Thesis for Degree of Master

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STABILIZATION OF LATERITIC SOIL WITH EGGSHELL POWDER

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ABSTRACT

Stabilization of Lateritic Soil with Eggshell Powder

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In tropical regions, lateritic soil is used in road construction. Therefore, it is accused of being the source of failure of roads due to its high compressibility. There have been many kinds of research on improving the strength of lateritic soil and found many materials to mix with lateritic soil to enhance its strength. Cement and lime were the frequently used stabilizers for lateritic soil, but their environmental impact halted the user's interests. Some eco-friendly materials were also used, but their availability and cost made them less famous. Researchers tried recyclable materials such as eggshell, for they are available as food waste and share the same chemical composition as lime. The effects of eggshell powder on the strength of lateritic soil were remarkable even though they could not replace lime when used at the same concentration.

The particle size of eggshell powder that could be convenient for making a good binding and the effect of the protein-membrane present in the eggshell on its stabilizing capacity were not investigated.

This research was fundamentally based on laboratory experiments and checked through numerical analysis on-road usage. The aim was on the impact of particle size of the eggshell powder and the effect of protein membrane. The Atterberg limit revealed that the liquid limit fall and the plastic index also fall for different particle sizes, but there were no significant differences within different particle sizes. The particle size affected neither the maximum dry density nor the optimum moisture content. However, the unconfined compression strength was very distinctive for each particle size used. The particle size of eggshell powder less than 150μm and greater than 88μm was the convenient size that could make a good stabilizer with a 3% content concentration at optimum. The protein-membrane was found to be reducing the stabilizing ability of the eggshell powder when the content of eggshell powder is less than 4% in soil. The results obtained in the laboratory tests were used in numerical analysis, and the road embankment model testified the improvement of the sub base when stabilized with eggshell powder.

Keyword: Stabilization, Laterite, Eggshell powder, Laboratory test, Numerical analysis, Road

Chapter 1. Introduction

1.1. Background and objectives

Soil is a material that composes the crust of the earth. It is one of the main constituents of the roads and airfields, not only for being their foundation but also being the principal material used for their construction (Road Research Laboratory 1952). Several studies focused on the properties and the use of soil have uncounted difficulties when the natural soil could not perform the intended work because of the limitations of the soil strength (Ola, 1978). Hence, the improvement of soil strength has been a necessity in civil engineering works, and several researchers have developed different techniques to enhance the strength of the soil.

Some studies have developed several types of material that can enhance soil strength to a certain extent. Their impact in civil engineering was remarkable, for by utilizing those materials, people can handle many projects that seemed to be impracticable by classic material.

Furthermore, mixing soil with other materials for improving its strength has faced challenges based on the variety of soil properties and different use requirements (Rahman, 1986). Chemical materials are currently more commercialized in soil stabilization to ameliorate soil engineering properties, but their cost and environmental impact halted their use (Ojuri et al., 2017).

Lateritic soil is one of the soils used in road construction, especially in the tropical region. The poor workability, low strength, high compressibility, and insufficient bearing capacity for lateritic soil led to road failure in tropical regions (O. O. Amu & Salami, 2010). Studies made different stabilization mechanisms to improve the engineering properties of this type of soil. There are biomaterials used to stabilize lateritic soils. Those biomaterials are environmentally friendly and can reduce cost compared to the chemical industrial materials (Adeboje et al., 2017). In some studies, recycled materials such as eggshells were used, and their influence in the improvement of engineering properties of lateritic soil was considerably eminent at an extent where at a particular concentration they were able to perform as good as some other renowned stabilizer agent such as cement and lime (Oluwatuyi et al., 2018).

Eggshell and its protein membrane are waste food even though its structure reveals a natural source of calcium carbonate and protein. It shares the same chemical composition with lime, the prominent soil stabilizer (O. O. Amu & Salami, 2010).

In precedent studies, the effect of milled eggshell was evaluated based on its concentration when mixed with lateritic soil and compared with other stabilizing agents to evaluate the required concentration that would generate the same effect as other chemical industrial stabilizers. They investigated the possibility of replacing those chemical industrial-based agents. Thus a comparative test was conducted on the lateritic soil mixed with cement and milled eggshell of the particle size less than 75 micrometers, which enhanced the strength of soil to the satisfaction of the author (Oluwatuyi et al., 2018).

In consequence, they tackled the possibility of stabilizing lateritic soil with eggshell powder. However, it reported that the particle size of milled eggshell and the presence of the protein-membrane would affect the performance of the stabilizing ability of the milled eggshell (O. Amu et al., 2005).

This research aims to investigate the convenient particle size of the eggshell powder and the effect of protein-membrane in the stabilizing ability of milled eggshell. Further, the outcomes are constitutive parameters in numerical modeling of the road subbase.

1.2. Contents and scope

This research focuses on the use of eggshell powder to stabilize the soil. Eggshells are available as food waste. They need to be helpful not to burden the public, contrarily be a source of construction material in road construction and saving the environment.

The research is limited to engineering laboratory tests and the numerical analysis of road layers.

At first, the research targets stabilizing natural lateritic soil. However, the natural lateritic soil was unavailable to the author. A composite mixture of kaolinite clay that fulfills the chemical composition of natural lateritic soil clay was considered to replace the clay percentage in lateritic soil. The environmental effect on soil strength was observed, and the climate in tropical regions, typically Rwanda, was considered.

The research investigated the optimum content of the eggshell powder at an efficient low possible concentration, the convenient particle size of eggshell powder that would enhance the strength of the lateritic soil, and the effect of protein-membrane on the strength of the soil. The relevant soil mixture scenarios were observed in a scanning electron microscope.

Laboratory tests such as basic geotechnical tests (sieve analysis, Atterberg limit, etc.), compaction tests, and unconfined compression tests were performed.

The relevant result was used in a numerical analysis of a road design considering the improvement of the subbase layer.

Chapter 2. Materials

2.1. Overview

In this research, the material was selected based on previous research on improving the engineering properties of lateritic soil using non-industrial chemical material, preferably recyclable materials.

Lateritic soil was involved in this research because it is a type of soil widely available in tropical regions. It is commonly used as a predominant material in the tropical region for road construction.

The eggshell powder was typically introduced in this research to recycle food waste that could reduce the expenses that appropriately go with its disposal. Eggshells could be a source of income for countries that are not industrially developed as it would require fewer preparation skills, and machinery for the row material would be available.

O. O. Amu & Salami (2010) defines soil stabilization as a process of improving some soil properties to make it more useful for a specific purpose. Soil stabilization can be done by mechanical means of mixing various materials. its effectiveness relies on obtaining a uniform mixture, the amount of required stabilization, and the conditions for use.

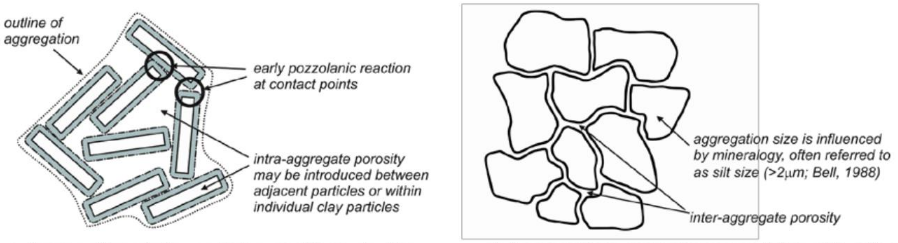
Lime is one of the stabilizers mixed with soil when mechanical stabilization of soil cannot provide the required geotechnical properties. Commercially, Lime is available in two forms: quick lime (calcium oxide), which is more effective but very corrosive to equipment and causes burns to personnel of skin damage, and hydrate lime of slaked lime in some literature (calcium hydroxide) recommended by Ingles and Metcalf (1992). When lime gets mixed with soil responds as summarized in <Table 2-1>.

<Table 2-1> Response of soil treated with lime (Beetham et al., 2015)

Treatment intent	**Physico-chemical process**	**Common terminology**	**Indicative lime requirements**	**Typical time required***
Lower the moisture content of wet /low strength soil towards OMC. Either for compaction as a general fill or to enhance trafficability.	1. Removal of free moisture by reaction with quick lime; 2. Cation exchange/clay mineral aggregation effectively increasing the OMC.	Lime Improvement	Low, e.g.0.5-0.4%. (initial moisture content/clay content dependent)	1. Immediate 2. Rapid (0-72 hours)
Reduced plasticity/ potential for volume change	3. Cation exchange/ clay aggregation reduces clay mineral's effective surface area and affinity for water. 4. Allow Early pozzolanic reactions restrict subsequent dispersion of aggregations	Lime improvement	↓ Increasing	Rapid (0-72 hours)
Substantially improved engineering properties, i.e., strength, stiffness, and durability.	5. The pozzolanic reaction between lime-clay soil system.	Lime stabilization	Above the ICL value, e.g.2-10%; (actual binder addition determination by site-specific mix design)	Ongoing improvement from 72 hours continuing for months/ years

a. Diffuse double layer is initially deep, causing clay particles to align in a disperse arrangement

b. Substitution of Ca^{2+} cations for Na^{+}/K^{+} cations reduces diffuse double layer thickness



c. Aggregation of clay particles as diffuse double layer 'buffer' reduction results in repulsion of like charges on clay particles

d. Aggregations act as larger particles with adjacent surfaces separated by inter-aggregate pore-space

<Figure 2-1> Sequence of lime-clay reaction(Beetham et al., 2015)

However, lime increases the pH value of the soil that makes it highly alkaline(Diamond & Kinter, 1965). Works of literature show that Lime stabilization is a known technique long ago as and its efficiency was remarkable. In road construction, lime was used to stabilize either subbase, subgrade and not frequently used to stabilize base material (Christopher et al., 2006).

Lime stabilization significantly reduces liquid limits, the plastic index for clay soil, the optimum dry density, and swell. It increases the moisture content and strength of the expanding clay., unconfined compressive strength and the cohesion increased with the increase of the lime content; furthermore, the internal angle of friction reduced considerably (O. Amu et al., 2005).

Researchers done on the lime stabilization for different soil types gave different results but mainly converged that lime is a potential soil stabilizer, especially for road usage.

Different soils stabilized by lime, and its results of the effects obtained are in <Table 2-2> below(Christopher et al., 2006).

<Table 2-2> Examples of characteristics of soil stabilized with lime (Christopher et al., 2006)

		Atterberg Limits			Strength	
Soil	Lime %	*LL*	*PL*	*PI*	q_u[a]	CBR
1. CH, residual clay[b]						
(a) Site 1, Dallas–Ft.	0	63	33	30	76	
Worth Airport,	2	62	48	14	123	
residuum from Eagle	3	60	47	13	202	
Ford shale, Britton member	4	56	46	10	323	
(b) Site 2, Dallas–	0	60	27	33	70	
Ft Worth Airport,	2	48	32	16	171	
residuum from Eagle Ford	3	45	32	13	177	
shale, Tarrant member	5	48	34	14	184	
(c) Site 3, Irving, Texas,	0	76	31	45	64	
residuum from Eagle Ford	2	61	45	16	116	
shale, Britton	3	56	45	11	193	
member	5	57	45	12	302	
2. CH, Bryce silty clay,[c]	0	53	24	29	81	
Illinois, B-horizon	3	48	27	21	201	
	5	NP	NP	NP	212	
3. CH, Appling sandy loam,[d]	0	71	33	38	92	
South Carolina, residuum	3				147	
from granite	6				171	
	8				206	
4. CH, St Ann red bauxite	0	58	25	33	119	
clay loam,[d] Jamaica,	3				127	
limestone residuum	5				334	
5. CL,[e] Pelucia Creek Dam,	0	29	18	11		
Mississippi	1	32	19	13		
	2	31	22	9		
	3	30	21	9		
6. CL, Illinoian till, Illinois,[c]	0	26	15	11	43	
glacial till	3	27	21	6	126	
	5	NP	NP	NP	126	
7. SC, sandy clay, San Lorenzo,	0	54	23	31		8
Honduras[f]	5	61	38	23		20
8. MH, Surinam red earth,[d]	0	60	32	28	72	
Surinam,	3				130	
residuum from acidic	5				136	
metamorphic rock						
9. OH, organic soil with 8.1%	0	63	27	36	4	
organics[g]	2			36	4	
	4			24	8	
	8			25	7	

[a] Unconfined compressive strength in psi at 28 days unless otherwise noted; different compaction efforts used by investigators.

[b] McCallister and Petry, 1990, accelerated curing.

[c] Thompson, 1966.

[d] Harty, 1971, 7-day cure.

[e] McElroy, 1989.

[f] Personal communication, Dr. Newel Brabston, Vicksburg, Mississippi.

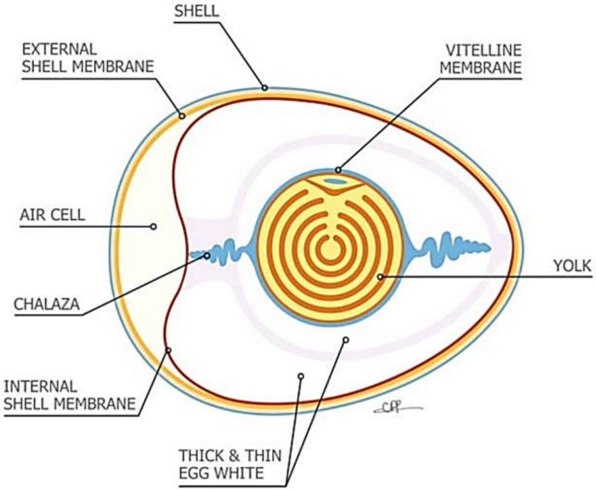
[g] Arman and Munfakh, 1972, limits at 48 hours, q_u at 28 days, strength samples prepared with moisture content at the *LL*.

2.2. Eggshell

Most birds, reptiles, and formerly dinosaurs produce calcareous eggs in their reproduction process (Hincke et al., 2012). According to Pennington (1933), eggs were included in the human diet as a prized food since the prehistorical time where the domestication of chicken and other birds was not yet started. From many birds, species chicken is the most raised livestock (FAO,2012). In particular developing countries such as Africa, it was found that poultry is trending mainly for consumption and cash sales(Eugene et al., 2020).

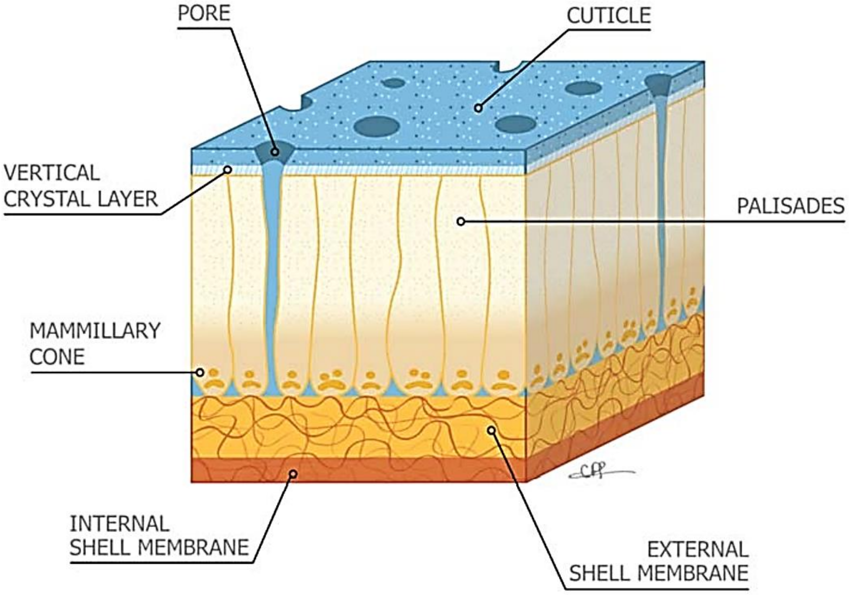
In a country like Rwanda, where commercial poultry is at its infancy stage (Miklyaev et al., 2017), the egg production from indigenous chickens was 243.7 million annually in 2017 (Cocchini & Steeg, 2019). However, egg consumption per capita is still low compared with the FAO recommendations.

Many researchers used the eggs of domestic chicken in their studies for it is readily commercially available as human nutrition. Biochemical studies were conducted on the structure and chemical composition of an egg and each component that forms the entire egg.



<Figure 2-2> Longitudinal section of a chicken egg (Hockle et al.2014)

The eggshell is defined as the outer covering of the egg. It has gone through evolution to resist physical and pathogenic challenges that the egg was facing from the external terrestrial environment. It essentially serves for metabolism and nutrition for the embryo by letting water and gas exchange and being a calcium store (Vicent, 1990). Eggshell types are categorized into three categories: membrane-like for snakes and lizards, rigid for all birds, some turtles, all crocodiles, some gecko and dinosaurs, and finally, the pliable type for most turtles (Hincke et al., 2012).



<Figure 2-3> Cross-sectional view of chicken eggshell: (Hincke et al.2012)

The eggshell structure generally is protein matrix lines with mineral crystals. It is mainly a composition of calcium carbonate with the trace of magnesium boron, manganese, copper, silicon, iron, molybdenum sulfur, zinc, and arsenic (bee, 2011).

It has been confirmed by biochemical and immunological tests to consist of collagen that there is hydroxyproline in hydrolysates of membrane layer of the eggshell membrane (Hendrix et al., 1984). Collagen is one of the types of fibrous protein found in nature. It can connect and support other bodily tissues and internal organs, It can be found in teeth, and It has excellent tensile strength. Bovines, swine skins, and bones are the primary sources for collagen in the pharmaceutical, biochemical and cosmetic industries. However, there is an enforcement on the trade of collagen due to the outbreaks of bovine mad cow disease, foot, and mouth disease, and autoimmune (King'ori, 2011). For eggshell membrane is high in bio-safety and has very low autoimmune and allergic reactions (Frank et al., 2005).

The physical and chemical characteristics of eggshell and eggshell membrane showed that the pore properties of eggshell were similar to the one of the eggshell membrane, and the trues density was quite different from the two biomaterials. It was also found that the two are nonporous and/or macropores in nature (Tsai et al., 2006).

2.3. Lateritic soil

Overview.

Usually, lateritic soil is founded in wet tropical and subtropic regions with a hot climate and annual rainfall of 150mm to 300mm. The formation of lateritic soil is basically from the removal of silica (lateralization), alkali, and alkali earth from the weathered soils. The concentration of iron and aluminum oxides determines the lateralization difference in temperate climatic weather and producing clay (hydrous aluminum silicate) (Goldish, 1987). A Soil material of low concentration of oxides with fine-grained sands, gravel, and soft rocks and a porous of vesicular appearance is referred to as lateritic soil. The particles of some lateritic soil are easily crushable when are subjected to an impact that makes its soil material plastic (O. O. Amu & Salami, 2010).

Lateritic soils appear as being in a wide variety of red, brown, and yellow with a light texture and cemented soil (O. O. Amu & Salami, 2010). The presence of Iron and aluminum oxides determines the color of the soil material. The degree of lateralization is estimated from the ratio of silica to sesquioxide ($SiO2/Fe2O3 + Al2O3$) (Of et al., 2020)(Oluwatuyi et al., 2018).

History of lateritic soil.

A French naturalist named Henri Mouhot, while crossing the jungles of Indochina in 1860 searching for species of plants, about 150 miles north of Phnom Penh, the from the capital of Columbia he comes on tangled wildness where he saw the sculptured towers of the ancient temple that were later proven to be for a lost civilization that was in that area from 19th to 16th century.

There was a great walled city, Angkor Thom, and other edifices just nearby the temple. The other wooden structure parts were long ago decayed, but the walls, floors, stairs, towers, and sculptures' works were still standing firmly without being touched by the time. They reported that those structures were made with sandstones and a durable material that rich in minerals. When exposed to air, it turns into the brick-like form of rock where it gets its name “laterite” from the Latin word for brick given by Dr. Francis Buchanan-Hamilton. (American et al., 1964).

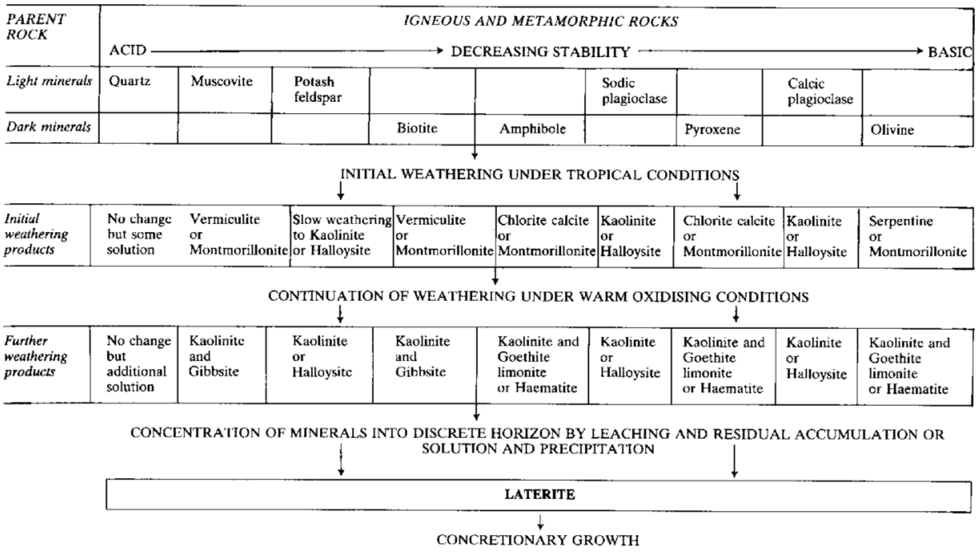
Formation of lateritic soil.

Lateritic soil is the result of lateralization, a function of soil climate-related to atmospheric climate. It is formed from the leaching of soil mainly due to heavy rainfall and other tropical weather conditions. The high temperature and heavy rainfall that last the year in tropical regions are the fundamental cause of soil lateralization in the region. The luxuriant growth of bacteria, insects, earthworms, and other organisms that aerate the soil and break down the organic matters in soil are produced due to the high temperature and dampness that characterizes the weather of the tropical region. The soil is much porous. The oxygen in the air is easily permeating the soil, oxidizes the aluminum and iron in the soil, and makes it chemically acidic and low in silica (American et al., 1964). Netterberg (2014) reported the formation of Laterite in three phases of action to be produced:

- The minerals of Laterite need humid tropical weather
- These minerals have to be concentrated in a discrete zone
- And the development of Laterite has to be concretionary within the horizon

According to Charman (1988), around 250C of mean annual temperature and seasonal warm and wet period with at least 750mm annual rainfall are required for laterite formation.

The following table summarises the process involved to form Laterite in the tropic was reported by Charman (1988).



PARENT ROCK	*IGNEOUS AND METAMORPHIC ROCKS* ACID → DECREASING STABILITY → BASIC								
Light minerals	Quartz	Muscovite	Potash feldspar			Sodic plagioclase		Calcic plagioclase	
Dark minerals				Biotite	Amphibole		Pyroxene		Olivine

INITIAL WEATHERING UNDER TROPICAL CONDITIONS

Initial weathering products	No change but some solution	Vermiculite or Montmorillonite	Slow weathering to Kaolinite or Halloysite	Vermiculite or Montmorillonite	Chlorite calcite or Montmorillonite	Kaolinite or Halloysite	Chlorite calcite or Montmorillonite	Kaolinite or Halloysite	Serpentine or Montmorillonite

CONTINUATION OF WEATHERING UNDER WARM OXIDISING CONDITIONS

Further weathering products	No change but additional solution	Kaolinite and Gibbsite	Kaolinite or Halloysite	Kaolinite and Gibbsite	Kaolinite and Goethite limonite or Haematite	Kaolinite or Halloysite	Kaolinite and Goethite limonite or Haematite	Kaolinite or Halloysite	Kaolinite and Goethite limonite or Haematite

CONCENTRATION OF MINERALS INTO DISCRETE HORIZON BY LEACHING AND RESIDUAL ACCUMULATION OR SOLUTION AND PRECIPITATION

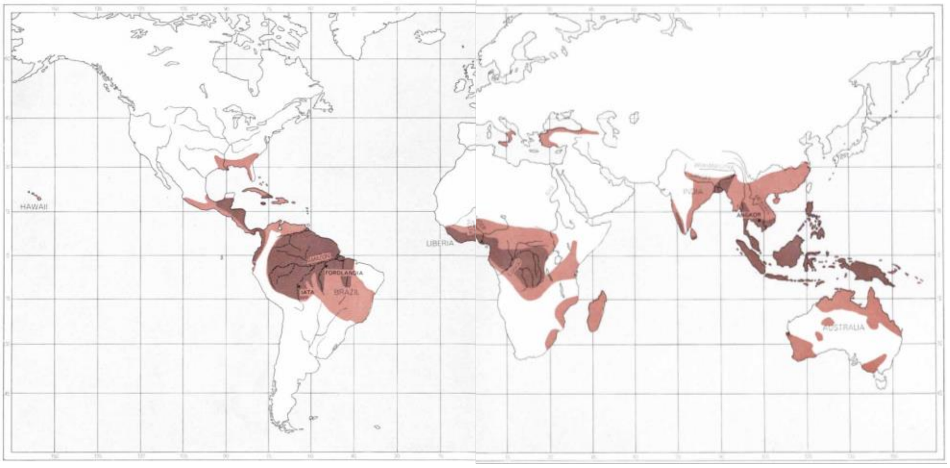
LATERITE

CONCRETIONARY GROWTH

<Figure 2-4> summary of the laterite formation process (Charman 1988)

Lateritic soil frequent location.

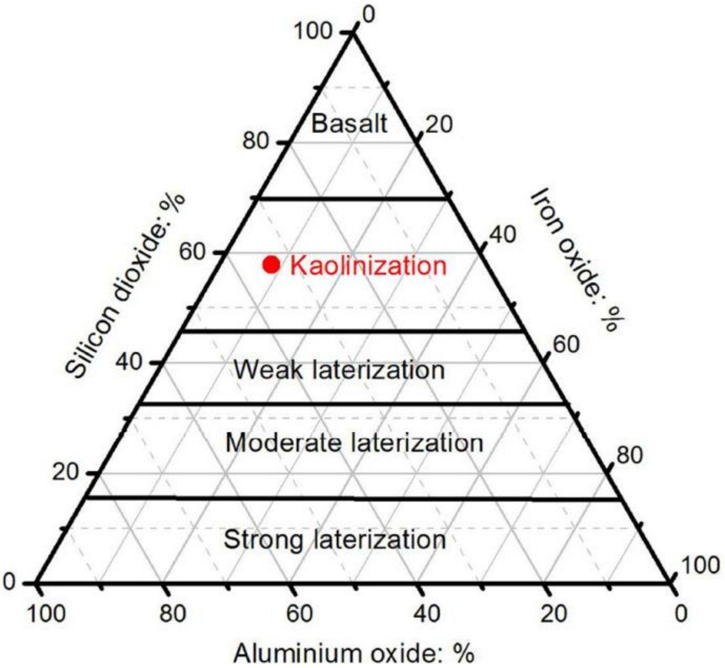
In the tropical region, from 30 degrees north to 30 degrees south, it is where mostly the lateritic soil naturally dwells. For lateralization is a climate function, the various type of underlaying rock that shows the layers of Laterite have been observed in the strata of exposed hillsides in southeast Asia, India, Afirca< Australia Central America, and South America. It is significantly covering the basins and great plain where they have been deposited and raised due to the uplift of the earth’s surface to form plateau and hills(American et al., 1964).



