of nano A and B, which maximises the strength improvement for the construction material in this study.

4.2 Sieve analysis

4.2.1 Particle size distribution

Table 4-1 provides the outcome of the sieve analysis that was performed for this study. The particle size distribution analysis provides details or information about the soil sample for this research, and the experiment reviews the percentage of fines, gravel, and dust or clay for the specimen. The maximum aggregate size for the research material is 37,5 mm, and its grading coefficient G_c is 22,42, within the recommended value of 16 - 34 (COLTO, 1998). The material has a grading modulus (GM) of 2,3 above the minimum 1,2 requirements for a G6 material; hence, classified as G6 (TRH14, 1985).

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Table 4-1: Sieve analysis for the G6 gravel material.

Sieve size (mm)	Mass of soil retained	Cumulative mass retained	Percentage retained on each sieve	Percentage finer
53,00	-	-	-	-
37,500	134,20	134,20	4,48	95,52
26,500	175,40	309,60	10,33	89,67
19,000	154,50	464,10	15,48	84,52
13,200	264,50	728,60	24,30	75,70
9,500	229,10	957,70	31,94	68,06
6,700	266,30	1224,00	40,83	59,17
4,750	267,10	1491,10	49,74	50,26
2,000	414,80	1905,90	63,57	36,43
0,850	273,80	2179,70	72,71	27,29
0,425	181,30	2361,00	78,75	21,25
0,250	159,00	2520,00	84,06	15,94
0,150	134,00	2654,00	88,53	11,47
0,075	100,00	2754,00	91,86	8,14
Pan	244,00	2998,00	100,00	-
Total	2998,00	-	-	-

Analysing soil grains and their characterisation is crucial to understanding the performance of construction materials when in service. The soil's constituents' quality and percentages of the various particle sizes can be determined through the sieve analysis procedure, as evident in Figure 4-1, showing a semi-log graph of a cumulative per cent passing for the soil sample against the sieve size (mm). The semi-log graph in Figure 4-1 indicates a particle size range of 37,5 mm to 0,075 mm for the test sample. The summary of the unstabilised material's properties for this research is contained in Appendix 1, Table 7-1.

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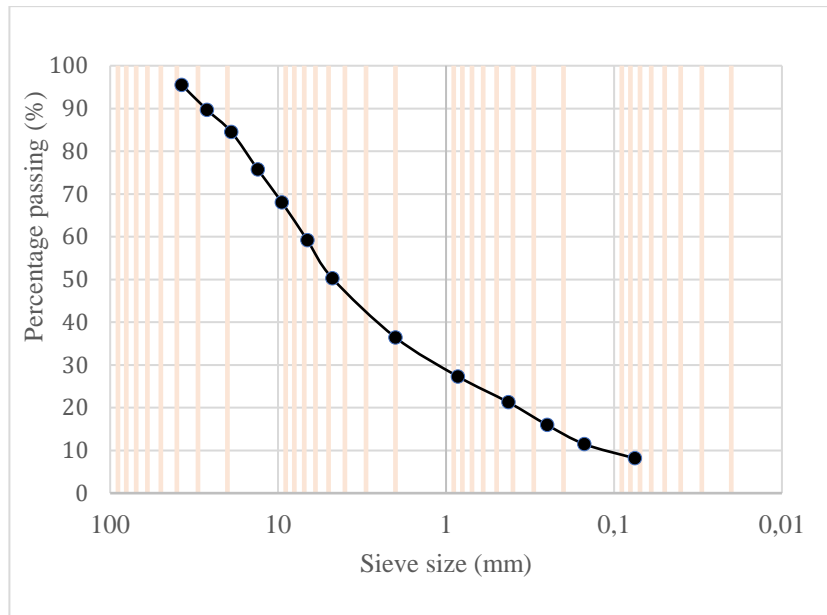


Figure 4-1: Particle size distribution curve.

4.3 Atterberg limits

The liquid limit for the test sample is 30% at 25 numbers of blows, its plastic limit is 26%, and the plasticity index is 4. Soils with high plasticity index indicate an abundance of clay minerals; such materials have a high affinity to water and water retention capacity. It is essential to highlight that soil's liquid limit varies with its mineral composition; hence, the liquid limit range for kaolinite is 35 -100, for Illite, 55 – 120, and for montmorillonite, 100 – 800 (Das, 2021). According to TRH4 (1996), the maximum plasticity index PI value for a G6 material is 12%; hence, the research material's ($PI = 30 - 26 = 4\%$) PI is within the recommended PI value. Tables 4-2 and 4-3 below show the liquid and plastic limits results for the G6 material.

Table 4-2: Liquid limits determination

Item	Test No.	
	1	2
Can + Wet Soils (g)	70	70
Can + Dry Soils (g)	67	67
Weight of Can (g)	57	57
Weight of Dry Soils (g)	10	10
Weight of Moisture (g)	3	3
% Moisture	30	30
Number of blows	25	27

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Table 4-3: Plastic limits determination

Item	Test No.		
	1	2	3
Can+ Wet Soils (g)	104,00	60,00	59,00
Can + Dry Soils (g)	103,00	59,00	58,00
Weight of Can (g)	98,00	56,00	54,00
Weight of Dry Soils (g)	5,00	3,00	4,00
Weight of Moisture (g)	1,00	1,00	1,00
% Moisture	20,0	33,3	25,0

4.4 X-ray diffraction test

The X-ray diffraction test of the sample that passes through the 0,075 mm sieve indicated that the bulk of the specimen is quartz. The chemical formula for quartz is SiO_2 , the most significant polymorph of silica (Götze et al., 2021). The sample analysis indicates 58 % quartz, 36,5 % clay mineral, and 7,7 % mica (44,2% for all clay types). The mineral composition of clay, mica, and its sub-group muscovite makes them undesirable in construction materials because of excessive water absorption due to the increased porosity of the compacted layers by these minerals (TRH14, 1985). Table 4-4 shows the X-ray diffraction analysis for the study. Due to the hardness of the mineral composition of quartz, it does not decompose, unlike the minerals of plagioclase, Microline, diopside, and hematite. Figure 7-2 of appendix 4 provides further details about the X-ray diffraction scan and general report for the soil sample.

Table 4-4: Mineralogy report for the G6 material.

