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RESEARCH ARTICLE

FLY ASH STABILIZED LATERITIC SOIL AS SUBBASE MATERIAL: A REVIEW

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ABSTRACT

The aim of this review is to gain insights of the geotechnical properties of lateritic soil that make it suitable to be used as a subbase material, and discuss the improvements done on the properties to further strengthen them. Several additives are reviewed for the lateritic soil stabilization, and fly ash is chosen to be the material of interest. This is so to answer the problem statement of would fly ash be a potential material for soil stabilization. Based on this review, it is understood that lateritic soil is commonly found in tropical and subtropical regions and is classified as sandy clay or silty clay. Studies also have shown that fly ash is potential to be used as a stabilizer in soil improvements. The presence of free lime may react with the silicates and aluminates, resulting to a long-term strength gain in soil. Class C fly ash contains more free lime that would lead to better strength gain in the earlier stage as compared to Class F fly ash. In addition to that, the particle size of the fly ash would also affect the improvement results, as smaller particle size allows more effective surface for the pozzolanic reaction to occur. The significance of this review is to show the potential of fly ash in improving lateritic soil, other than providing more evidence to encourage the incorporation of industrial waste in soil stabilization.

KEYWORDS

Lateritic soil, subbase material, fly ash, soil stabilization

1. INTRODUCTION

Improvement of infrastructure is more crucial nowadays with the ever-increasing population growth and modernization. Better road condition and network is required to ensure faster and more efficient transportation of materials, and safer travel of citizens in commute. With improper consideration, the performance of the road may degrade overtime, and in certain cases would be dangerous to be used. A report in 2016 by the Ministry of Transport stated that there is an increase of approximately 40% of road accident from 2007 to 2016 (Kementerian Pengangkutan Malaysia, 2016). One of the factors that would lead to such outcome may be due to the road condition. Degradation of the road may be intensified it is subjected to prolonged load (heavy traffic and vehicles), weather factors (wetting and drying of the road), and improper stabilization of the subbase and subgrade. This begs the question of how we improve the road further withstand the harsh conditions it is subjected to.

Lateritic soil is a type of soil in which is formed through the weathering of rocks in tropical climate. Occurrence of laterite and lateritic soil is mainly in Central and South America, Africa, India, Australia, and South-East Asia (Sujeeth, 2015). In such climate, the alternating conditions of high rainfall and draught cause the rock to be broken down into finer particles in a manner that most of the mobile minerals leach out first. These minerals are leached out by the moving water and air, making the lateritic soil to be relatively infertile. Lateritic soil originates from various types of rocks and during the process of laterization, the properties of the parent rocks mostly remain in the soil. During the laterization process, in which the silicate compounds like kaolinite and illite are leached out forming the hydrous oxides of aluminum and iron (Oluremi et al., 2018). This gives the soil its distinctive red-brownish appearance due to the presence of iron oxide. The tropical weathering process also causes the soil to be lacking growing nutrients for plants. Bacterial breakdown of humus and leaching of nutrients causes the soil to be lacking essential minerals and unsuitable for agriculture. Hence, researches have been done to uncover its alternative usage such as building material or as sub-grade materials for road constructions (Oluyinka and Olubunmi, 2018). Numerous researches have been done to study the natural and stabilized properties of the lateritic soil and its applicability as a subbase material.

This review intends to explore the properties of lateritic soil and observe the potential of fly ash as a stabilizer for the soil. The motivation of this review revolves around two main themes. The first theme is to study the properties of lateritic soil that makes it a good candidate for subgrade material, and the second theme involves studying the characteristics of fly ash that shows its potential as a stabilizer. This review will be organized into three parts. The first part will discuss the natural properties of lateritic soil, its occurrence, and geotechnical issues related to the application of the lateritic soil. In this part, the properties of lateritic soil in Malaysia will be discussed and compared with the samples from other countries to further establish the characteristics of lateritic soil in general.

The second part will discuss the research done in stabilizing the soil properties using various materials. The focus of this part is discussing the use of industrial wastes in stabilizing the lateritic soil. This is an attempt to establish the applicability of industrial waste in improving the lateritic soil characteristics. From here, the choice of admixture is further narrowed to the application of fly ash as an admixture, which will be discussed in detail in the third part of the review. In this part, the properties of fly ash will be reviewed, and inferences will be established

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as to why it makes a good candidate for lateritic soil stabilization. A total of 48 references are used as a basis for this review.

2. Lateritic Soil

2.1 Natural Properties of Lateritic Soil

Based on its characteristics, lateritic soil falls under the Oxisols and Ultisols soil order. Oxisols and Ultisols are known for its weathering degree (USDA, 1999). Figure 1 shows the global distribution of the soil groups. Oxisols are commonly found in tropical and subtropical regions, with no distinct horizon. USDA stated that the natural vegetation for Oxisols ranges from tropical rainforest to deserts (USDA, 1999). The significant difference in the geographic distribution of Oxisols shows that the parent rocks have undergone rigorous weathering process through varying climatic settings. In other words, the parent rocks have been transported from wet areas to dry areas over the course of the weathering process. Due to this weathering process, Oxisols are commonly found in gentle slopes of aged ground surface. Oxisols possess little amount of weatherable minerals and very low cation-exchange capacity.

A term used to define this low value of weatherable minerals soil layer is called the oxic horizon. From Figure 1, Oxisols is commonly found near the equator of the earth, in which the climate is mainly tropical and subtropical. The Ultisols, on the other hand, is formed through alternating changes in the rate of precipitation and evapotranspiration processes. This leads to the leaching of bases from the parent rocks, and the bases are mostly held by the vegetations in the upper level of the soil. In Figure 1, the region of occurrence of Ultisols is more widely distributed compared to the Oxisols, but it is still relatively near to the equator of the earth. The difference in properties of Ultisols and Oxisols is the location of the oxic horizon and the percentage of clay. According to USDA, the upper boundary of the oxic horizon of Oxisols must be within the 150 cm of the soil surface and contains 40% or more clay (by weight) in the first 18 cm depth of the soil (USDA, 1999). Nonetheless, both Oxisols and Ultisols have relatively similar properties.

As mentioned before, laterite soil is identifiable through its red-brownish appearance, due to the presence of iron oxide. This is a product of intense weathering process, in which is controlled by several factors. According to study, there are three types of weathering occurs in a rock, namely the physical, chemical, and biological weathering. All these weathering processes are interrelated with each other, in which one of them causes the other, and would intensify the other weathering process. The biological weathering in a rock is due to the organisms moving within the rock and consuming the mineral, or through the process of root growth of vegetations on the surface. The chemical weathering occurs when soluble and mobile minerals are leached out of the rocks through the interactions with water or enzymes deposited by organisms. These two weathering processes lead to the physical weathering of the rock, in which the rock breaks down to smaller fragment. This process releases internal energy within the rock, forming smaller and more stable particles. As the size of particles reduces, it creates more surface area for more chemical and biological weathering to occur.

