Journal of the Korean Geo-Environmental Society
23(1): 5～13. (January 2022) http://www.kges.or.kr

ISSN 1598-0820 (Print)
ISSN 2714-1233 (Online)
DOI https://doi.org/10.14481/jkges.2022.23.1.5

Stabilization of Lateritic Soil with Eggshell Powder

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Received: September 10th, 2021; Revised: September 14th, 2021; Accepted: November 18th, 2021

ABSTRACT : In tropical regions, lateritic soil is frequently used in road embankment. However, it is one of the sources of road failure owing to its low strength. Generally, cement and lime are used as stabilizers for lateritic soil, but they are not environmentally friendly. Some studies try to use eggshells, for they are food waste and share the same chemical composition as lime. Previous researchs have shown that eggshell powder could enhance the strength of lateritic soil. This research investigated the effect of particle size of the eggshell powder and the effect of the protein-membrane presence in the eggshell on stabilizing capacity of soil. Through laboratory tests, unconfined compressive strength was examined for various particle sizes. The particle size of eggshell powder ranging between 150 μm and 88 μm was appropriate size that made an excellent stabilizer at 3% concentration. On the other hand, the protein-membrane reduced the stabilizing ability of the eggshell powder when the content of eggshell powder is less than 4% in soil. Numerical analysis of road embankment was performed based on the results obtained in the laboratory tests. It is shown that the eggshell powder has improved the stability of the sub-base of the road embankment.

Keywords : Stabilization, Laterite, Eggshell powder, Laboratory test, Numerical analysis, Road stabilization

1. Introduction

Some studies have found several materials that can enhance soil strength to a certain extent. However, mixing soil with other materials for improving its strength has faced challenges based on the variety of soil properties and different usage requirements (Rahman, 1986). Chemical materials are currently more commercialized as soil stabilizers to ameliorate soil engineering properties, but their cost and environmental impact negatively influenced their use (Ojuri et al., 2017). For this reason, interest in eco-friendly or recycled materials that can replace chemical materials are increasing recently.

Lateritic soil is one of the soils used in road construction, especially in tropical regions. Its poor workability, low strength, high compressibility, and insufficient bearing capacity easily lead to a road failure (Amu & Salami, 2010). Some studies made different stabilization mechanisms to improve the engineering properties of lateritic soil. Cement was mainly used, but recently biomaterials are used to stabilize lateritic soils being environmentally friendly and reduce costs compared to 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. Eggshell and its protein-membrane are food waste even though its structure reveals a natural source of calcium carbonate and protein. Moreover, it shares the same chemical composition with lime (Amu & Salami, 2010).

In previous studies, they investigated the possibility of replacing those chemical industrial-based agents. The effect of milled eggshells was evaluated based on their 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. In addition, a comparative test was conducted on the lateritic soil mixed with cement and milled eggshell of the particle size less than 75 micrometers, enhancing soil strength (Oluwatuyi et al., 2018). Amu et al. (2005) 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. However, studies on this effect have not been confirmed.

This research aims to investigate the convenient particle size of the eggshell powder and the effect of protein-membrane

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in the stabilizing ability of milled eggshells. Further, the outcomes are constitutive parameters in numerical modeling of the road subbase.

In this study, eggshell powder is used to stabilize the soil. Eggshells are food waste and can be easily sourced. Eggshell could be useful and not burden the public, contrarily be a source of construction material in road construction and saving the environment. The research mainly focused on engineering laboratory tests and the numerical analysis of road embankment. At first, the research targets stabilizing natural lateritic soil. Laboratory tests were planned to obtain the optimum content of the eggshell powder at an efficient low concentration, the convenient particle size of eggshell powder, the effect of protein-membrane on the strength of the soil, and the result wa used in the numerical analysis of a road.

2. Materials

2.1 Lateritic soil

Lateritic soil was involved in this research because it is a type of soil widely available in tropical regions used for road construction. Usually, lateritic soil is founded in a wet, hot climate and annual rainfall of 150 mm to 300 mm. The formation of lateritic soil is basically from removing 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) (Goldberg, 1989). In addition, the presence of iron and aluminum oxides determines the color of soil material. The degree of lateralization is estimated from the ratio of silica to sesquioxide ($SiO_2/Fe2O_3 + Al_2O_3$) (Oluwatuyi et al., 2018).