Mineral Groups	Total Sample		0,075 mm Fraction	
	Single	Combined	Single	Combined
Quartz	58	-	20,4	-
	-	58	-	20,4
Plagioclase	20.1	-	17,8	-
Microline	20,6	-	16,9	-

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Table 4-2: Continued				
Diopside	0,1	-	0	-
Hematite	0	-	0,7	-
	-	40,8	-	35,4
Mica				
Muscovite	1	-	7,7	-
	-	1	-	7,7
Clay Minerals				
Kaolinite	0,2	-	23,9	-
Smectite	12,6	-	12,6	-
	-	12,8	-	36,5

Note: 0 = n.d. – not detected above the detection limit of 0.5-3 weight per cent

4.5 Strength test

4.5.1 Optimum moisture content and maximum dry density

This section examined the relationship between the moisture content and dry density for the stabilised and control materials (unstabilised G6 material). The OMC for the unstabilised specimen is 5,8%, while the MDD is 2148 kg/m³, as shown in Table 7-2, appendix 1. It is necessary to highlight that increasing the moisture content from 5,8% decreases the specimen's dry density and vice-versa, as evident in Figure 4-2 below. At 1% of nano A, OMC was reduced by 1,7%, MDD increased by 2,6%, while at 1,5%, OMC was exceeded by 3%, and MDD dropped by 1%. Furthermore, at 0,75% of nano A, MDD increase by 1,3%, and OMC drops by 1%. There was no significant change in the OMC and MDD with samples stabilised with nano B.

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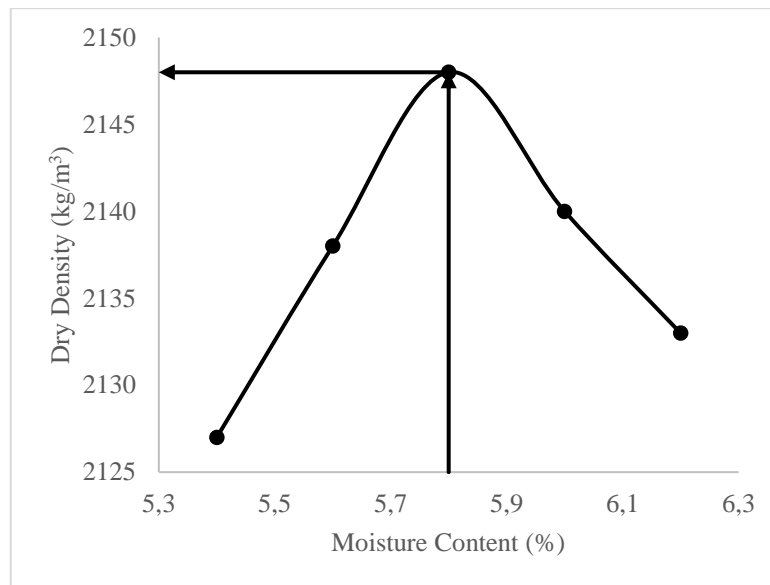


Figure 4-2: Moisture content vs dry density.

4.5.2 California bearing ratio results (CBR)

The outcome of CBR tests of stabilised and unstabilised specimens in Figures 4-4 to 4-6 below shows appreciable improvement in the results due to nano A and B. The CBR was evaluated at 1% and 1,2% for nano A and B, respectively. The CBR test was performed for the stabilised and unstabilised samples subjected to rapid curing conditions. A soaked CBR of 25%, 32%, and 38% at 93%, 95%, and 98% Mod AASHTO compaction was achieved for the unstabilised specimens. CBR values at 40%, 46%, and 53% at the optimum content for nano A were obtained, while nano B gave a CBR at 87%, 88%, and 92% at the preceding Mod AASHTO compaction. The analysis indicates that nano B has the highest impact on the soaked CBR value due to its hydrophobic effect created in the soil matrix, resulting in a firm interlocking of the particles within the specimen; however, this is not the same for nano A as evident in the results. The hydrophobic properties of the CBR samples were done by visual inspection of the sample. A key significant attribute of the soaked CBR test is evaluating the bearing capacity of soil material on site when in contact with a water source (a surface or an underground). The CBR of 25% and 32% for the unstabilised material at 93% and 95% MOD AASTHO satisfies the minimum CBR requirement of 25% at the preceding density for a G6 material (TRH4, 1996, TRH14, 1985). The CBR of samples stabilised with nano A at 98% Mod AASHTO is below the minimum CBR requirement (80%) for a base course layer; however, this requirement was exceeded with nano B (TRH4, 1996). Figure 7-1 (a) of appendix 2 shows the setup for the CBR test.

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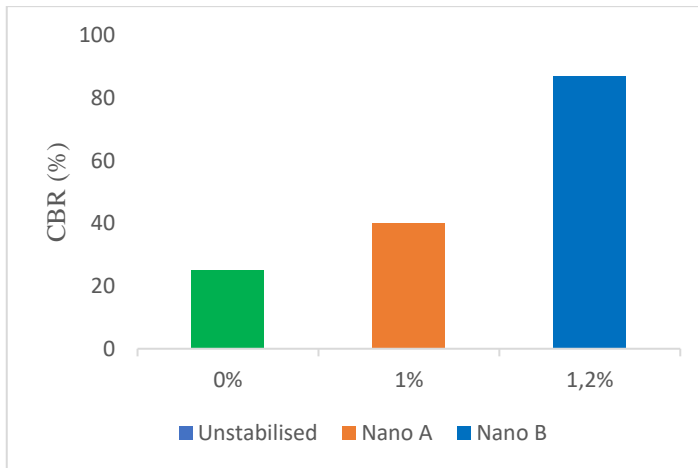


Figure 4-3: The CBR for the stabilised and unstabilised specimens at 93% Mod AASHTO.

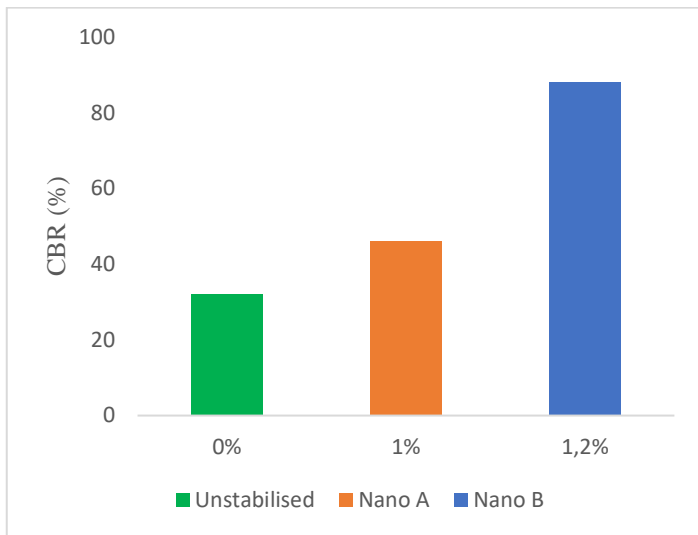


Figure 4-4: The CBR for the stabilised and unstabilised specimen at 95% Mod AASHTO.

