PERFORMANCE OF UNPAVED LATERITE ROAD TREATED WITH CHEMICAL ADDITIVES AND WASTE TIRE

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To my beloved parents, brothers, sisters, all my past and present teachers, and the almighty who courage and compassion have taught me humility.

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ABSTRACT

Lateritic unpaved roads are widely spread in Malaysian territory. These red-yellow lateritic layers normally have poor engineering properties such as large settlements, low shear strength and bearing capacity. Major difficulties may arise during the construction of a lateritic layer which are deterioration and diffusion of dust on the road surface, and also durability problems associated with cyclic loading repetition. Waste tires are encountered all over the world in increasing numbers. Shredded scrap tires and crumbs-soil mixtures are currently used in a wide range of civil engineering structures like lightweight fills for slopes, retaining walls, embankments etc. This thesis presents and discusses the condition of lateritic soil stabilized by using the shredded tires, tire crumbs and traditional active additive materials such as cement and lime for unpaved road application. Experimental tests such as X-ray diffraction (XRD), scanning electron microscope (SEM), california bearing ratio (CBR), consolidated undrained (CU) triaxial, permeability, and highway accelerated loading instrument (HALI) tests were carried out to evaluate the microstructures, elements, durability and geotechnical strength properties of tropical laterite soils. These tests were conducted to determine the influence of stabilizers on the surface of the lateritic soil layers in terms of loading cycles, and short term behaviour. The quick undrained triaxial and CBR tests were carried out on samples at different curing times to establish the optimum mix design. The strength parameters were determined from CU triaxial tests on unsoaked samples. The HALI test was used to study the strength, durability and deformation after determination of the best formulation for each stabilizer in combination with laterite soils under accelerated trafficking load, simultaneously. The close range Photogrammetry technique was also used to capture images of deformed untreated and treated surface. The camera data were analysed using software known as Australis, and Surfer 10 were used to evaluate the performance of unpaved road stabilization with traditional active additives and waste tires. After eliciting of results and data and use of the comparison curves, the behaviour of stabilized soil with different combination were determined. The highest and lowest permeability were STc (soil and tire crumbs) and SC (soil and cement) at 14 days, respectively. The highest CBR values occurred for SC on unsoaked condition in 14 days. The HALI test shows that the highest reduction in settlement was exhibited by SL (soil-6%lime) after 14 days curing. Also, the experimental results show that 6% of lime/cement and 6% of shredded tires/tires crumbs changed the soil strength, durability, and permeability properties of the lateritic soil for unpaved road applications. The results indicate that the shredded scrap tire and crumbs mixed with active additive had reduced the settlement significantly and also had increased the strength. The analysis of data by close range Photogrammetry technique shows a close approximation to the data obtained from LVDT's equipment (less than 4.5% variance). The numerical simulation results carried out using ABAQUS 6.11 show a noticeable similarity to the results obtained by full scale HALI model and it is recommended using ABAQUS to simulate the unpaved road behaviour under cyclic loading to save time and cost.