Researches reported laterite to have some unique geo-technical properties in road construction that are often not conforming with the test result of other materials and make it behave differently when subjected to conventional specification requirement. 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. Amu et al. (2005) tried the eggshell as a replacement for lime to stabilize lateritic soil, the eggshell powder was able to increase the cohesion. Amu & Salami (2010) used the common salt and eggshell powder to enhance the lateritic soil strength, and Oluwatuyi et al. (2018) compared the cement and eggshell powder as a stabilizer for lateritic soil.

2.2 Eggshell

The eggshell powder and membrane was introduced to recycle food waste to reduce the expenses that go with its disposal. Eggshell is largely divided into eggshell and eggshell membrane. The eggshell structure generally is protein matrix lines with mineral crystals. It is mainly a calcium carbonate composition 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 the membrane layer of the eggshell membrane (Hendrix et al., 1984).

3. Sample preparation

3.1 Eggshell powder preparation

Chicken eggshells were mainly collected at food waste from restaurants. The collected eggshells were separated, one for eggshell with protein-membrane and another for eggshell without protein-membrane. They were cleansed with water and air-dried at room temperature. New (2013), and Yoo et al. (2009) gave methods, procedures, and apparatus for separating protein-membrane and shell material in waste eggshells. In this research, the separation of protein-membrane with shell was made manually while the eggshells were wet. The eggshells were ground in powder using a kitchen grinder and sieved in the BS 1377 standard sieves into five con-secutive particle sizes. Different sizes of eggshell powder retained in each sieve and pan were; Eggshell powder with protein-membrane (EWM, 425μm ~ 75μm), eggshell powder without protein-membrane (EWTM, 150μm ~ 75μm). The eggshell powder was stored separately in an airtight plastic bag and stored at room temperature.

3.2 Soil mixture perparation

It is difficult to get a natural laterite, we made a soil mixture that has close properties to natural laterite. Oluwatuyi et al.

(2018) was the model for soil mixture. The soil mixture was imitating the residual soil in tropical and subtropical regions (laterite) using Jumunjin sand, river sand and kaolinite.

Through different soil alterations leading to lateralization, kaolinization is in the first stages of lateralization (Netterberg, 2014). Therefore kaolinite was selected as the predominant clay composite of the lateritic soil. The chemical composition of kaolinite clay particles was identified from the supplier prescriptions. It was compared with the lateritic soil used in the previous research (Oluwatuyi et al., 2018) and soil mixture in Table 1. Chemical analysis of clay particles and concentration in percentage was evaluated and compared with the natural laterite to make the similarity. Paige-Green et al. (2015) state that the degree of lateralization in lateritic soil is below 2. Thus Kaolinite has 1.25.

Jumunjin sand and river sand were used for particle sizes larger than 75 μm, and kaolinite was used for particles smaller than 75 μm. Fig. 1 shows the particle size distribution curve of soil mixture. A set of sieves as prescribed by the AASHTO 88 were used to obtain a similar curve of laterite.

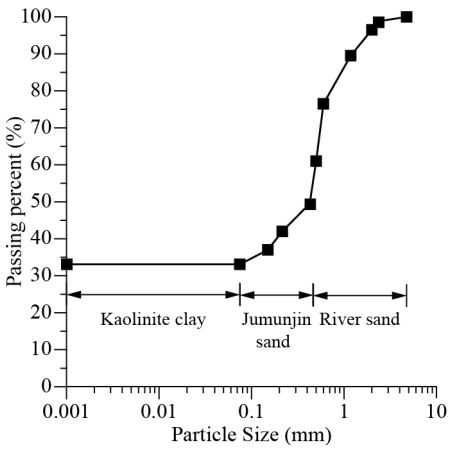


Fig. 1. Particle distribution curve for soil mixture

Table 1. Chemical composition of natural laterite and kaolinite

Chemical composition	Lateritic soil (Oluwatuyi et al., 2018)	Kaolinite
Silicon oxide (SiO_2) %	52.59	47.57
Aluminum oxide (Al_2O_3)%	30.8	37.06
Iron oxide (Fe_2O_3) %	7.57	0.93
Calcium oxide (CaO) %	0.68	0.24
Sulfur trioxide (SO_2) %	0.01	-
Potassium oxide (K_2O) %	3.51	0.86
Titanium dioxide (TiO_2) %	-	0.2
Magnesium oxide (MgO) %	-	0.02
Phosphorus pentoxide (P_2O_5) %	-	0.04
Sodium oxide (Na_2O) %	-	0.05
The laterization degree (SiO_2 / (Fe_2O_3 + Al_2O_3))	1.37	1.25

3.3 Basic geotechnical characteristics of soil mixture with eggshell powder

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. To understand of the basic characteristics of soil mixture with eggshell powder, atterberg limit and compaction test were performed.

