

Review Article

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Chemical stabilization techniques for clay soil: A comprehensive review

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Abstract: The instability of clay soil as a road subgrade due to its high shrinkage properties, results in frequent road damage. Therefore, adequate soil improvement is required to improve soil performance in order to satisfy post-construction stabilization requirements. Soil improvement is one of the efforts made to overcome it, such as the soil stabilization method. In recent years there has been an increase in research related to the chemical soil stabilization to improve the physical and mechanical properties of soils. The addition of chemicals such as palm bunch ash, lime, fly ash, and cement to clay soil results in hydration and pozzolanic reactions. This process results in changes in the physical and mechanical properties of the soil. The degree of soil stabilization is influenced by the type of additive, additive content, length of treatment, and soil mineralogy. This study discusses the changes that can affect clay soil when chemical stabilization is carried out, based on information provided by the authors.

Keywords: cement, chemical stabilization, clay soil, fly ash, lime, palm bunch ash

1 Introduction

Clay soils have low bearing capacity, high shrinkage properties, high compressibility, and take a long time to consolidate. It also has a low shear strength values with variations of 20–40 kPa [1,2]. Low soil bearing capacity of a road can lead to construction failure [3,4]. High shrinkage conditions also have a major effect on road construction, in dry conditions it will shrink and in wet conditions it will expand [5,6]. Shrinkage expansion in clay soils is

influenced by clay mineral content, moisture content, and loading conditions. Chemical soil stabilization on clay soil will affect the cation size of each chemical element and potassium cations do not absorb water so the nature of the soil containing potassium will not be expansive (soil shrinkage) to improve the physical and mechanical properties of clay soil and increase the bearing capacity of clay soil [6]. Some clay minerals such as montmorillonite have high volume changes when interacting with water. The inter-particle contact stress and shear strength of clay soils are reduced due to loss of water suction. Strength decreases and pore voids increase due to swelling of the soil as a result of increased water [7].

If the road subgrade is unable to provide stability and serviceability during the planned life, then soil improvement measures can be taken. Soil stabilization is a soil improvement method that aims to improve the physical and mechanical properties of soft soil [8–10]. Soil stabilization is the process of improving soil properties through many methods such as compaction, mixing with chemicals, and non-destructive methods [11]. Soil stabilization consists of mechanical and chemical stabilization. The purpose of chemical stabilization is to add chemicals (stabilizers) such as lime, fly ash, cement, and palm bunch ash to the soil [12,13]. There are two types of soil stabilizers: traditional stabilizers and non-traditional stabilizers. Lime, fly ash, cement, and palm bunch ash are traditional stabilizers, while asphalt is the non-traditional stabilizer [11,13].

Clays are formed from weathering due to chemical reactions that form a group arrangement of colloidal-sized particles with grain diameters smaller than 0.002 mm. Clay minerals are composed of aluminum octahedra and tetrahedral silica. Clay minerals are very sensitive to changes in moisture content, if there is a change in moisture content, then it will be followed by extreme volume changes. This will affect the characteristics and technical properties of clay soil such as permeability, stability, deformation characteristics, and stress distribution within the soil layers. Chemical soil stabilization in clay soil will affect the cation size of each chemical element and potassium cations do not absorb water so the nature of the soil containing potassium will not be expansive (soil shrinkage) to improve the

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physical and mechanical properties of clay soil and increase the bearing capacity of clay soil [14,15]. The behavior of each of these chemicals is different in its treatment or use on soil and has certain limitations. Condition of the soil to be improved is very important to know comprehensively, both the physical properties and chemical properties of the soil, especially those concerning the chemical composition of existing soil minerals. This is very decisive in choosing the type of stabilizer that is suitable for soil improvement, so that the desired improvement target can be achieved, by the characteristics and needs of the construction that will be built on the soil layer [10]. The mechanism of soil stabilization and the resulting properties after stabilization vary depending on the heterogeneity of soil composition, differences in micro and macrostructure, and differences in chemical reactions that occur in the soil due to the applied stabilizer mixture [11]. The selection of the dosage level of the stabilizer is largely determined by the type and mineralogical properties of the soil to be improved. Understanding soil characteristics is crucial for selecting the appropriate stabilizer materials for chemical soil improvement, as different soils react differently to various chemical additives. This ensures the chosen method effectively addresses the specific soil issues and achieves the desired outcome [10].