ABSTRAK

Terdapat banyak jalan laterit tidak berturap di Malaysia. Lapisan-lapisan laterit merah-kuning biasanya mempunyai ciri-ciri kejuruteraan yang lemah seperti pemendapan yang besar, dan kekuatan ricih dan keupayaan galas yang rendah. Masalah utama yang mungkin timbul semasa pembinaan lapisan laterit termasuk kemerosotan dan resapan debu pada permukaan jalan, dan juga masalah yang berkait dengan pembebanan berkitar. Bilangan sisa tayar di seluruh dunia semakin meningkat. Sisa tayar tercincang dan campuran remah-tanah kini digunakan dalam pelbagai struktur kejuruteraan awam seperti isian ringan untuk cerun, tembok penahan, benteng dan banyak lagi. Tesis ini membentangkan dan membincangkan keadaan tanah laterit yang distabilkan dengan menggunakan sisa tayar tercincang, remah tayar dan bahan tambahan aktif seperti simen dan kapur untuk kegunaan jalan tidak berturap. Ujian seperti pembelauan X-ray (XRD), mikroskop pengimbas elektron (SEM), nisbah galas california (CBR), ujian terkukuh taktersalir tiga paksi (CU), kebolehtelapan, dan ujian HALI telah dijalankan untuk menilai struktur mikro, elemen-elemen, ketahanan dan sifat-sifat kekuatan geoteknik tanah laterit tropika. Kajian ini telah dijalankan untuk menentukan pengaruh penstabil pada permukaan lapisan tanah laterit dari segi kitaran beban, dan kelakuan jangka pendek. Ujian ujian terkukuh taktersalir tiga paksi dan ujian CBR telah dijalankan ke atas sampel-sampel pada berbeza umur untuk mendapatkan rekabentuk campuran yang optimum. Parameter-parameter kekuatan ditentukan daripada ujian terkukuh taktersalir yang dijalankan ke atas sampel-sampel tidak terendam. Ujian HALI telah digunakan untuk mengkaji kekuatan, ketahanan dan perubahan bentuk selepas pengenalpastian formulasi terbaik bagi setiap penstabil bersama gabungan tanah-tanah laterit di bawah beban trafik terpecut, secara serentak. Teknik fotogrametrik jarak dekat juga digunakan untuk mengambil imej permukaan takterawat dan terawat. Data-data kamera telah dianalisis dengan menggunakan perisian-perisian yang dikenali sebagai Australis dan Surfer 10 untuk menilai prestasi penstabilan jalan tidak berturap dengan bahan tambah aktif dan sisa tayar tercincang dan remah. Selepas memperolehi keputusan dan data serta penggunaan keluk perbandingan, kelakuan tanah stabil dengan kombinasi yang berbeza dapat diperolehi. Kebolehtelapan tertinggi dan terendah adalah STc dan SC berumur 14 hari masing-masing. Nilai CBR tertinggi berlaku pada SC yang tak terendam berusia 14 hari. Ujian HALI menunjukkan bahawa pengurangan pemendapan tertinggi telah berlaku pada SL (tanah-6% kapur) pada redaman 14 hari. Selain itu, keputusan ujian menunjukkan bahawa 6% kapur/simen dan 6% sisa tayar tercincang/remah tayar telah mengubah sifat kekuatan tanah, ketahanan, kekuatan dan kebolehtelapan tanah laterit untuk aplikasi jalan tidak berturap. Keputusan menunjukkan bahawa campuran sisa tayar tercincang dan bahan tambah aktif telah mengurangkan pemendapan secara signifikan dan juga telah meningkatkan kekuatan. Analisis data dengan teknik fotogrametrik jarak dekat menunjukkan nilai yang amat hampir dengan data yang diperoleh dari alat LVDT (kurang dari 4.5% varians). Keputusan simulasi numerikal yang dilakukan dengan menggunakan perisian ABAQUS 6.11 menunjukkan persamaan yang ketara dengan keputusan yang diperolehi menerusi model skala penuh HALI dan adalah disarankan untuk menggunakan ABAQUS bagi mensimulasikan kelakuan jalan tidak berturap di bawah kitaran beban bagi menjimatkan masa dan kos.

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AAS	-	Atomic absorption spectrophotometer
ADU	-	Data acquisition unit
AEC	-	Anion exchange capacity
Al	-	Aluminum
Al^{3+}	-	Aluminum cation
$Al(OH)_3$	-	Aluminum hydroxide
Al_2O_3	-	Aluminium Oxide
APH	-	Aluminate phosphate hydrate
$AlPO_4$	-	Aluminum phosphate
ASTM	-	American society of testing material
AT	-	Acid treated
Ba	-	Barium
Ba^{2+}	-	Barium cation
$BaCl_2$	-	Barium Chloride
BET	-	Brunauer emmett and teller
BS	-	British standard
c	-	Constant
Ca	-	Calcium
Ca^{2+}	-	Calcium cation
$CaCO_3$	-	Calcium carbonate
CAH	-	Calcium aluminate hydrate
CaO	-	Calcium oxide
$Ca(OH)_2$	-	Calcium hydroxide
CASH	-	Calcium aluminate silicate hydrate
$CaSO_4$	-	Calcium sulphate

CEC	-	Cation exchange capacity
Cl	-	Chloride
CSH	-	Calcium silicate hydrate
Cs	-	Concentration adsorbed on soil surfaces
C_e	-	Concentration in water
CO_2	-	Carbon dioxide
cps	-	Counts per second
Cu	-	Copper
d	-	Distance of interplanar spacing as function of θ
D	-	Dielectric constant of medium
DTA	-	Differential thermal analysis
DTG	-	Derivative thermal gravimetric
e	-	Electronic charge
EDAX	-	Energy dispersive x-ray analysis
EE	-	Equilibrium extraction
F	-	Fluoride
Fe	-	Iron
Fe^{2+}	-	Iron (II) cation
Fe^{3+}	-	Iron (III) cation
Fe_2O_3	-	Ferric Oxide
FESEM	-	Field emission scanning electron microscopy
FTIR	-	Fourier transform infrared
GB	-	Green Bentonite
H	-	Hydrogen
H^+	-	Hydrogen cation
HCL	-	Hydrochoric acid
H_2O	-	Water
H_3PO_4	-	Phosphoric acid
H_3PO_3	-	Phosphorous acid
HPO_3^{-2}	-	Phosphonate ion
ICL	-	Initial consumption of lime
ICP	-	Inductively coupled plasma
K	-	Potassium