<Figure 2-5> Map showing the extent of lateralization(American et al., 1964)

Characteristics of lateritic soil.

Lateritic soils usually appear to be rusty red or yellow depending on the concentration of iron and aluminum content that accounts for its color. Thurston, E. (1913) reported that Laterite soil deffer from other residual soil from the fact that it contains alumina mainly in a free state that makes it closely resembling bauxite, the source of aluminum.The parent material of the lateritic soil is chemically rich in iron and aluminum oxides and hydroxides(sesquioxides). Its clay minerals are mainly kaolinitic, and from the above effect, the silica content is reduced (Netterberg, 2014). The iron and aluminum oxide (sesquioxides) content mainly governs the strength of the concretions and the extent to which the concretion particles have been dehydrated. Sufficient hydrated oxides of iron and aluminum are needed to act as catalysts for cementation or start a precipitation growth in the development of concretions. In return, the engineering properties of the laterite materials significantly depend on the degree of development of the concretion that reflects its appearance (Frank Netterberg, 2014). Laboratorio Nacional de Engenharia Civil (LNEC) et al., 1959, 1969): Defines the lateritic soil as soil with clay fraction of molecular composition silica-sesquioxides ($SiO2/R2O3$) ratio (S/R ratio) less than two and of low expansibility. The S/R ratio is a necessary precaution for applying the ”relaxed” specifications of lateritic soil in Bresil (Frank Netterberg, 2014).



<Figure 2-6> Ternary diagram showing the composition of lateritic soil and laterite (Oluwatuyi et al., 2018)

Netterberg (1985) reported the typical chemical composition of lateritic material, and again Netterberg (2013) summarised the sesquioxide minerals accounted in laterites, respectively, as shown in <Table 2-3>.

<Table 2-3> Examples of lateritic soil chemical composition(Frank Netterberg, 2014)

Component	% By Mass	Main form of occurrence
SiO_2	5 - 70	Quartz, feldspar, clay minerals
Al_2O_3	5 - 35	Feldspar, clay minerals, gibbsite
Fe_2O_3 [2]	5 - 70	Goethite, hematite
TiO_2	0 - 5	Anatase, rutile
MnO	0–5?	?
P_2O_5	0-1	
H_2O +	5 - 20	Clay minerals, goethite, gibbsite
Loss on Ignition	5 - 30	Clay minerals, goethite, gibbsite, organic matter
Organic matter	0,2 - 2	Organic matter

Notes:

[1] Bauxites are excluded.
[2] Total iron as Fe_2O_3.

<Table 2-4> Lateritic soil clay's major characteristics (F. Netterberg, 1994)

Major Element	Mineral [1]	Composition [2]	Colour [2]
Fe	limonite [3]	$Fe{\cdot}OH{\cdot}nH_2O$	yellow to brown
	goethite	$\alpha - FeO(OH)$	yellow to brown to black
	lepidocrocite	$\gamma - FeO(OH)$	orange
	haematite	$\alpha - Fe_2O_3$	red, reddish brown to black
	maghemite	γ - Fe_2O_3	reddish brown
	magnetite	Fe_3O_4	Iron black
	ferrihydrite	$Fe_5HO_8{\cdot}H_2O$ [4]	reddish brown
Al	gibbsite	$\gamma - Al(OH_3)$	white, greyish, greenish or reddish white
	boehmite	$\gamma - AlO(OH)$	white, grey, pale lavender, yellow-green
	diaspore	α –-AlO(OH)	white grey, pale lavender, yellow-green
Mn	pyrolusite?	MnO_2	iron black
	manganite?	MnOOH	grey to black
Ti	anatase	TiO_2	red, reddish brown to black
	rutile	TiO_2	red, reddish brown to black
	ilmenite	$FeTiO_3$	Iron black

Geotechnical properties.

Three factors govern the geotechnical properties of laterite soil (AFCAP,2014) reported.

- Parent rock or characteristics of the weathered rock
- The development stage as the lateralization
- The nature of the repacing minerals (Sesquioxide)

Laterite can exhibit some differences in behavior compared to the other traditional soil(soil formed in the temperate zone) for it the clay mineral and cementing and replacing minerals in laterite are different from the traditional soil formed in a temperate zone, which consists of discrete particles that have been already derived through current geotechnical experiences and specifications.

In fact, during the development of Laterite, clay, silt, and sand particles tend to flocculate, aggregate, and cemented into particles of silt to the gravel size. Moreover, the strength and porosity vary, making these particles break or not in a laboratory test or during construction.

For example, the water content and Atterberg limits in traditional soil mechanics are assumed that water is outside the particles. In lateritic soil, the porous particles will increase the moisture content determination and the Atterberg limits.

Kaolinite being the predominant clay mineral in lateritic soil makes the material less likely to expand when wet even though the sesquioxides in Laterite may hydrate. Morin and Todor (1976) came out with an account of “relaxed” specifications adopted to Laterite compared to the traditional specifications.

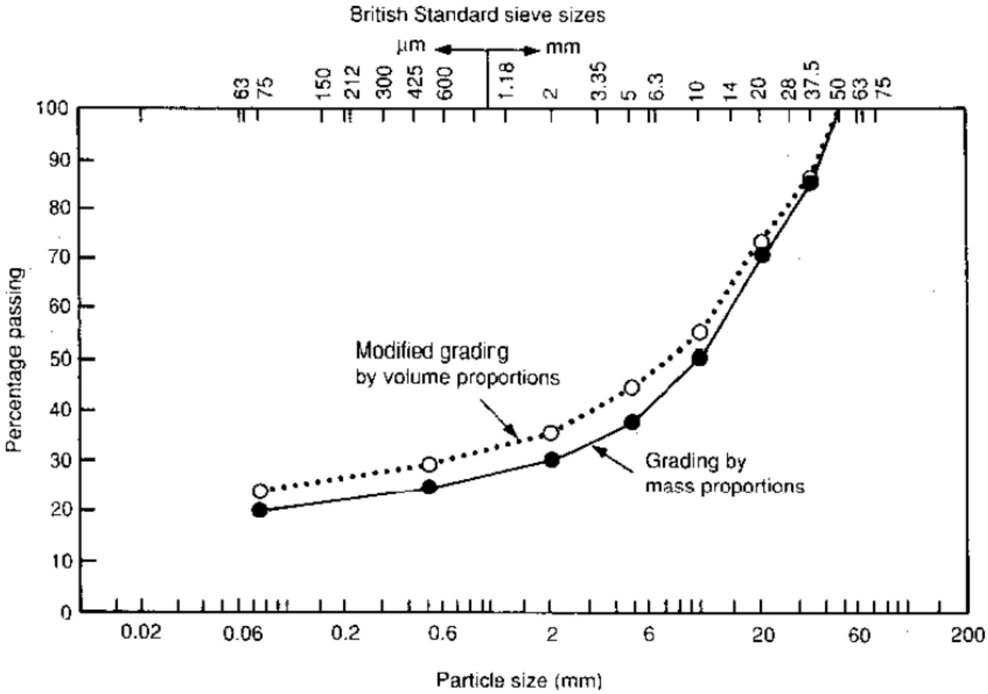
Therefore the actual engineering test results for Atterberg limits and grading can not be interpreted based on the traditional soil mechanics to understand its geotechnical behavior.

Here are the relevant geotechnical properties that govern the performance of Laterite in general:

- Particle size distribution
- Atterberg limit
- Coarse particles strength
- Bearing strength and compaction
- Time-dependent improvement

Particle size distribution of soil reveals the sizes of different particles that form a soil material. In immature laterite soil, grading analysis is essential than in mature Laterite. The analysis depends on the test and calculation method adopted (Frank Netterberg, 2014). While assessing laterite material using grading analysis, its composition has to be assessed for if the difference in Bulk relative density (BRD) of the fines and the coarse portion is significant, the grading should be calculated based on the volume proportion and by mass proportion and if the difference is not significant the mass grading is used considering the BRD to be constant throughout the whole soil mass. It is recommended to use the wet sieving method and avoid any tendency to fracture the coarse particles during the sample preparation.

Charman (1988) presented the difference in curve grading based on mass or volume proportion.



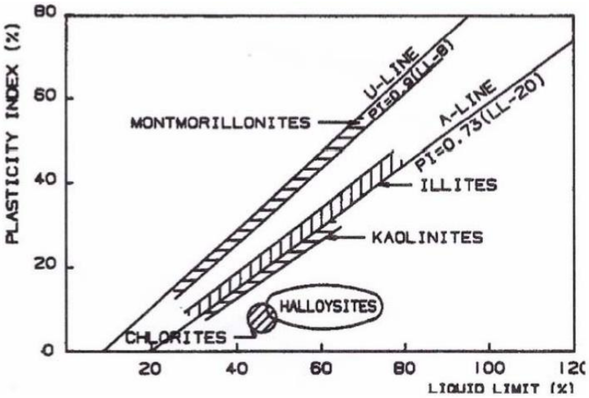
<Figure 2-7> laterite material particle size distribution (Charman,1988)

Krinitsky et al. (1979) reported a range from 2.67 to 3.46 with a mean of 3.06 to be the values of the Apparent relative density (ARD) for 28 laterites on a worldwide basis. On the other hand, Gidigasu(1979) reported values from 2.2 to 4.6 considering the fraction that passes a 2mm sieve. Therefore laterite ARD is high than 2.65, which is assumed to be for most traditional soil (Frank Netterberg, 2014).

Atterberg limits (PI and LL) are defined as the essential geotechnical measurement of critical water content for a typical fine-grained soil (ASTM,2010).

For traditional soil, Atterberg limits are one of the most used specifications in fine-grained soil classification (Craig, 1992). However, Atterberg Limits in lateritic soil presents some complication for the prediction of the geotechnical behavior. The plasticity of Laterite varies mainly in seven ways. Within the material itself, it can be identified that, from one borrow pit to another and within the pit because of the stages of lateralization in the material.

Secondary, the fine grains sample preparation may lead to the difference in the result based on preparation while drying and reworking. Thirdly this test is sensitive to the drying conditions, whether it is in an oven or air-dried. <Figure 2-8> indicates the difference between air drying and oven drying on lateritic soil; therefore, it is recommended to set the dying condition at a temperature between 50 and 600C for Laterite. Forth the mixing period affects the values of Atterberg limits on lateritic soil. Fifth is the standards that are used in the test; it is quite different results when BS and AASHTO are taken for the testing procedure. Sixth is how the data are plotted on the Casagrande plasticity chart; <figure 2-9> shows that Laterite and lateritic soil are plotted on both sides of the A-line contradictory based on the formal specification. Seven is the swelling of lateritic soil, which is low even though the Atterberg is high (Townsend et al., 1988).



<Figure 2-8> location of common clay minerals on Casagrande's chart (Morin and Todor,1976)

Silica/sesquioxide ratio is an important parameter to classify laterites and the prediction of their behavior. Charman (1988) proposed 2 as the maximum value to define Laterite; moreover, another author (Persons, 1970) has described 2 as maximum for lateritic soil and 1.33 for Laterite.

Oluwatuyi et al. (2018) have used [$SiO_2/(Al_2O_3 + Fe_2O_3)$] to determine the S/R value in his test, on the other hand, (DNIT, 2010) Brazil standard recommends the following formula:

$$\frac{S}{R} = \frac{\frac{SiO_2}{60}}{\frac{Al_2O_3}{102} + \frac{Fe_2O_3}{160}} \qquad \text{Eq (2.1)}$$

where; SiO2:Silica and Al2O3 + Fe2O3: Sesquioxide

Even though different methods and approaches are used in different literature, the ranging values do not change. However, the sample size selection appears to be another problem for some researchers who use fine fractions; others use the entire grading.

Compaction of Laterite is also a parameter that could not be rejected while studying the geotechnical behavior of Laterite. During the compaction test, the optimum moisture content (OMC) is identified, and the maximum dry density (MDD) is then calculated (Craig,1991). However, the sample preparation affects the result while dried in an oven or air-dried (Morin & Todor, 1977).

Triaxial and resilient properties are essential in modern mechanistic-empirical analysis and design modering technics. The Poisson's ration and resilient modulus are parameters trending in the design modeling. Commercial laboratories do not widely do this test for it is costly and more specialized; it has been left for research laboratories. Even if this test is not routinely carried out, it is essential to understand the behavior of soil material when loaded. A simplified method of triaxial test, which is an unconfined compression test, has served much research to predict the behavior of soil material numerically (Nogami & Villibor, 1991).

Hardening and self-stabilization of lateritic soil material were the first definitions given to thee. When DR Buchanan tried to define laterites, he emphasized their ability to harden with time after being watered and dried. He attributed the hardening ability to Kaolinite and Iron in the material(ALEXANDER & CADY, 1963). A high concentration of Iron in the material can seem to be weak but performs much better than a much stronger material in wet conditions; that strength comes to the fact of its formation under alternate wet and dry conditions while in situ (Frank Netterberg, 2014). The test method adopted to view the self-stabilizing ability of laterite material includes the petrification degree test and the soaked CBR. Different authors reviewed this test to be efficient when the material is soaked after being compacted in a mold and let for wetting and drying cycles. Five times were recommended to be more efficient (Gidigasu, 1974).

There are more properties to identify the difference between Laterite and other soil material, but the listed above are essential to the author's knowledge. Other properties such as aggregate strength/hardness/ durability and DN values are listed by other research. However, the indicator values are not highlighted to differentiate laterite soil from other soils material.

The use of lateritic soil.

Laterite soil has been in use from early in the prehistoric time as the sculpture of the ancient civilization indicates like it has been observed in the city of Angkor Thom in Khmer civilization. Until now, Laterite is used in construction, mainly in building construction where it is used to make brocks and bricks, in dam construction where the fill of embankments are made by laterite soil, and in road construction where it can be suitable for different layers of the road section(American et al., 1964).

Building construction in the tropic and subtropic regions is mainly based on the local materials. It focuses on low-rise houses as many developing counties are located in the said region. Therefore the use of Laterite in brick and block fabrication is widely spread in the region. The main criteria for construction material are the frost resistance in the region out of the tropic (developed counties), where the weather is so cold compared to the tropical region. However, the compressive strength and the erosion resistance are only enough to satisfy the requirement of a building in the tropical region. (Mbumbia et al., 2000).

Dams also are made for different purposes in which we can highlight for the reservoir of water, water supply, Irrigation, Hydropower, and transportation. Laterite is used as a filling material for small dams, especially in developing countries located in the tropic and subtropical regions. Its efficiency was notably excellent and recommended by several reports (Stephens & FAO, 2010).

Laterite is further used in road and highway construction in different areas worldwide, especially South Asia, Brazil, and Africa (American et al., 1964). Road and highways are vital infrastructures for a nation, and governments invest much money in constructing roads. However, in developing countries, besides efforts made by governments, the cost of roads and highways are still high compared to be capacity and the wealth of the country. Moreover, the research on material that can reduce the cost spent on low volume roads are being done by other research, and some have come out with the proposal that seems to satisfy the problem to a certain extent even though the improvement of the existing research is required (Frank Netterberg, 2014).

Researches reported Laterite to have some unique geotechnical properties in road construction that are often not conforming with the test result of other materials and make it behave differently as it can be predicted using the conventional specification requirement. For the above reason, Laterite has been rejected for use even though it has proved to surprisingly perform well in road construction (Frank Netterberg, 2014). Gidigasu and Dogdey (1980) reported poorer grading laterite than local residual granitic gravels in Ghana, but the poor grading laterite performed well.

The preparation of Laterite in the laboratory leads to a poor grading amid its nature particle size distribution for many particles are broken during sample preparation before testing. Therefore the results in the laboratory are different to as-built conditions. Material of weak aggregates particles in gravel size range needs good particle size distribution approach to make enough grain sizes particles to fill the voids to allow contacts of gravels that improves the support for larger particles and make them bearing larger loads without fracturing as the internal stress has reduced. Letting coarse aggregates floating in the fines is an approach that is inferior to the continuously graded material. Furthermore, frost damage is a fundamental fact that led to many limits for the fines in the road construction material currently set in a temperate climate yet is not a threat in the tropical region (Frank Netterberg, 2014).

Literature exposes numerous specifications with different requirements based on local experiences that different road authorities have proposed. North America (AASHTO M147-65,2011) developed formal material specifications applied in many places in the world. However, it was founded that they were too conservatives for other soil materials such as lateritic soil in terms of grading and plasticity requirements. Some of le local authorities in the tropical region developed empirical specifications for Laterite available locally. Researchers also proposed different criteria for the selection of materials depending on their use and general specifications.

Charman (1988) recommended the criteria for selecting lateritic gravels to be used in subbase and base under a thin bituminous concrete surface in the tropical region.

<Table 2-5> lateritic soil characteristics for use in road construction (source: Charman, 1988)

USE	ROAD BASE			SUB-BASE
TYPE OF ROAD	MINOR	MAJOR RURAL	AND URBAN	ALL
TRAFFIC (X10^6 esa)	<0.3	0.3-1	1-3	<3
Grading	Grading Modulus ≥1.5[1]	Grading envelopes in Charman, 1988.		specifications
Plasticity index (%)				
Moist, wet tropical	≤ 12	≤ 10	≤ 6	≤ 25
Seasonal tropical	≤15	≤12	≤10	≤25
Semi-arid & arid	≤ 20	≤ 15	≤ 12	≤ 25
Plasticity modulus [2]				
Moist, wet tropical	≤ 300	≤ 200	≤ 150	≤ 500
Seasonal tropical	≤ 400	≤ 250	≤ 200	≤ 750
Semi-arid & arid	≤ 500	≤ 350	≤ 250	≤ 1 250
CBR (%)	≥ 45 [3]	≥ 65 [4]	≥ 80 [4]	≥ 25 [3]
Durability				
Los Angeles Abrasion value (%) [5]	≤ 65	≤ 50	≤ 50	n.s
10% fines value (saturated) (kN)	n.s	≥50	≥50	n.s.

NOTES:

n.s. = not specified

[1] Grading modulus = $\frac{300-(P2.0+P0.425+P0.075)}{100}$

Where P2.0 is percentage passing 2 mm sieve
P0.425 is percentage passing 0,425 mm sieve
P0.075 is percentage passing 0,075 mm sieve
Values of grading modulus are between 0 and 3.

[2] Plasticity modulus = plasticity index multiplied by percentage finer than 0.425 mm sieve.

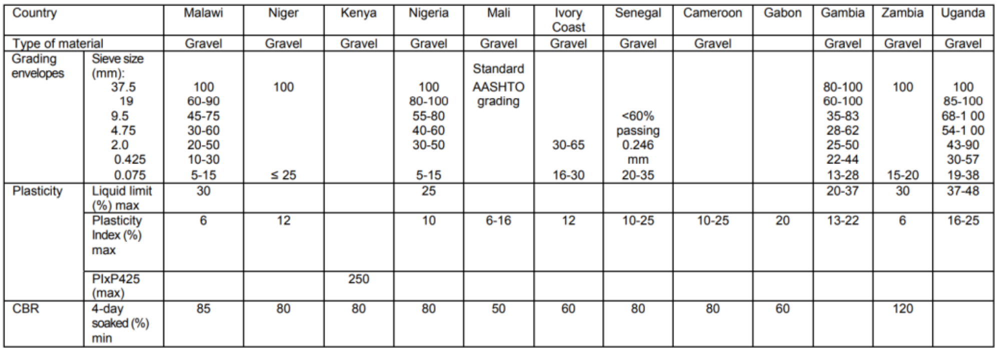
[3] CBR on samples compacted to 95% of modified AASHO or BS (heavy) MDD and soaked for 4 days.

[4] CBR on samples compacted to 100 % of modified AASHO or BS (heavy) MDD and soaked for 4 days.

[5] Los Angeles abrasion value on fraction coarser than 2 or 2.36 mm.

Krinitzsky et al. (1976) also summarized the specifications of base courses for some African countries where laterite soil use is predominant, and relaxation on traditional specification is allowed.

<Table 2-6> Laterite specifications by countries (Krinitzsky et al.,.1976)



Country		Malawi	Niger	Kenya	Nigeria	Mali	Ivory Coast	Senegal	Cameroon	Gabon	Gambia	Zambia	Uganda
Type of material		Gravel	Gravel	Gravel	Gravel	Gravel	Gravel	Gravel	Gravel		Gravel	Gravel	Gravel
Grading envelopes	Sieve size (mm):					Standard AASHTO grading							
	37.5	100	100		100						80-100	100	100
	19	60-90			80-100						60-100		85-100
	9.5	45-75			55-80			<60% passing 0.246 mm			35-83		68-1 00
	4.75	30-60			40-60						28-62		54-1 00
	2.0	20-50			30-50		30-65				25-50		43-90
	0.425	10-30									22-44		30-57
	0.075	5-15	≤ 25		5-15		16-30	20-35			13-28	15-20	19-38
Plasticity	Liquid limit (%) max	30			25						20-37	30	37-48
	Plasticity Index (%) max	6	12		10	6-16	12	10-25	10-25	20	13-22	6	16-25
	PIxP425 (max)			250									
CBR	4-day soaked (%) min	85	80	80	80	50	60	80	80	60		120	

Previous studies to improve lateritic soil.

The specification was done to make lateritic soil usable in several countries, but some of the laterites do not fulfill the required specification for some specific purpose. Therefore, research was done to improve and stabilize lateritic soil to make it more suitable for either base course or subbase. Researches attempted to stabilize lateritic soil for roads and highway use by adding different admixtures.

<Table 2-7> Summary of the response of lateritic soils to different improvement as reported in the literature

RESEARCH	**ADMIXTURE**	**TEST CONDUCTED**	**EFFECT ON SOIL PROPERTIES**
(O. Amu et al., 2005)	Eggshell powder and Lime	Atterberg limit test, compaction test, California Bearing Ratio, Unconfined Compression test, and Undrained Triaxial Test	Reduction of PI, and MDD, an increase of OMC, CBR value, and UCS value. Increase of cohesion (C) and reduction of Internal friction angle
(O. O. Amu & Salami, 2010)	Common Salt and eggshell powder	Atterberg limit test, compaction test, California Bearing Ratio.	Reduction of PI, OMC, and MDD, an increase of CBR value.
(Oluwatuyi et al., 2018)	Eggshell powder and cement	Atterberg limit test, compaction test, California Bearing Ratio, Unconfined Compression Test, Durability and Microstructure analysis	Reduction of PI and MDD, an increase of OMC, CBR value, and UCS value. Increase of the durability under tropical conditions
(Bello et al., 2015)	Cassava Peels Ash	Atterberg limit test, compaction test, California Bearing Ratio, Unconfined Compression Test,	Reduction of PI and OMC, an increase of MDD, CBR value, and UCS value.
(Rahman, 1986)	Rice husk ash, lime, and cement	Atterberg limit test, compaction test, California bearing ratio, unconfined compression test,	Reduction of pi and MDD, an increase of OMC, CBR value, and UCS value.

Chapter 3 Experimental Methods

3.1. Overview

Experiments are done based on international or local conventions and standards. Engineering tests are well prescribed in different standards that exist. Currently, there are numerous standards developed in different areas and for different purposes. The researcher selects the best standard that satisfies his intended findings.

A Standard is defined as a technical document created by bringing together all interested parties in a domain (manufactural, consumer, regulator, etc.) for increasing safety, quality, and the representable way in doing something. Therefore it became a consensus-built rule, guideline, or definition for a particular domain (Standardization, 2010). The selection of standards is essential to ensure the reliability of the outcomes and the safety of the research. Standards also provide limits that facilitate the research to focus on relevant tests and straightforward interpretation of the results (Standards et al., 2009).

Even though every place has its particularity but as globalization prevails, several standards have come to a specific common understanding for good practice(Standardization, 2010).

In engineering, especially in the geotechnical field, there are several standards such as the American Association of State Highway and Transportation Official (AASHTO), American Society for Testing and Material (ASTM), British standards (BSI), European Standards (EUROCODE), Unified Soil Classification System (USC), Brazillian system of soil Classification, Western Australia Main Roads Department (MRWA),… etc.

In this research, we have adopted several standards based on the recommendations from the literature and the available tools and equipment in our possession.

The unit used in this research is mainly the International System of Units (SI); other unit systems were used when referring to other research findings.

3.2. Eggshell powder preparation.

This study uses the chicken eggshells mainly obtained as food wastes from a toaster shop near the Konkuk University campus in Seoul, South Korea. The toaster shop owner collected the eggshell in a plastic bag after using the edible part of the egg (Yellow egg and white egg) and then gave them to us for our experiment. After collecting them to the toaster shop, we first cleaned them from the residual of the white egg and other impurities with water.

(a) Row eggshell (b) Air Drying

<Figure 3-1> Eggshells collection

The eggshell was separated into two portions at this stage, one for eggshell with protein-membrane (ESWPM) another one for eggshell without protein-membrane (ESWTPM).

The portion of eggshells with protein-membrane was directly air-dried at room temperature for about 48 hours, and in the other portion, we separated shells with their protein-membrane (PM).

Several technics could be used for removing the protein membrane. Data (2011); Frank et al. (2005); New (2013); Walsh & Data (2001) gave methods, procedures, and apparatus for separating protein-membrane and shell material in waste eggshells. Yoo et al. (2009) used a simple method to separate protein-membrane and shell by physical means in the so-called Dissolved air floatation (DAF) separation and other chemical-based methods such as vinegar treatment, yeast treatment, and high-temperature treatment (Yoo et al., 2009).

In this research, the separation of protein-membrane with shell was made manually while the eggshells were wet. The shell materials were also air-dried for 48hours at room temperature.


(a) ESWPM (b) ESWTPM (c) PM

<Figure 3-2> Protein membrane separation

The eggshells were ground in powder using a kitchen grinder, and the powdered eggshell was sieved in the BS 1377 standard sieves into five consecutive particle sizes.

<Figure 3-3> Kitchen grinder for grinding

The eggshell powder passing 425μm sieve refers to (Kumar M & V S, 2014), passing 88μm is the closest particle size to portland cement powder (Yerramala, 2014), passing 75μm sieve refers to Oluwatuyi et al. (2018). The rest was an attempt made by the author to fill the gap between 425μm and 88μm.