Hence, the rock continuously breaks down until it reaches a stable energy state, which is in a form of soil. Elevated surrounding moisture content and temperature intensifies the chemical and physical weathering of the parent rocks (Oyelami and Van Rooy, 2016). The type of lateritic soil formed is also controlled by the minerals and drainage conditions of the locations. For instance, in locations with alternating wet and dry season, the lateritic soil formed will be lacking mobile elements such as sodium, potassium, and calcium. The leaching of the mobile minerals occurs during the wet season, in which the minerals are washed away by the moisture. During dry seasons, the solution of leached ions will be transported to the surface by capillary actions and will then be washed away during the wet season. In locations with poor drainage and high content of aluminum and iron, lateritic soil may form alongside another form of soil, known as black cotton soil. This type of soil has high amount of smectite clay.

Lateritic soil mainly consists of sand and gravel, with high variation of percentage of silt and clay by weight (Chindaprasirt et al., 2020). Sujeeth mentioned in his thesis that lateritic soil is commonly known for its clay-like particles, and ranges from fine to gravel (Sujeeth, 2015). The Unified Soil Classification System (USCS) and the American Association of State Highway and Transportation Officials (AASHTO) classification system are two common standards used as a basis to evaluate the geotechnical properties of soil and highway construction. According to the Unified Soil Classification System (USCS), a soil sample is classified as fine-grained if more than 50% of the particle passes through the No. 200 sieve (0.075 mm). The distribution of the particle size and composition of lateritic soil varies with the climatic factors in each region.

A study was done Ogun State of Nigeria to study the geotechnical properties of lateritic soil as subgrade and base material for road construction. According to this research, the particles passing the No. 200 sieve is relatively below 35% and classified as clay and silty clay (Oluyinka and Olubunmi, 2018). The Atterberg limit test of the sample showed that there is a huge range of liquid limit value, ranging from 12.0% to 40.1%, and a plastic limit value of between 10.0% and 22.0%. This result is in accordance with another test perform on soil sample in the state of Ondo (eastward to Ogun), in which the particle size analysis shows percentages finer than Sieve No. 200 ranging from 6% to 53%, indicating sandy soil property (Owolabi and Aderinola, 2014). Both regions are in southwestern Nigeria, which have a climate of partly tropical with high humidity.

These conditions are a catalyst to the chemical and physical weathering process in the formation of lateritic soil. Other than that, some geotechnical studies were performed on the lateritic soil sample obtained from southwestern Nigeria produced indistinguishable results as well. The soil had a liquid limit average value of 49%, plastic limit ranged between 17% to 27%, and plasticity index of within 18% to 35%. The soil in this region was classified as sandy clays (Okunlola et al., 2015). There are also instances in which the percentage of particles passes through the No. 200 sieve reaches up to 90%. Research done on the soil samples collected from the eastern Halmahera Island in Indonesia obtained percentages of finer than No. 200 sieve of 91% to 95% (Saing et al., 2016). In this specific location, the lateritic soil is known as Halmahera ferro laterite soil due to its high content of ferrous metal. Due to the tropics and subtropics climate of the region, vigorous chemical weathering has occurred resulting to high content of fine particles. Similar to this, another research was done on the soil samples collected from Sorowako East Luwu Regency South Sulawesi to study the characteristics of stabilized laterite soil as a road foundation (Saing et al., 2017). In this research, the laterite soil has percentages of sand and silt/clay of 5% and 95% respectively.

The climate in Malaysia is classified as equatorial (hot and humid throughout the year), which would be an optimum condition for the formation of lateritic soil. Research was conducted on soil samples collected in Nibong Tebal, Malaysia provided an indicative example of lateritic soil in Malaysia (Rosli et al., 2017). 17 samples were collected which served as a representative of lateritic soil in northern part of Perak and southern part of Kedah. In this research, it was found out that the distribution of gravel, sands, and fines were 10.96%, 45.94%, and 43.10% respectively.

The average values of liquid limit, plastic limit, and plasticity index were 55.68%, 35.22%, and 20.40% respectively, indicating moderate clay contents. These results showed that the soils samples were clayey sand or silty sand, in accordance with the American Association of State Highway and Transportation Officials (AASHTO) and USCS. Another research was done on the in Nilai to study the geotechnical properties of lateritic soil in the town area. The result showed that the lateritic soil has less than 10% aggregates present in the sample, with fines ranging from 4% to 21%. The liquid limit of the samples ranged between 22% to 43%, plastic limit between from 17% to 21%, and plasticity index ranged between 5% to 16%. These indicated that the samples are sandy clay or sandy silt (Sujeeth, 2015).

Aside from the particle size distribution, the mineral content of a lateritic soil would also affect the property of the lateritic soil. The presence of certain metals and bases highly dependent on the composition of the parent rock and the leaching of minerals during the chemical weathering process. The minerals present in the lateritic soil is important as it would react with the chemicals in stabilizers used with it during stabilization process. The importance of these minerals will be explained in the stabilization of lateritic soil in this review, in which the minerals would form cementitious materials when hydrated. A study was also conducted on the soil samples collected near a dam in Midwest of Brazil would give a good representation of the mineral content of lateritic soil (Vilhena et al., 2020).

The soil sample collected in this region is classified as lateritic soil of the Oxisols and Ferrasol soil type. The lateritic soil originated from metamorphic rock that has undergone intense weathering process. There were high amount of iron and aluminum presented in the soil, which gave dark to medium red-orange color to it. Further analysis of the soil sample showed there were traces of muscovite and iron oxides, with kaolinite and quartz being the main component. The mineral contents are aligned to the results obtained in research done to study the deformability characteristics of Brazilian laterites (de Medina et al., 2006). In this research, the laterite consists of predominantly quartz (50-70% of natural mass), followed by kaolinitic clay (20-30%), and iron oxides and hydroxides (10-20%). These samples are lacking mobile metals such as potassium due to the leaching process. The Central west of Brazil from which the samples were extract possess a sub-humid tropical climate, with 1250 mm to 2700 mm rainfall annually.

Other than natural climate factors, the composition of lateritic soil is also affected by natural disaster occurring in the region. Australia is known for the natural bushfire incidents. The burning of vegetations may affect the mineralogy of the soil in the region (Yusiharni and Gilkes, 2012). The temperature during a forest fire may reach as high as 1500 oC (Neary et al., 1999). At this temperature, minerals such as kaolinite and gibbsite undergo decomposition process (dehydroxylation), resulting to a lower amount of the minerals. Based on the samples collected in Darling Range, Western Australia, the Wundowie bushfire has caused the kaolinite and geothite in the topsoil to decompose into amorphous compounds, while increasing the salts content in the soil such as calcium, potassium, and magnesium. The increase in salts is due to the plant ashes present after the bushfire. This is a good example of the effect of natural disaster that could alter the mineral composition of lateritic soil.