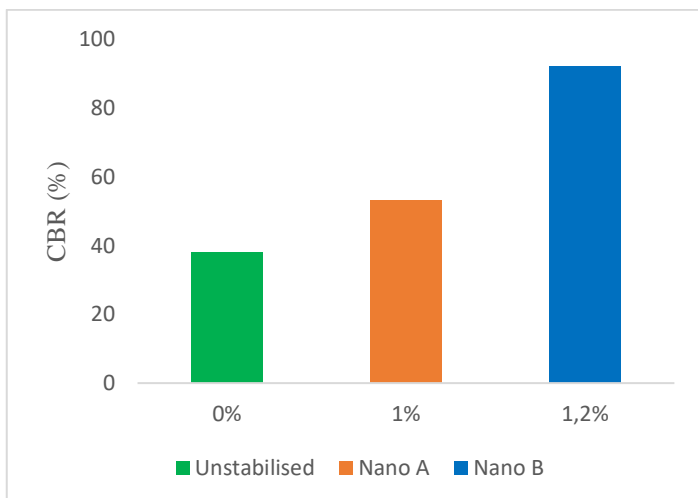


Figure 4-5: The CBR for the stabilised and unstabilised specimen at 98% Mod AASHTO.

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4.5.3 Formulation of the mix for the stabilisation process

Figure 4-6 indicates that the CBR of the unstabilised material at 95% Mod AASHTO is 32%, and the quantity of the material that passed through the 0,075 mm sieve is 8,14%, while the quantity for all types of clay in the sample is 44,2%. The preceding results are indicated in Figure 4-6 with the aid of an arrow headline. The required application rate for nano A and B lies within zone two; therefore, the stabilisers were mixed with the soil sample at 0,75% to 1,5%.

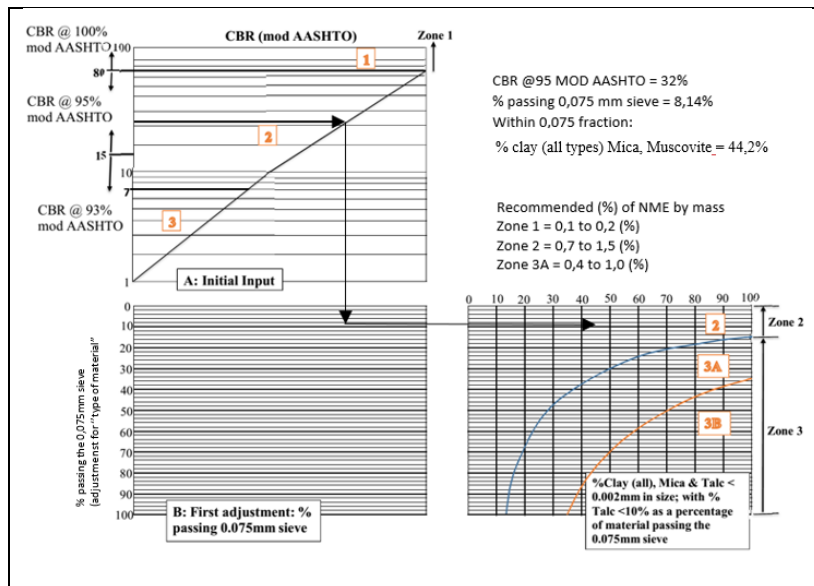


Figure 4-6: Selection of an appropriate NME technology for naturally available material (Modified from Jordaan and Steyn, 2021b).

4.5.4 Indirect tensile strength (ITS) results

The laboratory results in Tables 4-5 and 4-6 indicate how nano A and B improved the ITS of the specimens compared to unstabilised specimens. The average variation in ITS_{dry} results for the unstabilised specimen, subjected to rapid and 28 days of curing, is 2,4%. The rapid and 28-day curing conditions resulted in a maximum ITS_{dry} at 152 kPa and 168 kPa for nano A, at 1%. Figure 4-8 shows the ITS results of the stabilised (0,7 to 1,5%) and unstabilised samples. Samples stabilised at 1,5% with nano A contain more moisture after the rapid curing process than samples stabilised at 1%; this resulted in a slight decrease in the ITS_{dry} results at 1,5% with nano A, as shown in Table 4-5.

Another crucial aspect of this study was the determination of the specimens' ability to resist water absorption through the retained tensile strength, RTS, which is the percentage ratio of the wet and dry ITS specimen (ITS_{wet}/ITS_{dry} %) and retained tensile strength with respect to the

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minimum wet condition ($RTS_{\text{effective}}$) as evidenced in Table 4-6. Nano B at 1,5% gave a maximum ITS_{dry} of 152 kPa, and ITS_{wet} of 148 kPa for specimens subjected to rapid curing.

At 0,7% of nano B, a significant improvement was attained in the ITS_{dry} compared to the ITS_{wet} results. Figure 4-8 shows that as the content of nano B increases from 0,7% to 1,5%, the ITS_{wet} results increased significantly; however, the results vary slightly from 1,2% to 1,5%. The resistance of the ITS specimens to water absorption during the four hours of soaking indicates the hydrophobic effect of nano B on the specimens. Tables 4-5 and 4-6 also indicate that the moisture loss in the specimens (after curing) decreases as the stabilisers' content increases while the resistance to water absorption in the specimens increases with an increase in the stabilisers' content.

Table 4-5: ITS of nano A.

Percentage of nano A	0%	0,75%	1%	1,5%
Curing condition (1)	Rapid curing			
ITS_{dry} (kPa)	124	143	152	149
Moisture loss in the specimens (%)	5	4,9	4,7	4,2
Curing condition (2)	Air curing 28 days			
ITS_{dry} (kPa)	127	147	168	161
Moisture loss in the specimens (%)	4,9	4,8	4,4	4,0
Average water absorption in specimens (%)	-	-	9,3	8,9
ITS_{wet} (kPa)	-	-	-	-
RTS (%) = $ITS_{\text{wet}}/ITS_{\text{dry}}$	-	-	-	-
$RTS_{\text{effective}}$	-	-	-	-

The resistance to water absorption in the specimens was investigated by placing the ITS specimens in water for four hours. Upon submerging the unstabilised ITS specimens in water, there was an increased absorption and subsequent collapsing of the specimens after about thirty minutes. Similarly, the specimen stabilised with 0,75% of nano A collapsed in the water after approximately two hours of soaking, while the samples with 1% and 1,5% of nano A were stable throughout the soaking period; however, these samples had no significant strength during the ITS_{wet} test. The resistance to water absorption by the stabilised material increases as nano B

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content increases (0,7 to 1,5%). A retained tensile strength of 97,9% and an $RTS_{\text{effective}}$ of 142.1% were obtained with nano B at 1,2%.

Table 4-6: ITS of nano B.

Percentage of nano B	0%	0,7%	1%	1,2%	1,5%
Curing condition (1)	Rapid curing				
ITS_{dry} (kPa)	124	148	142	148	152
ITS_{wet} (kPa)	-	79	115	145	148
Moisture loss in specimens (%)	5,0	3,4	2,8	2,7	2,5
Average water absorption in specimens (%)	-	1,0	0,58	0,59	0,45
$RTS (\%) = \frac{ITS_{\text{wet}}}{ITS_{\text{dry}}}$	-	53,4	81,0	97,9	97,4
$RTS_{\text{effective}} (\%)$	-	42,2	93,1	142,1	144,1

The results of the rapid curing for nano B show that the ITS_{dry} is 2,0% greater than the ITS_{wet} at 1,2%, which indicates how the specimen's hydrophobic property was improved with this stabiliser. Specimens stabilised with nano A indicate more than 70% loss in moisture after rapid and 28 days of curing, while those of nano B showed a slower curing rate (moisture loss is < 70%) after subjecting to rapid curing. The preceding implies that samples stabilised with nano A cured faster during the rapid curing process than samples stabilised with nano B. Finally, the minimum criteria for ITS in terms of RTS (65%) and $RTS_{\text{effective}}$ (100%) were satisfied by nano B only. Figure 4-7 shows the ITS specimen splitting at its centre due to the tensile stress causing the specimen to separate at the point of load application. Finally, the average difference in the ITS_{dry} results for specimens stabilised with nano A and subjected to rapid and 28 days of curing is about 4,2%.