K^+	-	Potassium cation
k	-	Boltzmann constant
KBr	-	Potassium bromide
k_{des}	-	Desorption rate
k_{ads}	-	Adsorption rate
LC	-	Laterite Clay
LL	-	Liquid limit
LOI	-	Loss on ignition
LT	-	Lime treated
LVDT	-	Linear variable displacement transducer
MAS	-	Magic angle spinning
MDD	-	Maximum dry density
mEq	-	milliequivalents
Mg	-	Magnesium
MgO	-	Magnesium oxide
MM	-	Mercury microporosimetry
M	-	Months
n	-	Order of diffraction
n_0	-	Eelectrolyte concentration
Na	-	Sodium
Na^+	-	Sodium cation
Na_2O	-	Sodium oxide
NH_4	-	Ammonium ion
Nm	-	Number of molecules
NMR	-	Nuclear magnetic resonance
NO_3	-	Nitrate
O	-	Oxygen
OC	-	Organic content
(OH)	-	Hydroxide ion
OMC	-	Optimum moisture content
P	-	Phosphorous
Pb	-	Lead
PI	-	Plasticity index

PL	-	Plastic limit
P_2O_5	-	Phosphorus oxide
PO_4^{-3}	-	Phosphate ion
ppm	-	parts per million
PS	-	Pink Soil
Pt	-	Platinum
S	-	Soil
SC	-	Treated soil with cement
SCTc	-	Treated soil with cement and tire crumbs
SCTm	-	Treated soil with cement and shredded tire
sec	-	Seconds
SEM	-	Scanning electron microscope
Si	-	Silicon
SiO_2	-	Silica
SL	-	Treated soil with lime
SLTc	-	Treated soil with lime and tire crumbs
SLTm	-	Treated soil with lime and shredded tire
SO_4	-	Sulfate
SSA	-	Specific surface area
Su	-	Sulfur
T	-	Temperature
STc	-	Treated soil with tire crumbs
TEM	-	Transmission electron microscopy
TG	-	Thermal gravimetric
TGA	-	Thermal gravimetric analysis
STm	-	Treated soil with shredded tire
UCS	-	Unconfined compressive strength
UT	-	Untreated
v	-	Volume of gas adsorbed per unit weight of clay at a pressure
v_m	-	Volume of gas adsorbed for monolayer coverage
WK	-	White Kaolin
XRD	-	X-ray diffraction
XRF	-	X-ray fluorescence

Zn	-	Zinc
1/k	-	The effective thickness of the diffuse layer
ν	-	Cation valence
ε_0	-	Permittivity of vacuum
ε	-	Strain
μ	-	Micro
λ	-	Wave-length
θ	-	Critical angle of incidence of the x-ray beam on the crystal plane

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Roads have a very important role in the progress and promotion of a country. Transportation and public services can be done based on the availability and performance of the roads. Therefore, maintenance and quality of them is a key for every country. The roads are classified to be paved and unpaved based on their pavement characteristics. Unpaved roads and low-type paved roads are usually used for the low volume traffic. They serve as access roads and play a very important role in the rural economy, resource industries (forest, mining, and energy), and the transportation for military purposes. Furthermore, the rural and forest roads are basic elements in the economic progress and also for the social promote procedures of health, income, facilitate future development, technology transfer, and education potential of the communities of remote areas. Based on the fast growing development of Malaysia, it is essential to establish low cost remote access roads to gain the natural or less populated areas. These roads are built to provide faster and better access to local villages or uninhabited areas from main roads or major cities. In most cases the unpaved roads have to be constructed on a soft foundation soils where large deformations can occur this increases the maintenance cost and lead to interruption of traffic service.

In Malaysia, a large amount of the residential tropical unpaved roads are built on the lateritic soil (Newill and Dowling, 1969). Eisazadeh *et al.* (2010) reported that the

tropical lateratic soils with high moisture contents are one of the most available soils in Malaysia. A number of difficulties has always limited the use of lateritic soil as a good subgrade during the construction such as their workability, field compaction, and strength.