Bushfire might be an uncommon occurrence in Malaysia, but flooding and heavy rain are customary. The annual rainfall upsurge in Malaysia mainly occurs between November and February, during the northeast monsoon season (Tang, 2019). During this time, the amount of precipitation increases and may lead to flash flooding, especially in coastal areas and floodplains. The floods and heavy rain may intensify the weathering and leaching of the soil, resulting to the lower mobile metals occurrence. Research was done to some lateritic soil samples in Malaysia showed that the main mineral present in the samples are kaolinite, gibbsite, goethite, and quartz (Latifi et al., 2016).

There are also traces of oxides in the soil sample, with iron oxide and aluminum oxide being the predominant oxides. A studied the lateritic bauxite distribution in Peninsular Malaysia, and he stated in his literature that aside from warm and humid condition, the weathering process is also highly dependable on the amount and period of rainfall (Baioumy, 2016). He stated that a combination of high carbon dioxide concentration and long period of rainfall of tectonic stability would catalyze the chemical weathering process even more (Baioumy, 2016). His results showed the degree of lateritization of the bauxite samples collected in Rompin, Kuantan, and Johor area were reflected by the abundance of kaolinite and quartz.

From this discussion, it is known that lateritic soil mainly occurs in regions with topical and sub-tropical climate. Table 1 shows the climate of regions where the lateritic soil is in abundance. In these regions, the alternating wet and dry season would intensify the weathering process of the parent rock, causing the more mobile minerals to leach out from the soil. This results to the infertile characteristics of the soil. In addition to that, the presence of different minerals in the soil would also affects the physical properties of the soil. As mentioned above, lateritic soil is commonly used in road and building constructions. In the following section, the geotechnical issues related to lateritic soil will be discussed that would provide a better understanding of the theme of this review.

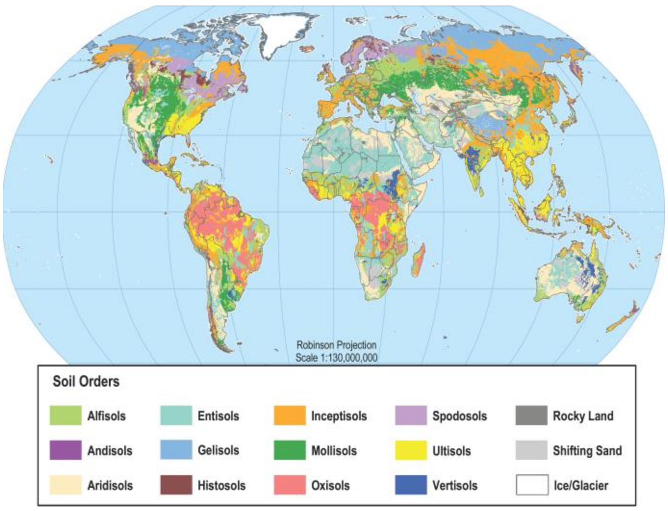

Figure 1: Global Soil Regions Map (Source: USDA 2005)

Table 1: Comparison of climate in regions with lateritic soil

Location	Climate
Southeast Asia (Malaysia, Indonesia, Thailand)	Tropical with average temperatures above 25 °C throughout the year
Southern India	Tropical wet and semi-arid, with average temperatures above 25 °C throughout the year
Southern China	Humid subtropical
Central Africa	Tropical (rainforest, monsoon, and savannah)
South America	Rainforest (high temperatures and rainfall throughout the year), savanna (high temperatures and rainfall during summer season), and Mediterranean (warm to high temperatures with rainfall during autumn and winter season)

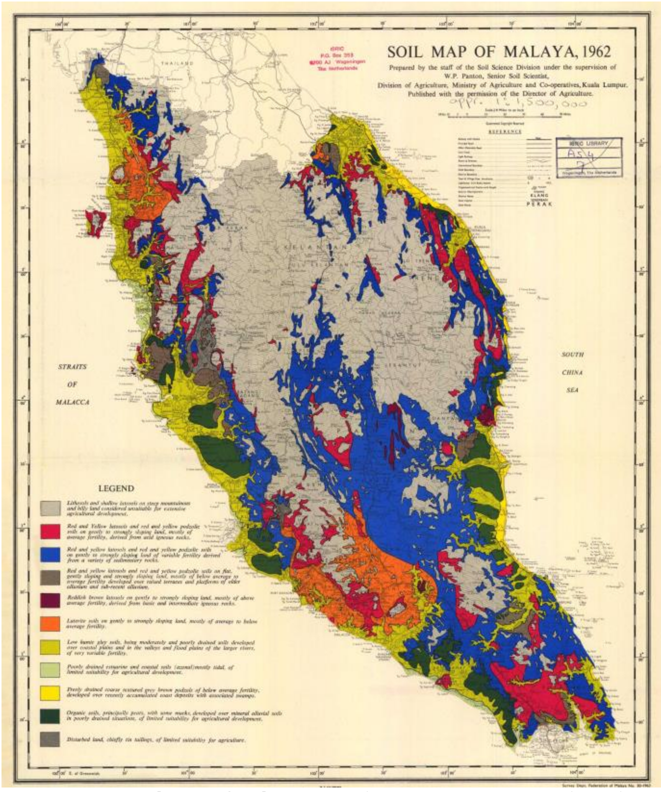

Figure 2: Soil Map of Malaya, 1962 (Source: Panton, W. P. (1962)

2.2 Geotechnical Issues of Lateritic Soil as Subbase

One of the applications of lateritic soil is subgrade for road constructions. The subbase used for the road construction is subjected to varying traffic load as vehicles passes through the road. The traffic action would lead to deformation of the road over time. The deformation of the road can be classified into elastic deformation (recoverable) and plastic deformation (unrecoverable). Surface depression and uneven road condition would occur when the road is subjected to plastic deformation over a long period of time and would also cause the functionality of the road to degrade (rutting). An experiment was conducted to simulate a traffic load on fine-grained soil. In this experiment, the fine-grained soil is subjected to continuous load (to simulate a passing train) and intermittent load (to simulate the load between two adjacent trains). The experiment was done to simulate more real situation of traffic load subjected on subgrade, with the inclusion of intermittent stage (Nie et al., 2020).

The results showed that under the same period of load, the axial strain formation on the samples was significantly reduced in the intermittent stage as compared to continuous load. The accumulation of pore water pressure was also negated in the intermittent stage, as the pore water pressure dissipated during the intermittent stage of the load application. Through this, the effective stress between the particles within the sample was increased, resulting to the improvement of dynamic stability of the sample under cyclic loading. This paper is a good example of prediction of permanent deformation of subgrade subjected to traffic load. The intermittent stage simulates the real-world situation better, in which the road is subjected to a period of continuous load stage (heavy traffic load) and intermittent stage (no traffic load). Without the intermittent stage, the pore water pressure accumulation and plastic strain of the subgrade may be overestimated, which in turn would cause the possibility of failure to be overestimated as well.