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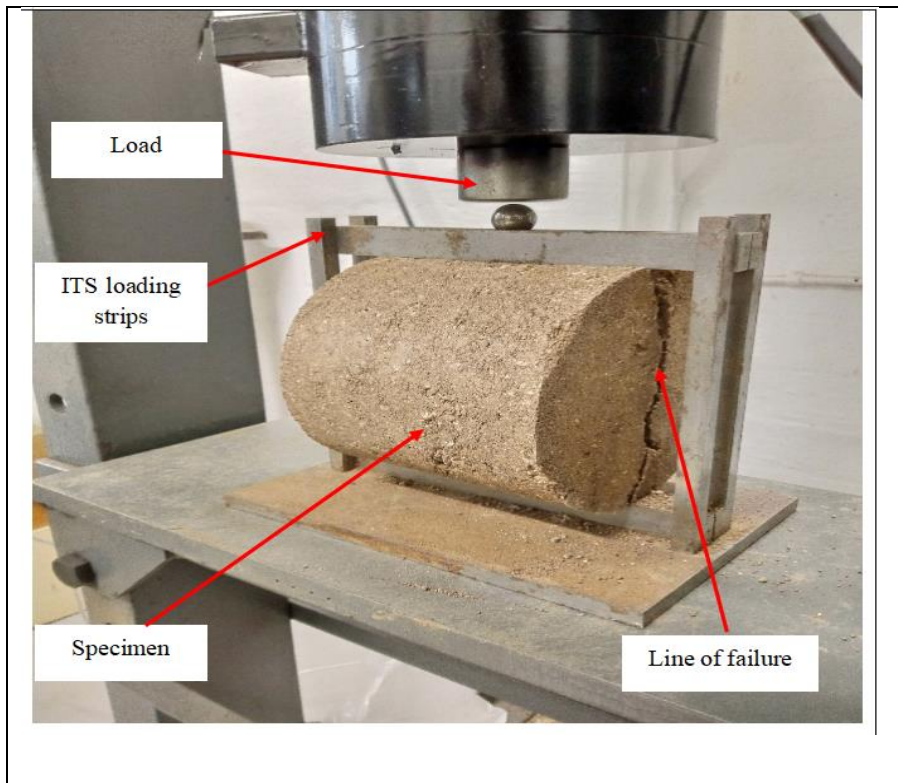


Figure 4-7: Specimen subjected to ITS test

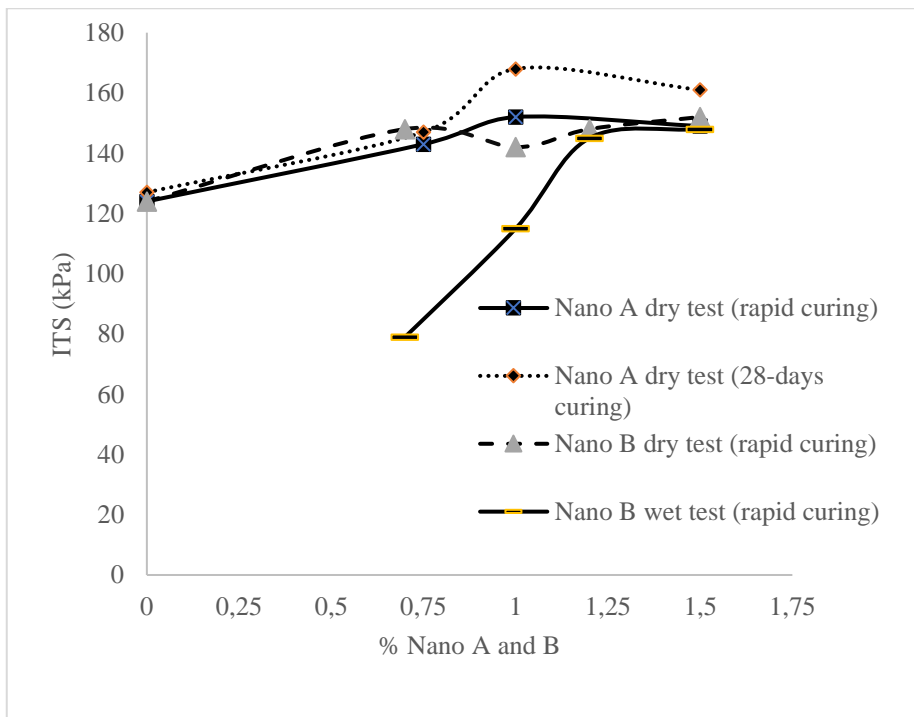


Figure 4-8: ITS_(dry and wet) for the stabilised and unstabilised specimens

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Note; the 0% specimens in Figure 4-8 above failed in water before the wet test.

4.5.5 Unconfined compressive strength (UCS) results

The appropriate content of the nano A and B (0,7 to 1,5%) is necessary to ensure maximum UCS results for the stabilised material. Table 4-7 below compares the UCS results for specimens undergoing a rapid curing process and those cured in the air for 28 days for nano A. The control specimen gave a UCS_{dry} at 1,76 MPa and 1,83 MPa for rapid and 28-day curing conditions. The impact of the curing conditions on the UCS_{dry} specimen indicates that the specimen stabilised at 1% with nano A and cured rapidly gave a maximum UCS_{dry} of 2,17 MPa, while a UCS_{dry} of 2,29 MPa was achieved for those cured for 28 days. At 1% of nano A, the UCS_{dry} results for specimens subjected to 28 days of curing are 5% higher than those subjected to rapid curing. The 5% difference between both curing conditions complies with Jordaan and Steyn's (2021b) recommendation that the UCS and ITS results for the rapid and 28-day curing condition should vary by not more than 5%. The average variation in UCS_{dry} results for samples subjected to rapid and 28 days of curing is 5,8%. The UCS result of samples stabilised with nano A at 28 days of curing is slightly higher than those cured rapidly. The preceding could result from moisture variation in the specimens owing to the impact of the curing conditions. The unstabilised specimens have no resistance to water ingress, while those stabilised with nano A showed little resistance to water absorption during the four-hour soaking period. The moisture absorbed by samples stabilised with nano A (1% and 1,5%) is above the OMC after the four hours of soaking in water, compared to nano B (0,7% 1,5%), which is below the OMC. Figure 7-1 (b) of appendix 2 shows the setup for UCS tests.