- Passing 425μm sieve and retained in 250μm sieve (<425μm)
- Passing 250μm sieve and retained in 150μm sieve (<250μm)
- Passing 150μm sieve and retained in 88μm sieve (150μm)
- Passing 88μm sieve and retained in 75μm (<88μm)
- Passing 75μm and retained in the pan (<75μm)

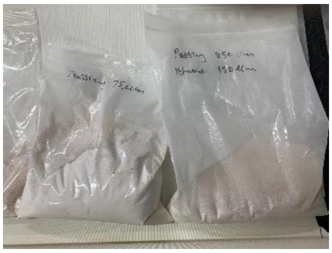
(a) ESPWPM<425μm (b) ESPWPM<250μm (c) ESPWPM<150μm

(d) ESPWPM<88μm (e) ESPWPM <75μm

(f) ESPWTPM <150μm (g) ESPWTPM <75μm

<Figure 3-4> Egghell powder particle sizes

After making the eggshell powder, it was stored separately in an airtight plastic bag and stored at room temperature.



<Figure 3-5> Stored eggshell powder

3.3. Basic geotechnical test.

Our first attention went to soil classification as the fundamental geotechnical aspect that we first identified. We carried out several tests to allow us to classify the soil we were investigating. Knowing the type of soil, we were working on allowed us to predict its further geotechnical behaviors.

We started with The nature of the soil, where we selected the lateritic soil as our scope material for it widely used in road construction in developing countries located in the tropical and subtropical region. The natural laterite was not available to the author. Therefore author tried to make the soil mixture that has close properties to natural laterite. Chemical analysis of clay particles in natural laterite and their concentration in percentage was evaluated compared with the natural laterite to make the similarity. The chemical composition of clay particles and the corresponding concentration were identified from the supplier prescriptions.

(a) Kaolinite clay (b) kaolinite clay in Bag

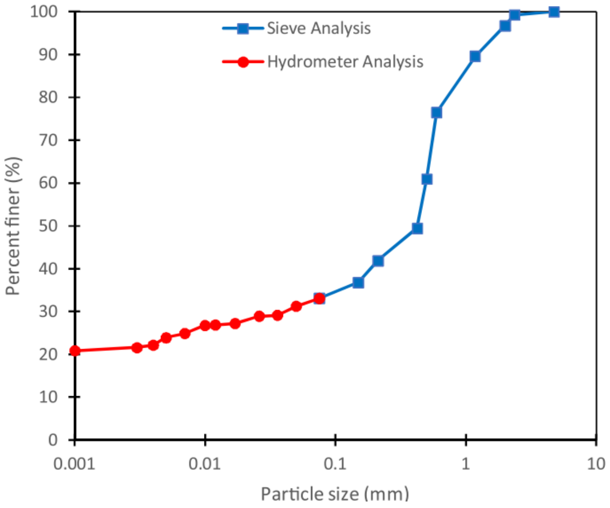
<Figure 3-6> Industrial Kaolinite

The soil sample was prepared according to BS 1377. Several soils were mixed bases on their sizes; the clay particle was industrial Kaolinite, Jumunjin sand as sand particles, and river gravels as coarse aggregates. Local companies supplied all the material we used in this research.

The sand and coarse particles were first washed by running water in a sieve of 75μm to remove all the impurities and the dust; after washing, the sand and coarse soil were oven-dried for 72 hours and clay soil dried for 24 hours before use.

<Figure 3-7> Microwave oven

Then Particle size analysis followed. The particle size intends to determine the percentage in weight of particles in a particular size range. The particle size of the prepared soil mixture was made trying to simulate the particle size distribution curve from the literature. Oluwatuyi et al., 2018, was the model for soil mixture. Therefore a set of sieves as prescribed by the AASHTO T88 were used to make a similar curve (4.75mm, 3.36mm, 2.26mm, 2mm, 850μm, 425μm, 250μm, 150μm, 88μm, 75μm, and pan).



<Figure 3-8> Particle distribution curve (Oluwatuyi et al., 2018)

The sieves were superposed from the largest on the top and the lowest down. A semilogarithmic curve that presents the percentage of passing in each sieve against the size of the sieves was plotted.

(a) Electronic balance (b) Set of Sieves (c) Sieve shaker machine

<Figure 3-9> Required equipment for sieve analysis

Plasticity

The plasticity of fine-grained soils is an essential parameter in soil classification. Plasticity is currently defined as the ability of a mass of soil with constant volume to undergo an unrecoverable deformation without crumbling or cracking.

The factors that govern the plasticity of a soil mass are the nature of clay minerals and the organic material present in fine grains of a soil mass. The fine-grained soil mass can be in the liquid state, plastic state, semi-solid, and solid-state, depending on the water content. The lower water content at which soil mass changes from plastic to semi-solid state is the plastic limit (PL), and the upper water content at which soil mass changes from plastic to liquid is the liquid limit (LL). The water content at which soil mass is within the plastic state is called plastic index (PI).

$$\mathrm{PI} = \mathrm{LL} - \mathrm{PL} \tag{3-1}$$

In this research, the soil was prepared according to BS 1377 (Part 2). A soil sample that passes the sieve of 425μm was used in the experiment. Then soil was dried in the oven for 24 hours, and then five samples containing different eggshell powder with different particle sizes were prepared.

<Table 3-1> Sample prepared for Atterberg limit

Samples	**Description of admixture**		**ESP content**
	Nature	**Particle size**	
S1	Eggshell powder with protein-membrane	note applicable	0 %
S2	Eggshell powder with protein-membrane	Passing 425μm and retained on 250μm sieve	4%
S3	Eggshell powder with protein-membrane	Passing 250μm and retained on 150μm sieve	4%
S4	Eggshell powder with protein-membrane	Passing 150μm and retained on 88μm sieve	4%
S5	Eggshell powder with protein-membrane	Passing 88μm and retained on 75μm sieve	4%
S6	Eggshell powder with protein-membrane	Passing 75μm sieve and retained on the pan	4%

Liquid limit

Two methods for testing the liquid limit are in the BS 1377 (Part 2), the cone penetrometer (definitive method), and the Casagrande apparatus method. The cone penetrometer test is an apparatus fitted with a 30^o cone of stainless steel, 35mm long, attached to a sliding shaft, and the whole weight of 80g.


(a) Distilled water (b) Liquid limit cone penetrometer apparatus

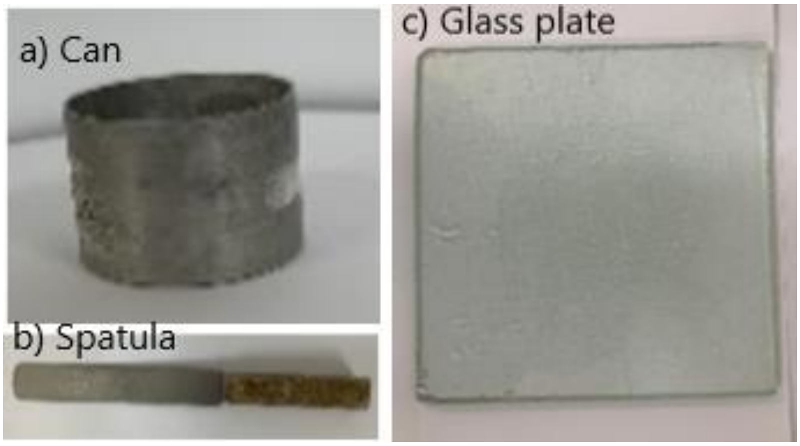
<Figure 3-10> Require equipment for Liquid limit

The samples were handled separately. First, the soil sample was mixed with distilled water and formed a homogeneous paste, then stored in an airtight plastic bag for 24 hours. The paste was placed carefully in a cylindrical metal can of 55mm internal diameter and 40mm deep, avoiding any trap of air in the paste. The surface was leveled before lowering the cone to touch the surface of the paste and let it fall freely for 5 seconds and locked again. The penetration depth was measured. A bit more soil paste was added to the paste in the can before the penetration was repeated until a consistent penetration value was found. A small representative sample was collect from the can, weighted and oven-dried for 24 hours to get the water content. The same sample paste gets watered more, and the entire test was repeated at least four times. The penetration value should have to cover a range from 15mm to 25mm.

The cone penetration against the water content graph was plotted, and the best straight line was plotted. The liquid limit is a (nearest integer) percentage of water content that corresponds to the penetration of 20mm. All the samples were done, and the results were recorded.

Plastic limit

The plastic limit test was also conducted according to BS 1377 (part 2). At every paste used to test the liquid limit, a portion of paste was used to conduct the plastic limit test. The paste was molded onto a ball then split into four, and one is formed into a thread of approximately 6mm diameter utilizing the first finger and thumb of each hand. The thread is then placed on a glass plate and rolled with the tips of the finger and the hand until its diameter is reduced to 3mm, then remolded again and the procedure repeated until the thread shears longitudinally and transversely before getting to 3mm diameter. The soil samples were collected, weighted, and oven-dried to get the water content. The same procedure was used for the other three portions, and the average percentage of water content (nearest integer) is then presented as the plastic limit. All the samples were tested, and the results were recorded.



<Figure 3-11> Equipments for the Plastic limit test.

Soil description was given by BS 5930. The basic soil types defined based on the particle size according to this standard were investigated.

The British soil classification system was used in this research, referring to the plasticity chart. From the laboratory tests, we were able to place the point in a specific zone that determines the group and subgroups where it belongs.

We used the unified soil classification based on the laboratory test results associated with the plasticity chart.

3.4. Standard Proctor compaction test

The process of increasing the density of a soil mass while packing it in a solid container to allow particles to get closed and reduces the air volume is called compaction in soil mechanics. However, no significant change in the volume of water present in the soil mass. The degree of compaction governs the shear strength and compressibility of the compacted soil mass. Therefore, the degree of compaction is measured through dry density. In return, Water content and compaction energy govern the dry density of compacted soil (American Society for Testing and Material, 2007).

Laboratory tests can assess the compaction characteristics. The procedures of the laboratory compaction test are in BS 1377 (part4). The standard gives three procedures: Proctor test, Modified AASHTO test, and Vibrating hammer test.

(a) Mold and rammer (b) Edge cutting tool

<Figure 3-12> Proctor compaction equipments

The Proctor tests were fitting our prescriptions. The samples were first prepared for composite soil. Six samples were prepared separately, as in table 6. The soil sample was mixed with distilled water at a low concentration equivalent to approximately 8%, then fill in the mold of 1l volume and a defined weight. The mold was filled in three equal layers, compacting each layer with 25 blows of a rammer of 2.5kg falling at 300 mm. The mold and the compacted soil were weighted, and the soil sample was collected for water content. Soil samples were weighed before being dried in the oven for 24 hours. After oven-dry, the soil samples were weighed again, and the results were recorded. The soil in the mold was removed from the mold, add 2% water, and repeated the same procedure at least five times until the weight of the mold with soil falls below the previous.

The dry density (ρ_d) was calculated using the following formula:

$$\rho_d = \frac{\rho}{1+w} \tag{3.2}$$

where ρ is the bulk density of the tested soil and w being the corresponding water content

The graph of dry density against water content was drowned, and the peak of the curve was being used as the maximum dry density ($\rho_{d_{max}}$) corresponding to the optimum moisture content (OMC). The curves of all the samples were plotted and compared.

<Table 3-2> Soil Samples used in compaction tests

Samples	Description of admixture	
	Nature	Particle size
S1	Eggshell powder with protein-membrane	Not applicable
S2	Eggshell powder with protein-membrane	Passing 425μm and retained on 250μm sieve
S3	Eggshell powder with protein-membrane	Passing 250 μm and retained on 150 μm sieve
S4	Eggshell powder with protein-membrane	Passing 150 μm and retained on 88 μm sieve
S5	Eggshell powder with protein-membrane	Passing 88 μm and retained on 75 μm sieve
S6	Eggshell powder with protein-membrane	Passing 75 μm sieve and retained on the pan

3.5. Unconfined compressive strength (UCS) tests

The unconfined compression test is a test conducted in the laboratory to determine the compression strength of cohesive soil without lateral confining pressure. For cohesive soil, the total stresses are provided approximately by this test. This test is only applicable to cohesive soils, which will not expel water or bleed when loaded (ASTM D2166-06, 2010). This test is the most popular, simple, fast, and cheap method to determine the compressive strength and shear strength of cohesive soil (Piratheepan et al., 2012). The stresses were tested based on the sequences of the investigated cases.

<Table 3-3> Cases of soil investigation for the unconfined compressive test

Case No	**Cases**	**Soil condition**
1	Investigation on the optimum concentration of admixture	Using Eggshell powder with protein-membrane for particles size <425μm, <250μm, <150μm, <88μm, and <75μm, cured for seven days, to find the optimum content ratio for Eggshell powder. ○ 0% ○ 1% ○ 2% ○ 3% ○ 4% ○ 5% ○ 6%
2	Investigate the Eggshell powder convenient particle size	Using Eggshell powder with protein-membrane for particle size: - <425μm - <250μm - <150μm - <88μm - <75μm It cured for seven days to find the convenient particle size of the eggshell powder.
3	Investigate the effect of protein membrane	Using Eggshell powder without protein-membrane for particle size: - <150μm - <75μm It cured for seven days to find the effect of the protein-membrane to make the chemical reaction.

Assumptions are made in this test; during the sample preparation and compression test, there is no loss of pore water, and the sample was regarded as held by effective confining stress from the negative pore water pressure. As the pore water pressure is unknown, the effective stress is also. Hence the undrained shear strength is expressed in terms of total stress (Jinping, 2017).

The sample was prepared separately at the optimum moisture content and the maximum dry density.

In every soil condition, three (3) samples were prepared to perform the unconfined compression test. The soil first was weighted based on the dry density obtained in the compaction test (280g) of soil was used, then the soil was mixed with the admixture in terms of percentage of the weight, and the soil sample was mixed with the admixture to get a homogenous composite soil. Water was added according to the optimum moisture content obtained from the compaction test (14%). The soil mixture was again mixed until it seems to be a homogenous paste. Afterward, the soil was filled in the mold in four equal layers, each layer receiving 20 blows of the lightweight rammer and ten blows of the heavy rammer. The mold has 50mm of diameter and 150 cm height but is filled until 100cm.

(a) Plastic mold (b) Lightweight Stell rammer (c) Heavy steel rammer

<Figure 3-13> Required equipment for UCS sample preparation

The sample is then placed in the humidity chamber set at 21^{o} temperature and 75% humidity. After one day, the sample was unmolded and left to cure for the remaining six days before being crushed in a compression machine.

The compression machine has the capacity of loading up to 5000kgf, set to a strain of 0.5-2%/min, and connected to a recording monitor. After shearing samples with specific load, the load was released, and the breaking angle was measured before the storage of the sample.

(a) Compressive machine (b) Humidity chamber

<Figure 3-14> Required equipment for curing and compressing

We produced the graphs that compared different results from the test and deduced other parameters.

The major principal stress was calculated as follow:

$$\sigma_1 = \frac{\mathrm{F}}{\mathrm{A}} \tag{3.3}$$

F was the applied load at the desired strain percent, and A was the cross-section area of the sample. As the height was decreasing during the compression, the volume was constant; therefore crossectional area increased. The cross-section was calculated as follow:

$$A = \frac{\mathrm{A}_0}{1-\varepsilon} \tag{3.4}$$

Where ε is the desired percent stain, A0 was the initial cross-section area, and A was the desired cross-section corresponding to the desired strain percentage.

3.6. Microstructure analysis

The microstructure analysis was done using the SEM (Scanning Electron Macroscope). This analysis was mainly for the investigation of the chemical reaction between the admixture and the soil. The investigation carried out on nine samples likely to show the impact of the admixture on the microstructure of soil.

The samples were prepared according to the relevant cases in the Unconfined compression test and then cured for seven days before being tested in an SEM machine. A small quantity equivalent to 100g was enough.

<Table 3-4> Selected samples for SEM

Samples	Description of soil+admixture		
	Nature of soil	The particle size of the admixture	Admixture percentage
S1	Soil without admixture	N/A	N/A
S2	Soil + Eggshell powder with protein-membrane	Passing 75 μm sieve and retained on the pan	3%
S3	Soil + Eggshell powder with protein-membrane	Passing 88 μm and retained on 75 μm sieve	3%
S4	Soil + Eggshell powder with protein-membrane	Passing 150 μm and retained on 88 μm sieve	3%
S5	Soil + Eggshell powder with protein-membrane	Passing 250 μm and retained on 150 μm sieve	3%
S6	Soil + Eggshell powder with protein-membrane	Passing 425 μm and retained on 250 μm sieve	3%
S7	Soil + Eggshell powder without protein-membrane	Passing 75 μm sieve and retained on the pan	3%
S8	Soil + Eggshell powder without protein-membrane	Passing 150 μm and retained on 88 μm sieve	3%

<Figure 3-15> Scanning Electron microscopy

Chapter 4. Results and Discussion

4.1. Overview

This chapter focuses on the results obtained during laboratory tests and then discusses their impact on geotechnical, especially road construction.

This research aimed to investigate the impact and effect of particle size and protein membrane in soil stabilized by eggshell powder. Four cases were investigated, the optimum concentration of the admixture (eggshell powder), the optimum particle size required to make a good stabilization, the effect of protein-membrane on the stabilized soil, and the microstructure of the stabilized soil compared with the ordinary soil.

The results are presented in graphs, and the discussion is based on their use in road construction.

The research did not cover all the required tests for selecting the material to be used in road construction. It focused on the simplified tets method to allow the researcher to identify the influence and distinction between the selected cases.

4.2. Soil description and classification

The basic geotechnical test conducted to allow the soil classification was the nature of the soil, nature of the clay particles, particle size distribution, and plasticity.

First, the soil was imitating the residual soil in tropical and subtropical regions called laterite. Through different soil alterations leading to lateralization, kaolinization is in the first stages of lateralization (Frank Netterberg, 2014). Therefore Kaolinite was selected as the predominant clay composite of the lateritic soil. The supplying company prescribed the chemical composition of the Kaolinite used in this research. It was compared with the lateritic soil used in the previous research (Oluwatuyi et al., 2018) as in the <Table 4-1>.

<Table 4-1> Chemical composition of natural Laterite and Kaolinite

Chemical composition	**Lateritic soil (Oluwatuyi et al., 2018)**	**Kaolinite**
Silicon oxide ($Si0_2$) %	52.59	47.57
Aluminum oxide (Al_20_3) %	30.8	37.06
Iron oxide (Fe_20_3) %	7.57	0.93
Calcium oxide (Ca0) %	0.68	0.24
Sulfur trioxide ($S0_3$) %	0.01	-
Potassium oxide(K_20) %	3.51	0.86
Titanium dioxide ($Ti0_2$) %	-	0.2
Magnesium oxide (Mg0) %	-	0.02
Phosphorus pentoxide (P_20_5) %	-	0.04
Sodium oxide (Na_20) %	-	0.05
The laterization degree (SiO_2/ (Fe_2O_3 + Al_2O_3))	**1.37**	**1.25**

(Paige-Green et al., 2015) states that the degree of lateralization in lateritic soil is below 2. Thus Kaolinite has 1.25, which made it behave like lateritic soil.

The importance of grain particle size distribution was discussed in chapter 2. The grains of soil can sometimes be broken while processing. We used the granular river sand and the model for particle size distribution curve for natural lateritic soil from Oluwatuyi et al. (2018). The graph was identified, and the soil was designed to be identical to its selected model.

In this referenced model natural lateritic soil, the percentage of silt and clay particles passing the sieve 75 µm was 33.1%. The granular material was presented in a semi-logarithmic scale graph that has the abscissa as the size of sieves in base 10 logarithmic scale, and the ordinate is the percentage of the particle finner than the sieve size, in other words, the percentage of passing by weight in linear scale (figure 17). Identifying the corresponding values was done using the geometric mean on the logarithmic scale.

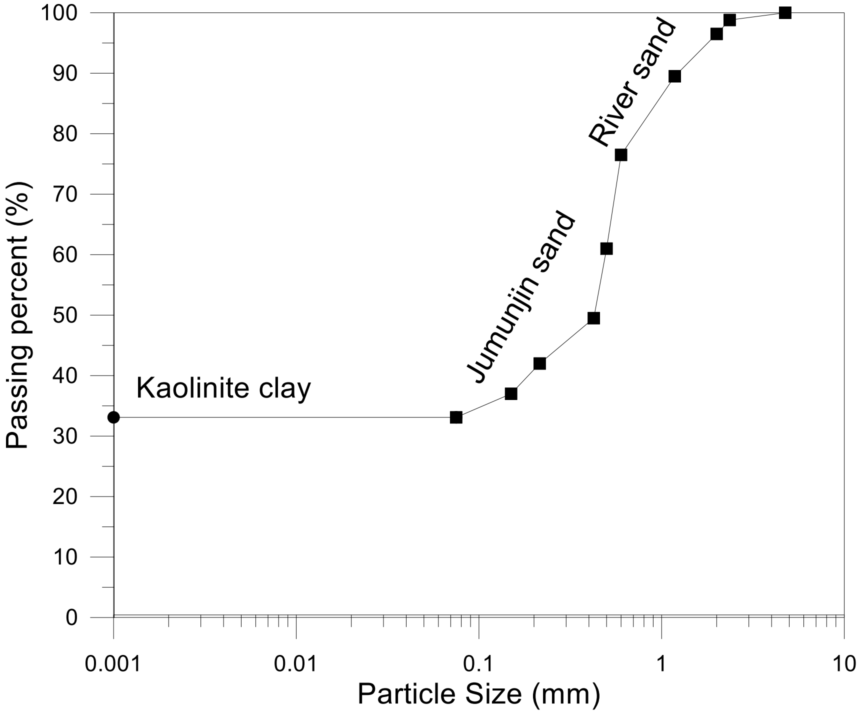
Where Geometric mean is the value of x between x1 and x2

$$x = \sqrt{x_1\, x_2} \tag{4.1}$$

For the soil was more than 30% is fine material the soil is said to be fine-grained. The coefficient of uniformity could not be calculated.

<Table 4-2> Particle size distribution for tested samples

Sieve No AASHTO T88	Sieve size (mm)	Percentage of passing by weight (%)	Percentage of retained by weight (%)
4	4.75	100	0
8	2.36	98.8	1.2
10	2	96.5	2.3
16	1.18	89.5	7
30	0.6	76.5	13
36	0.5	61	15.5
40	0.425	49.5	11.5
60	0.215	42	7.5
100	0.15	37	5
200	0.075	33.1	3.9
Pan	-	0	33.1



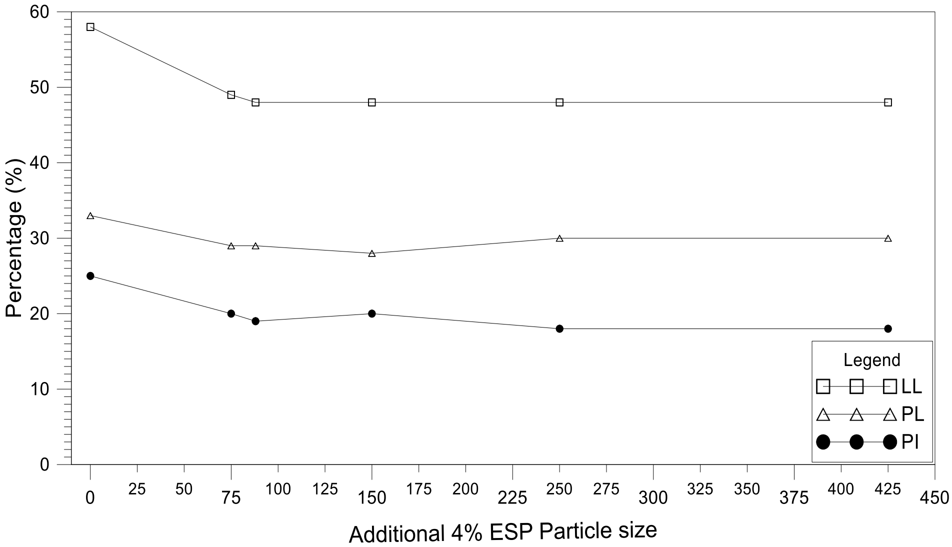
<Figure 4-1> Particle Distribution Curve for composite soil

Furthermore, the plasticity of soil was done, and the Atterberg values were calculated.

The plasticity of soil was investigated on soil and soil with eggshell with protein membrane. The liquid limit, the plastic limit, and the plastic index are presented as founded from the six samples of admixture particle size.

<Table 4-3> Atterberg limit of tested samples

Sample number	**Sieve size (mm)**	**Liquid limit (LL) in %**	**Plastic limit in % (PL)**	**Plastc index in % (PI)**
S1	N/A	58	33	25
S2	75	49	29	20
S3	88	48	29	19
S4	150	48	28	20
S5	250	48	30	18
S6	425	48	30	18



<Figure 4-2> Atterberg limit of soil stabilized with 4% ESPWPM

The above data allowed us to classify the soil based on different standard classifications, the AASHTO classification, BS classification, and USCS classification. We compare the properties of the used soil with the model natural lateritic soil.