Other than traffic load, the water content in the soil would also affect the subbase deformation. This would be a prominent issue in tropical and subtropical regions, as the alternating wet and dry season causes a fluctuation of water content in the ground. The resilient modulus is affected significantly at elevated water content due to the reduction in stiffness of the soil (Silva et al., 2021). The resilient modulus of a lateritic soil is especially affected with the changes in water content (Freitas et al., 2020). This can be explained through the behavior of the macropores of the lateritic soil during the wetting and drying process. The macropores mainly formed between the silt and clay particles in the lateritic soil, held together by clay bridges. Due to the meta- stable condition of the clay bridges, the macropores are highly influenced by the fluctuations of water content. This is verified from the results obtained (Freitas et al., 2020). It is found out that as the degree of saturation of the lateritic soil increases, its resilient modulus decreases and at excessively wet conditions (degree of saturation more than 90%), the samples failed at the beginning of the test. This result shows the sensitivity of the mechanical behavior of lateritic soil towards the changes in water content.

A group researchers studied the effect of water content in lateritic soil on its deformation to validate this hypothesis (Silva et al., 2021). Repeated load triaxial (RLT) test and permanent deformation test were performed on the lateritic soil at varying water content and its effect on the sample's deformation was evaluated. The results showed that higher compaction water content would lead to a decrease in resilient modulus of the samples and more prominent plastic deformation. This is due to the decrease in the stiffness of the samples as the water content increases. The increase in water content would cause the skeleton structure of the sample to be unstable as the friction between the particles in the sample is reduced, leading to a decrease in its resilient modulus (Nie et al., 2021).

A good indicator of soil strength is through its unconfined compressive strength UCS. Table 2 shows the UCS values recommended for base and subbase material (Biswal et al., 2020). The minimum value recommended is 1.5 MPa for a soil to be used for subbase. California Bearing Ratio (CBR) is also another indicator used to verify the suitability of soil as a subgrade. According to the Federal ministry of Works and Housing, the standard values of CBR for road base, subbase and subgrade should be more than 80% (under unsoaked condition), 30% (under soaked condition) and 10% (under soaked condition) respectively (Amadi et al., 2015; Bello, 2012). Table 3 shows the comparisons of CBR values under soaked condition from the literatures. From the literatures, the UCS values of natural lateritic soil is significantly below the recommended values.

On top of that, the lateritic soil in its natural state mostly passes the requirement for subgrade but does not pass the requirement for subbase and road base. It is recommended that the lateritic soil to be stabilized to improve the CBR values before being used as subbase material. Based on these geotechnical issues, it can be concluded that the natural property of lateritic soil is rather unsuitable to be used on its own as a subbase material. Stabilizations should be performed to further improve its property so that it could withstand higher load and harsher environmental conditions with minimum degradation over longer period of application. The next section will discuss the improvements done on lateritic soil with various additives, focusing on the utilization of industrial and agricultural wastes.

Table 2: UCS values for subbase and base layers in pavements (Source: Biswal et al., 2020)

References	UCS (MPa)	
	Medium to high volume roads	Low volume roads
NCHHRP	1.72 (subbase) 5.17 (base)	1.72 (subbase) 5.17 (base)
Austroads	2	1-2
IRC	1.5-3 (subbase) 4.5 (base)	1.7 (subbase) 3 (base)

Table 3. Comparison of CBR values of lateritic soil

Author(s)	CBR Values	UCS Value (MPa)
Amadi et al., 2015	• 10 samples were tested • 2 samples passed the requirement for road base (unsoaked CBR >80%) • 5 samples passed the requirement for subbase (soaked CBR >30%)	-
Bello, 2012	• 8 samples were tested • 2 samples passed the requirement for road base (unsoaked CBR >80%) • 6 samples passed the requirement for subbase (soaked CBR >30%), but the values are close to the minimum requirement	-
Saing et al., 2016	• 3 samples were tested, and all 3 samples failed the CBR test for road base (the values of unsoaked CBR were between 11% to 21%)	Between 0.07 to 0.128
Latifi et al., 2016	-	0.27
Sani et al., 2020	-	0.1

3. Improvements on Lateritic Soil

3.1 Industrial Waste Admixtures

The natural properties of lateritic soil discussed in the previous section showed that lateritic soil is a potential candidate to be used as a subbase. In order to overcome the geotechnical issues, admixtures are added in lateritic soil to improve its strength so that it could withstand higher load and harsher environmental conditions. This part will discuss the various materials used to stabilize the lateritic soil in terms of soil strength index test. This includes compaction test, unconfined compression strength, shear strength, and California Bearing Ratio (CBR). The common standards being used as a reference for the test are American Standards for Testing and Materials (ASTM) and British Standards (BS). In this portion of the review, the discussion will involve the assessment of past researchers that utilized industrial wastes in stabilizing the lateritic soil.

This part of the review will explore some of the improvements done on lateritic soil by incorporating agricultural waste and industrial aggregates. Due to the increasing concerns of waste accumulation, researchers are looking into the possibilities of utilizing both agricultural and industrial byproducts as soil stabilizers. One of the materials used is glass fiber. An experiment was conducted by mixing glass fiber with soil samples obtained in Ibadan, Nigeria at different percentages by weight and the strength index was measured to study the improvement. Due to the versatility and availability of the glass fiber in the region, this material was chosen as a replacement to chemical stabilizers. From the result, it was noticed that the liquid limit and plastic limit of the soil increased with addition of the glass fiber. This may be due to the tendency of the glass fiber to absorb water. The plasticity index was reduced with the increasing glass fiber concentration.

This showed that the soil was becoming more incompressible when the glass fiber was added. The result from the compaction test depicted that the MDD of the soil increased until it peaked at 0.6% of glass fiber concentration. As more glass fiber was added past the 0.6%, more water was absorbed causing the fiber to swell up in the soil. This led to an increase in volume and hence, a reduction in density (Kehinde et al., 2020). From this research, it is sufficient to conclude that with the addition of glass fiber, there is an improvement occurred to the properties of lateritic soil and would be a potential candidate for soil stabilization.

In other research, Tire-Derived Aggregates (TDA) is used to stabilize the lateritic soil properties. In a study done on soil samples collected from Universiti Teknologi Malaysia (UTM) Skudai campus, TDA and micro silica (MS) were added at varying concentration and their effects on the strength properties of the soil were observed. From this study, it was found out that the flexibility of the soil sample, which is the maximum strain of the sample before failure, was increased when TDA was incorporated. However, the elasticity modulus of the samples was significantly reduced with increasing TDA concentration. The MS was added to overcome this issue and it was found out that with addition of MS, the elasticity modulus was improved. In this research, two additives were used to further enhance the strength of the soil. The results from stabilization using the TDA alone is rather underwhelming in improving the soil strength, but with the addition of MS, the results started to show better prospects. Hence, it can be concluded that a mixture of TDA and MS has potentials in stabilizing the lateritic soil (Gordan and Adnan, 2015).