Table 4-7: UCS results for nano A.

Percentage nano A	0%	0,75%	1%	1,5%
Curing condition (1)	Rapid curing			
UCS _{dry} (MPa)	1,76	1,93	2,17	2,06
Moisture loss in the specimen (%)	5	4,9	4,7	4,2
Curing condition (2)	Air curing 28 days			
UCS _{dry} (MPa)	1,83	2,09	2,29	2,36
Moisture loss in the specimen (%)	4,9	4,7	4,5	4,0

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Table 4-7: Continued				
Average water				
absorption in specimens (%)	-	-	9,3	8,9
ITS _{wet} (kPa)	-	-	-	-
RTS (%) =	-	-	-	-
ITS _{wet} /ITS _{dry}	-	-	-	-
RTS _{effective}	-	-	-	-

Table 4-8 provides the dry and wet UCS results for samples stabilised with nano B. The analysis indicates a little increase in the UCS_{dry} results as the nano B increases from 0,7% to 1,5%. The minimum requirements of 65% and 100% for RCS and RCS_{effective} (RCS in relation to the minimum wet condition) by Jordaan and Steyn (2021b) were satisfied at 1%, 1,2%, and 1,5% content of nano B. The UCS_{dry} results for nano A and B exceed the requirement by TRH4 (1996) for a cemented natural gravel (C4) base course layer equivalent to NME4 (natural stabilised material). Tables 4-7 and 4-8 also provide the results for the stabilised and unstabilised specimens. Figures 4-9 and 4-10 provide the trend in strength properties for this study's stabilised and unstabilised specimens, while appendix 3 shows the test results for UCS and ITS samples.

Table 4-8: UCS for nano B.

Percentage of nano B	0%	0,7%	1%	1,2%	1,5%
Curing condition (1)	Rapid				
UCS _{dry} (MPa)	1,76	2,41	2,46	2,42	2,55
Moisture loss in specimens (%)	5	3,6	3,0	2,7	2,5
UCS _{wet} (MPa)	-	0,82	1,65	1,77	1,99
Water absorption rate (%)	-	1,0	0,58	0,59	0,45
RCS (%) =	-	34,0	67,0	73,0	78,0
UCS _{wet} /UCS _{dry}	-	34,0	67,0	73,0	78,0
RCS _{effective}	-	62,0	246,0	288,0	345,0

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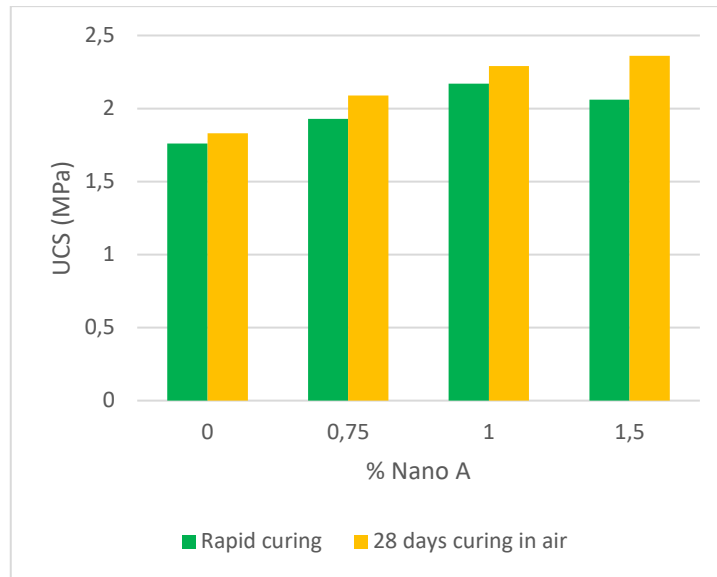


Figure 4-9: UCS_{dry} for samples stabilised with nano A.

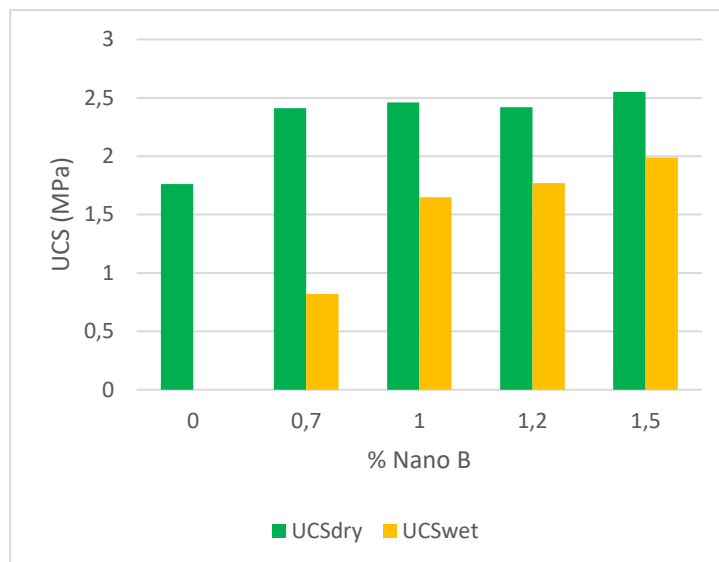


Figure 4-10: UCS_(dry and wet) for samples stabilised with nano B after rapid curing.

4.6 The impact of the curing conditions on the strength of the specimens

The unstabilised specimens absorbed excess water and disintegrated during the four hours of soaking. Samples stabilised with nano A and subjected to rapid curing have a higher impact on the ITS_{dry} results, while those of nano B have a higher impact on the UCS_{dry} results. The rapid curing process expelled more moisture than 28 days of curing for samples stabilised with nano A; however, the strength of specimens subjected to rapid curing is slightly lower than those subjected to 28 days of curing conditions. The 48 hours of rapid curing expels more than 70% of moisture from samples stabilised with nano A; however, the moisture loss for samples

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stabilised with nano B is below 70% after the rapid curing process. Proper curing is necessary to ensure strength gain in stabilised materials; therefore, the slow curing rate in samples stabilised with nano B could affect its strength properties.

Specimen treated with nano A at 0,75% - 1,5% improved UCS_{dry} and ITS_{dry} however, it had little effect on the specimen during the four hours soaking period. The samples stabilised with nano B and subjected to four hours of soaking resulted in a 2% and 26,8% decrease in the ITS_{wet} and UCS_{wet} results at 1,2% compared to the ITS_{dry} and UCS_{dry} results. The minimal reduction in the ITS_{wet} results indicates high stiffness characteristics in the construction material to prevent tensile strain. It can be deduced from the results that the RTS and RCS will provide the stabilised material's characteristics and resistance to forming potholes when in contact with water (Jordaan and Steyn, 2021a). Finally, a CBR of 92% was attained with nano B compared to nano A with a CBR of 53% at 98% Mod AASHTO.

4.7 Summary

The study's results have been presented and discussed in this chapter, including the results in tables and figures. This chapter also compares the strength attained for the stabilised and unstabilised specimens. The summary of this investigation is as follows.