3.3.1 Atterberg limits

The samples for the atterberg limits were prepared according to BS 1377 (Part 2). Soil mixture was compared with five samples containing 4% EWM for different eggshell powder particle sizes (450 μm, 250 μm, 150 μm, 88 μm, 75 μm). As a result of the atterberg limit test in Fig. 2, when EWM was added to soil mixture, the liquid limit is greatly reduced up to 10%, and the plastic limit is up to 3%, which is not much of a decrease.

The results of particle distribution curve and atterberg limits allowed us to classify the soil based on different standard classifications, the AASHTO classification, BS classification, and USCS classification. The properties of the soil mixture are compared with those of the model natural lateritic soil (Oluwatuyi et al., 2018) as in Table 2. It was confirmed that the model natural lateritic soil and soil mixture were very similar.

3.3.2 Proctor compaction test

The proctor compaction test aimed to determine the maximum dry density and the optimum moisture content of soil miture

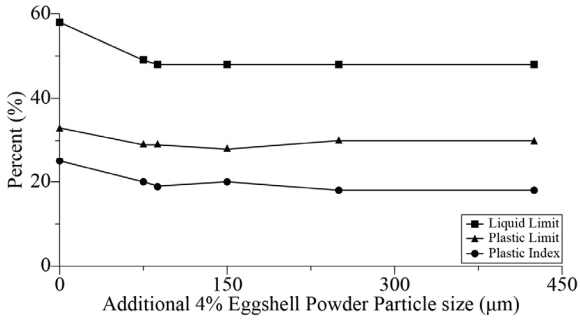


Fig. 2. Atterberg limits of soil mixture with 4% EWM

Table 2. Basic geotechnical parameters

Properties	Results	
	Natural Laterite (Oluwatuyi et al., 2018)	Soil mixture
Colour	Redish brown	White
% 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

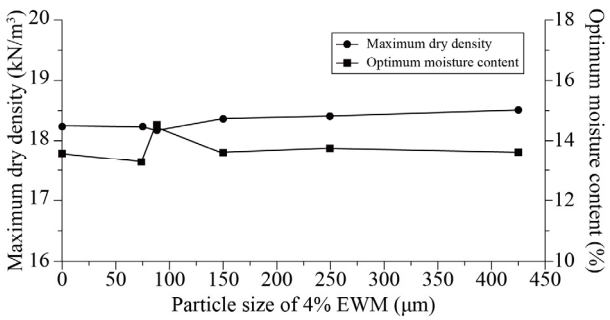


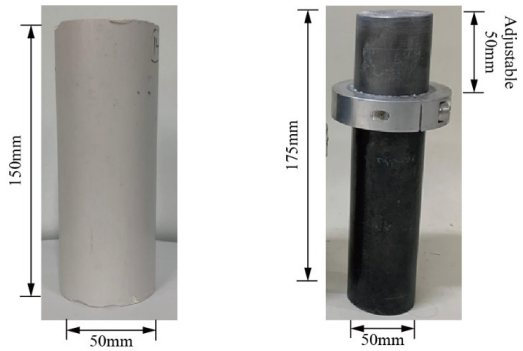
Fig. 3. Proctor compaction test results

and stabilize soil with 4% EWM for different eggshell powder particle sizes (450 μm, 250 μm, 150 μm, 88 μm, 75 μm) and then make a comparative analysis from them before using those parameters in further tests. BS 1377 (part4) enclosed the procedures used for the proctor compaction test. Test resuls are shown in Fig. 3.

The maximum dry density and the optimum moisture content do not vary significantly from one case to another. The difference of maximum dry density and the optimum moisture content being such small, the maximum dry density and the optimum moisture content for the specimen molding are 18.25 kN/m³ and 14%, respectively.

3.4 Specimen molding

To make the specimen, plastic mold and steel rammer in Fig. 4 were used. The soil was weighted based on the dry density obtained in the compaction test (280 g), then the soil was mixed with the EWM or EWTM in terms of percentage of the weight. Then, according to the compaction test, the optimum moisture content, distilled water, was added (14%).