The amount of mineral valence, and cation size of each chemical element (description of specific surface), also determines the ionic substitution process in chemical reactions in soil. The ability of cation substitution is based on the specific surface of each type of clay. This mechanism will change the index properties of the chemical-amended soil due to the formation of a diffused double-layer thickness that can reduce the liquid limit, plastic limit, and plasticity index (PI) of the soil, which are included in the physical properties of the soil. Reducing the water content in the soil has the effect of reducing the shrinkage expansion properties of the soil to increase the bearing capacity of the soil such as increasing the value of California bearing ratio (CBR) of the soil and the free compressive strength value of the soil included in the mechanical properties of the soil [11].

The properties of chemical reactions that occur between soil minerals and the chemicals contained in stabilizers influence the effectiveness of soil stabilization. What must be avoided in the use of chemicals, is the spread of the chemical reaction process to soil masses that are not targeted for improvement. This is very detrimental to the environment, and can even be fatal if the reaction propagation zone reaches the soil mass that already supports other buildings. Thus the effect of the reaction propagation will have a direct impact on the building it supports, which can be in the form of deformation due to the

decomposition of soil minerals, differential settlement of the affected building, and so on [11].

The presence of water greatly affects the properties of the clay soil. In fine-grained soils such as clays, the presence of water makes the specific surface area larger. Similarly, variations in water content will affect the plasticity properties of the soil. The negatively charged clay surface will attract cations (+) of calcium and water molecules (dipoles), leading to the formation of a multi-layered "water double layer." Chemical reactions that occur in clay soil due to chemical additives cause the crystal conditions of Potassium (K⁺) ions to have a larger radius than Lithium (Li⁺) and Sodium (Na⁺) ions, thus potentially replacing them (ionic substitution). Conversely, in solution conditions, K⁺ is very easily substituted by Na⁺ and Li⁺ ions. Other specific properties of K⁺ ions include that K⁺ ions do not absorb water (H₂O) and this property results in potassium-containing soils not being expansive. This process reduces water in clay soils and impacts the permeability of clay soils [11,14].

Several factors should be considered when selecting the type and method of soil improvement for any soil stabilization project. These include the type and characteristics of the soil, such as its chemical and physical properties and mineralogy; the type and requirements of the planned construction, particularly the construction load; the specific soil parameters that need improvement based on construction needs; the depth of the soil layer requiring treatment; the chemical and physical properties of the stabilizer; the cost-effectiveness of the stabilizer, especially in terms of repair efficiency; the availability of materials and equipment at the improvement site; and the existing environmental conditions [15,16]. Chemical soil stabilization of clay soils will affect the cation size thereby increasing the shear modulus of the soil, and the formation of diffused double-layer thickness thereby decreasing the liquid limit, the plastic limit of the soil, and the PI of the soil. Long-term reactions occur over days, weeks, months, and/or years. The reactions that occur at this stage are called pozzolanic reactions. The presence of H⁺ and OH⁻ ions in the soil will greatly affect the acidity of the soil. The formation of anions in the soil indicates that the reaction will cause a decrease in the cation substitution capacity of the soil. If this kind of soil has technical parameters that do not support construction, the chemical stabilization action that can be taken is to use acidic stabilizers (pH < 7.00), because they can actively react to capture negative charges (anions) in the soil. Thus, anion substitution occurs, which will result in a more stable soil mass and better technical parameters [11].

The latest advancement of reference is the study of the stabilization of clay soil with Marble dust. Marble dust is a hardened metamorphic rock that has been exposed to

hydrothermal processes. The manufacture of marble dust consists of grinding and cutting to produce non-plastic dust with a very fine particle size that is almost like a perfect grater. The addition of marble dust to clay soils reduces the liquid limit, plastic limit, and PI of the soil. Soil stabilization technology has made significant progress in recent years. Nanotechnology has opened up new possibilities in soil stabilization by introducing nanomaterials such as nano-silica, nano-clay, and nano-lime. These materials have a high surface area to volume ratio, allowing them to penetrate soil particles more effectively and improve soil stability. Nano-particles can fill the voids between soil particles, increasing soil density and strength. In addition, nanoparticles can chemically react with soil minerals to form stable compounds, further improving soil properties [17–19].