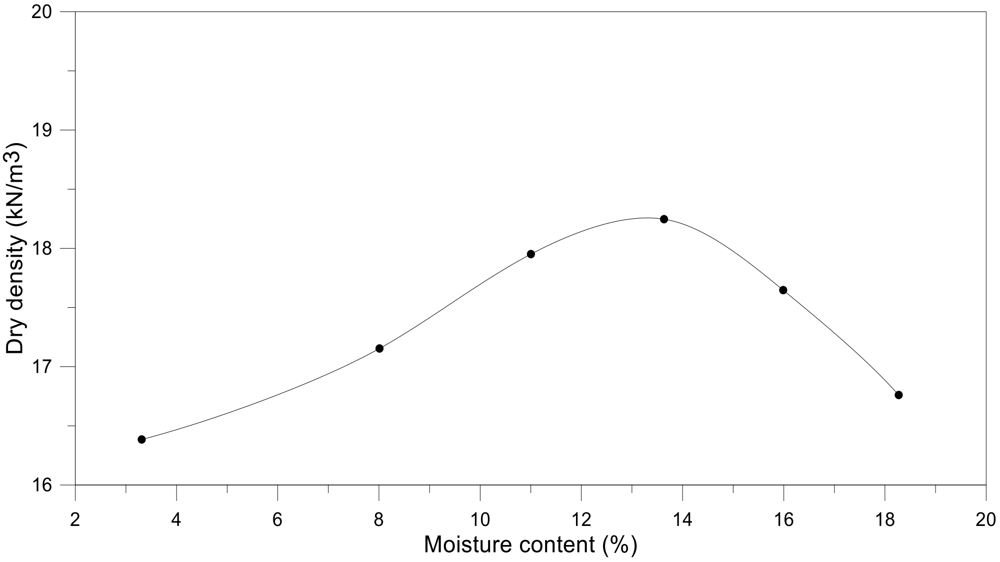
<Table 4-4> Basic geotechnical parameter

Properties	**Results**	
	Natural Laterite (Oluwatuyi et al., 2018)	**Composite soil**
Colour	Ressidh brown	Wheat
% passing through sieve 75 µm	33.1	33.1
Natural moisture content (%)	10.0 ± 2.0	N/A
Liquid limit (%)	45.0 ± 3.5	58.0
Plastic limit (%)	30.0 ± 2.5	33.0
Plasticity index (%)	15.0 ± 2.9	25.0
AASHTO classification (Group Index)	A-2-7(1)	A-2-7
USCS classification	SM (Silty sand)	SM
Unconfined compressive strength (kN/m^2)	227.8 ± 9.8	385.2 ± 15.3

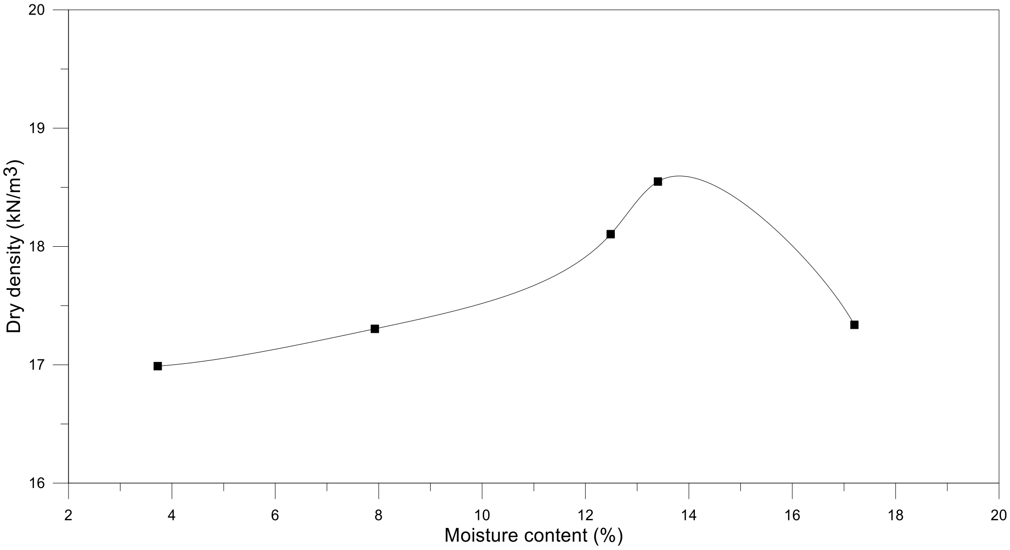
4.3. Compaction

The compaction aimed to determine the maximum dry density and the optimum moisture content of ordinary soil and stabilize soil at different stabilizer concentrations and then make a comparative analysis from them before using those parameters in further tests.

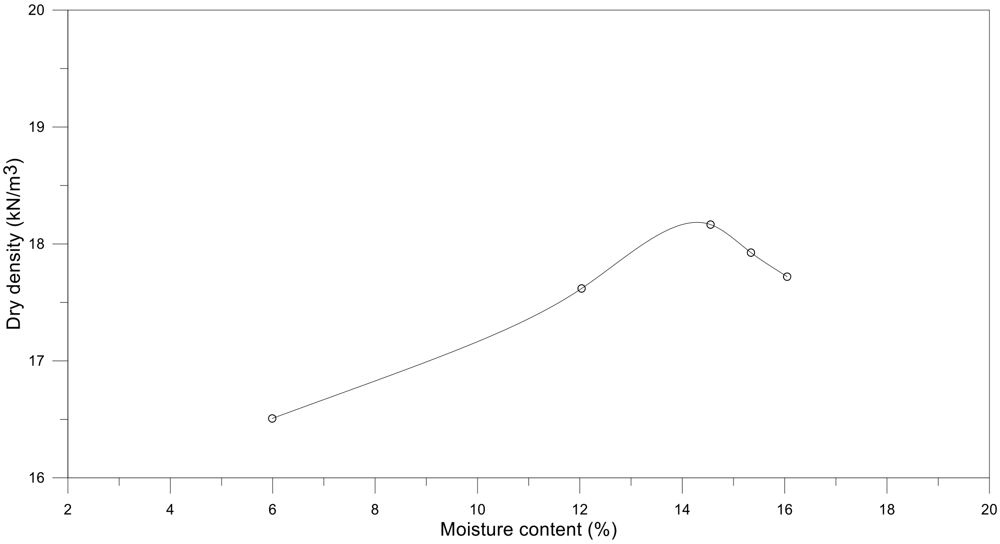
The dry density results against the moisture content for soil with and without stabilizer are presented in graphs. The maximum dry density and optimum moisture content of each case are identified, as tested separately through the graph.



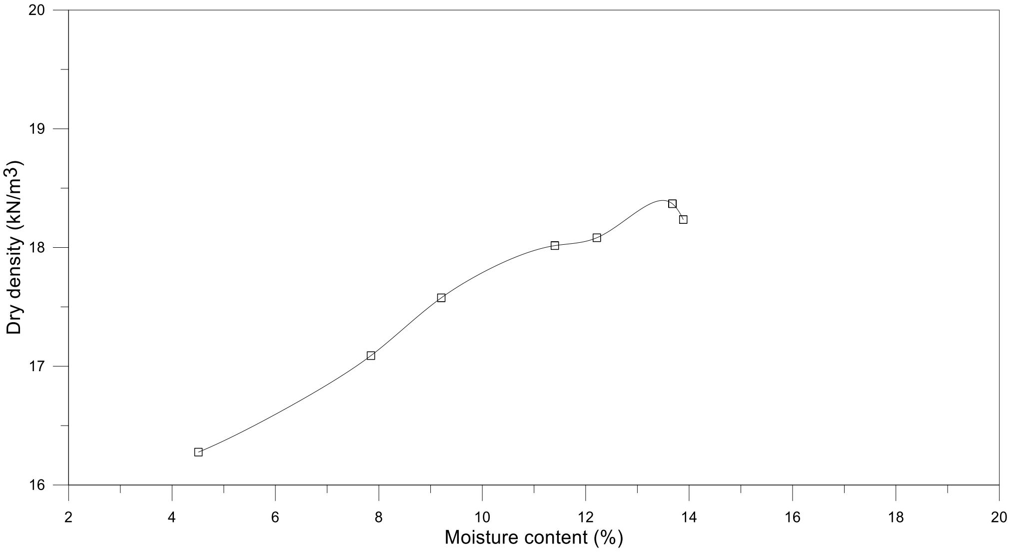
<Figure 4-3> Dry density and moisture content (ordinary soil)



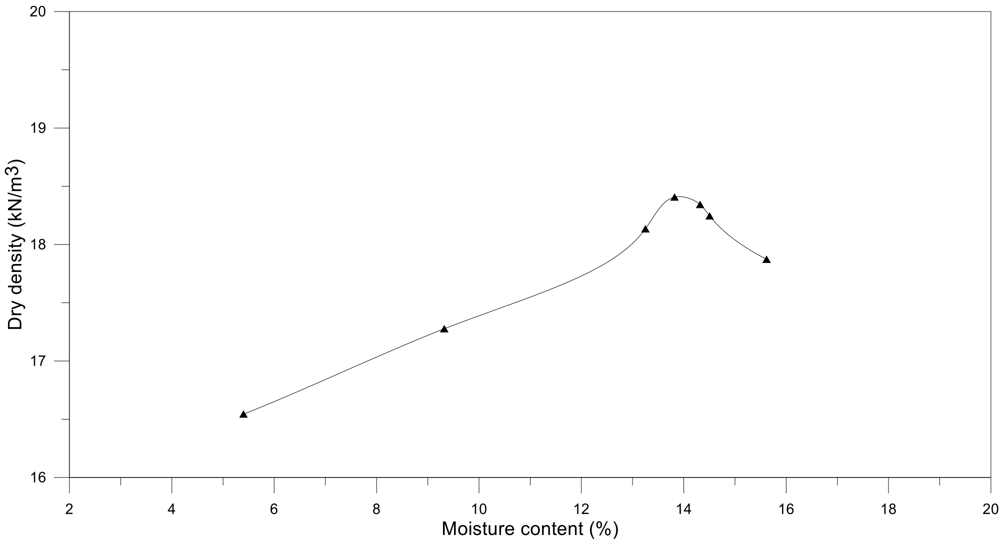
<Figure 4-4> Dry density and moisture content (4% of ESPWPM<75μm)



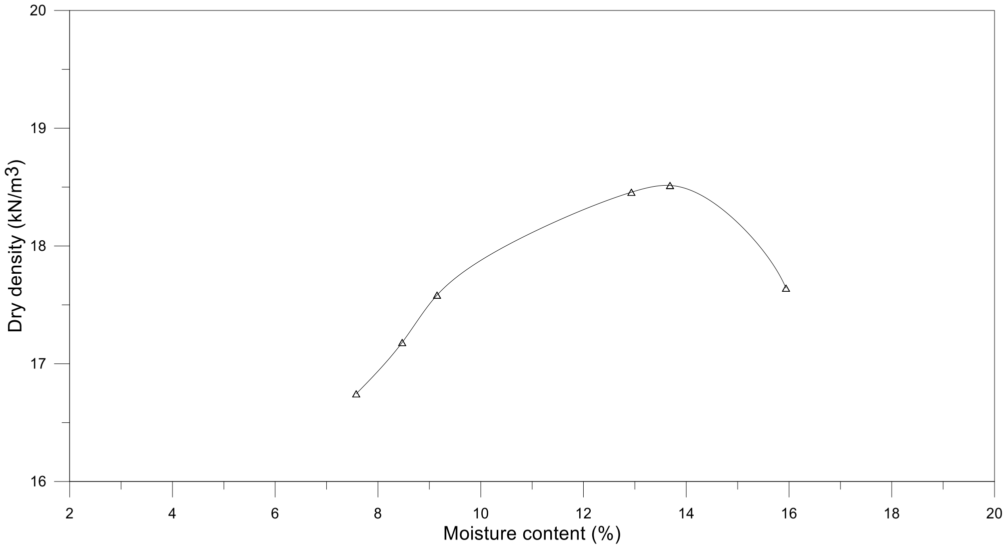
<Figure 4-5> Dry density and moisture content (4% of ESPWPM<88μm)



<Figure 4-6> Dry density and moisture content (4% of ESPWPM<150μm)

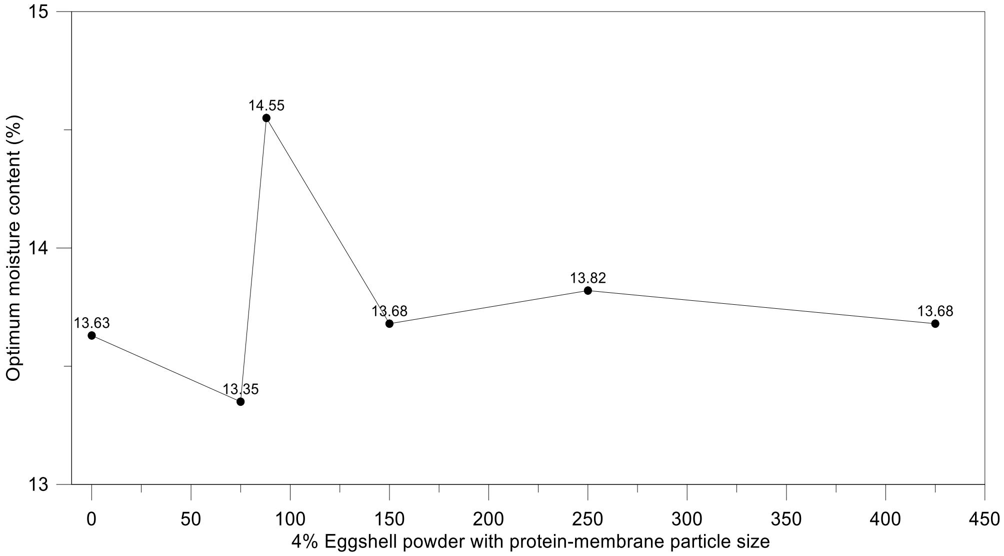


<Figure 4-7> Dry density and moisture content (4% of ESPWPM<250μm)



<Figure 4-8> Dry density and moisture content (4% of ESPWPM<425μm)

Based on the dry density graph, we can identify the optimum moisture content and its corresponding maximum dry density in each case and make a comparative graph.

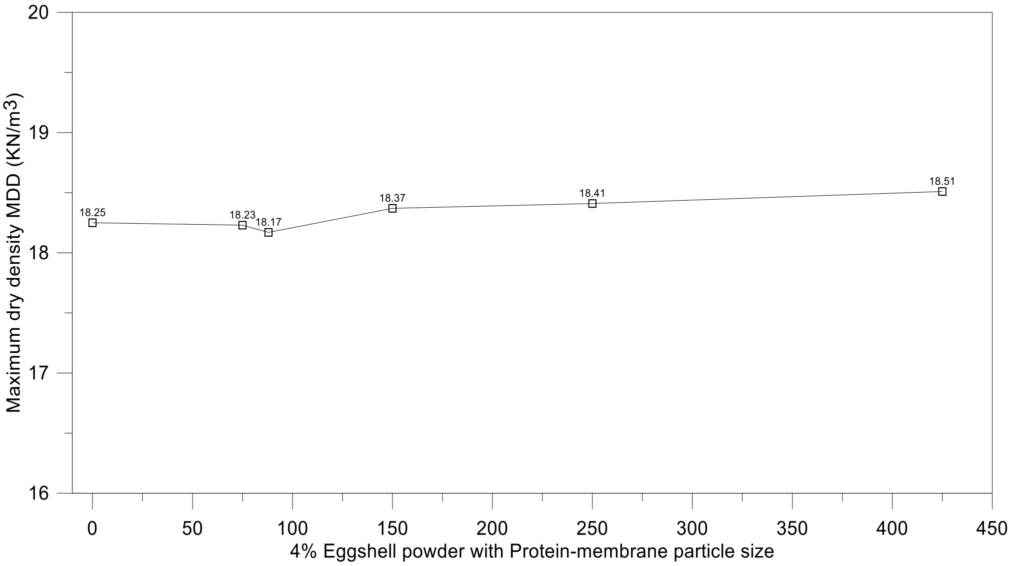


<Figure 4-9> Optimum moisture content and ESPWPM particle sizes

The optimum moisture content does not vary significantly from one case to another. The shallow difference in the moisture content can be explained in two ways.

First, the difference in liquid limit seems to be narrow, especially in stabilized soil at different particle sizes of stabilizers. Second, the chemical reaction between soil and stabilizer seems to be slow. The sample preparation of soil for Atterbegr limit takes 24 hours, allowing a chemical reaction, while the compaction tests only require few minutes to stabilize.

The difference being such small, 14% was the nearest integer that could simplify the mixture in the further test.



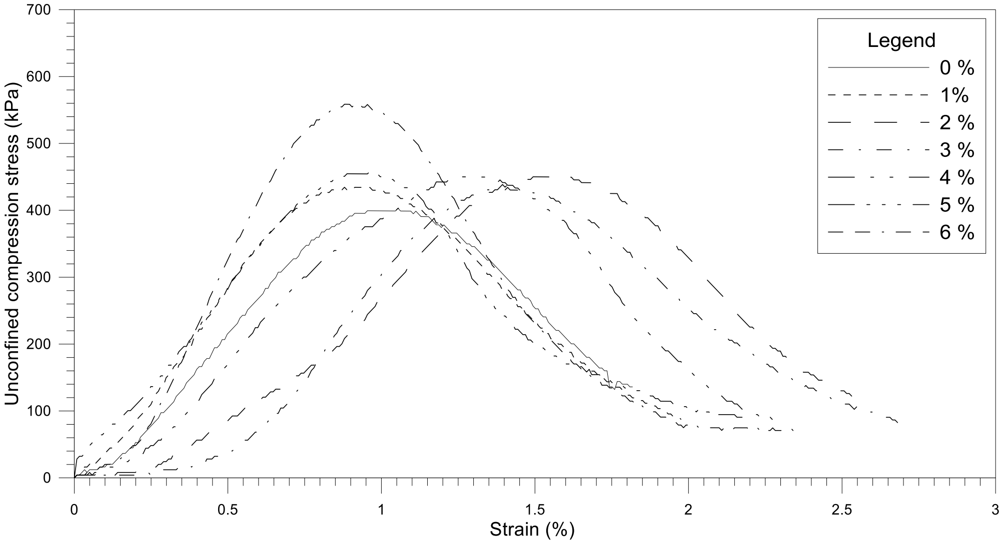
<Figure 4-10> Maximum dry density and ESPWPM particle sizes

The maximum dry density did not vary from different cases. The optimum moisture content is almost the same; there is no expectation of changes in the maximum dry density. The nearly constant maximum dry density in all cases could be attributed to the exact cause as for the optimum moisture content. The maximum dry density for the further test was set to 18.25 KN/m3.

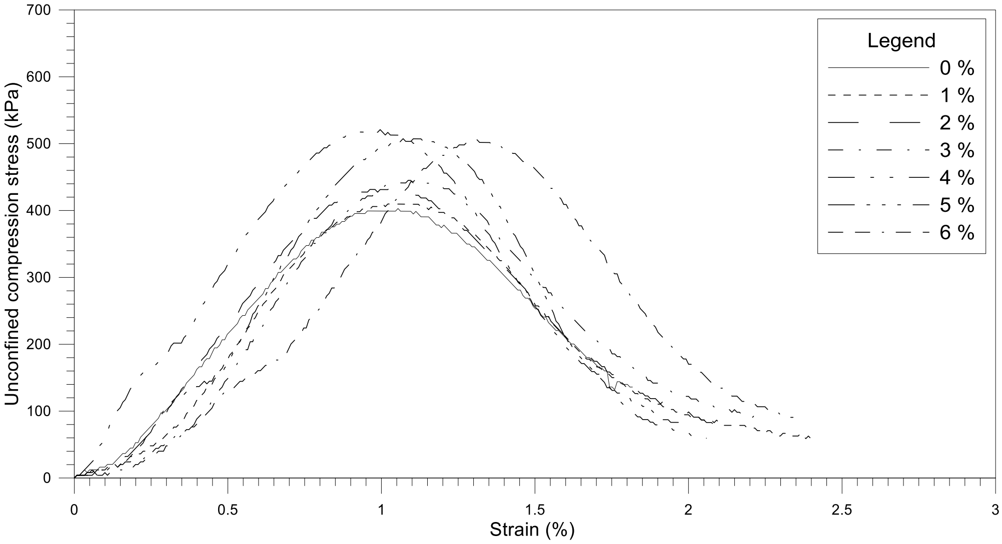
4.4. Unconfined Compression behavior

The unconfined compression stress test was conducted to get the difference in stress when soil is stabilized with eggshells of different particle sizes and with or without protein membrane. In other words, to investigate the effect of the particle size of eggshell powder on the soil when used as a stabilizer and the effect of protein-membrane in stabilizing the soil using eggshell powder.

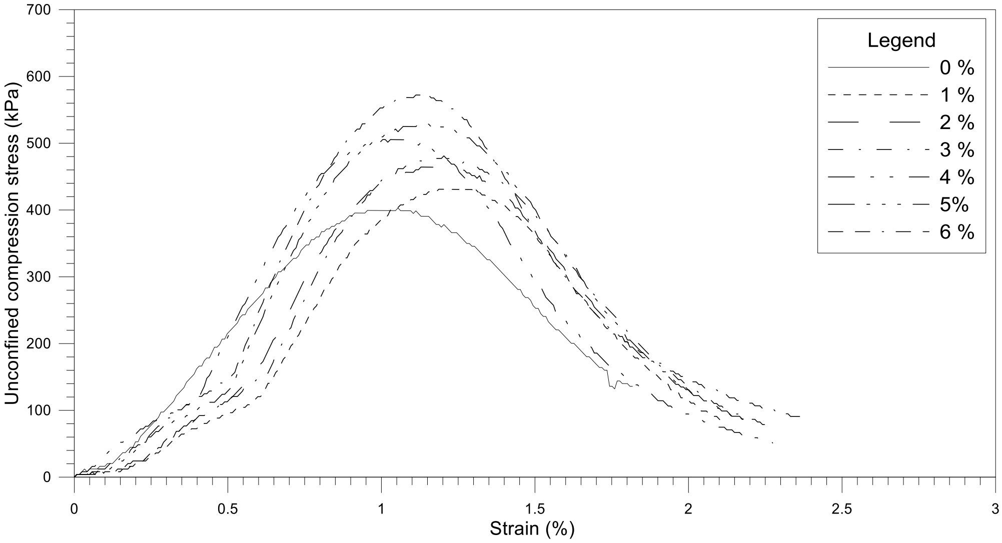
The optimum content of eggshell powder was investigated. The eggshell powder with protein-membrane of different particle sizes was used as a stabilizer and was cured for seven days long in a controlled humidity chamber. The stress-strain behavior in different cases.



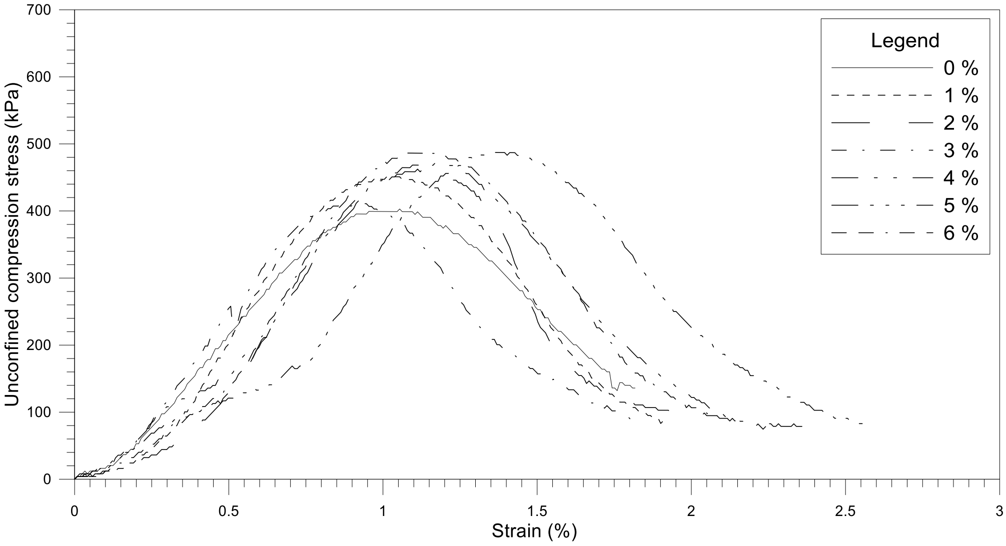
<Figure 4-11> Stress-strain curve for soil stabilized with ESPWPM<75μm



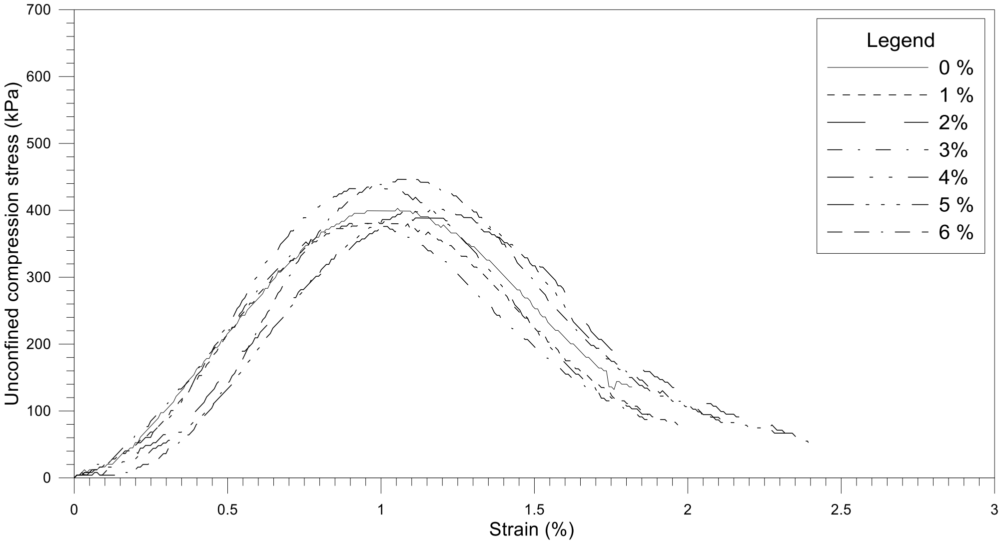
<Figure 4-12> Stress-strain curve for soil stabilized with ESPWPM<88μm



<Figure 4-13> Stress-strain curve for soil stabilized with ESPWPM<150μm

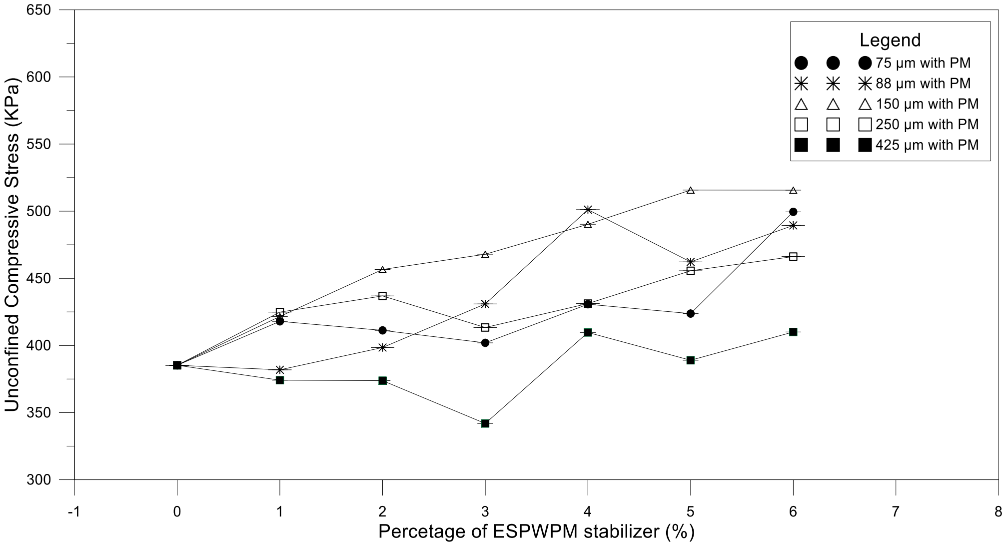


<Figure 4-14> Stress-strain curve for soil stabilized with ESPWPM<250μm



<Figure 4-15> Stress-strain curve for soil stabilized with ESPWPM<425μm

From the stress-strain curves, it was observed that the soil stabilized with ESPWPM gained its strength with the increase of the stabilizer contain except the ESPWPM<425μm, which seems to make a nonsignificant improvement of the soil strength. Soil stabilized with ESPWPM<88μm was interesting for, at 4 %, it acquires high stress relatively more significant than the other stabilizer at 6%.