(a) Plastic mold (b) Steel rammer

Fig. 4. Proctor compaction test results

Afterward, the soil was compacted in four equal layers, ten blows of the rammer. The specimen is then placed in the humidity chamber set at 21°C and 75% humidity. After one day, the sample was unmolded and left to cure for the remaining six days.

4. Test method

4.1 Unconfined compressive strength (UCS) tests

The unconfined compressive test was conducted to get the difference in stress when soil is stabilized with eggshell powder of different particle sizes and with or without protein membrane. The eggshell powder contents were tested from 0, 1, 2, 3, 4, 5, and 6% for various eggshell powder particle sizes with and without protein membrane. The compression machine has the capacity of loading up to 5,000 kgf, set to a strain of 0.5-2%/min. In every cases, the unconfined compressive test were performed with three samples and mean unconfined compressive strength was calculated.

4.2 Microstructure analysis

The microstructure analysis was done using the SEM (Scanning Electron Macroscope). This analysis was mainly for the investigation of formation mechanism between the admixture and the soil. The investigation carried out on four samples likely to show the impact of the admixture on the microstructure of soil in the unconfined compressive strength test.

5. Results and Discussion

5.1 Unconfined Compressive behavior

The optimum content of eggshell powder was investigated by performed unconfined compressive test. EWM of different particle sizes was used as a stabilizer and cured seven days long in a controlled humidity chamber. In the test result shown in Fig. 5, the unconfined compressive strength of the soil mixture with 0% ESP was 385 kPa, which is within the range of unconfined compressive strength of natural laterite (293.48 ~ 484. 03 kPa, Bello et al., 2015; Yusoff et al., 2017). It was observed that soil stabilized with EWM gained its unconfined compressive stress (UCS) with the EWM increase except for the EWM 425 μm. On the other hand, soil stabilized with EWM 88 μm at 4% concentration acquired high stress relatively more significantly than the other stabilizer at 6%.

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

Two cases were investigated to compare eggshell power with and without protein-membrane in Fig. 6. EWTM showed a more active cementation ability compared to EWM. A high pH (over 10) is required for the protein-membrane to dissolve and adhere to soil mixture. However, it is expected that the protein-membrane did not dissolve due to the low pH (about 6-7) of the distilled water used to make the sample, so it seems that if the protein-membrane was included, its adhesion did not reveal.

Stress increases with the increase of the stabilizer concentration, but for EWTM 150 μm, after a sharp increase of up to 3%, the strength drops down at 4% to 6%. The optimum was observed at 3% when EWTM 150 μm was used as a stabilizer.

The elastic modulus was calculated in soil mixture and when stabilized with eggshell powder. We calculated the stiffness (Young's modulus) as the slope of the corrected straight line from the corrected curve. In Fig. 7, Soil stabilized with EWM 150 μm showed a significant difference in stiffness. The 5% concentration was optimum, but 4% also stays closer.

The effect of the protein-membrane was observed when we compared of the stiffness of soil stabilized with EWM and EWTM when their particle size range between 150 μm and 75 μm. As shown in Fig. 8, contrary to the UCS results for concentrations of eggshell powder with and without protein-membrane, the stiffness is low when protein-membrane