The wheel tires are composed of rubber and synthetic polymer materials. They have low unit weight, and other unique properties such as high permeability, insulating, tensile strength, flexibility, and high friction resistance. The mechanical properties of whole tires remain even after its ordinary life as a car wheel element has expired. Reusing the waste whole tire is known as a good solution for saving the environment by preventing burning and stockpiling of old tires. The use of waste tire crumbs stabilizer material reduces the sand mining which helps to achieve a more sustainable construction. In most countries including Malaysia, scrap tires are used for various purposes such as facing elements of backfills and retaining walls. Huat *et al.* (2008) stated that the application of waste tires crumbs for reinforcement requires a good understanding of both the physical and mechanical strength properties. In addition, the durability of the tires is a key issue. Currently, there is little information and not even suitable testing standard or guideline to test the tensile strength of scrap tire for such applications.

Ingles and Metcalf (1972) stated that the soil stabilization is a chemical, thermal, and mechanical process in which some of undesirable properties of soil can be overcome. In real engineering practice, the main properties of soils that may require improvement are strength, permeability, and durability. One of the most widely recognized form of stabilization methods is the compaction technique, which can improve the mechanical stability of soil. However, the compaction method alone is often insufficient to improve the behaviour of fine-grained soils.

The stabilization of clayey soils by incorporation of calcium based stabilizers such as lime is widely used throughout the world. In this method, the combination of high pH grouts will provide natural pozzolans in order to have sufficient pozzolanic reactions. However, in some cases involving soils with high sulfate contents, treatment with conventional calcium-rich additives has led to excessive swelling and heaving

(Hunter, 1988; Kota *et al.*, 1996; Mitchell and Dermatas, 1992; Rollings *et al.*, 1999). In addition, the improper use of chemical stabilizers may led to loss of millions of dollars (Wiggins *et al.*, 1978).

Huat *et al.* (2008) studied on the required additive types and quantities, the magnitude of strength improvement and the relative strength improvement by unconfined compressive strength (UCS). Gow *et al.* (1961) performed California Bearing Ratio (CBR) tests to compact the treated soil sample in both soaked and unsoaked conditions in order to demonstrate the effectiveness of stabilizer. The highway accelerated loading instrument (HALI) was recently developed for the assessment of concrete block and asphalt pavement deformed during their lifetime in Technology University of Malaysia (UTM). It was designed to ensure that a full-scale life cycle assessment of the paving materials could be achieved. The examination of a pavement's durability is permitted since the design guidelines allow the evaluation of different base and surface materials.

Hence, there is a need to initiate a study to improve knowledge on stabilization techniques. An available solution for the stated problems is to improve the construction materials such as using active additives and/or waste polymer as the natural soil stabilizer for unpaved roads. The main aim of this study is to perform and improve the geotechnical and serviceability condition of unpaved roads by treated with proper mixtures of cement, lime, and waste tire crumbs. This experimental research was evaluated the durability and geotechnical strength properties of tropical laterite soils. The behaviour of treated laterite specimens were assessed to determine their impact on the improvement of unpaved roads constructed on the tropical climate. The study also focused on determination of soil rate durability, strength achievement, protection against weather conditions, and also providing long term sustainability.

1.2 Statement of the Problems

The response of geotechnical engineers to the growth in developmental projects, the difficulty in understanding soil conditions and the failures associated with tropical soils, and the need to address these failures and the related problems in the tropics, has led to the apparent increase in research on the tropical soil types and their engineering properties. The importance of laterite tropical soils cannot be more emphasized as they are being used as construction and engineering material for roads and airfield sub-bases and sub-grades in the tropics. In many regions, it is the dominant soil type. The research on the laterite soil significantly increased (Gogo-Abite, 2005). There is a strong intention for geotechnical engineers to adopt soil classification, testing methods, and preparing recommendations for temperate regions in order to classify the laterite soils in the tropical conditions. The reported testing methods presented for the temperate region soil classification often failed to predict the field performance of lateritic soils accurately. This is because the index tests are not usually reproducible for the lateritic soils (Tuncer and Lohnes, 1977). In addition, the environment in which the soil is located influences largely the development of soil texture, structure, and mineralogy (Gidigasu and Kuma, 1987; Nnadi, 1987; Skempton, 1953).