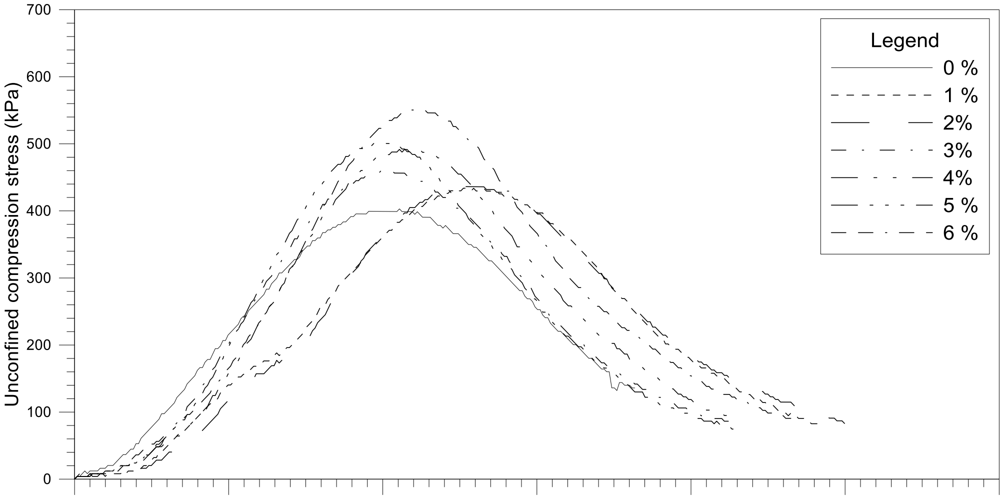


<Figure 4-16> Unconfined compression stress and the ESPWPM content

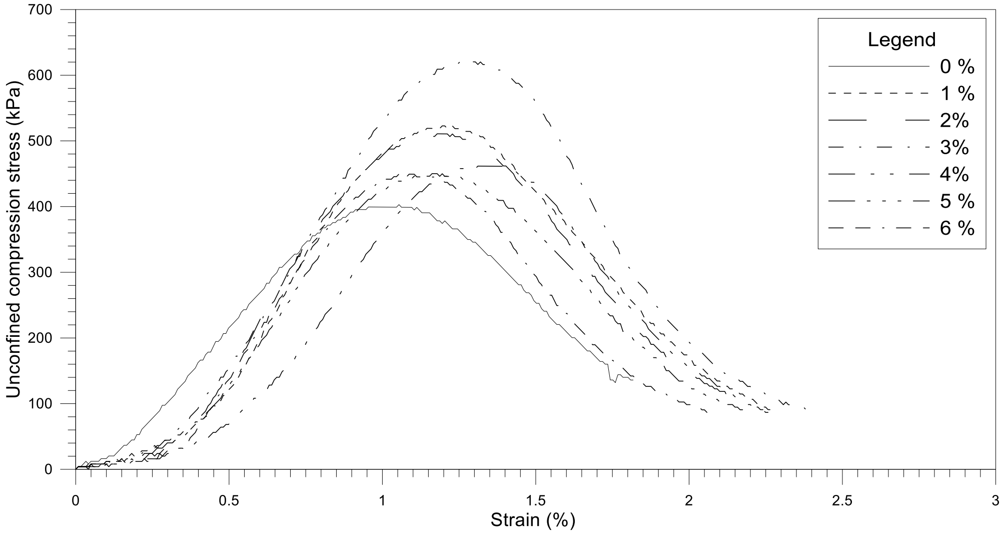
The effect of the particle size was observed; the soil stabilized with ESPWPM<150μm resisted the highest stress. The trend of the stress line tends to get higher as the concentration percentage increases. Therefore ESPWPM<150μm is selected as the convenient particle size that stabilized the soil.

After we realized that the particle size of ESPWPM <150 μm was the optimum particle size, we can investigate the effect of the protein-membrane through the unconfined compression test of soil stabilized with eggshell powder without protein membrane. Only two cases were investigated, the eggshell powder without protein membrane of less than 150 μm particle and the eggshell powder without protein-membrane containing particles less than 75 μm size.

After evaluation, the stress-strain curves for eggshell powder with protein-membrane, the stress-strain curve for soil stabilized with eggshell powder without protein-membrane are as follow:

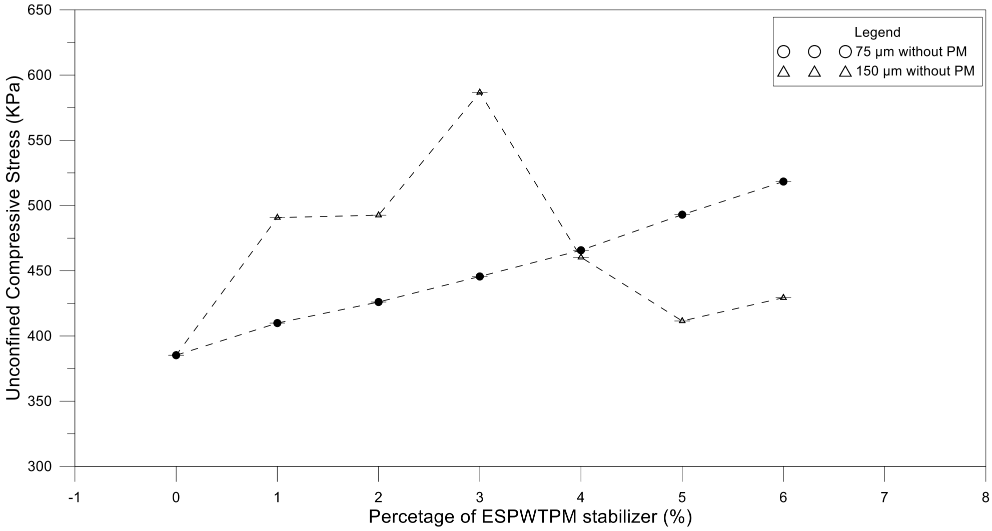


<Figure 4-17> Stress-strain curve for soil stabilized with ESPWTPM<75μm



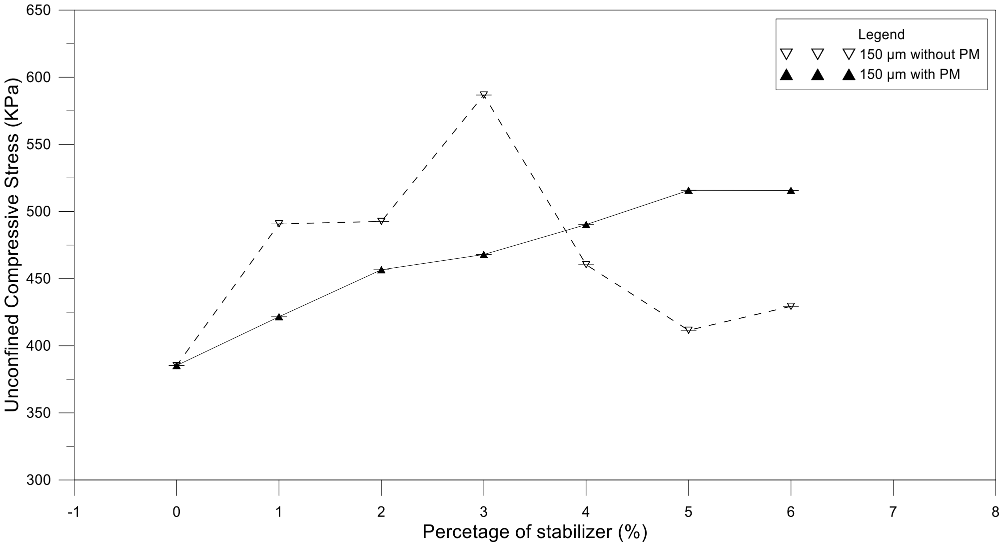
<Figure 4-18> Stress-strain curve for soil stabilized with ESPWTPM<150μm

The eggshell powder without protein-membrane showed a more active cementation ability compared to the eggshell powder with protein-membrane. Stress increases with the increase of the stabilizer concentration, but for ESPWTPM <150μm, after a sharp increase of up to 3%, the strength drops down at 4% to 6%.



<Figure 4-19> Unconfined compression stress and ESPWTPM content

The optimum was observed at 3% when ESPWTPM <150 μm was used as a stabilizer. The effect of the Protein membrane was observed when we compared the optimum particle size of eggshell powder with protein-membrane and the optimum particle size of eggshell powder without protein membrane.



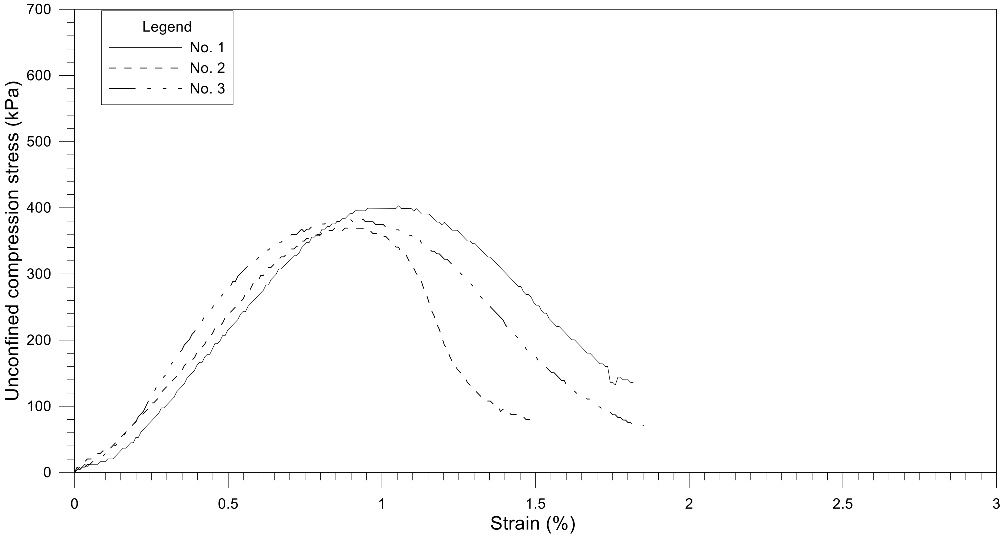
<Figure 4-20> Unconfined compression strength of stabilized soil

Stiffness

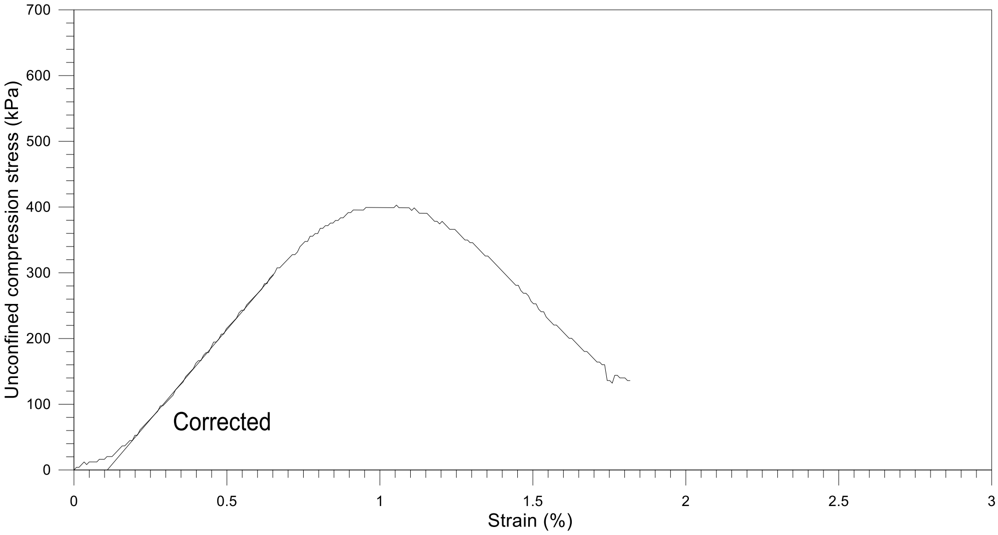
The stiffness of the soil is an essential parameter in linear numerical analysis. From the unconfined compression stress curve, the elastic modulus (Young's modulus) was calculated.

$$E = \frac{\sigma}{\varepsilon} \tag{4.2}$$

E is Young's modulus, pressure units, σ is uniaxial compression stress, pressure units, ε is a strain or proportional displacement, dimensionless. The graph was subjected to a modified stress curve to get a uniform elastic curve. The elastic modulus was calculated in cases different cases when soil is in its ordinary state and when stabilized with eggshell powder with different concetration and different sizes.

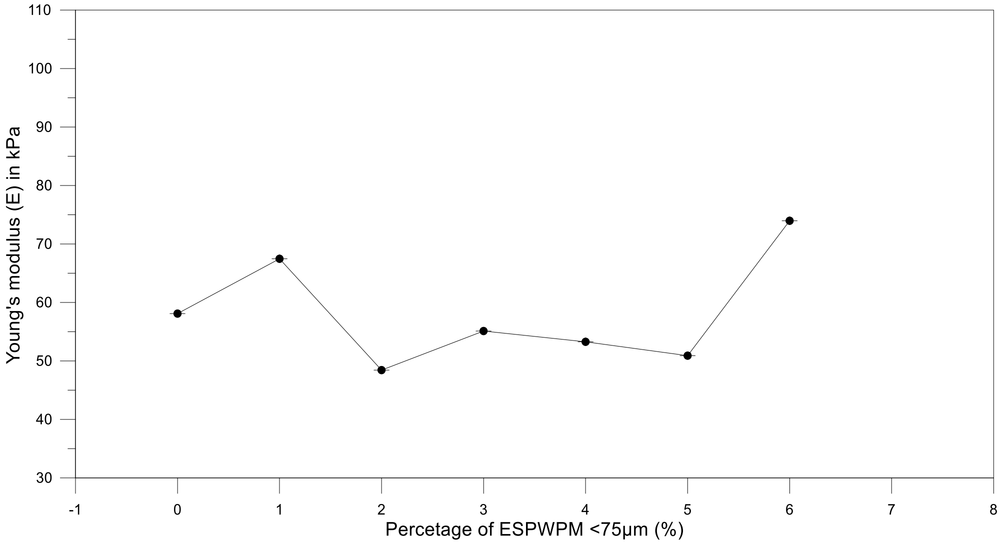


<Figure 4-21> Original stress-strain curve for ordinary soil

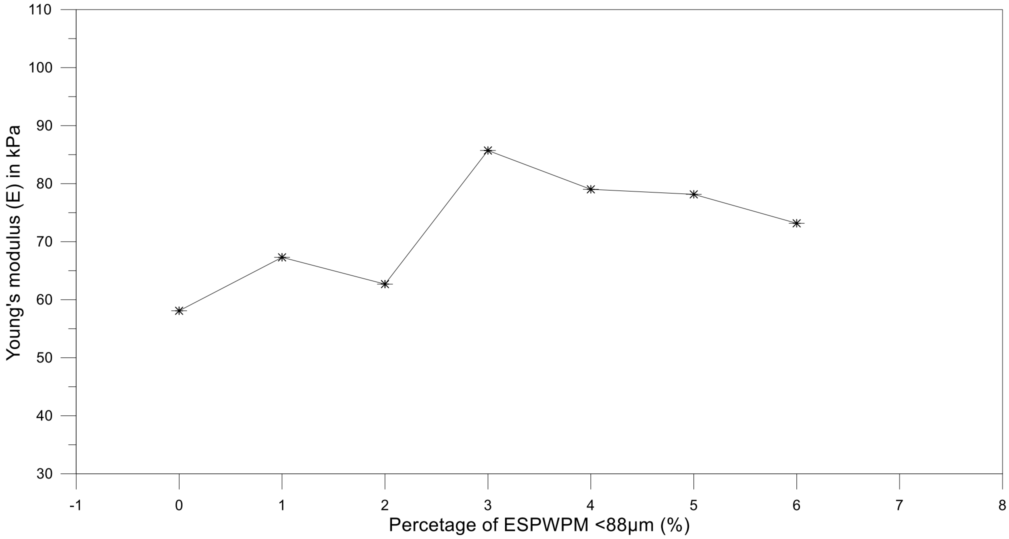


<Figure 4-22> Corrected stress-strain curve of ordinary soil

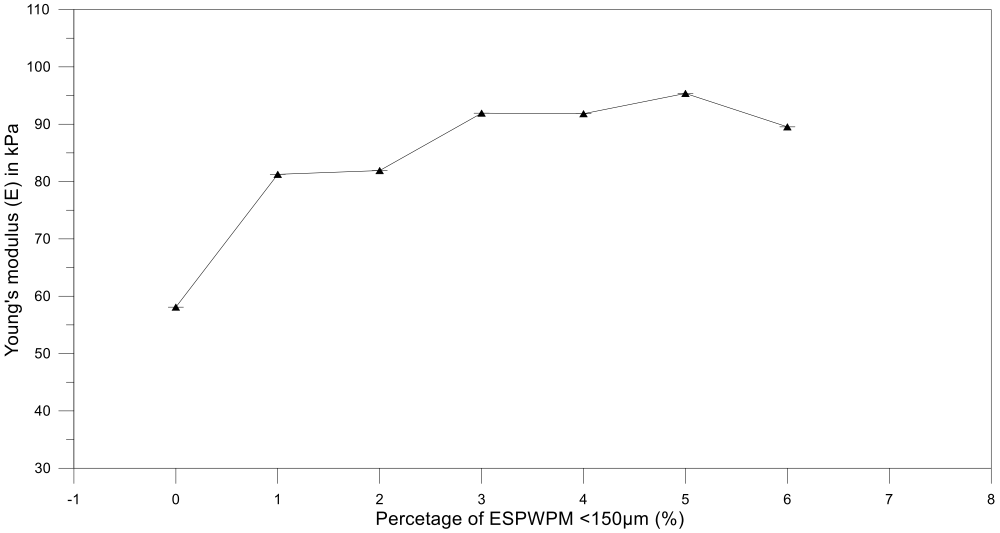
We were able to calculate the stiffness (Young's modulus) as the slope of the corrected straight line from the modified curve. The stiffnesses were calculated from all the tested samples, and the combined graph was plotted to identify the general trend of stiffness.



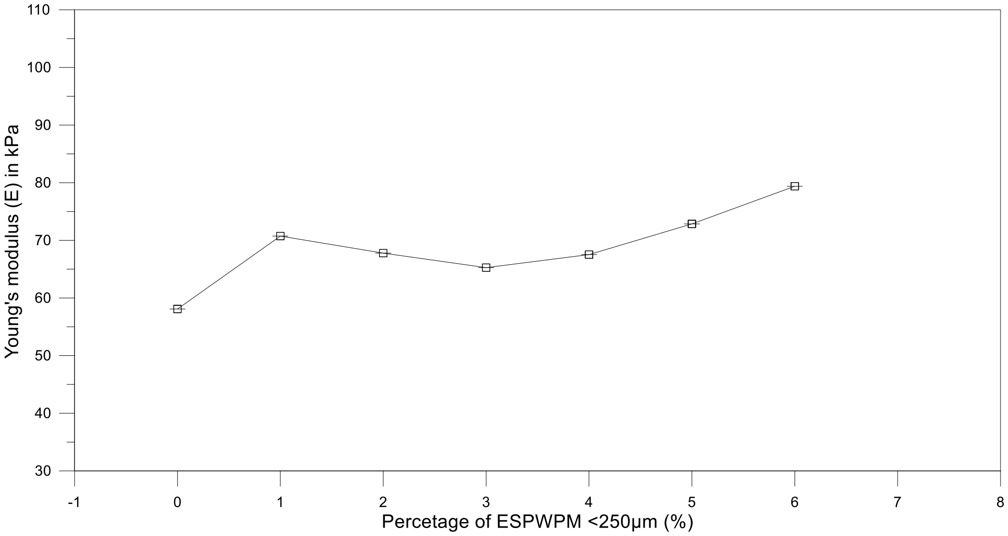
<Figure 4-23> Elastic Modulus of soil stabilized with ESPWPM<75μm



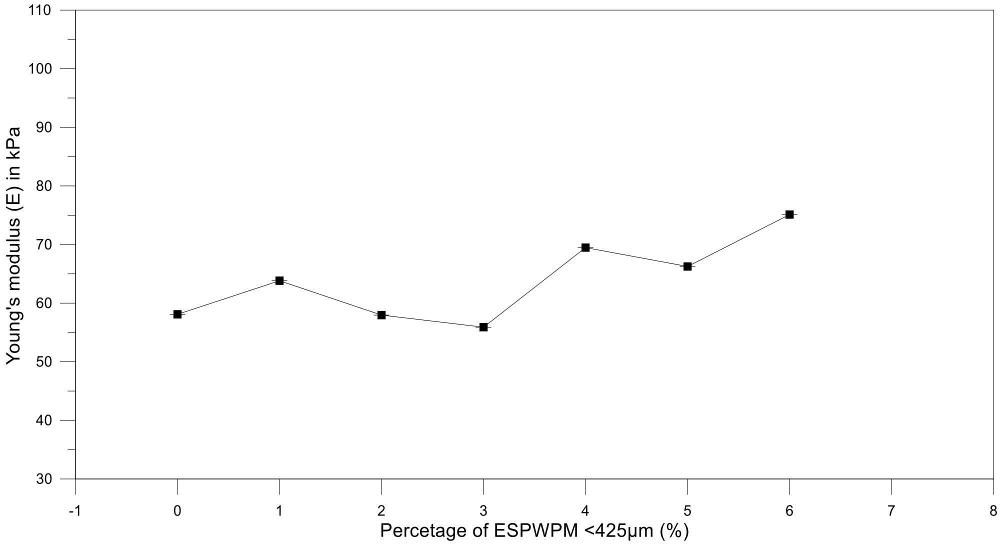
<Figure 4-24> Elastic Modulus of soil stabilized with ESPWPM<88μm



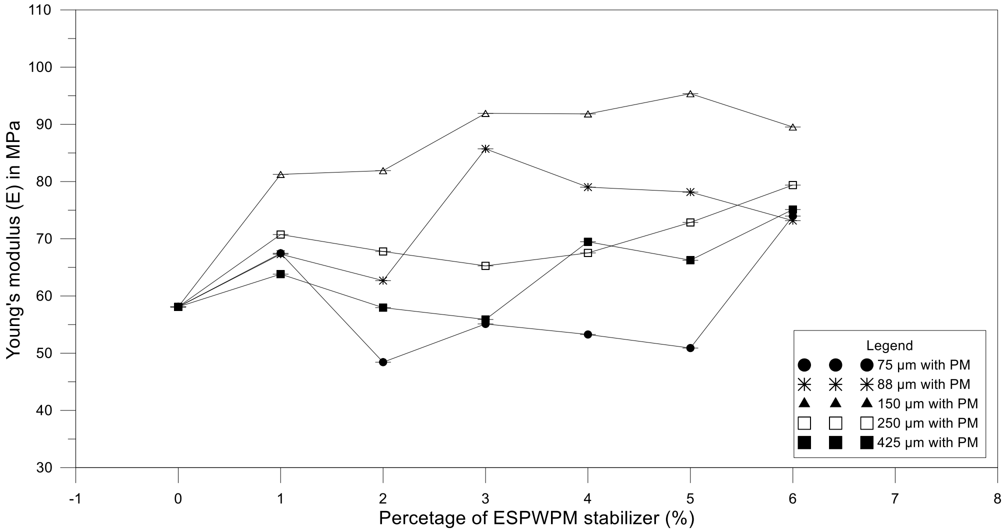
<Figure 4-25> Elastic Modulus of soil stabilized with ESPWPM<150μm



<Figure 4-26> Elastic Modulus of soil stabilized with ESPWPM<250μm

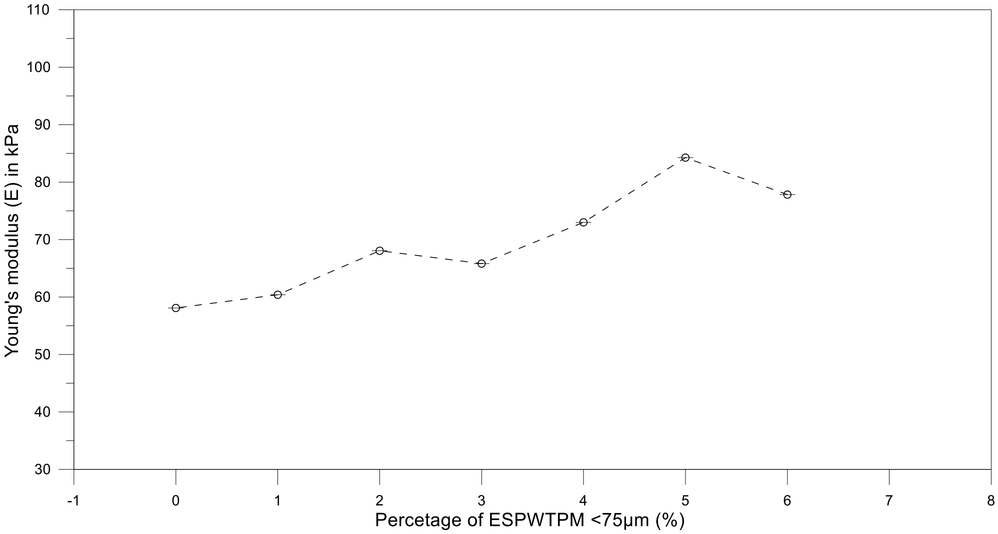


<Figure 4-27> Elastic Modulus of soil stabilized with ESPWPM<425μm

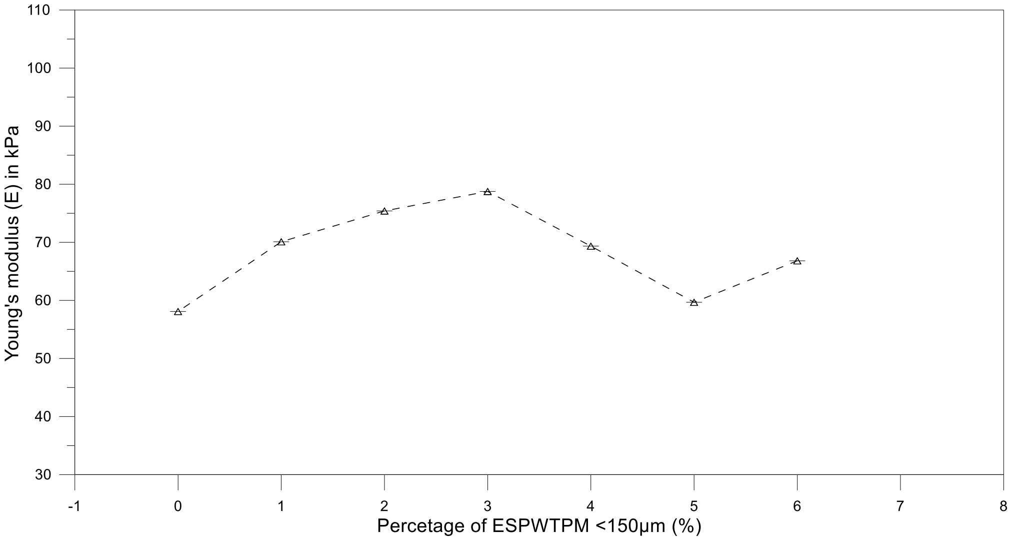


<Figure 4-28> Elastic Modulus of soil stabilized with ESPWPM

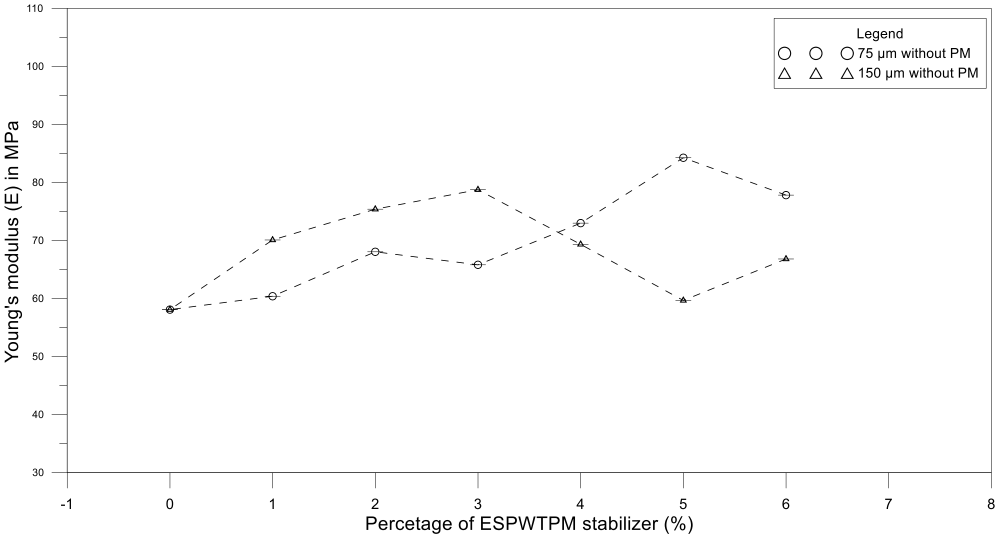
Unfortunately, the soil stabilized with eggshell powder with protein membrane of particle size less than 150 μm showed a significant difference in stiffness. The 5 % concentration was optimum, but 4% also stays closer.Furthermore, the soil stabilized by eggshell powder without protein-membrane was calculated and evaluated in the same process. The data were presented separately and combined in the following graphs:



<Figure 4-29> Elastic Modulus of soil stabilized with ESPWTPM<75µm



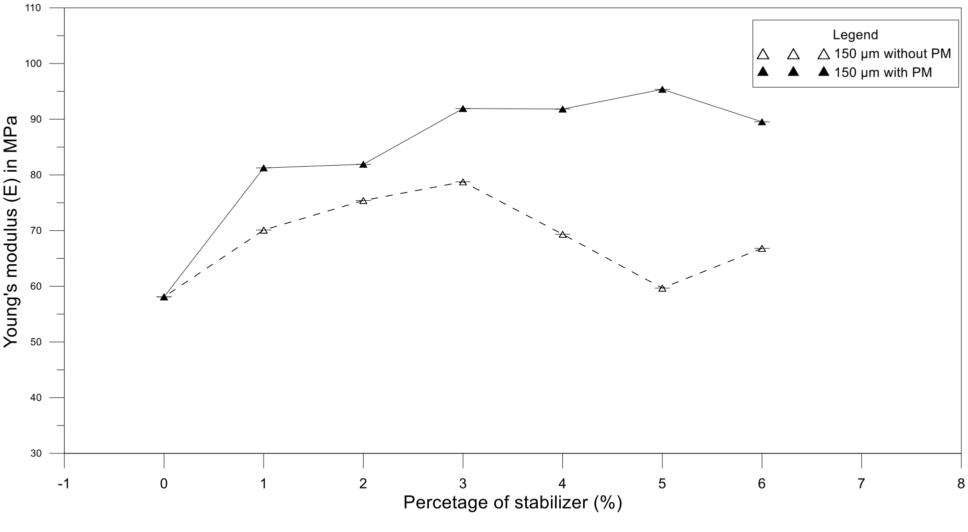
<Figure 4-30> Elastic Modulus of soil stabilized with ESPWTPM<150µm



<Figure 4-31> Elastic Modulus of soil stabilized with ESPWTPM

The trend was as for concentration. The stiffness got the optimum at 3% of eggshell powder without protein-membrane and then decreased at 4% and 5%.

The effect of the protein-membrane was observed when we compared the graph of the stiffness of soil stabilized with eggshell powder with protein-membrane and stiffness of soil stabilized by eggshell powder without protein-membrane when their particle sizes are less than150 μm.



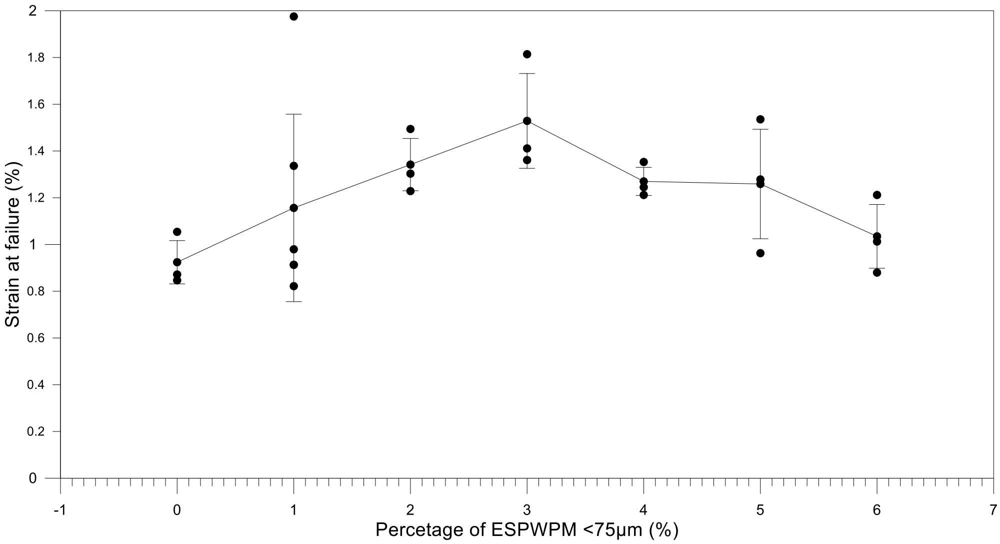
<Figure 4-32> Elastic Modulus of stabilized soil

Contrary to the previous results for concentrations of eggshell powder with and without protein-membrane, the stiffness is low when protein-membrane are removed.

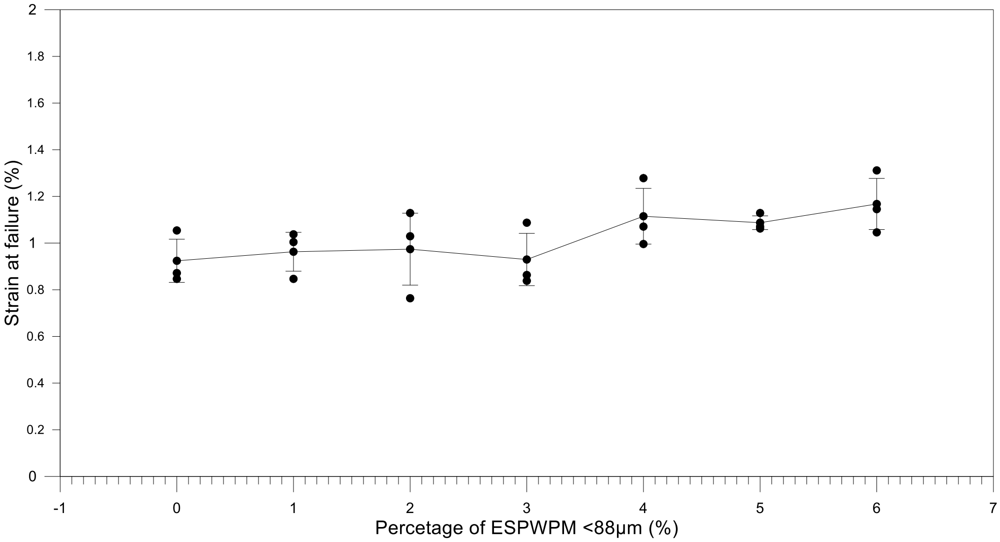
Displacement (strain)

The displacement also is a parameter that can influence the performance of structural soil. Therefore the ultimate strain at the failure point was evaluated and presented in graphs.

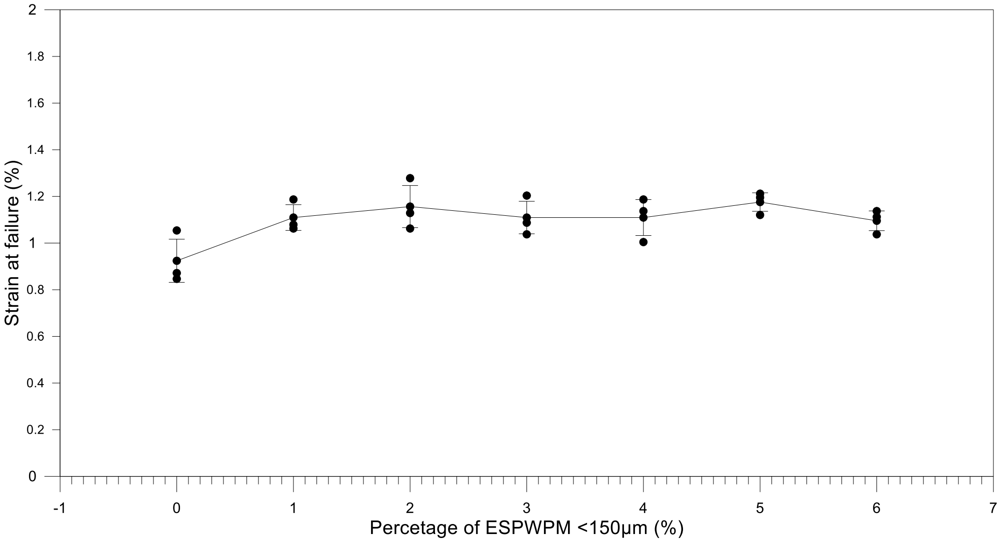
The ultimate strain was taken as the displacement at the failure of the sample in unconfined compression tests.



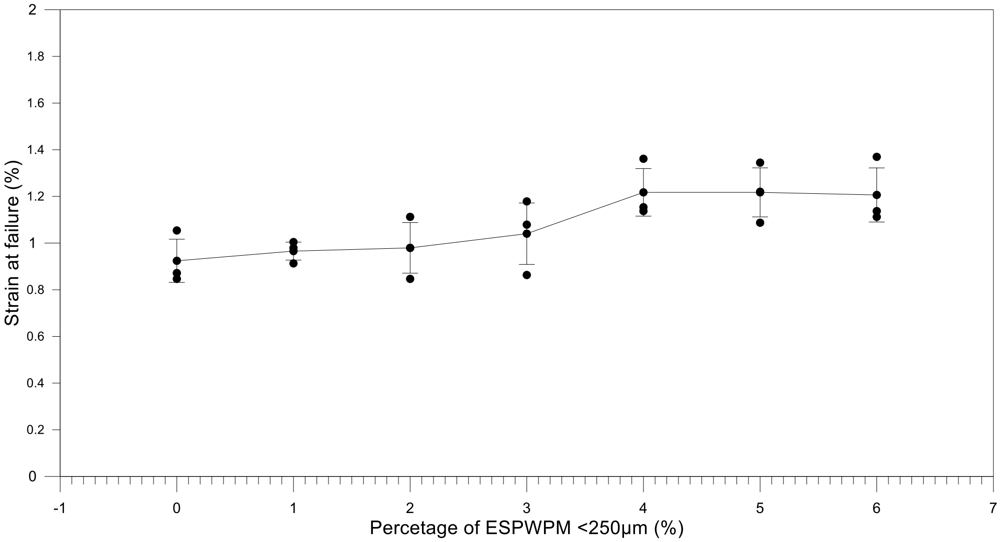
<Figure 4-33> Strain of soil stabilized with ESPWPM<75μm



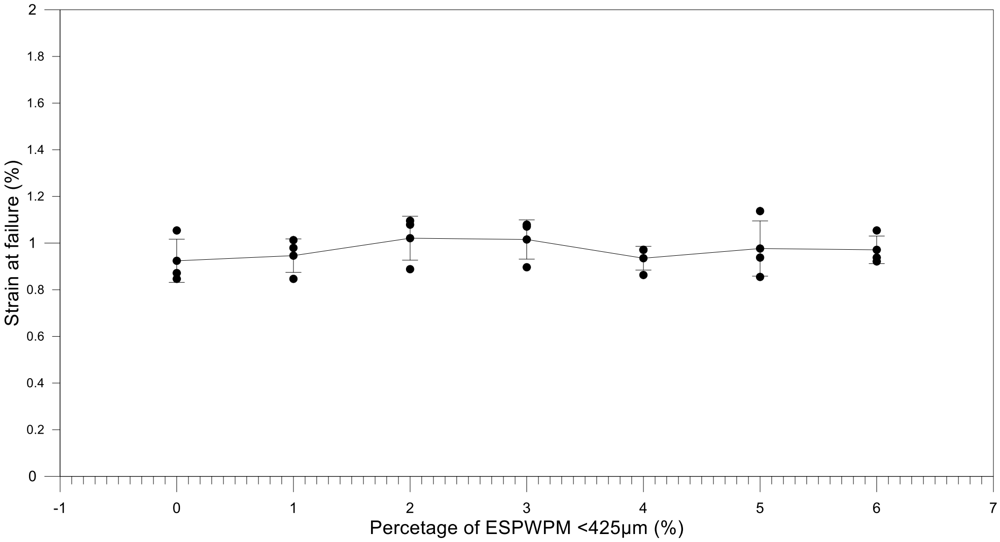
<Figure 4-34> Strain of soil stabilized with ESPWPM<88μm



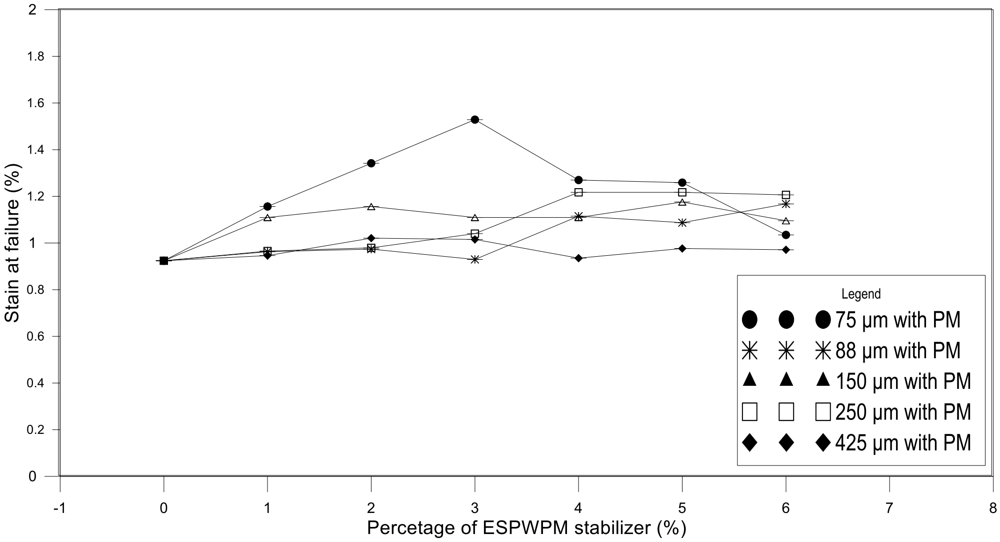
<Figure 4-35> Strain of soil stabilized with ESPWPM<150μm



<Figure 4-36> Strain of soil stabilized with ESPWPM<250μm

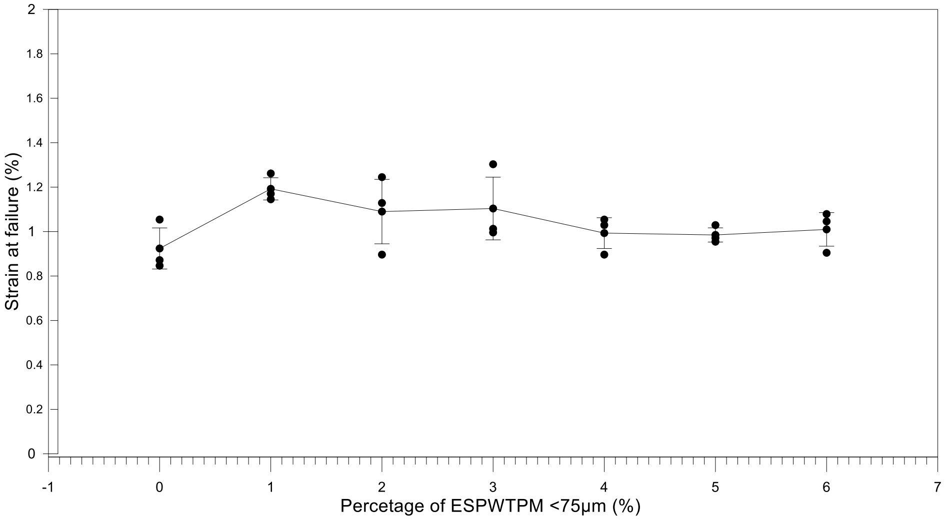


<Figure 4-37> Strain of soil stabilized with ESPWPM<425μm

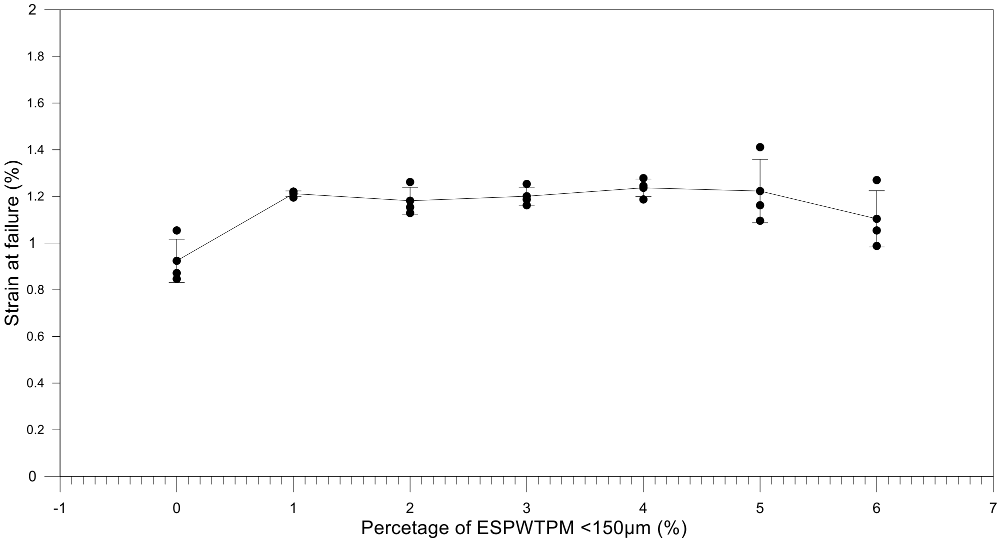


<Figure 4-38> Strain of soil stabilized with ESPWPM

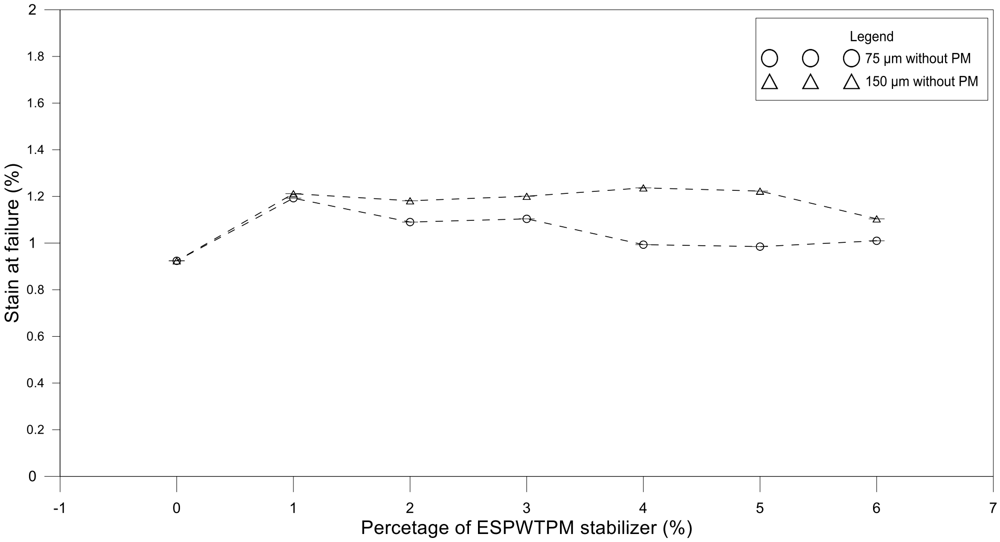
The strain result revealed that the soil stabilized with eggshell powder with protein-membrane at 3% is optimum when the particles sizes are less than 75 µm. Soil stabilized by eggshell powder without protein-membrane are presented in graphs separately and combined.



<Figure 4-39> Strain of soil stabilized with ESPWTPM<75µm

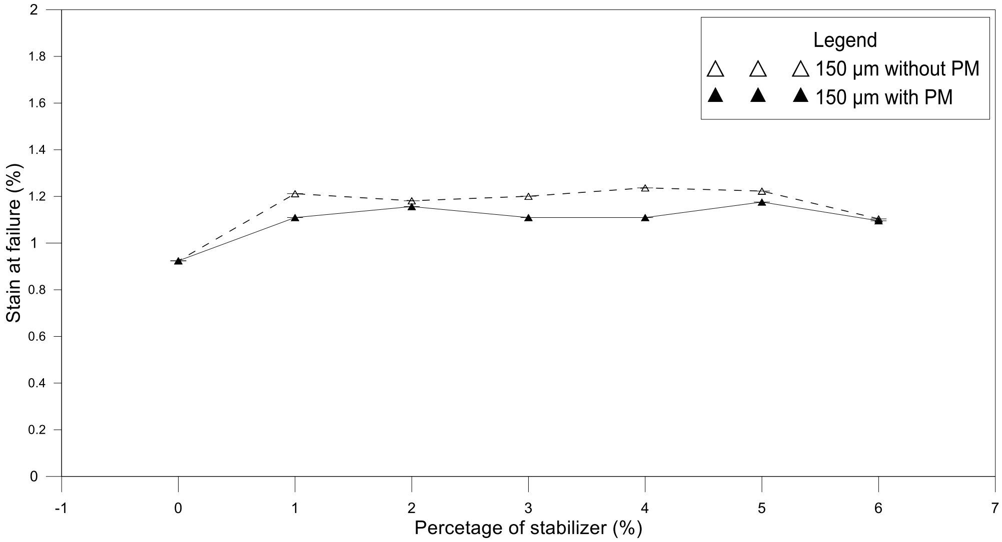


<Figure 4-40> Strain of soil stabilized with ESPWTPM<150μm



<Figure 4-41> Strain of soil stabilized with ESPWTPM

The strain for the soil stabilized with eggshell powder without protein-membrane was high at 3% concentration when the particles sizes are less than 150 μm. The effect of protein-membrane on the strain was observed when we compared the soil stabilized with eggshell powder with and without protein membrane.

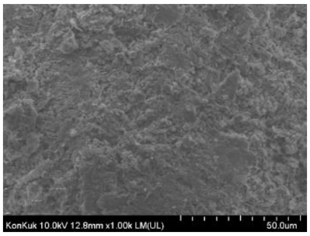


<Figure 4-42> Strain of stabilized soil

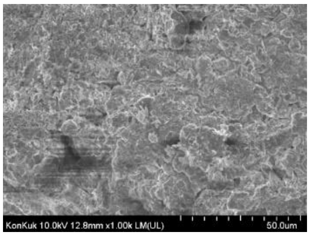
The protein membrane reduced the strain in the samples we considered at a percentage lower than 6%.

4.5. Microstructure analysis

The microstructure of the soil stabilized with eggshell powder with and without protein-membrane was analyzed utilizing SEM, and the extracted images do not reveal much difference except the change in texture and substance that reflecting light seems like cementation.



(a) Ordinary soil



(b) Soil with ESPWPM<75μm

(c)soil with ESPWPM<88μm (d) Soil with ESPWPM<150μm

(e) soil with ESPWPM<250μm (f) soil with ESPWPM<425μm

(g) Soil with ESPWTPM<150μm (h) Soil with ESPWTPM<75μm

(i)ESPWPM. (j) ESPWTPM

<Figure 4-43> SEM images

Chapter 5. Numerical analysis of the Stabilized Road Embankment

5.1. Overview

5.1.1. Introduction

In this chapter, the results selected from the findings in chapter 4 are systematically integrated into instability and displacement numerical models to examine the applicability of the eggshell powder stabilizer in flexible pavement road construction. This numerical model will provide a rational basis for understanding the behavior of the stabilized soil when used as a subbase.

5.1.2. Method and assumptions

Numerical modeling in geotechnical is associated with a set of mathematical equations that can describe the behavior of material or geotechnical structure based on the relationship between stress and strain (Zhang et al., 2013).

We assumed that the values of stress, strain, and deflection components could be calculated at any defined structural point from the structural geometry and surface loading (Brown, 1996). Wheel loading is represented as a static, uniformly distributed load. The real non-linear stress-strain relationship between soil and granular layer and the plastic behavior of the surfacing layer is not considered.

5.2. Numerical modeling

5.2.1. Finite elemenet method (FEM)

The finite element method is one of the techniques for solving approximately a boundary-value problem (Bathe, 1996). This method involved subdividing a solution domain into simple finite elements subdomains using variational concepts to approximate solutions by collecting finite elements.

FEM is constructed in steps from Discretize the continuum, Selecting the interpolation functions, Finding the properties of the element, Assembling the element equations, Solving the global equation system, and Computing additional results.