Soil stabilization with cement and lime has long been used and with the development of time slowly began to research industrial waste additives [14]. The purpose of soil stabilization is to increase soil strength, change soil technical properties such as compressibility, permeability, soil development potential, and sensitivity to changes in moisture content [16]. Fly ash is a traditional stabilizer derived from waste coal combustion [20,21]. Soil improvement with lime is more rapidly developing, because it has been more widely used for various infrastructure development purposes, both for highways, airplane runways, land reclamation, backfill in retaining wall construction, and so on. The use of lime as a stabilizer for soil improvement was used by the military during the Roman Empire, to build dirt roads to support the mobilization of troops and their war equipment. Chemical methods of soil improvement with lime was again developed more widely, during World War I and World War II, which was not only used in road construction but also applied to the construction of fighter runways and military transport aircraft [22,23]. Palm ash is a pozzolana without binder, a waste from burning palm fiber, rich in silica and low in lime (CaO) [24,25]. Cement is widely used for clay stabilization and the percentage used is usually 20% or higher [26].

The challenge faced by soil stabilization in the field is that it requires a lot of stabilizers in field conditions so the mixing process also needs to be considered so that the soil is evenly mixed. Duration of application also affects soil stabilization. The lime-soil reaction starts about 1 h after mixing. The time lag between soil-lime mixing and compaction in the field needs to be considered as does the delay in compaction. The time lag tends to bind the soil grains and thus increases the porosity of the soil through the formation of clods. These clods have individual grains and provide stronger resistance to compaction efforts, leading to reduced maximum dry density (MDD) and increased optimum moisture content (OMC) [10,27]. Chemical stabilization of clay soil changes its physical and mechanical properties.

Chemical reactions that occur with clay mineral content result in reduced water content in clay so that the bearing capacity of the soil increases due to changes in its physical and mechanical properties. For road construction, if the bearing capacity of the soil is good, it will be able to carry the load on it and reduce the occurrence of land subsidence [27].

Specifically, the criteria for clay soils that are effective for chemical stabilization methods are acidic clay soil type (pH, 7.00), clay soil with high plasticity, high swelling potential, high compressibility, and high permeability [10–12]. All chemicals for stabilizers are carried out with different variations depending on the chemical reactions that occur in each stabilizer. In general, the addition of cement alone cannot improve the workability of clay soils, nor can lime alone bring the strength of highly expansive clays up to the desired level. However, the combined effect of cement and lime in proportions of 1:1 tends to give much higher strengths with better workability. When the pozzolan content in the soil is less, very little increase in strength is obtained by adding either lime or cement. Either by the addition of lime or cement. To overcome this problem, pozzolanic materials need to be added to the soil. Fly ash is one of the most widely used pozzolanic materials. This is partly due to the high percentage of silica present in it [5,6,28].

Chemical stabilization of clay soil changes the physical and mechanical properties of clay soil. Chemical reactions that occur with clay mineral content result in reduced water content in clay so that the bearing capacity of the soil increases due to the changes in its physical and mechanical properties. For road construction, if the bearing capacity of the soil is good, it will be able to carry the load on it and reduce the occurrence of land subsidence [10]. The innovation of this research is the chemical reaction that occurs in chemical stabilization that causes improved soil performance by changing the physical and mechanical properties of the soil so that it increases the bearing capacity of the soil.

This article reviews literature on the chemical stabilization of clay soils using palm bunch ash, lime, fly ash, and cement. It discusses the chemical composition of these stabilizers and their effects on the properties of clay soils. The stabilizers discussed in this article are traditional stabilization materials. This study explores the chemical reactions that occur during the stabilization process, the dominant parameters influencing soil stability, and their role in increasing the soil's bearing capacity.