Next, this review will discuss some of the agricultural waste used to improve the properties of lateritic soil. Coconut coir aggregates is one of the materials used to stabilize the lateritic soil. A group researchers incorporated coconut coir aggregates into the soil-cement mixture to study its effects on the strength properties of the soil (Marathe et al., 2015). It was observed that the CBR value was improved significantly as the percentage of coconut coir content curing time increased. The result from the compaction test followed a similar trend for the MDD, which proved that the soil samples were becoming denser with the addition of coconut coir. Another experiment was done to study the effect of maize husk ash (MHA) on the strength index of lateritic soil was done (Oluremi et al., 2018). In their research, MHA was added at different concentrations into the soil and the strength properties of the soil was studied.

It was found out that with the addition of MHA, the higher compaction value was achieved at lower moisture content, as the MHA increased the dry density of the soil. In addition to that, the treated soil samples achieved relatively higher value of CBR and UCS compared to the untreated soil. These results showed that the MHA can lower the lateritic soil cohesive value. Finally, sugarcane straw ash (SCSA) is also a potential candidate in stabilizing the geotechnical properties of lateritic soil. A study was done on some soil sample collected in western part of Nigeria, in which the lateritic soil was mixed with increasing percentages of SCSA. The result showed that the CBR value increased with percentage of SCSA, but the overall soil strength dropped passed the 12% SCSA content. The liquid limit and plastic limit of the treated sample were higher as compared to the untreated sample, which results to a decrease in plasticity index.

Hence, the study concluded that SCSA is a potential candidate for lateritic soil stabilization (Olowofoyeku et al., 2021). Table 4 shows the summarized comparison of the different industrial wastes used to stabilize the lateritic soil. These research highlight the potential use of industrial wastes in improving the geotechnical properties of the lateritic soil. The motivation of such utilization of waste materials is the main interest of this review, which is the incorporation of waste material in ground stabilization. Through this, the issue of waste accumulation may be tackled and reduced. The following subtopic will discuss the chemical stabilization performed on lateritic soil.

Table 4: Comparison of Different Industrial Wastes Used for Lateritic Soil Stabilization

Industrial Waste	Author	Results
Glass Fiber	Kehinde et al., 2020	• Liquid limit and plastic limit increased • Reduction in plastic limit • Increase in MDD
TDA and MS	Gordan & Adnan, 2015	• Improvements on the flexibility of the soil when TDA was added, but greatly reduce the modulus of elasticity • Improvement on modulus of elasticity when MS was added
Coconut coir	Marathe et al., 2015	Improvements on CBR and MDD values
MHA	Oluremi et al., 2018	• Higher compaction values at lower moisture content • Improvements on CBR and UCS values
SCSA	Olowofoyeku et al., 2021	• CBR values improvement up to a certain percentage • The values of liquid limit and plastic limit increased, and the plasticity index decreased

3.2 Chemical Stabilization

The most popular mean of chemical stabilization of laterite soil is by curing it using cement and lime. The soil strength is improved due to the pozzolanic reaction between the soil and lime (Amadi and Okeiyi, 2017; Saing and Djainal, 2018; Vilhena et al., 2020). In this reaction, cementitious materials are created through the reaction of water molecule, lime compound, and silica mineral present in the soil and cement, resulting an increase in the strength of the soil. A study was done to observe the effect of stabilization through lime on the vertical deformation of laterite soil in Halmahera Island, North Maluku Province, Indonesia. In this study, lime was added at percentages of 3% to 10% to the soil samples, subjected to a static loading, and the vertical deformations of the samples were recorded. It was concluded that the vertical deformation of the treated samples was reduced as much as 3 times than the untreated soil samples.

Other than the vertical deformation, the compressive strength of cement-treated lateritic soil showed a favorable result in comparison to the untreated samples. A study was performed on lateritic soil samples collected at Kartanaka, India cured with cement cured at varying curing time yielded a positive result. The unconfined compressive strength (UCS) of the samples was observed to be increasing over time, depending on the percentage of the cement (Jha and Sivapullaiah, 2015; Marathe et al., 2015). This is due to the formation of binding agents through the hydration of the cement. In this research, the treated soil with higher percentages of cement yielded an increasing UCS value as the curing time increases because there is more binding agent present in the sample. The binding agent serves as an additional support within the soil which enables it to withstand higher load. Similar results were obtained from both papers reviewed, which makes it suffice to conclude that cement and lime has a favourable outcome in soil stabilization.

Comparing the Atterberg test of untreated and lime treated lateritic soil also is a good indication of the changes in soil through stabilization. Some researchers showed in their research that there was a reduction in liquid limit (Jha and Sivapullaiah, 2015). When lime is added into the soil, the concentration of calcium ion is increased, resulting to higher concentration of electrolyte pore fluid. This causes the liquid limit of the treated soil samples to be lower than the untreated soil samples. The plastic limit of the soil is defined as the amount of water content in the soil in which it reaches a certain shear resistance. By adding lime into the soil, it elevates the concentration of ion charges in the pore fluid, resulting to an increase in the shear resistance, causing the plastic limit of the treated soil sample to be higher than the untreated soil sample.

Due to the decrease in liquid limit and the increase in plastic limit of the treated soil, the plasticity index of the treated soil was observed to be higher than the untreated soil sample. Based on the same research, compaction tests were performed on both untreated and treated soil samples and the results were compared. It was found out that the optimum water content (OMC) increased and maximum dry density (MDD) decreased with increasing lime content. The increase in OMC may be due to the improving water bearing capacity within the flocculated soil matrix when lime was added into the soil, whereas the reduction in MDD may be due to the increase in volume of pore, resulting from the agglomeration of soil when lime was added.

Salt compound is also used to stabilized lateritic soil. A study was performed on the lateritic soil collected from Niger Delta, Nigeria mixed salt compound. In this study, it was observed that the OMC decreases with addition of the salt compound, whereas the MDD increases with salt compound content. The UCS was also found to be improving with the increase of salt compound percentage. The research concluded that the salt compounds are potential material to be used as a lateritic soil stabilizer (Otoko and Manasseh, 2014). Other than that, polymer is also one of the stabilizers used to improve the property of lateritic soil. A study was conducted on soil sample obtained from an excavated hillside in Skudai mixed with liquid polymer. The liquid polymer was mixed at different concentrations with the soil and each concentration was cured in 4 different curing times.