Tropical lateratic clays with high moisture contents is one of the most common soils in Malaysia particularly in Malaysian peninsular along the west coast at Johor and Malacca. The laterite deposits are formed under the tropical weathering conditions where precipitation is relatively high, and there is a good drainage to ensure leaching of cations and iron from acidic granitic rocks. The use of laterite soil, however, as subgrade are limited by a number of difficulties in construction such as their workability, field compaction, and insufficient strength.

During the past few decades, due to the fast growing economy, there has been an increasing demand in road transportations. This has forced governments to build more roads and interstate highways. On the other hand, the presence of weak clay deposits at various sites and the need for their replacement with a superior material has imposed great costs on the construction projects. In such problematic soils, chemical stabilization techniques have proven to be very effective (Eisazadeh *et al.*, 2010). Van

Herreweghe *et al.* (2002) reported that laterites are defined broadly as a group of soils that have undergone advanced weathering, with the leaching out of silica and a resultant increase in iron and alumina content. Most of the laterites, when plotted on the Casagrande plasticity chart, are close to the A-Line. Also, they tend to have high maximum dry density and low optimum moisture content. The engineering properties of laterites such as liquid limit and shear strength vary with depth (Van Herreweghe *et al.*, 2002).

The rural and/or forest roads are important elements in the economic progress of every country. It will help to promote procedures for health, income, facilitate future development, technology transfer, and education potential of the communities. Based on the fast growing development of Malaysia, it is essential to establish remote access roads on the natural or less populated areas. Almost all of the remote access roads are built to provide faster and better access to local villages or uninhabited areas from main roads or major cities. However, problems may arise during the construction of unpaved roads. Some of the major weakness of unpaved road are deterioration of the road surface, diffusion of dust on the road, and serviceability problems of these roads during the wet and dry seasons. The mentioned weakness become a source of problem even for a low traffic flow road and their maintenances and repairs is very costly.

An available solution for the stated problems is to improve the construction materials. The used construction materials through the construction of the unpaved roads could be stabilized by using various stabilization techniques. The supplies of lime and polymer in the mix form of hydrated lime and different types of polymers are relatively high in Malaysia. These mix forms can make lime and some polymers economically viable option for the treatment of tropical soils. However, due to an extensive variability in the amount of impurities dictated by extreme weathering conditions, for instance the high amounts of iron and aluminium oxides present in the laterite clays, the success of lime treatment technique has been rather conflicting. Furthermore, the acidic nature of tropical soils has raised doubts about the efficiency of soil-lime reactions in a low pH environment and hence the long term improvement (Kassim and Chern, 2004).

The implementation of lime, cement, shredded tire and waste polymers crumb as a soil stabilizer in an actual field project requires standard laboratory test on untreated and treated samples. The mentioned laboratory tests should be prepared under controlled conditions where it can be used to predict its potential effectiveness in modifying the engineering properties of tropical soils. This research study is focused on the unpaved roads constructed on the laterites in Skudai, Johor, Malaysia. It is related to pavement performances including design, construction specifications, maintenance procedures, and pavement management techniques. These items were reviewed in an effort to identify causes for early pavement deterioration in order to hopefully reduce the further maintenance costs. Substantial geotechnical testing were also performed to correlate the observed paving distress to existing unpaved road conditions.

1.3 Objectives of the Study

The aim of this research is to performance of unpaved laterite roads treated with chemical additives and waste tyre to ensure that the long-term geotechnical properties of treated material are sufficient to provide the structural capacity required over their design life's span particularly in Malaysia. The objectives of this research are:

1) To determine guideline for the basic geotechnical properties and physicochemical behaviour of stabilized lateritic soil with waste tire crumbs, lime and cement used in unpaved roads applications.

2) To estimate the optimum amount of stabilizer for the laterite soils to provide the necessary strength and geotechnical properties when it is used for unpaved roads.

3) To evaluate the structural performance and physicochemical behaviours of the treated laterite soils subjected to full-scale highway accelerated loading instruments (HALI) test at different loading cycles.

4) To carry out numerical simulations of the performance of the treated unpaved laterite road and compare with the results of laboratory tests using HALI.

5) To use close range photogrammetry technique as an easy and fast new method of surface measurement for unpaved roads.