The difference between this research and previous research is that this research describes various chemical stabilization literature on clay soils with materials that are often used, namely, cement and lime, as well as waste materials, such as fly ash from coal combustion residues

and oil palm waste, namely, oil palm bunch ash. Researchers [1,24] investigated the chemical stabilization of expansive soil with lime, cement, and fly ash. Lim and Shakri [25] studied stabilization using waste materials, such as fly ash and rice husk ash, for soil stabilization purposes. Yao *et al.* [26] researched about chemical stabilization using lime, cement, chemical, fly ash, rice husk ash, bituminous, thermal, and electrical stabilization. The main contribution of this research is its potential use as a reference for studies on clay stabilization using palm bunch ash, lime, cement, and fly ash. It also provides insights into the variation of stabilizers and the types of soil that can be treated.

2 Stabilization of palm bunch ash

Oil palm bunch ash is the residue of burning oil palm bunches, in the form of flour and is very alkaline with a pH of 12 so that it can be used to neutralize acid in the soil [29,30]. Palm bunch ash is produced by the palm oil industry through burning palm kernel shells, fiber, and empty palm bunches, which are used as fuel to generate electricity at temperatures of 800–1,000°C. This waste is dumped around the mill and if left unchecked will damage the environment [30,31].

Basic oil palm bunch ash contains a large amount of burnt carbon, absorbing most of the superplasticizer carbon properties [32]. Some researchers conducted studies to remove most of the unburned carbon in the bottom ash of oil palm bunches by heating it at 500°C for approximately 60 min [32], thus reducing the loss on ignition (LOI) content and increasing $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$, which becomes finer and moves to the surface position. The color dark gray and gray produced by palm bunch ash is due to the heating process.

Table 2: Properties of palm bunch ash [24]

No.	Testing	Results
1.	Specific gravity (Gs)	1.69
2.	Sieve analysis	
	Sand (%)	0.05
	Silt (%)	99.5
	Clay (%)	0.0
3.	Classification [45]	Class F

2.1 Chemical content of palm bunch ash

The chemical content of palm bunch ash taken from the studies of several researchers is shown in Table 1.

The amount of SiO_2 increases as the fineness of the palm bunch ash increases. The strength and durability of soil stabilized with palm bunch ash is proportional to the amount of reactive silica present in the palm bunch ash [44]. Oil palm bunch ash contains more K_2O , this is because the oil palm trees absorb K_2O during cultivation. The difference in oxide content is due to the temperature during the combustion process, the part of the oil palm tree used, and the fineness of the particles produced [44]. According to American Society for Testing and Materials [45], $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ content in palm bunch ash >50% so that it is classified as class C pozzolan and if the amount is >70%, it is included in class F pozzolan. Palm bunch ash has been successfully used in soft soil stabilization because it is rich in silica and low in lime (CaO) [24]. The physical properties of palm bunch ash are shown in Table 2.

The classification of palm bunch ash based on ASTM C618 is shown in Table 3.

Table 1: Chemical content of palm bunch ash based on literature

Oxide	SiO_2	Al_2O_3	Fe_2O_3	K_2O	CaO	MgO	Na_2O	LOI	$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$
Conc (%) [33]	57.8	2.3	9.6	3.5	3.6	1.4	0.56	20.7	69.7
Conc (%) [34]	79.34	3.15	7.12	3.23	2.79	1.21	—	—	89.58
Conc (%) [35]	66.24	3.52	3.93	6.7	5.21	4.48	0.16	4.41	73.69
Conc (%) [36]	59.17	3.73	6.33	8.25	5.8	4.87	0.18	16.1	69.23
Conc (%) [31]	64.17	3.73	6.33	8.25	5.8	4.87	0.18	—	74.23
Conc (%) [37]	62.3	3.2	13.6	7.9	4.9	3.7	—	—	79.1
Conc (%) [38]	69.02	3.9	4.33	6.9	5.01	5.18	0.18	1.8	77.25
Conc (%) [39]	63.7	3.68	6.27	9.15	5.97	4.11	—	—	75.37
Conc (%) [40]	62.6	4.65	8.12	9.05	5.7	3.52	—	6.25	73.65
Conc (%) [41]	65.3	2.6	2.0	5.7	6.4	3.1	0.3	10.1	69.9
Conc (%) [42]	65.3	2.5	1.9	5.7	6.4	3.0	0.3	10.0	69.7
Conc (%) [43]	59.62	2.54	5.02	7.52	4.92	4.52	0.76	8.25	67.18