In geotechnical modeling using FEM, generally, the goal is to determine the unknown displacement, that puts the body in equilibrium. The principal governing equation:

$$\{\Delta\sigma\} = [\mathrm{D}]\{\Delta\varepsilon\} \tag{5.1}$$

where $\{\Delta\sigma\}$ represents the difference in stresses, D the relationship between straess and strain, $\{\Delta\varepsilon\}$ the difference in strain.

As for mohr's coulomb yield surface criterial the stress, the equation is

$$f^{m} = \frac{1}{2}(\sigma_1 - \sigma_3) + \frac{1}{2}(\sigma_1 + \sigma_3)\, sin\, \emptyset - c\, cos\, \emptyset \tag{5.2}$$

where,

σ_1 is maximum principal stress

σ_3 is minimum principal stress

c is the cohesion of soil material

$\emptyset$ is the internal angle of friction

Midas GTX NX is used to carry out the numerical modeling and analysis in this research using the Finite Element Method (FEM) in a two-dimensional model. Soil behavior was simulated using the Mohr-Coulomb model as soil behaves as elastoplastic material(continuum material) and the surfacing asphalt concrete as a linear elastic isotropic model. The primary justification of using elastic theory is that most pavement responds resiliently when single load application is considered (Brown, 1996).

5.2.2. Strength reduction Analysis

A safety factor is an approach in design where a failure mechanism using acceptable shear strength parameters is first postulated and compared with the load causing the failure. This ratio of this comparison is then called the factor of safety. Therefore, soil structure stability is observed through the factor of safety;

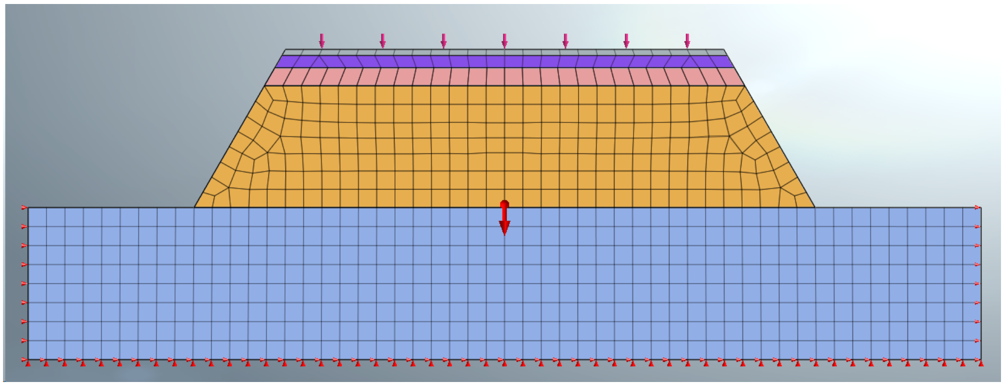
the more the factor of safety is, the more likely stable the structure is.

In geotechnical numerical analysis, the reduction of the soil shear strength is applied to fix the imperfection between the real strength of soil and soil strength obtained in the laboratory at disturbed or not disturbed samples.

5.2.3. Model selection

The numerical modeling was based on a comparative study that implies the data from the research of Hashem & Abu-baker (2013). In that research, they worked on the flexible pavement from which we borrowed the structural pavement dimensions and used the same method to get comparable results.

Model



<Fugure 5-1> 2D model of a road embankment

<Table 5-1> Table of the Road embankment Transversal section

Road section layers	Surface course	Base course	Subbase course	Compacted subgrade	Natural subgrade
Depth	10cm	20cm	30cm	200cm	250cm
Uniformly distributed load	1000KN				

5.3. Analysis of cases

The selection of the case we examined was based on the performance of the stabilizer to conventional laboratory tests. The unstabilized soil is compared with soil stabilized by ESP with and without protein-membrane at different particle sizes. The stabilizer that revealed an improvement to the parameters that govern the structural behavior of soil was selected to be used for further numerical analysis.

The cases were selected based on their relevance in the research. The first case was selected to represent the behavior of the soil when it is no stabilized; the second case was selected to examine the impact the stabilization with eggshell at optimum particle size has on the performance of the soil in road application. Lastly, the third case was selected to manifest the effect of protein-membrane in soil stabilization.

Case 1: Unstabilized soil

Case 2: Soil stabilized with eggshell powder without protein-membrane<150μm at 3 % mass concentration.

Case 3: Soil stabilized with eggshell powder with protein-membrane <150μm at 4 % mass concentration.

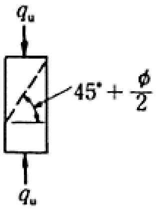
5.4. Properties and Analysis procedure

In modeling, the properties of the materials are essential. Some of the properties are founded immediately through laboratory tests; others are derived from a particular test. Numerical analysis requires parameters from the unconfined compression test. Samples were from stiffer clay, a distinct failure plane was formed. A picture of the failure plane was taken and then measured using AUTOCAD software. The Mohr's circle indicates that the maximum value of the unconfined compression strength (σ_1) and the confining stress is $\sigma_3 = 0$.

The Young modulus (E) is calculated from the stress-strain curve as in chapter 4, the Poisson's ratio is estimated from literature(Hadi & Bodhinayake, 2003)(Christopher et al., 2006), the cohesion and angle of friction are calculated approximately using the mohr-coulomb failure theory.

$$c = \frac{q_u}{2\tan(45+\frac{\emptyset}{2})} \tag{5.3}$$

Where C is the cohesion of soil, q_u is the maximum unconfined compression stress, $\emptyset$ friction angle, and $(45+\frac{\emptyset}{2})$ be the breaking angle in the unconfined compression test

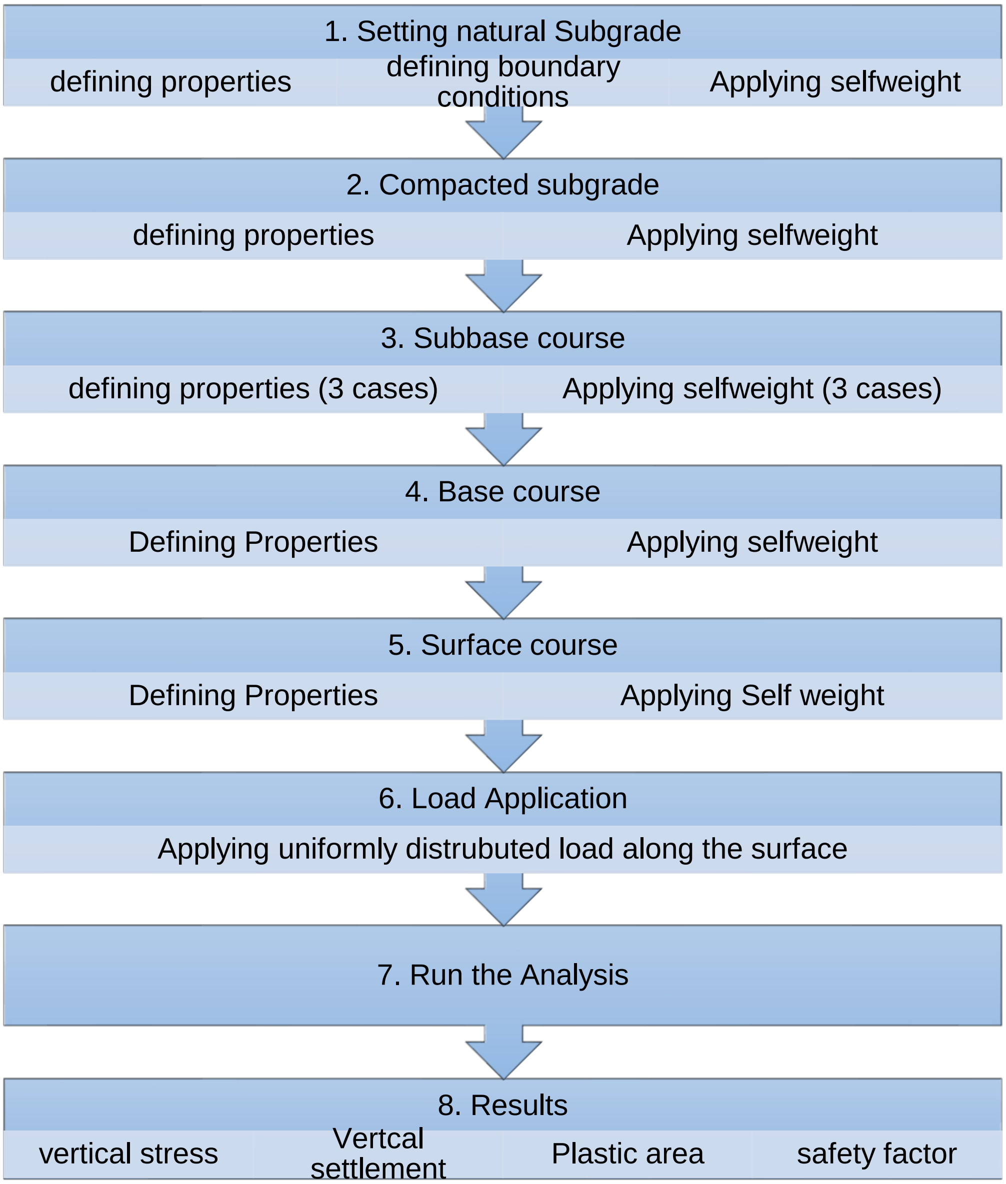


<Figure 5-2> Breaking angle for an unconfined compression test

<Table 5-2> Required properties of layering materials

Material parameters	Surface course	Base course	Sub-base course			Compacted subgrade	Subgrade
			case1	case2	case3		
Model	LE	M-C	M-C	M-C	M-C	M-C	M-C
Young's Modulus E(kPa)	1.8 x10^6	1.4 x 10^3	66845	78125	94637	50000	55000
Poisson's ratio ν	0.3	0.4	0.4	0.4	0.4	0.3	0.35
Dry density KN/m^3	24.5	23	17.9	18.15	18.14	17	17
Cohesion C(kPa)	-	0	17	145	65	15	28
Friction angle ϕ		40	18	65	75	20	20

The flow chart of the analysis procedure follows eight (8) essential steps to do the numerical modeling in Midas GTX NX.

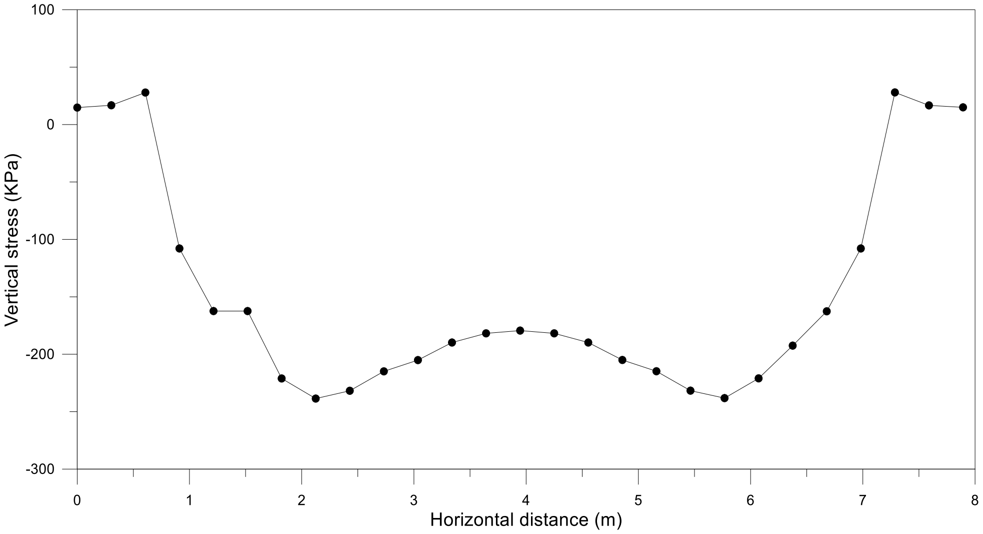


5.5. Numerical Analysis Results

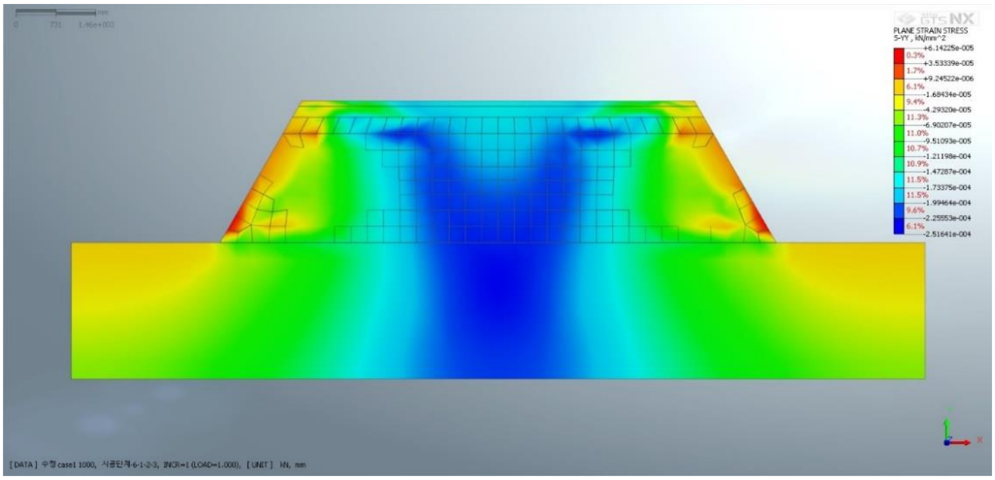
The result obtained from the model was mainly focused on the subbase zone where our interests were. The vertical stress, verticle settlement, and plastic area was presented graphically

①Vertical stress of the subbase course

Case 1

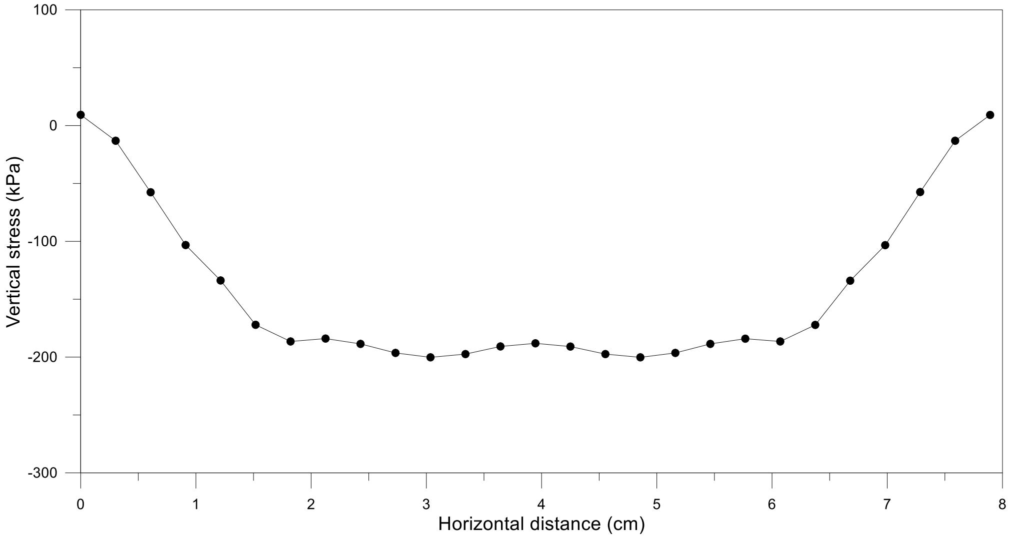


<Fugure 5-3> Vertical stress of sub base when soil is unstabilized

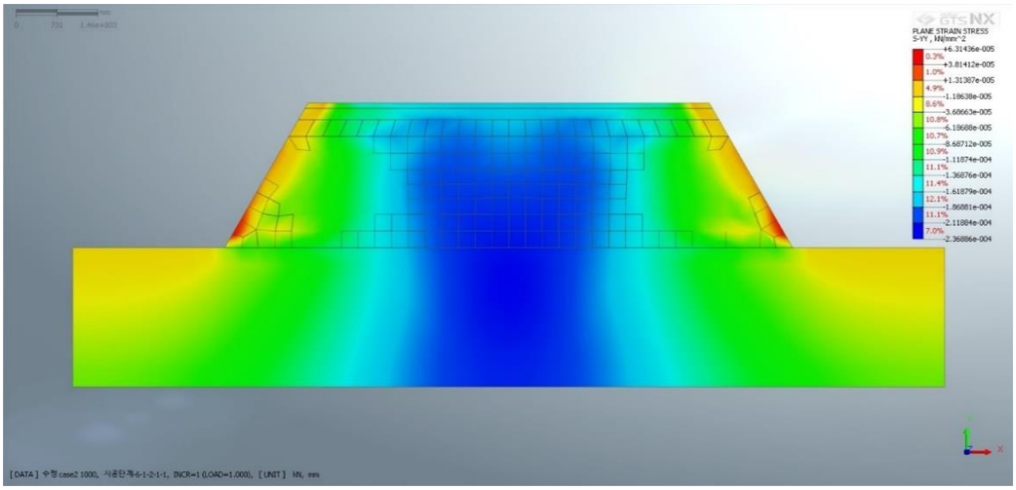


<Fugure 5-4> Vertical stress of subbase in when soil is unstabilized

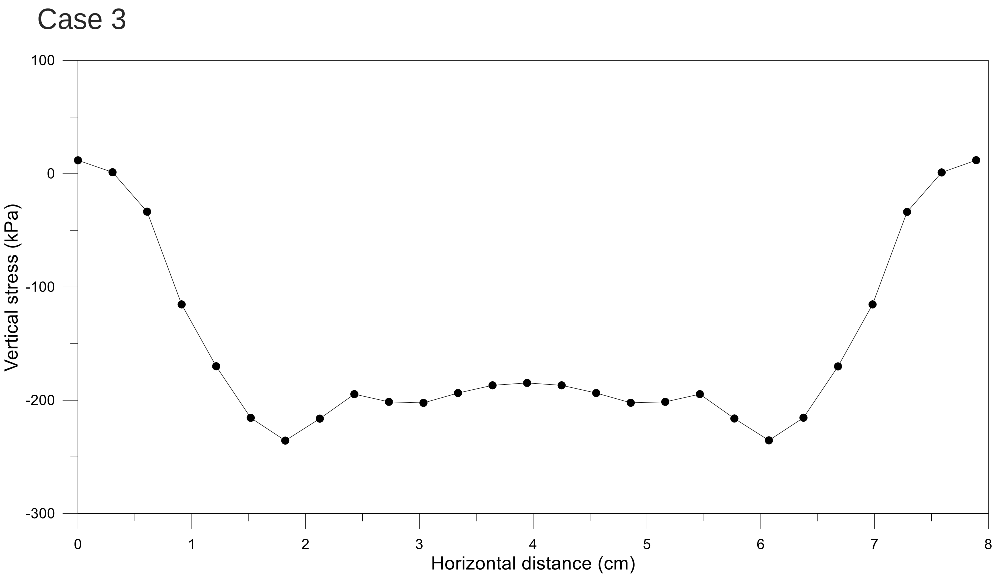
Case 2



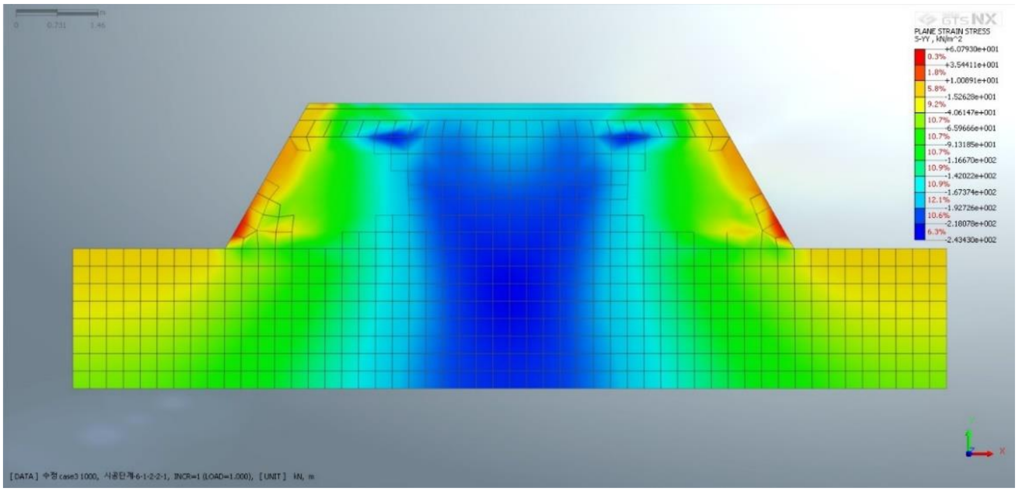
<Figure 5-5> Vertical stress when subbase stabilized with 3% ESPWTPM<150µm



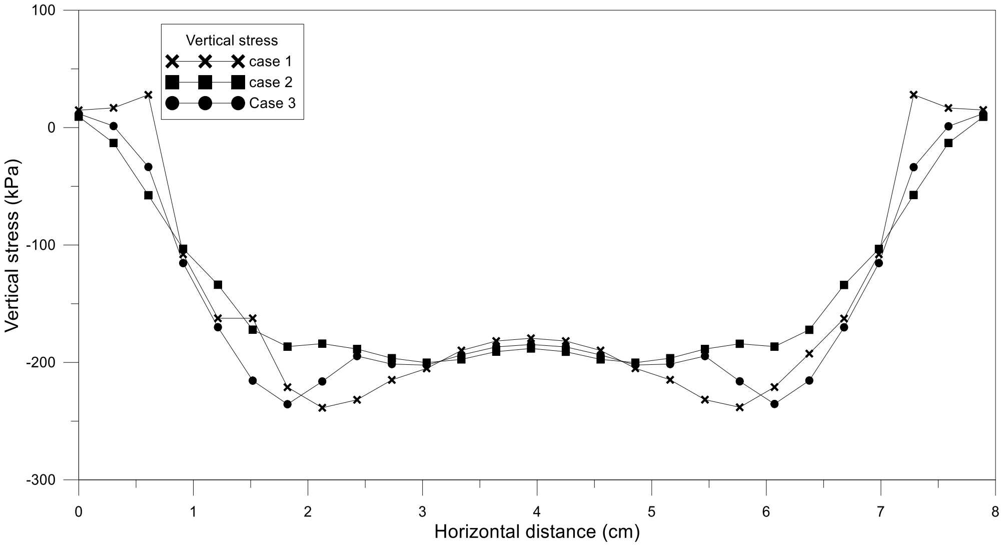
<Figure 5-6> Vertical stress when subbase stabilized 3% ESPWTPM<150µm



<Figure 5-7> Vertical stress when subbase stabilized 4 % ESPWPM<150μm



<Figure 5-8> Vertical stress when subbase stabilized 4 % ESPWPM<150μm

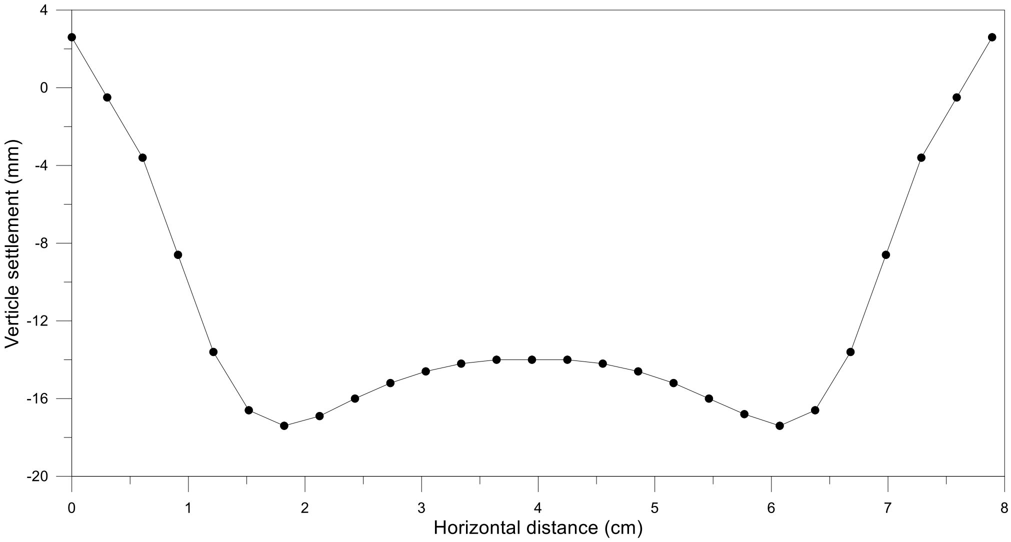


<Figure 5-9> Vertical stress of sub-base for 3 cases

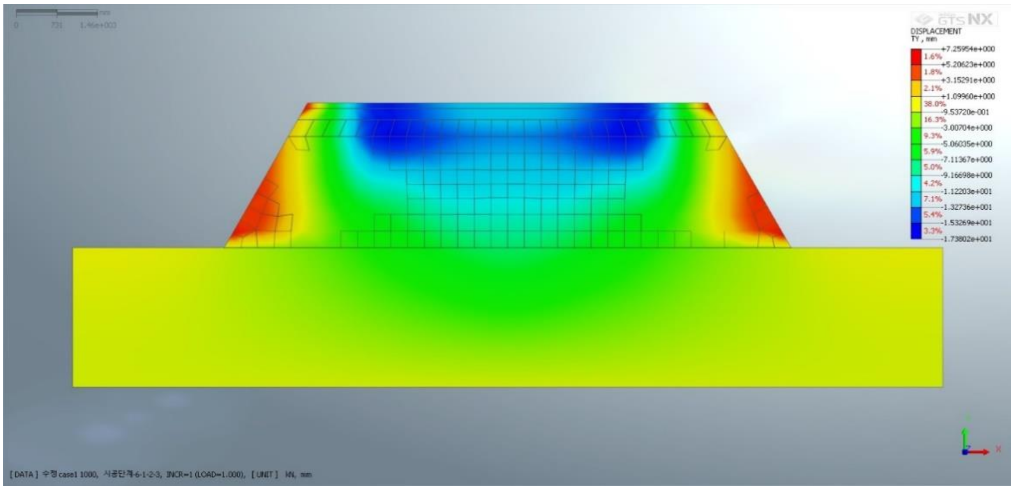
The total vertical stresses are compression (negative) and tension (positive). The compressive stress increases from the edges towards the center, where they get their peaks around 2m distance from the edges. 238.6 kPa, 200 kPa, and 235.6 kPa were the peaks of vertical stress estimated in three consecutive cases, respectively. The numerical analysis reveals that stresses are high in unstabilized soil and low in the soil stabilized with eggshell powder without protein-membrane at 3% mass concentration.