1.4 Importance of Local Unpaved Roads

Unpaved roads are common in Malaysia across the rural and plantation areas. A familiar sight in rural communities, unpaved roads offers a sense of timelessness, helping residents connect with the days of cart paths and carriage roads. The unpaved roads often narrow and bordered by stone walls and mature shade trees. It is also often following an alignment parallel to streams and brooks. It will offer a scenic escape from the realities of concrete and pavement. The preservation of unpaved roads is important to the character of the landscape. Aside from their value as a scenic and often historic resource, unpaved roads have several advantage comparing to the paved roads such as; (i) lower construction costs, (ii) it requires less equipment and skilled operators, and (iii) it generate lower speeds than their paved counterparts. Yet, like paved roadways, dirt and gravel roads require regular maintenance to keep them passable and safe. Well-maintained dirt and gravel roads can serve traffic appropriately. Thereby, they are considered as a legitimate road surfacing option, not just something a community grudgingly maintains while it waits for paving.

1.5 Scope and limitation of the Study

The scopes of this research are:

- Tropical natural laterite soils collected from two different locations in Johor, Malaysia.
- The hydrated lime, cement, waste tire crumbs used as the stabilizers.

- Strength and geotechnical tests that they are performed with Unconfined Compression Strength (UCS), California Bearing Ratio (CBR) and HALI tests.
- The research also investigated the chemical and mineral composition of stabilized soils.
- Soils cured at 14 days under control room temperature of 27±2°c.
- Preliminary tests that carried out were: natural water content, particle size distribution, Atterberg limits, moisture-density relationship using standard Proctor effort, organic content, sulfate content, and mineralogy of the soil.
- The UTM geotechnics, highway, mechanic laboratories and Ibnu Sina institute were used further experimental investigation.

1.6 Significance of the Study

The unpaved roads constructed on the laterite soils are usually facing with many problems such as swelling, shrinkage, cracking, and may even be subject to waterlogged condition. Therefore, it is important to develop appropriate techniques to construct and/or repair old roads using chemical stabilizers. In this study, lime and cement were used as traditional stabilizer and the shredded and crumbs of scrap tire were introduced as a very low cost waste material that can be used to improve the strength and geotechnical properties of the laterite soils. Current study is also an effort to find the best active additive materials in order to reduce the construction cost of the new unpaved roads and their maintenances in the humid tropical climate. Comparison were finally made to find the most suitable combination of active additive and waste tire crumbs as stabilizer that could effectively improve the strength stabilized lateritic soil.

As stated earlier, the unpaved roads have the advantage of lower construction costs than paved roads, it require less equipment and skilled operators, and generate lower speeds than their paved counterparts. Yet, like paved roadways, dirt and gravel roads require regular maintenance to keep them passable and safe. Well-maintained dirt and gravel roads can serve traffic very satisfactorily, and should be considered as a

legitimate road surfacing option, not just something a community grudgingly maintains while it waits for paving.

1.7 Thesis Organization

This thesis aims to investigate the structural performance of stabilized unpaved road using chemical active additives mixed with mechanically scrap polymer materials. This is to ensure that the long-term durability of stabilized material is sufficient to provide the structural capacity required over the design life on different weather conditions encountered in Johor Malaysia.

In Chapter 1, a generally brief background on the role of physicochemical stabilization in soil improvement and the necessity to understand the mechanisms associated with this process is presented. The research philosophy divided into five main sections namely; ‘problem statement’, ‘objectives of study’, ‘scope of study’, ‘importance of local unpaved roads’, and ‘significance of the study’.

In Chapter 2, the fundamentals of laterite soil mineralogy are presented. This was essential as it helps to better understand and elucidate the sophisticated soil-physicochemical reactions. Different physicochemical stabilization techniques were reviewed, thereafter, followed by the hypothesized mechanisms suggested on the formation of reaction products. In addition, there is outline for the laboratory strength and geotechnical tests, full scale modelling techniques and methodologies employed in the previous studies. Finally, based on the current scientific knowledge on the soil stabilization a suitable research framework was obtained.

Chapter 3 provides a comprehensive description on the research methodology and laboratory experiments exercised for this research. It describes the physicochemical and geotechnical analysis, the basic data collection, and the conducted methods for this research. In addition, the microstructure analysis of untreated and treated soils are also explained in this chapter. The laboratory experiments that was performed to

determine the geotechnical and strength properties of the soil was according to the British Standard Institute. Furthermore, the characterization study of the stabilized soil using various spectroscopic and microscopic techniques were carried out based on the available standards and published papers. Moreover, it is stated that the numerical simulations were carried out based on the performance of the treated unpaved laterite road and compare with the results of laboratory tests using HALI and using close range photogrammetry technique as an easy and fast new method of surface measurement for unpaved roads.

Then, the obtained results from these tests are presented and discussed in detail in Chapter 4. Finally, Chapter 5 concludes the outcome of this study and highlights areas where further research can be carried out.

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