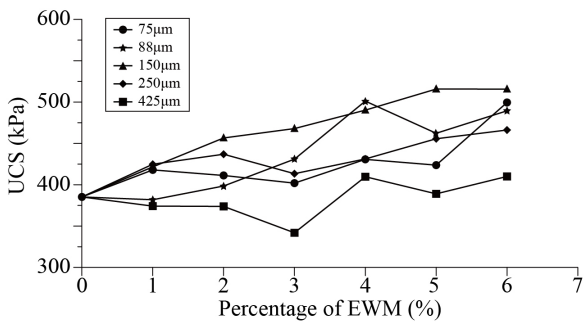


Fig. 5. Unconfined compressive stresss of the EWM content

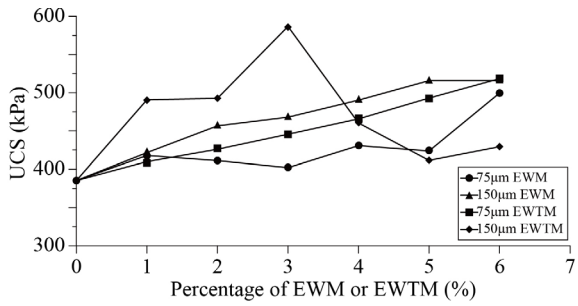


Fig. 6. Comparison of UCS between EWM and EWTM

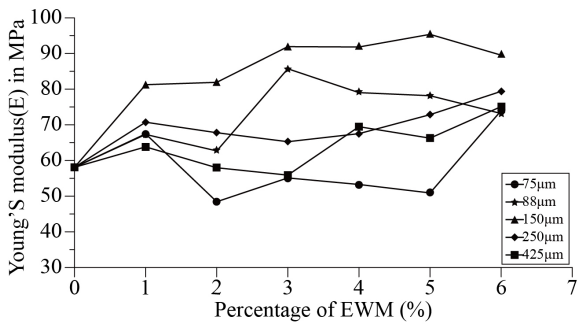


Fig. 7. Elastic modulus of stabilized soil

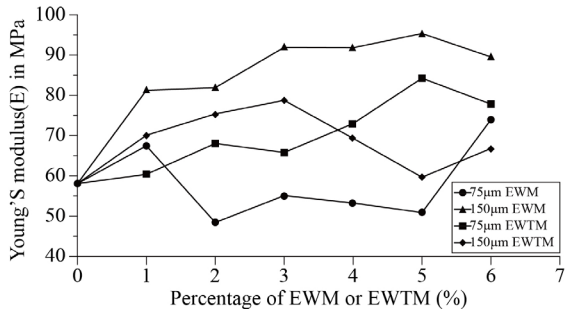


Fig. 8. Elastic modulus of stabilized soil

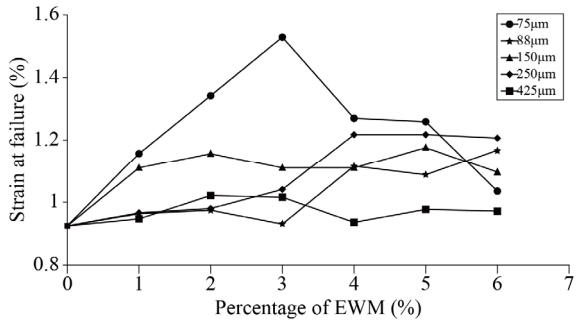


Fig. 9. Failure strain of soil stabilized with EWM

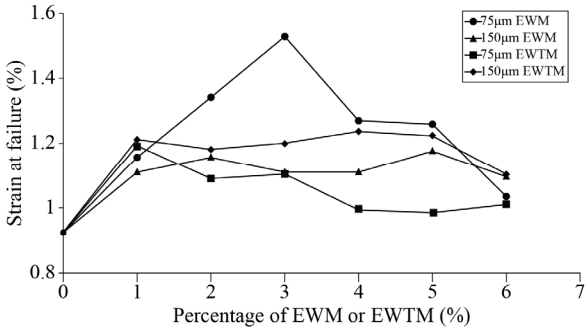


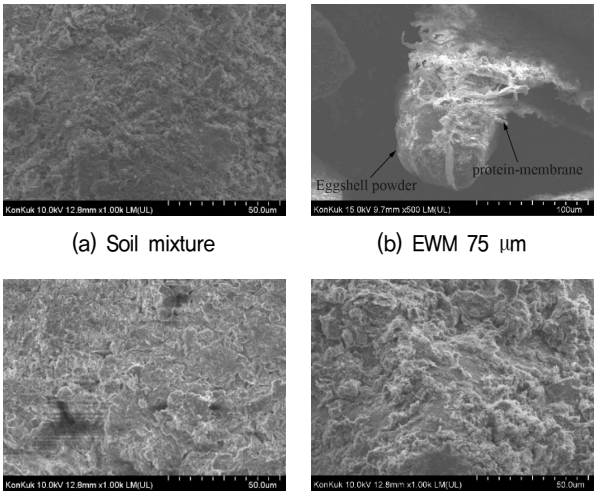
Fig. 10. Failure strain of soil stabilized with EWTM

are removed.

The failure strain was taken as the displacement at the failure of the sample in unconfined compressive tests in Fig. 9. The strain of soil stabilized with EWM 75 μm at 3% is maximum. Soil stabilized by EWTM is presented in Fig. 10. If the protein-membrane was added, the behavior of the sample tends to be ductile.