② Vertical settlement of the subbase course

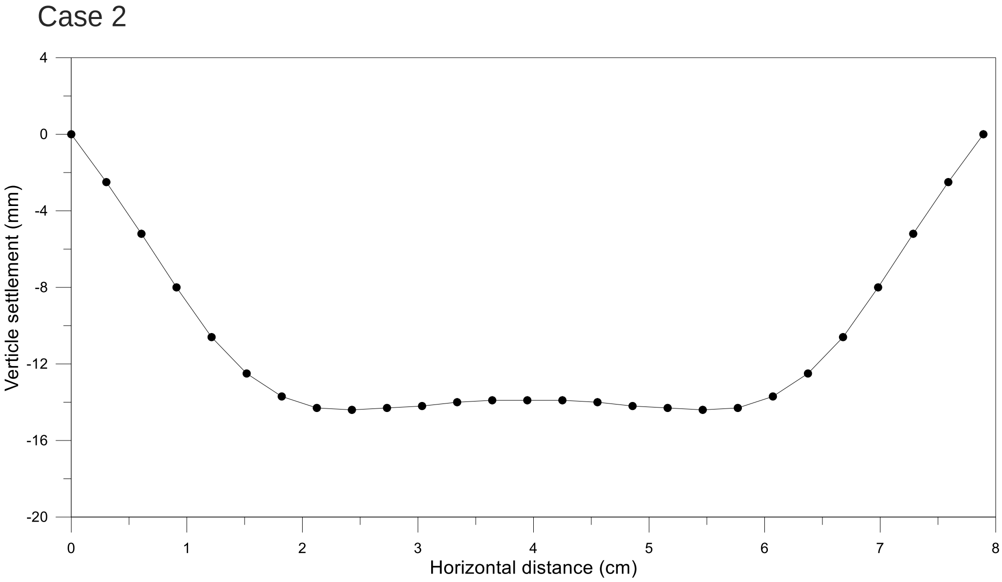
Case 1



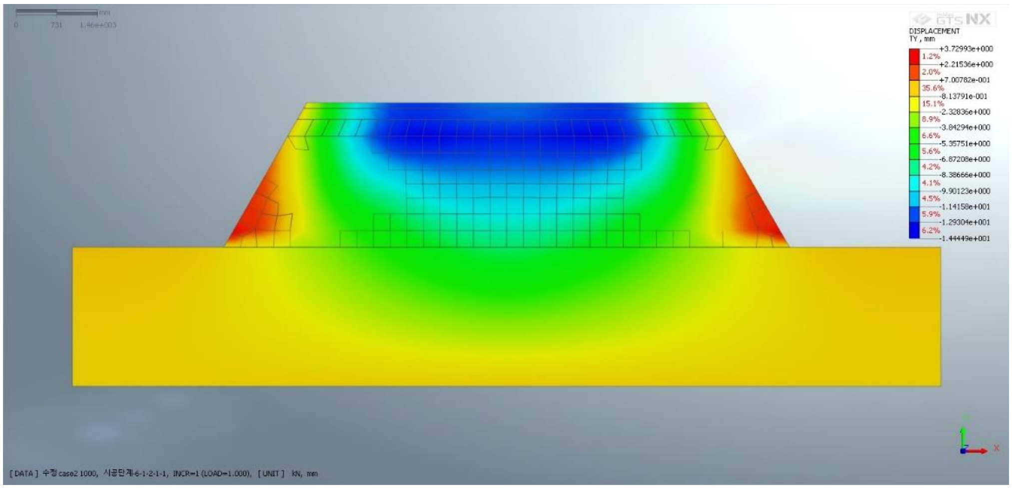
<Figure 5-10> Vertical settlement of sub base when the soil is unstabilized



<Figure 5-11> Vertical settlement of sub base when the soil is unstabilized

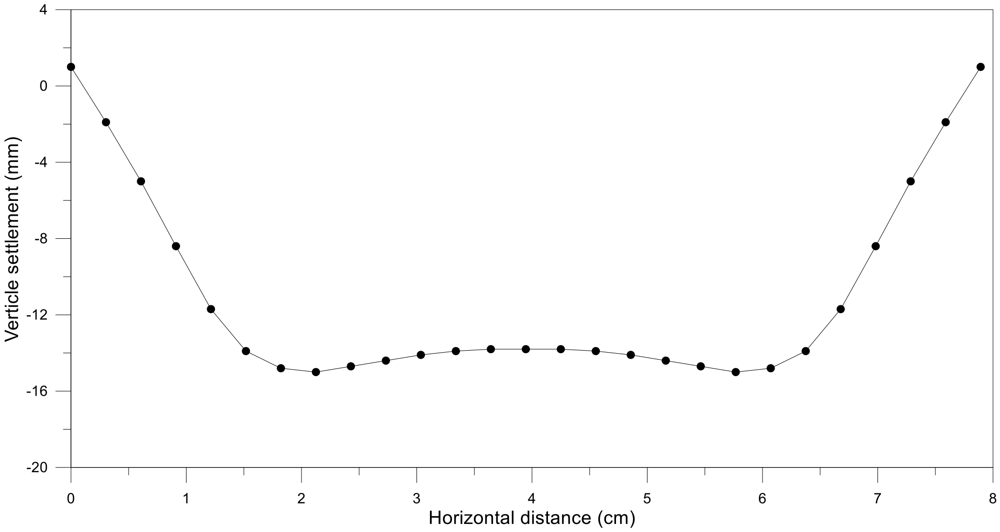


<Figure 5-12> Vertical settlement when subbase stabilized 3 % ESPWTPM<150μm

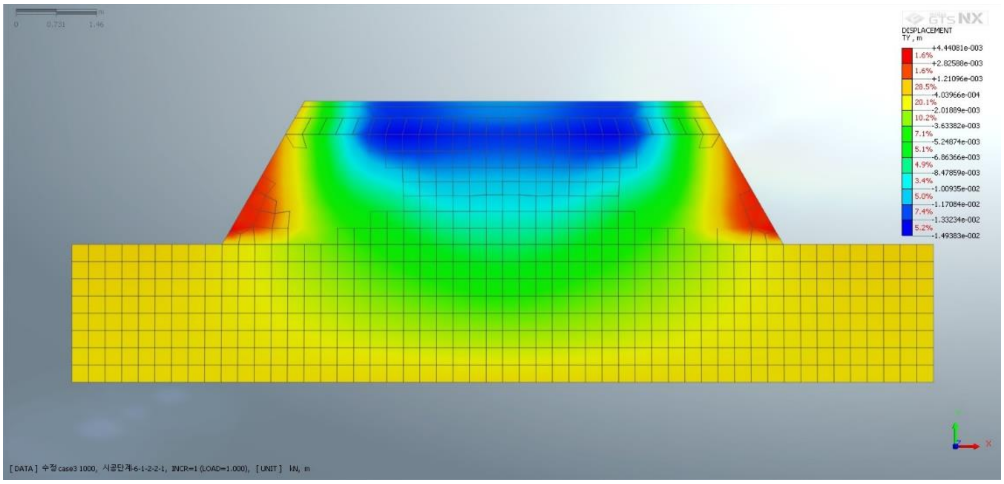


<Figure 5-13> Vertical settlement when subbase stabilized 3 % ESPWTPM<150μm

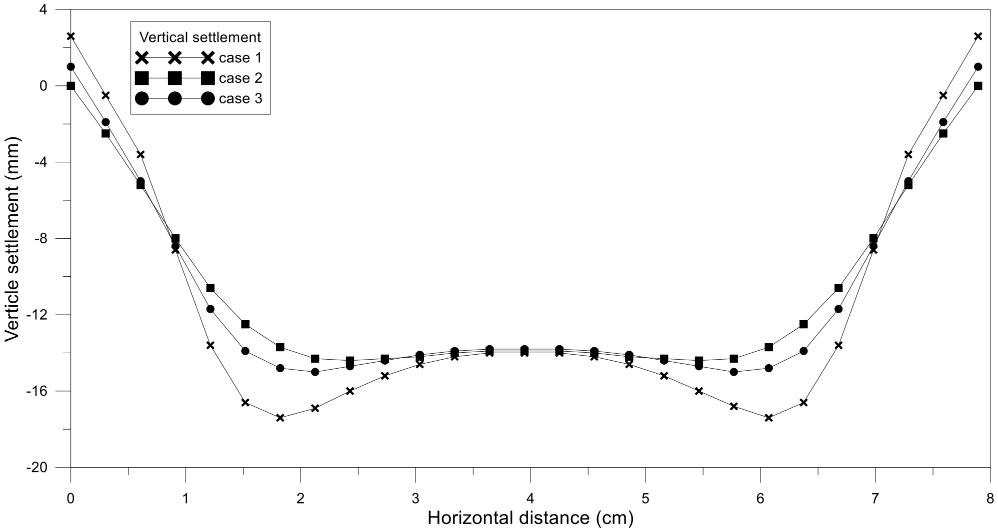
Case 3



<Figure 5-14> Vertical settlement when subbase stabilized 4 % ESPWPM<150μm



<Figure 5-15> Vertical settlement when subbase stabilized 4 % ESPWPM<150μm



<Figure 5-16> Vertical settlement of sub-base for 3 cases

The numerical analysis in MIDAS GTX NX considers the vertical settlement positive when whey are upward and negative when they are downward. The vertical settlement trends in the same way as the vertical stresses, where the settlement increases downward from the edges towards the center. The peaks are 17.4mm,14.mm, and 15mm downwards in the three consecutive cases, respectively. The eggshell powder reduces the settlement in the subbase at 17% and 14% in consecutive cases, respectively.

③ Stability

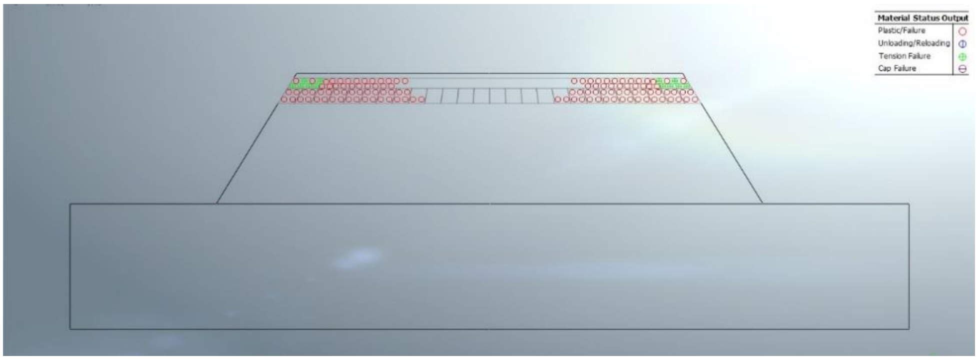
<Table 5-3> Factor of safety for different cases

cases	Vertical Settlements(mm)	Vertical Stress(kPa)(↓)	Safety Factor
Case1	17.4	238.6	1.31
Case2	14.4	200.2	1.50
Case3	15.0	235.6	1.43

The safety factor increased in the soil stabilized with eggshell power at 14% (from 13.1 to 1.5). The safety increased about 15% and 9%, respectively.

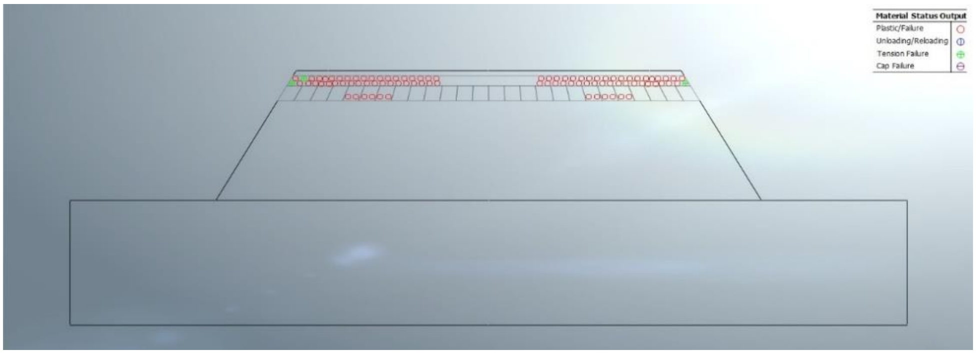
④ Plastic region

Case 1



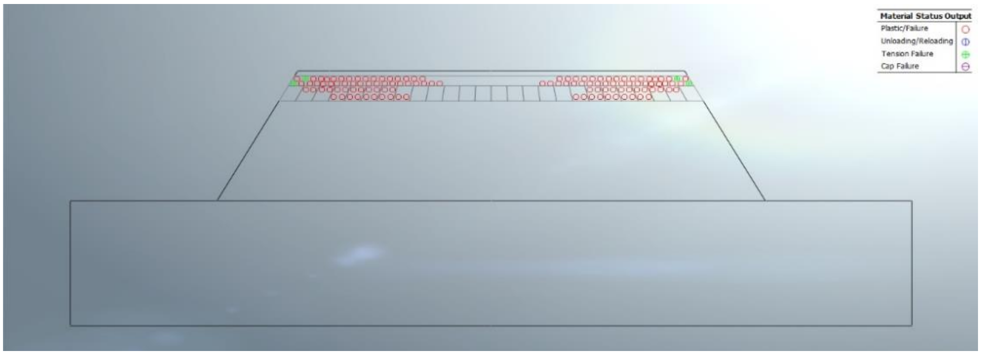
(a) Plastic region when sub-base soil is unstabilized

Case 2



(b) Plastic region when subbase stabilized 3 % ESPWTPM<150μm

Case 3



(c) Plastic region when subbase subbase stabilized 4 % ESPWPM<150μm

<Figure 5-17> Plastic region

The unrecovered settlement is significant in the unstabilized soil while it is reduced in the stabilized soil. The plastic failure caused the tensional failure in the superior layer (base coarse). In the second case, it can be observed slightly small area of plastic failure. Therefore stabilization worked well in the subbase.

Chapter 6. Conclusions

After the diligent work from literature throughout the laboratory test and the numerical analysis, the research concludes with exciting findings. Composite soil made with kaolinite as clay particles, Jumunjin sand as a sand particle, and river gravel can make the same properties as natural laterite for the tests carried out in this research.

1. Eggshell powder with protein-membrane can stabilize soil at a low percentage (at 6%) if the particle size of the eggshell powder is kept below 250μm. At least 34% increment of the unconfined compression stress was observed for soil stabilized with eggshell powder with protein membrane. The protein membrane being an organic material can make a temporal stabilization measure for it will be degraded with time.
2. Particle size below 150μm and greater than 88 μm of eggshell powder are the optimum particle size that can stabilize soil at a low mass concentration percentage.
3. The protein membrane reduces the stabilizing ability of eggshell powder when the particle sizes of eggshell powder are in the range of between 150 μm and 88 μm and the mass concentration is below 4%. When the stabilizer content is greater than 4%, it is preferable to use eggshell powder with protein membrane.
4. 3 % of eggshell powder without protein-membrane can stabilize the soil by 52% when the particle size of eggshell powder without protein membrane is below 150μm and greater than 88 μm, but after 3%, the stabilizing ability drop down considerably under the stabilizing with eggshell with protein membrane.
5. The SEM was not much distinctive, but white spots can be related to soil cementation due to the stabilizer.
6. The numerical analysis confirmed the behavior of soil stabilized with

eggshell when it reduces the settlement at 17%.

7. The numerical analysis also revealed the reduction of about 16% in the vertical stress after stabilizing the soil.
8. The vertical stress from the numerical analysis differs from the obtained in the laboratory test due to the assumptions made while doing numerical analysis and the factor of safety applied.
9. Finally, stabilizing soil with eggshell powder is feasible and economically effective because eggshells are available as waste. The treatment seems more effortless as you do not need to make much effort grinding them to get a very fine eggshell powder. Particles passing 150μm sieve are enough and much efficient than the finer particles.

References

ALEXANDER, L. T., & CADY, J. G. (1963). Genesis and Hardening of Laterite in Soils. *Soil Science*, *96*(1), 75. https://doi.org/10.1097/00010694-196307000-00015

American, S., America, N., & American, S. (1964). *Lateritic Soils Author (s): Mary McNeil Source : Scientific American , Vol . 211 , No . 5 (November 1964), pp . 96-106 Published by : Scientific American , a division of Nature America , Inc . Stable URL : https://www.jstor.org/stable/10.2307/24931695*. *211*(5), 96–106.

American Society for Testing and Material. (2007). ASTM D 698-07 Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort. *Gostroizdat*, *3*, 15.

Amu, O., Fajobi, A., & Oke, B. (2005). O. Amu et al 2005.pdf. In *Journal of Applied Science* (Vol. 5, pp. 1474–1478).

Amu, O. O., & Salami, B. a. (2010). Effect of Common Salt on Some Engineering Properties. *ARPN Journal of Engineering and Applied Sciences*, *5*(9), 64–73.

Bathe, K. J. (1996). Finite Element Procedures. In *Englewood Cliffs New Jersey*. http://www.amazon.com/Finite-Element-Procedures-Part-1-2/dp/0133014584

Beetham, P., Dijkstra, T., Dixon, N., Fleming, P., Hutchison, R., & Bateman, J. (2015). Lime stabilisation for earthworks: A UK perspective. *Proceedings of the Institution of Civil Engineers: Ground Improvement*, *168*(2), 81–95. https://doi.org/10.1680/grim.13.00030

Bello, A., Ige, J., & Ayodele, H. (2015). Stabilization of Lateritic Soil with Cassava Peels Ash. *British Journal of Applied Science & Technology*, *7*(6), 642–650. https://doi.org/10.9734/bjast/2015/16120

Brown, S. F. (1996). Soil mechanics in pavement engineering. *Geotechnique*, *46*(3), 383–426. https://doi.org/10.1680/geot.1996.46.3.383

Christopher, B. R., Schwartz, C., & Boudreau, R. (2006). *NHI Course No. 132040, Geotechnical Aspects of Pavements, Reference Manual / Participant Workbook (Report)*. *FHWA NHI-05-037*, 888. https://www.fhwa.dot.gov/engineering/geotech/pubs/05037/05037.pdf

Data, R. U. S. A. (2011). *(12) United States Patent*. *2*(12).

Diamond, S., & Kinter, E. B. (1965). Mechanisms of Soil-Lime Stabilization An Interpretive Review. *Highway Research Record*, *92*, 83–102.

DNIT. (2010). Pavimentação – base estabilizada granulometricamente com utilização de solo laterítico – Especificação de serviço. *Departamento Nacional de Infraestrutura de Transportes, Instituto de Pesquisas Rodoviárias*, *2961*, 9.

Frank, I., Long, D., Adams, R. G., Us, M. O., & Devore, D. P. (2005). *(12) United States Patent*. *2*(12).

Gidigasu, M. D. (1974). Degree of weathering in the identification of laterite materials for engineering purposes - a review. *Engineering Geology*, *8*(3), 213–266. https://doi.org/10.1016/0013-7952(74)90001-5

Hadi, M. N. S., & Bodhinayake, B. C. (2003). Non-linear finite element analysis of flexible pavements. *Advances in Engineering Software*, *34*(11–12), 657–662. https://doi.org/10.1016/S0965-9978(03)00109-1

Hashem, M. D., & Abu-baker, A. M. (2013). Numerical Modeling of Flexible Pavement Constructed On Expansive Soils. *European International Journal of Science and Technology*, *2*(10), 19–34.

Jinping, Y. (2017). *Nconfined ompression est*. 1–4.

Kumar M, M., & V S, T. (2014). Effect of Eggshell Powder in the Index and Engineering Properties of Soil. *International Journal of Engineering Trends and Technology*, *11*(7), 319–321. https://doi.org/10.14445/22315381/ijett-v11p261

Li, C., Ashlock, J. C., & Wang, X. (2019). Quantifying Repeatability Reproducibility Sources of Error and Capacity of a Measurement: Demonstrated Using Laboratory Soil Plasticity Tests. *Advances in Civil Engineering*, *2019*. https://doi.org/10.1155/2019/4539549

Mbumbia, L., Mertens De Wilmars, A., & Tirlocq, J. (2000). Performance characteristics of lateritic soil bricks fired at low temperatures: A case study of Cameroon. *Construction and Building Materials*, *14*(3), 121–131. https://doi.org/10.1016/S0950-0618(00)00024-6

Morin, & Todor. (1977). *Laterite and Lateritic Soils and Other Problem*. 1–92.

Netterberg, F. (1994). Low-cost local road materials in southern Africa. *Geotechnical and Geological Engineering*, *12*(1), 35–42. https://doi.org/10.1007/BF00425935

Netterberg, Frank. (2014). *Review of specification for the use of laterite in road pavements*. *60*(May), 1–60.

New, L. (2013). *Eggshell membrane separation process United States Patent No. 8,448,884 B2*. *2*(12).

Nogami, J. S., & Villibor, D. F. (1991). Use of lateritic fine-grained soils in road pavement base courses. *Geotechnical and Geological Engineering*, *9*(3–4), 167–182. https://doi.org/10.1007/BF00881739

Ojuri, O. O., Adavi, A. A., & Oluwatuyi, O. E. (2017). Geotechnical and environmental evaluation of lime–cement stabilized soil–mine tailing mixtures for highway construction. *Transportation Geotechnics*, *10*, 1–12. https://doi.org/10.1016/j.trgeo.2016.10.001

Oluwatuyi, O. E., Adeola, B. O., Alhassan, E. A., Nnochiri, E. S., Modupe, A. E., Elemile, O. O., Obayanju, T., & Akerele, G. (2018). Ameliorating effect of milled eggshell on cement stabilized lateritic soil for highway construction. *Case Studies in Construction Materials*, *9*(August), e00191. https://doi.org/10.1016/j.cscm.2018.e00191

Paige-Green, P., Pinard, M., & Netterberg, F. (2015). A review of specifications for lateritic materials for low volume roads. *Transportation Geotechnics*, *5*, 86–98. https://doi.org/10.1016/j.trgeo.2015.10.002

Patrick, D. M., & Townsend, F. C. (n.d.). *PROPERTY OF THE UNITED STA Lu3q*.

Piratheepan, J., Gnanendran, C. T., & Arulrajah, A. (2012). Determination of c and φ from IDT and Unconfined Compression Testing and Numerical

Analysis. *Journal of Materials in Civil Engineering*, *24*(9), 1153–1164. https://doi.org/10.1061/(asce)mt.1943-5533.0000493

Price, B. J., & Major, H. W. (1990). XRF analysis boosts QC in plastics processing. *Plastics Engineering*, *46*(8), 37–49. https://doi.org/10.1520/D2166-06.

Rahman, M. D. A. (1986). The potentials of some stabilizers for the use of lateritic soil in construction. *Building and Environment*, *21*(1), 57–61. https://doi.org/10.1016/0360-1323(86)90008-9

Soil_Mechanics-Craig.Pdf. (n.d.).

Standardization, E. C. for. (2010). The World of European Standards. *Compass*, 1–12.

Standards, B., Standards, U., Started, N. W., Cen, D. D., Clc, D. D., Iso, D. D., Iso, D. D. C. E. N., Iso, D. D. C. E. N., Iso, D. D. C. E. N., Iso, D. D. C. E. N., Iec, D. D., Iec, D. D., & Iec, P. D. (2009). *British Standards - Quick Reference Guide Update Standards Jul 2009 British Standards - Quick Reference Guide continued ... Update Standards Jul 2009*. *May*.

Stephens, T., & FAO. (2010). Manual on small earth dams, A guide to siting, design and construction. In *FAO drainage and irrigation paper, Number 64*.

Townsend, F. C., Manke, P. G., & Parcher, J. V. (n.d.). *Effects of Remolding on the Properties of a Lateritic Soil*. 76–84.

Walsh, P. E. P., & Data, R. U. S. A. (2001). *(12) United States Patent*. *1*(12).

Yerramala, A. (2014). Properties of concrete with eggshell powder as cement replacement. *Indian Concrete Journal*, *88*(10), 94–102.

Yoo, S., Hsieh, J. S., Zou, P., & Kokoszka, J. (2009). Utilization of calcium carbonate particles from eggshell waste as coating pigments for ink-jet printing paper. *Bioresource Technology*, *100*(24), 6416–6421. https://doi.org/10.1016/j.biortech.2009.06.112

Zhang, G., Fu, P., & Liang, F. (2013). Mathematical and numerical modeling in geotechnical engineering. *Journal of Applied Mathematics*, *2013*. https://doi.org/10.1155/2013/123485

Abstract (in Korean)

애그쉘파우더를 이용한 래터라이트 안정화 연구

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일반적으로 열대 지역에서는 도로 건설에 래터라이트가 사용된다. 하지만 높은 압축성으로 인해 도로 건설 실패의 원인이 되기도 한다. 그동안 래터라이트를 도로 성토재(보조기층)로 사용하기 위한 다양한 연구들이 있었고, 특히, 강도를 향상시키기 위해 래터라이트에 다양한 재료들을 혼합하는 시도가 있었다.

시멘트와 석회는 래터라이트에 자주 사용되는 안정제였지만, 환경 영향으로 인해 사람들의 관심이 줄었다. 일부 친환경 재료들이 사용되었지만, 사용성과 비용으로 인해 사람들의 흥미를 갖지 못하고 있다.

여러 연구자들이 애그쉘파우더와 같은 재활용이 가능한 재료들을 시도했는데, 이는 음식물 쓰레기를 이용하여 재활용 정책에 부합하고, 석회와 동일한 화학 성분을 공유하기 때문이다. 애그쉘파우더가 래터라이트의 강도에 미치는 영향은 석회를 동일한 농도로 사용했을때와는 비교할 수 없었지만 주목할만 했다. 좋은 결합을 만들 수 있는 애그쉘파우더의 입자 크기와 애그쉘에 존재하는 단백질 막이 안정화 능력에 미치는 영향은 이제까지 조사되지 않았다.

본 연구는 실험실에서의 실험을 기반으로 하고, 수치해석을 통해 애그쉘파우더의 강도증진 효과를 확인 하고자 하였다. 주요연구 목표는 애그쉘파우더의 입자 크기와 단백질 막의 효과에 관한 것 이다. 애터버그한계에서는 액성한계와 소성한계가 입자 크기에 따라 감소하지만 다른 입자 크기 내에서는 큰 차이가 없음을 보여주었다. 입자의 크기는 최대 건조 밀도나 최적 수분 함량에 영향을 미치지 않았다. 그러나 일축 압축강도에서는 입자 크기에 따른 영향이 뚜렸했다. 150㎛ 미만, 88㎛ 이상의 애그쉘 파우더의 입자 크기는 3%의 최적 함량농도로 좋은 안정제를 만들수 있었다. 단백질 막은 애그쉘 파우더의 함량이 4% 미만일 때 애그쉘 파우더의 안정화 능력을 감소시키는 것으로 확인되었다.

실험실에서 얻는 결과는 수치해석에 사용되었으며, 도로 성토해석에서 보조기층에 사용했을 때 개선됨을 입증했다.

주제어 안정화, 래터라이트, 애그쉘파우더, 실험실 실험, 수치해석, 도로