The results showed that with increasing concentration of the liquid polymer, the UCS and shear strength of the soil increased, and most of the strength improvement occurred within the first 7 days of the curing. The increment of strength was small after the 7th day of curing (Marto et al., 2013). Based on this discussion, the property of the lateritic soil is improved with the addition of additives. In the following section, the properties of fly ash will be explored that would make it a potential candidate as a stabilizer for lateritic soil.

4. Fly Ash Applicability As Stabilizer

4.1 Properties of Fly Ash

Fly ash is one of the byproducts from power generation industry. It is the fine residue formed when pulverized coal is pulverized and burnt (American Coal Ash Association, 2003). Due to the increasing demand of power in the society, the production of fly ash is gradually increasing over the years. Approximately 6.8 million tonnes of fly ash were produced in the year 2016 in Malaysia alone, and this mainly originates from electric power plant (Khan et al., 2019). Prior to the discovery of its potential in construction materials, fly ash was condemned to be nothing more than pollutant to the environment. As the society's environmental awareness grew and more movements push the boundary of the scientific research, a new window of opportunity opened for humankind to tap into the potential of this resource-in-disguise.

Researchers have found out that fly ash has a self-cementing capability, which allows it to be used widely in construction material such as cements and binders. According to American Coal Ash Association, fly ash mostly applied as pozzolan in concrete productions (American Coal Ash Association, 2003). This shows that fly ash is a potential candidate to be used as a stabilizer in pavement engineering. Before getting into its application in ground stabilization, this part of the review will discuss the fly ash properties to provide evidence to its potential as a stabilizer. The discussion will include studies done in determining the physical and chemical properties of fly ash. The properties of fly ash are dependent on several factors (Khan et al., 2019). The composition of the fly ash, for instance, is influenced by the type of coal used during the burning process.

Class C ashes is formed when sub-bituminous coals are burned, with the primary composition being calcium alumino-sulfate glass, free lime, and tricalcium aluminate. This class of ash normally contains high amount of free lime (calcium oxide) and commonly referred to as high calcium fly ash. The other type of fly ash is called Class F ashes and forms when bituminous and anthracite coals are burned. In this type of ash, the calcium component is comparatively low (calcium oxide percentage of below 10%) and primarily consists of alumino-silicate glass, quartz, and magnetite. Due to the high content of free lime in Class C fly ash, it is usually used on its own for stabilization process. This is because the free lime within the ash itself is sufficient to react with the silica to form silicate hydrate through the pozzolanic reaction.

On the other hand, Class F ash requires an additional lime to perform the pozzolanic reaction. It is usually mixed with cement or lime to promote the pozzolanic process. A study was performed to compare the effectiveness of Class C and Class F fly ash as a cement replacement by the Universitas Negeri Surabaya, Indonesia showed the compositions of both types of fly ash. Table 4 shows the XRF test from the study (Wardhono, 2018). Bases on the table, class C fly ash has a lower composition of silicate and aluminate than in class F fly ash but contains higher percentage of calcium oxide (highlighted in the table). This affects the ability of the fly ash to undergo the pozzolanic process. Class C contains more free lime that could form calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) during the hydration process. CSH and CAH are cementitious material that allow the fly ash to improve the strength of materials it is added into.

Wardhono compared the results of strength gain of the fly ash in two different curing temperatures: ambient temperature, and high temperature ($60\ ^{o}C$) (Wardhono, 2018). It was found out that the strength gain of class F fly ash at ambient temperature was lower compared to the class C fly ash. This is due to the lower concentration of free lime in the class F fly ash, resulting to lower cementitious materials during hydration. However, at high temperature, the rate of strength gain in class F fly ash exceeded the rate of strength gain class C fly ash, despite the lower concentration of free lime. This is due to the rate of geopolymerization process (Aygörmez, 2021; John et al., 2021). Higher temperatures promote the geopolymerization process within the fly ash, resulting to a higher yield at the early stage. However, the increase in yield at the high temperature is smaller at later stage, leading to similar total strength improvement at ambient temperature. Hence, it can be concluded that the curing temperature only affect the rate of strength gain in fly ash, while the final strength gain remains similar for both temperatures.

Table 5: Chemical composition of Class C and Class F fly ash (% mass) (Source: Wardhono, 2018)

Materials	Class C	Class f
Sio*3*	4.75	65.43
Al*2*o*3*	17.89	23.14
Fe*2*O*3*	59.11	1.46
CaO	12.65	2.09
MgO	0.00	0.00
K*2*O	0.65	1.04
TiO*2*	0.92	1.35
Mn*2*O*3*	0.55	0.07
SiO*3*	0.86	0.69

In terms of its particle size, fly ash possess a silt-liked particles which are relatively spherical. This characteristic may allow the fly ash to move into the pore space between soil particles, resulting to an increase in compressive strength of soil. A study was performed to evaluate the effect of nano fly ash incorporation in concrete performance (Harihanandh and Sivaraja, 2016). In this study, nano fly ash was incorporated into the cement and the mechanical properties of the cement was determined. It is found out that the compressive strength of the cement with the nano fly ash is higher than the conventional cement and cement incorporated with raw fly ash. Similar results were obtained for its tensile strength and flexural strength. Based on the SEM analysis, it is found out that the particles in the nano fly ash filled up the pores in the concrete more effectively than the raw fly ash. This resulted to a denser and stronger concrete (Aygörmez, 2021).

Aygörmez stated that smaller grain sizes led to a higher strength results (Aygörmez, 2021). Due to to the smaller particle size and its sperical shape, nano-sized fly ash effectively filled in the void space between the concrete particle, improving its cohesion. In addition to that, smaller particle size would also lead to higher surface area exposed for reactions to occur (John et al., 2021). A group researchers mentioned in their paper due to its more compacted microstructures, the acid resistance of fly ash geopolymer is improved with addition of nano-silica fly ash (John et al., 2021). On top of that, the setting time geopolymer paste is reduced with addition of 1-2% of nano-silica. This is due to the quick reaction within the geoploymer. From here, it can be seen that with the incorporation of nano-sized particles during stabilization, the rate of reaction and total surface area for reaction can be improved, leading to better strength gain during stabilization.

4.2 Soil Stabilization using Fly Ash

As forementioned, fly as has the self-cementing properties due to the presence of free lime in it. This makes it a favorable stabilizing agent as well for ground improvement. The first factor in studying the stabilization of soil is observing the microstructural changes occurred when soils are stabilized with fly ash. When fly ash is hydrated, cementitious materials are formed through the pozzolanic reaction and fill the pore spaces between the soil. An X-ray Diffraction (XRD) analysis was conducted on a sample of cohesive soil treated with fly ash and lime showed that calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) formed through the pozzolanic reaction (Sharma et al., 2012). This result was compared to the untreated soil, in which both compounds were absent. In Figures 3(b) and 3(c), the pore spaces between the soil particles are filled by the cementitious materials, as compared to untreated soil in Figure 3(a). Figures 4 and 5 are the XRD analysis result from the experiment, showing the formation of CSH and CAH in the treated soil. The intensity of both cementitious materials is higher in the soil stabilized with fly ash and lime due to the higher degree of pozzolanic reaction with increasing free lime content.