COLTO (1998) categorised soil as gravel, sand, and fine, depending on their size. The gradation results in this study indicate that the soil sample contains about 8,14% of fines (clay and silt) and 49,74% of gravel, referring to materials obtained from sieve 0,075 mm and materials collected on the 4,75 mm sieve, respectively. About 42,12% of the material is sand which refers to materials within the 4,75 mm and 0,075 mm sieves. The maximum aggregate size for this investigation is 37,5 mm and a grading modulus of 2,3, which complies with TRH14 (DoT, 1998) for a G6 material; therefore, the soil is suitable for this investigation.

The X-ray diffraction scan indicates that the specimen contains 58% quartz, a vital rock mineral having a high strength property, and 7,7% of mica, a mineral responsible for low strength and poor engineering characteristics in soil composition. Furthermore, clay minerals and micas are responsible for water absorption of construction material; however, the percentage of mica is 7,7 % below the 10% unacceptable limit (TRH14, 1985). The high amount of quartz in the research material is advantageous as it gives the material some degree of resistance and makes stabilisation process easier.

The OMC for the unstabilised sample is 5,8%, corresponding to the peak MDD at 2148 kg/m³. Nano A improves MDD from 2148 kg/m³ to 2203 kg/m³ and decreases the OMC from 5,8% to

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5,7% at the optimum concentration of 1%. The observation reveals that nano B has no significant impact on the specimen's OMC and MDD, possibly due to its high viscosity.

It has been observed that the percentage increase in CBR with nano A and B is 53% and 92% at 98% Mod AASHTO compaction relative to the CBR of unstabilised specimens. The results showed that nano B has higher CBR values and a significant hydrophobic effect on the specimen during the four days of soaking in water. This enhancement by nano B indicates that the stabilised base course layer will resist water ingress into the pavement, thereby ensuring better layer performance if utilised in road construction. The increased rate of water absorption in samples stabilised with nano A could be due to the material's low PI, resulting in a weak bond between the soil's matrix and elastomers of nano A. The CBR of nano A at 98% Mod AASHTO is below the minimum 80% CBR requirement for base course materials but satisfies the minimum CBR of 45% at 95% Mod AASHTO for a subbase layer (TRH4, 1996). The CBR of nano B at 98% Mod AASHTO is 92% which is above the minimum requirement for base course materials (TRH4, 1996).

The results of the ITS_{dry} for the unstabilised samples are 124 kPa and 127 kPa for rapid and 28-day curing conditions. Adding nano A and B to the sample at 0,7% - 1,5% significantly improves the ITS results in contrast to the unstabilised samples. At 1%, nano A improves the ITS_{dry} by 23% and 32,2% for rapid and 28-day curing conditions, while nano B improves the ITS_{dry} by 19,4% for specimens subjected to rapid curing at 1,2%. The degree of enhancement obtained at 1% with nano A is similar to that achieved with nano B at 1,2%. At 1%, the peak effect of nano A on the specimens was achieved; however, the minimum recommendation for RTS and $RTS_{effective}$ were not satisfied with this stabiliser. Nano B at 1% and 1,5% satisfy the preceding requirements. The control specimen has no resistance to water ingress, and nano A has a minimal impact on the specimens during the soaking period, which is because the polymers of this product do not undergo any chemical reaction with water to create a hydrophobic effect in the sample but rely only on the mechanical compaction to bind the elastomers of the polymers to the soil. Samples stabilised with nano B are resistant to water ingress because the polymers of this product react with water to formulate a hydrophobic effect which protects the soil structure from water ingress once cured. RTS and $RTS_{effective}$ above the minimum 65% and 100% recommendation by Jordaan and Steyn (2021b) were obtained with nano B.

Finally, the UCS_{dry} for the control specimen is 1,76 MPa and 1,83 MPa for rapid and 28-day curing conditions. Adding nano A and B at 0,7% to 1,5% to the sample improves the UCS results significantly. At the optimum content for nano A, the UCS_{dry} increased by 23% and 28,9% for rapid and 28-day curing conditions. At the optimum content, nano B improves the UCS_{dry} by 37,5%, while an RCS of 73% and $RCS_{effective}$ of 288% were obtained, which is above the

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minimum requirements for NME4 stabilised materials in Figure 3-3. The results also indicate that nano B has a higher impact on the UCS_{dry} than nano A. The unstabilised UCS specimens and samples stabilised with nano A have similar absorption properties as the ITS specimens during the four hours of soaking in water.

The recommendation for UCS by TRH4 (1996) for a cemented natural gravel (C4) base course layer (equivalent to NME4 stabilised material) was exceeded by the UCS_{dry} results for nano A and B. The enhancement in the UCS using this nano A and B will ensure that the stabilised layer will have sufficient strength to support the compressive traffic load.

Specimens subjected to rapid and 28 days of curing conditions have similar strength properties, although there are a few variations in the results, which maybe be attributed to environmental factors during curing. The preceding indicates that rapid curing can be used in the laboratory as an alternative method to obtain equivalent UCS and ITS results for specimens cured for 28 days in the air.

5 . CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

The limited availability of standard construction material in building roadways is not restricted to the province of KwaZulu-Natal, where this investigation was performed but is a general problem affecting South Africa and the world. The focus of this study was the determination of the strength and performance attributes of a substandard gravel material by conducting a laboratory investigation and comparing the results of unstabilised and stabilised soil material. Here, two nanoemulsions labelled as nano A and B were used in this investigation for stabilisation. This chapter provides a comprehensive summary of the key findings and results presented in chapter four of this research. Furthermore, this chapter contains the conclusion, highlights the limitations, and offers recommendations to ensure further study on nanoemulsions' use and application in stabilising substandard pavement construction materials.

5.2 Achievement of the predicted aims and objectives of the study

. The G6 material used in this study has several limitations or constraints, and as such, using them as a base material in their natural state would result in severe consequences on the strength of the pavement structure due to their susceptibility to failure; hence, the need for improvement with nanoemulsions. At this point, it is vital to evaluate how the aims and objectives of this study were satisfied, as discussed in the following paragraphs.

The review of chapter two provides the background for this study, hence accomplishing the first objective. It was found that substandard material consisting of unsuitable minerals has been used for road construction in South Africa and many other countries using traditional and non-traditional soil stabilisation methods. Based on the literature review, especially Sections 2.4.1 and 2.6.3.5, it was concluded that nontraditional stabilisers, including nanotechnology-based stabilisers, are compatible with most substandard construction materials that cannot be stabilised with traditional stabilisers.

Chapter four discusses this research's second objective. The outcome of the X-ray diffraction scan in session 4.4 of chapter four presents the various mineral composition, including the problem minerals for this study; the minerals are grouped as primary and secondary groups, satisfying the study's second objective. It concluded that mica (7,7%) and clay (36,6%) are the problem minerals in the soil.