5.2 Microstructure analysis

The microstructure of the soil stabilized with eggshell powder with and without protein-membrane was analyzed utilizing SEM. Fig. 11(a) shows the soil mixture. It is a form in which kaolinite is attached to large soil particles. Fig. 11(b) shows EWM. Protein-membrane is tangled as a fiber on the surface of eggshell powder particles. EWM and EWTM were mixed with soil mitxure and shown in Figs. 11(c) and (d). EWTM appears to have increased strength owing to agglomeration with kaolinite and adhesion to soil mixture particles. However, in EWM, kaolinite and eggshell powder attached to the soil mixture particles were hardly seen, so it was analyzed that the strength was relatively decreased.



(a) Soil mixture (b) EWM 75 μm

(c) Soil with EWM 75 μm (d) Soil with EWTM 75 μm

Fig. 11. SEM images

6. Numerical Evaluation of Road Stabilization

The results obtained from tests are systematically integrated into 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 sub-base. It is 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. Therefore, the real non-linear stress-strain relationship between soil and granular layer and the plastic behavior of the surfacing layer is not considered.

The finite element based Midas GTS NX of the two-dimensional road model is used to perform the numerical analysis. Soil behavior was simulated using the Mohr-Coulomb model as soil behaves as elastoplastic materia l(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 a single load application is considered (Brown, 1996).

6.1 Modeling of the road embankment

The numerical modeling was based on a comparative study that implies the data from the research of Hashem & Abu-

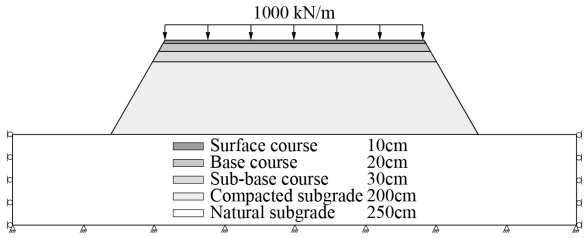


Fig. 12. 2D model of a road embankment

baker (2013). They worked on the flexible pavement from which we borrowed the structural pavement dimensions. The model for numerical analysis is shown in Fig. 12.

The unstabilized soil is compared with soil stabilized by eggshell powder with and without protein-membrane at different particle sizes. The analysis cases were selected based on their relevance in the research.

- Case 1: Unstabilized soil
- Case 2: Soil stabilized with eggshell powder without protein-membrane 150 μm at 3%
- Case 3: Soil stabilized with eggshell powder with protein-membrane 150 μm at 4%

The properties for numerical analysis are shown in Table 3. The properties are founded through laboratory test results. The Young's modulus (E) is calculated from the stress-strain curve, 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.

$$c = \frac{\sigma_1}{2\tan(45 + \frac{\theta}{2})} \quad (1)$$

Where C is the cohesion of soil, σ_1 is the maximum unconfined compressive stress, σ_1 friction angle, and σ_1 be the breaking angle in the unconfined compressive test.

Fixed supports were used for the lower part of the model and roller supports were used for both sides of the model, and the groundwater was not considered.

6.2 Results

The result focuses on the sub-base zone. The vertical stress, vertical settlement, and plastic area was presented graphically. Fig. 13 shows the vertical stress of sub-case at each case. The total vertical stresses are the compression (negative) and tension (positive). The compressive stress increases from the edges towards the center, where they get their peaks around 2 m distance from the edges. 238.6 kPa, 200 kPa, and 235.6 kPa were the peaks of vertical stress estimated in each case. The stresses are high in unstabilized soil and low in the soil stabilized with eggshell powder without protein-membrane at a 3% (Case 2).

The vertical settlements of numerical analysis results are shown in Fig. 14. The vertical settlements are positive when they are upward and negative when they are downward. The settlement increases downward from the edges towards the center. The peaks are 17.4 mm, 14 mm, and 15 mm downwards for each analysis case, respectively. The eggshell powder reduces the settlement in the sub-base at 17% and 14% in