Through the Thermo Gravimetric Analysis, it was found out that the expansive property of the soil is reduced due to the enhancement of montmorillonite decomposition with the addition of fly ash. Montmorillonite is a clay particle that expands when in contact with water. Figure 6 shows the reduction in weight for both untreated and treated soil. Montmorillonite decomposes at temperatures close to 700 oC, depicted by the sudden drop of weight in the graph (Peethamparan et al., 2009). The initial drop in weight (less than $100\ ^{o}C$ region) mainly because of evaporation of adsorbed water in the soil. From this graph, the decomposition of montmorillonite is enhanced with the addition of fly ash and lime, resulting to lesser amount of montmorillonite in the soil over time. This causes the soil to be less expansive when in contact with water. This result is in accordance with another research done to study the application of fly ash-based soil stabilization for soft subgrades (Karami et al., 2021).

Changes in the microstructural properties would lead to changes in the mechanical properties of the soil as well. The maximum dry density (MDD) of soil is noticeably decreased with addition of fly ash. This is mainly due to the introduction of fines (fly ash) that alters the gradation of the soil mixtures, as well as due to the lower specific gravity of the fly ash (Takhelmayum et al., 2013). In their study, they compared the compaction results of black cotton soil stabilized with fine and coarse fly ash, and similar trend of decreasing MDD was observed for both situations (Takhelmayum et al., 2013). This result is further supported by the result obtained by another research done to study the effect of fly ash and enzymetic fly ash on soil. The decrerasing MDD is accompanied by an increasing in optimum water content (OMC) (Renjith et al., 2021). The inclusion of fines (fly ash) into the soil resulted to higher affinity of water in the soil, leading to an increase in OMC with increasing fly ash content. From these results, it can be concluded that the stabilization mechanism is not dominated by the densification process. A group researchers stated in their literature review that agglomeration and flocculation reactions as well as cationic exchange could still be occurring despite the outcome of the compaction results (Renjith et al., 2021).

In terms of settlement, fly ash has a significant effect on the volumetric compression of soil. A group researchers ran a test to study the effect of addition of calcium bentonite clay (Ca-bentonite) and pulp mill fly ash (PFA) on organic soil (Pokharel and Siddiqua, 2021). The samples were subjected to incremental loading (to observe the primary consolidation) and creep loading (to observe the secondary consolidation). Figure 7 shows the result of the primary consolidation of the treated and untreated soil. Based on this figure, it can be seen that the untreated soil undergone significant volumetric compression compared to the treated soil, with 10% Ca-bentonite and 30% PFA being the optimum blend. Figure 8 shows the change in void ratio in the soil at each loading stage. The treated soil has significantly lower change in void ratio as compared to the untreated soil. This can be explained by the production of cementitious material induced by the mixture of the Ca-bentonite and PFA, filling the void between the soil particles. Similar result was obtained for the creep loading test. Significant improvement on the creep behavior was observed through the addition of Ca-bentonite and PFA, reaching up to 56% reduction of creep deformation on day 14. This result showed the potential of fly ash soil stabilization in generating long-term strength gain.

From here, it may conclude that the self-cementing properties of fly ash makes it a favorable candidate to be used as a stabilizer in lateritic soil. The ideal situation would be only incorporating the fly ash as a stabilizer in the lateritc soil, but in some of the cases discussed, fly ash alone might not be sufficient to produce long term strength gain. This may be due to the amount of available free lime in the fly ash, which is needed during the pozzolanic reaction. Hence, a combination of fly ash with lime is commonly used to allow more pozzolanic reaction to occur.

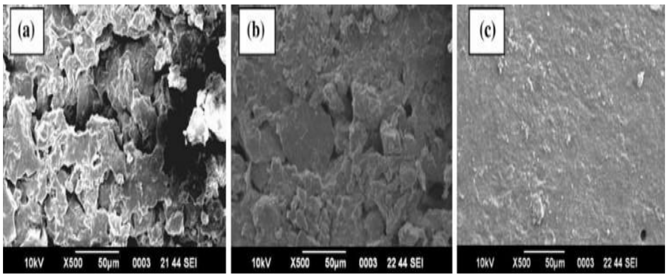

Figure 3: SEM image of (a) untreated soil, (b) soil + 20% fly ash, and (c) soil + 20% fly ash +8.5% lime. (Source: Sharma et al., 2012)

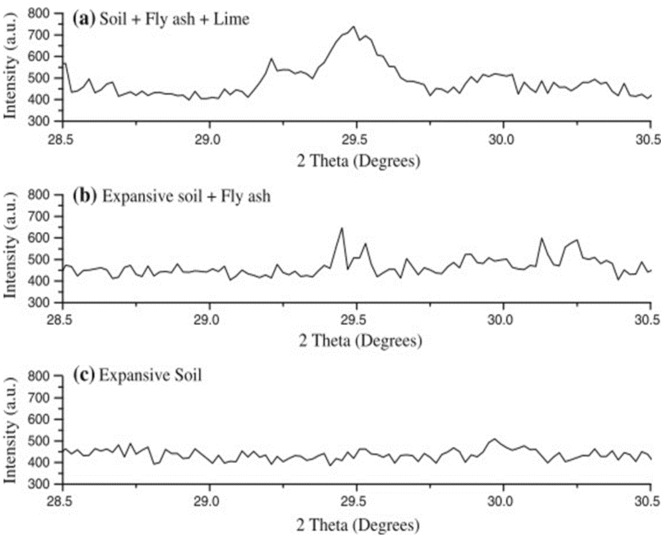

Figure 4: Formation of CSH (at 28.48°) (Source: Sharma et al., 2012)

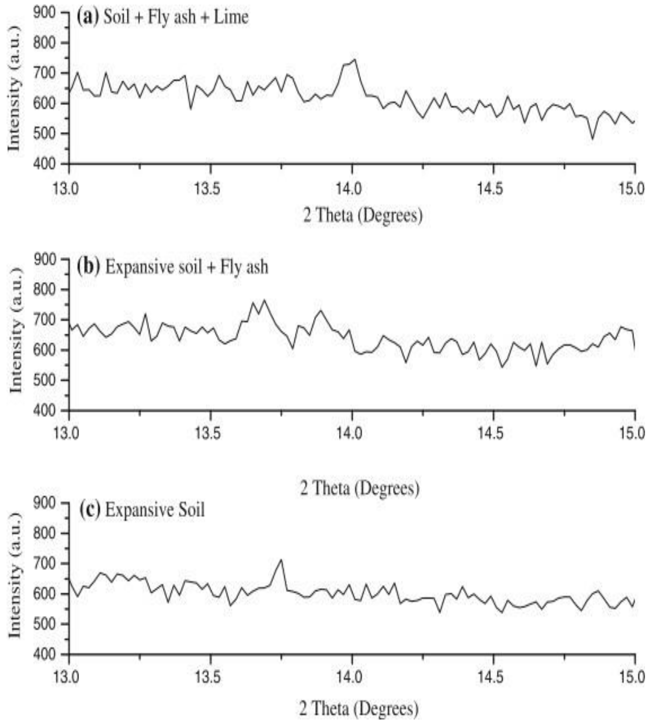

Figure 5: Formation of CAH (at 14.00°) (Source: Sharma et al., 2012)