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The third objective was met by following the recommendations of Jordaan and Steyn (2021b) to obtain the required stabiliser's content for this research, and this was done by considering the X-ray diffraction scan, quantity of material that goes through the 0,075 mm sieve, and the CBR of the unstabilised specimen at 95% Mod AASHTO. The required application rate for construction materials is in the range of 0,7% to 1,5%). The laboratory investigation confirms that 1% is the optimum content for nano A and 1,2% for nano B. The optimum range for these stabilisers yields the maximum strength results for this study.

The interaction of water with pavement materials is a critical condition that often activates the various distresses on pavement structure, and how these stabilisers react with the research material to resist water ingress is crucial. Chapter four satisfies the fourth objective as it analyses the impact of rapid and 28 days curing conditions on the specimens. Rapid curing is a laboratory procedure in which specimens are cured at an elevated temperature to ascertain the equivalent of strength gain after curing for a longer period, i.e., 28 days. In this study, the specimens were cured at 45 °C for 48 hours based on the recommendation of Jordaan and Steyn (2021b). The 28 days gain in strength for the UCS and ITS specimens stabilised with nano B was not investigated due to the limited time factor for this study; only rapid curing was performed for this stabiliser. It concluded that the effect of rapid curing on the strength properties (UCS_{dry} and ITS_{dry}) of samples stabilised with nano A is slightly lower than those attained at 28 days of curing. The effect is also the same for the unstabilised samples subjected to rapid and 28 days of curing. The rapid curing procedure confirms that nano A has a higher impact on the dry ITS results than nano B, while nano B has a higher impact on the dry UCS samples than nano A. Furthermore, the average variation in ITS results between the rapid and 28 days of curing is 4.2%, while those of UCS is 5.8%.

Finally, this dissertation indicates that nano A and B improved the strength of the specimens; however, in terms of resistance to water ingress, only nano B stabilised materials create a hydrophobic effect in the specimens due to the presence of nano silane in this stabiliser. These modifications to substandard materials using nano A and B will minimise the burden of hauling quality materials to the construction site. Since in situ materials can be utilised in building pavement through modification with nanotechnology, sustainable pavement construction can be attained in South Africa. Based on the recommendation of TRH4 (1996) for base and subbase layers, this investigation indicates that nano A is suitable for stabilising the subbase layer (CBR at 95% Mod AASHTO $\geq 45\%$), while nano B is adequate for stabilising the base course layer (CBR at 98% Mod AASHTO $\geq 80\%$).

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5.3 Recommendations for Future Study

Evaporation of moisture from samples stabilised with nano A and B is a prerequisite for strength gain. The 48 hours of rapid curing expels more than 70% of moisture from samples stabilised with nano A, while a slow curing rate was identified with samples stabilised with nano B, i.e., moisture loss after rapid curing $< 70\%$; therefore, a longer rapid curing duration (i.e., 72 hours) should be investigated for nano B.

Nano A improves the dry UCS and ITS results but has a low impact on the soaked specimens; therefore, further studies should consider investigating the plasticity index's effect on this stabiliser's performance. Nano B can be regarded as suitable for stabilising the base layer of pavement as it will offer robustness to the structure; furthermore, its hydrophobic effect is an essential property that will prevent the deterioration caused by water action and ensure the durability of the base layer. The enhancement obtained with nano B also indicates its suitability for stabilising the wearing course for unsurfaced roads. The effect of nano A and B on other types of substandard construction materials should also be investigated.

The similarities in the dry ITS and UCS results for rapid and 28 days of curing conditions using nano A indicate that rapid curing could be used to ascertain the 28 days gain in strength for the stabilised material; however, more study is required to verify the relationship. Although it was observed that the results obtained from the 28 days curing condition are slightly higher than those of rapid curing; therefore, more investigation is necessary to verify this occurrence. Finally, the construction of a trial section is recommended to provide a detailed understanding and applicability of these products in stabilising substandard construction materials using this research information, followed by the development of an adequate life cycle cost analysis for these nano polymers.

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7 . APPENDICES

Appendix 1: Material classifications

Table 7-1: Characteristic properties of the unstabilised G6 material

Soil classification	G6
liquid limit %	30
plastic lime %	26
plasticity index	4
linear shrinkage	-
Coarse (%)	49,7
Sand (%)	42
Clay and Silt (%)	8,14
Optimum moisture content %	5,8
maximum dry density (kg/m ³)	2148
CBR at 93, 95, and 98 % Mod	
AASHTO	25, 32, and 38

Table 7-2: OMC and MDD for the compacted specimen

Item	Test No.				
	1	2	3	4	5
Volume of mould M(cm ³)	2316,67	2316,67	2316,67	2316,67	2316,67
Mass of mould M ₁ (g)	4600	4600	4600	4600	4600
Mass of mould + compacted soil W ₂ (g)	9809	9836	9860	9841	9822
Mass of compacted soil M= M ₂ -M ₁	5209	5236	5260	5241	5222
Bulk density γ_b	2,25	2,26	2,27	2,26	2,25
Moisture content, d (%)	5,4	5,6	5,8	6	6,2
Dry density D (kg/m ³)	2127	2138	2148	2140	2133