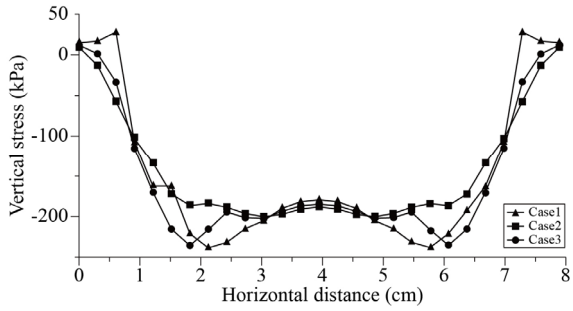


Fig. 13. Vertical stress of sub-base for 3 cases

Table 3. Chemical composition of natural laterite and kaolinite

Material parameters	Surface course	Base course	Sub-base course			Compacted subgrade	Natural subgrade
			Case 1	Case 2	Case 3		
Model	LE	M-C	M-C	M-C	M-C	M-C	M-C
Young's modulus E (kPa)	1.8×10^{-6}	1.4×10^{-3}	66,845	78,125	94,637	50,000	55,000
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	0	17	145	65	15	28
Friction angle Φ	40	40	18	65	75	20	20

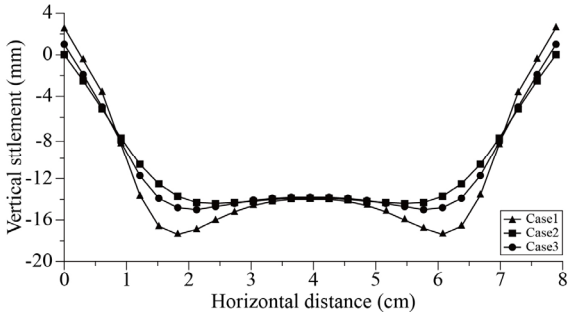


Fig. 14. Vertical settlement of sub-base for 3 cases

cases, respectively.

Using the Strength Reduction Method (SRM) in slope stability analysis in numerical analysis method, analyzes the minimum safety factor and failure behavior using various shapes, loads, and boundary conditions without previous assumptions. The shear strength and friction angle were gradually reduced until the calculation does not converge, and that point is considered as the failure point of the slope. Then, the maximum strength reduction ratio is used to calculate the minimum safety factor of the slope. The safety factor in Table 4 increased in the soil stabilized with eggshell power at 14% (from 13.1 to 1.5). Thus, the factor of safety increased by about 15% and 9%, respectively.

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 Fig. 15(b), it can be observed slightly small area of plastic failure. Therefore stabilization worked well in the sub-base.

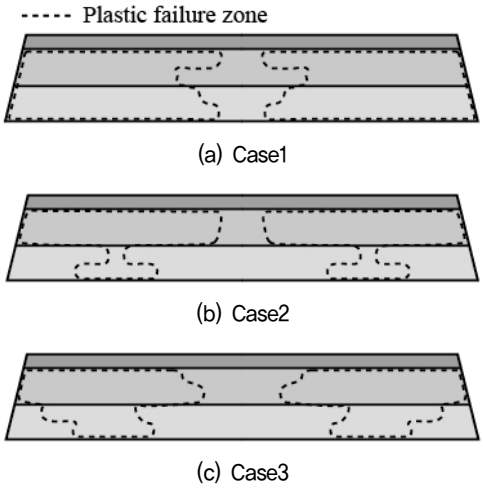


Fig. 15. Plastic region

Table 4. 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

7. Conclusions

Soil mixture was made with kaolinite, Jumunjin sand and river gravel which has the same engineering properties as natural laterite for the tests carried out in this research. Mechanical behavior of the soil mixture was investigated mainly based on laboratory tests. In addition, numerical analyses were carried out to evaluate the applicability of eggshell powder stabilizer to the sub-base of road embankment. The following results were obtained:

(1) Eggshell powder stabilized soil at a low percentage (at 6%) for any particle size of the eggshell powder except the particles ranging between 425 μm and 250 μm.
(2) The unconfined compressive stress increases with the eggshell powder content.
(3) Particle sizes ranging between 150 μm and 88 μm of eggshell powder are the optimum particle size that can stabilize soil at a low mass concentration percentage.
(4) 3% EWTM was the optimum content at about 52% increment compared with soil mixture at 0% EWTM.
(5) The protein membrane reduces the stabilizing ability of eggshell powder.
(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) Finally, stabilizing soil with eggshell powder is feasible and economically effective because eggshells are available as waste. In addition, the treatment seems more effortless as it doesn't need to make much effort grinding them to get a very fine eggshell powder. Particles passing 150 μm sieve are enough and much efficient than the finer particles.

Acknowledgement

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government (MSIT) (2019R1A2C1003488).

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