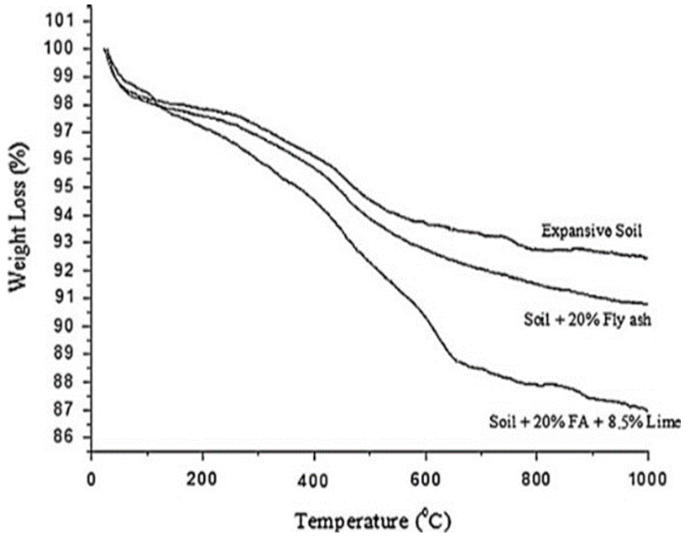

Figure 6: Thermo Gravimetric Analysis results for untreated and treated soils (Source: Sharma et al., 2012)

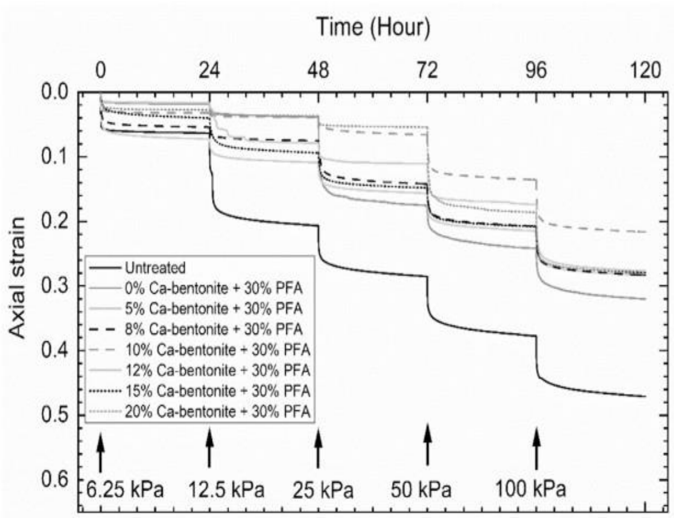

Figure 7: The effect of Ca-bentonite and PFA on the primary consolidation behavior of treated and untreated organic soil (Source: Pokharel and Siddiqua, 2021)

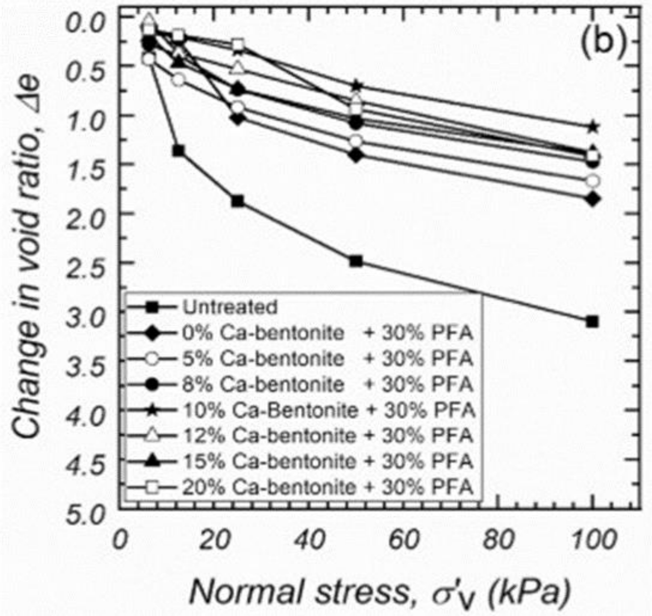

Figure 8: Change in void ratio after each loading increment (Source: Pokharel and Siddiqua, 2021)

5. Conclusion

Lateritic soil is considered as sandy clay or silty clay due to its fine-grained property. The reason behind this property of lateritic soil is due to the weathering process. Regions with tropical and subtropical climate would be the perfect location for the formation of lateritic soil. From the global distribution of lateritic soil, it is abundant near the equator region. However, due to its infertile property, lateritic soil is not suitable to be used in the agricultural sector. Hence, researchers have been performing tests to study its potential as construction materials.

In this review, the potential of lateritic soil as a material for road constructions is explored. It is understood that in its natural state, lateritic soil is only suitable to be used as subgrade material, not as subbase and road base. Therefore, additives were added to improve the properties its properties. In this review, industrial wastes were chosen to be discussed as stabilizers to lateritic soil. Different industrial waste improved the lateritic soil differently, and some of it worked better over the other, mainly due to the intensity of the pozzolanic reactions occurring during the stabilization process. However, more alteration and studies on the industrial wastes would be beneficial to yield the best outcome for them to be used as ground improvement stabilizers.

Among the industrial wastes mentioned, fly ash was chosen as the material of interest in this review. Fly ash originated from the burning of coal for power generation and possess the properties that makes it potential as a soil stabilizer. During hydration, the free lime within the fly ash undergoes pozzolanic reactions to produce cementitious materials. The cementitious materials are responsible for the self-cementing property and strength gain in the materials. The self-cementing capability of the fly ash is dependable on several factors, such as the amount of free lime available, curing temperature, and the particle size. The potential of fly ash as a ground stabilizer is shown by the various research performed up to current date. From this review, it is safe to assume that lateritic soil and fly ash are potential to be used as a subbase material in ground stabilization. The abundance of the materials make it seems attractive to be utilized, and with the support of scientific evidence, lateritic soil and fly ash may be useful in resolving the issues encountered in ground stabilization field such as land subsidence, alongside tackling the environmental issues of waste accumulation.

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