APPENDICES

Appendix 2: Strength test equipment

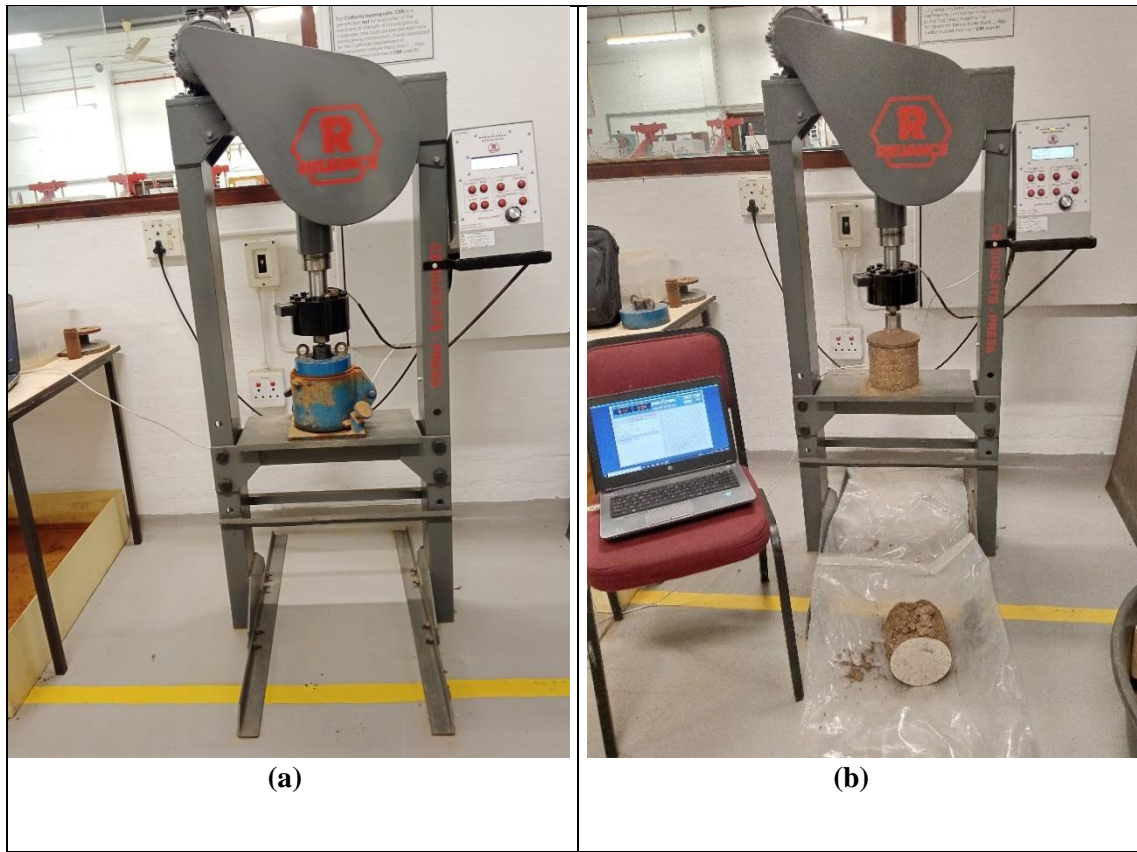


Figure 7-1: (a) California bearing ratio test (b) The setup for the UCS test and a personal computer connection with the machine.

APPENDICES

Appendix 3: Strength test results

Table 7-3: UCS (kN) for nano A

Nano A (%)	Rapid curing			28-day curing		
	S-1	S-2	S-3	S-1	S-2	S-3
0	30,05	34,09	32,04	37,43	32,23	34,09
0,75	34,08	36,32	35,47	35,39	41,42	38,07
1	39,29	39,22	40,25	42,22	40	43,17
1,5	33,75	39,12	40,17	40,72	45,32	43,25

Where S1-S3 = specimen

Table 7-4: ITS (kN) for nano A

Nano A (%)	Rapid curing			28-day curing		
	S-1	S-2	S-3	S-1	S-2	S-3
0	3,77	3,78	3,77	3,65	4,16	3,77
0,75	4,44	4,23	4,31	4,02	4,52	4,88
1	4,16	4,35	5,28	5,04	5,17	4,50
1,5	4,56	4,80	4,17	4,87	4,55	5,25

Where S1-S3 = specimen number

APPENDICES

Table 7-5: UCS (kN) for nano B subjected to rapid curing

UCS _{dry} (kN)					
Nano B (%)	0%	0,7%	1%	1,2%	1,5%
Specimen 1	30,05	41,47	42,63	41,77	48,30
Specimen 2	34,09	47,75	43,44	42,37	48,70
Specimen 3	32,04	42,75	48,19	48,17	42,70
UCS _{wet} (kN)					
Specimen 1	-	10,25	29,66	26,04	32,64
Specimen 2	-	19,33	30,75	32,91	35,70
Specimen 3	-	15,32	29,86	38,06	40,70

Table 7-6: ITS (kN) for nano B subjected to rapid curing

ITS _{dry} (kN)					
Nano B (%)	0%	0,7%	1%	1,2%	1,5%
Specimen 1	3,77	4,32	4,62	4,52	4,25
Specimen 2	3,78	4,69	4,72	4,39	4,59
Specimen 3	3,77	4,47	3,6	4,73	4,93
ITS _{wet} (kN)					
Specimen 1	-	2,34	3,33	4,79	4,47
Specimen 2	-	2,75	3,51	3,45	4,57
Specimen 3	-	2,07	3,51	4,99	4,36

APPENDICES

Appendix 4: X-ray diffraction report

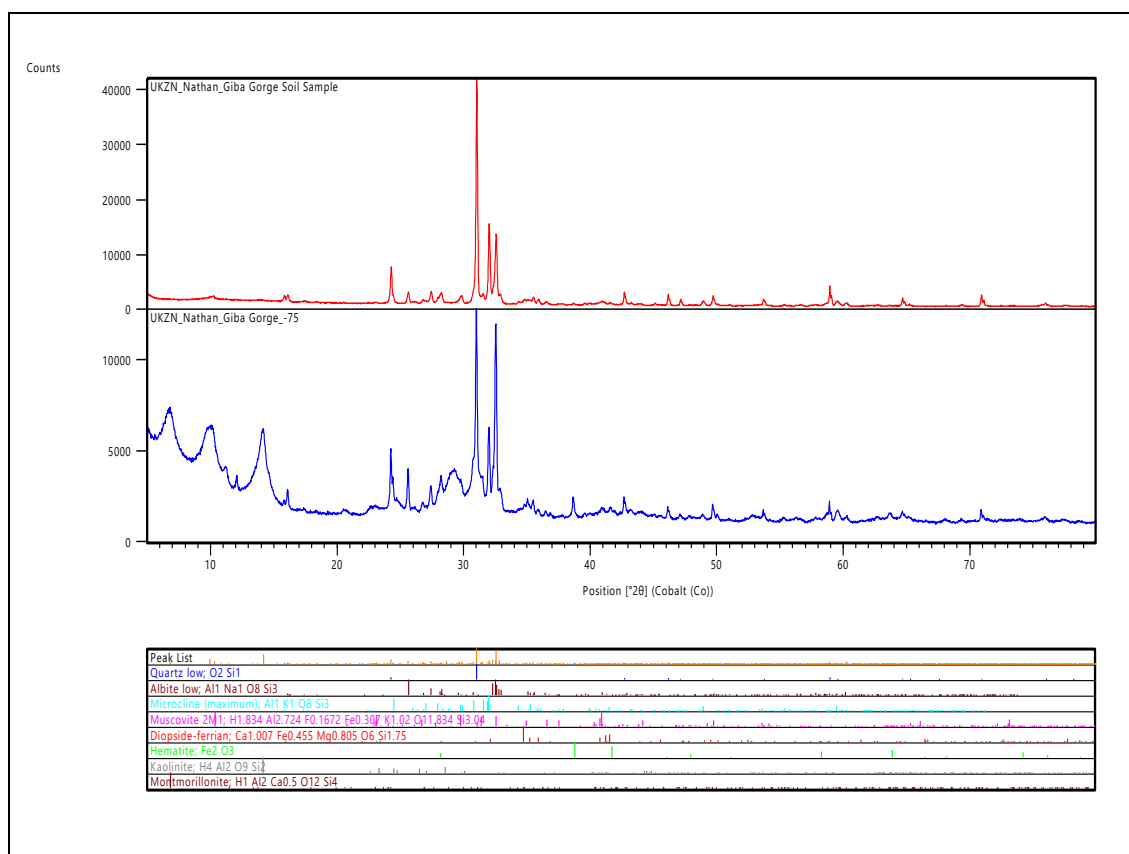


Figure 7-2: Graphical representation of the X-ray diffraction scan for the soil sample