Table 3: Classification of palm oil bunch ash based on ASTM C618 [45]

Properties		SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃	SO ₃	LOI
Chemical requirements of fly ash based on [45]	Class F (min-%)	70	5	6
	Class C (max-%)	50	5	6
Chemical results of oil palm bunch ash		77.9	0.08	4.2

2.2 Stabilization effect of oil palm bunch ash on clay soil

Oil palm bunch ash when used as a stabilizer on clay soil has a good effect because oil palm bunch ash contains SiO₂ chemistry as shown in Table 1, which is >50% [46]. The results of laboratory testing of clay stabilization with oil palm bunch ash are shown in Table 4.

by conducting laboratory studies such as triaxial testing [12,56] and unconfined compressive strength [56–58]. The addition of lime to clay affects the settling rate. The more lime content, the more the settling rate increases. The more lime content, the more turbidity suspension process is favored, because the average particle size becomes smaller in suspension [23]. This is shown in Figure 1.

The chemical theory of the reaction between lime and silicate, aluminate constituents in clay soils is complex [59] and includes cation exchange, flocculation and agglomeration, pozzolanic reactions, and carbonation [60]. These reactions affect changes in the physical, chemical, mineralogy, and microstructure of the treated soil [1]. Dissociation reaction of hydrated lime formed due to hydration of quicklime results in increased pH and high concentration of calcium ions in pore water [1,61]. An increase in pH can change the charge distribution on clay platelets, while calcium ions are released and lime replaces the exchangeable cations of the clay, leading to a reduction in the thickness of the double layer surrounding the clay [61].

3 Stabilization of clay with lime

The use of lime as a soil stabilizer has been used since the twentieth century and was first applied to highways in the United States in 1924 [1]. China and India have used lime mixtures for the construction of dams, bridge foundations, and basements. The Romans have used soil mixtures with lime for road subbases [11]. Lime used for soil stabilization can increase the shear strength of soil for road, runway, and railway construction. Lime can chemically react with soil grains to change the mineral properties of the soil [12]. Calcium in lime which has positive ions can stimulate the creation of soil adhesion, reduce the PI, reduce water content, reduce soil shrinkage properties, and increase soil stability [55]. Soil improvement using lime stabilizer is classified as a cementation reaction. The reaction mechanism between clay and lime is divided into two stages [55]:

- Immediate Reaction, which occurs within hours, causes a reduction in water content in the soil. This reaction takes place with the following mechanism: $\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca}(\text{OH})_2 + \text{heat}^*$. This reaction is followed by the process of flocculation and/or agglomeration of clay particles, indicated by changes in soil texture, which will lead to a decrease in plasticity, as well as an increase in the workability of soil.
- Medium and long-term reaction, which occurs in days, weeks, months, and years. The reaction that occurs at this stage is called the pozzolanic reaction between lime and clay particles.

The mechanical properties of clay mixtures with lime stabilization have been carried out by many researchers,

3.1 Lime chemical content

Lime is generally obtained by burning limestone in a kiln with the quality of lime depending on the material and process of production. There are five types of lime, namely [62]:

1. High calcium and quick lime (CaO)
2. Hydrated and high calcium lime (Ca(OH)₂)
3. Dolomitic lime (CaO + MgO)
4. Normal, hydrated dolomite lime (Ca(OH)₂ + MgO)
5. Pressure, hydrated dolomite lime (Ca(OH)₂ + MgO₂)

The chemical content of lime is shown in Table 5.

When lime is used as a soil stabilizer, there will be a chemical reaction involving cation exchange because each soil particle carries an electrical charge. Soil particles have relatively weak ions on the surface, so they can be easily replaced with other ions. Water is attracted to soil particles but because it is already bound by exchangeable ions, the attracted water is replaced by a process called sorption [10]. This means that the mixture of lime in clay soil, and

Table 4: Overview of research results of stabilization of loamy soil with palm bunch ash

No.	Author	Testing model	Parameters researched	Research results
1	[47]	Laboratory testing of the effect of temperature and length of curing	Unconfined compression strength (UCS)	The addition of oil palm bunch ash increases the free compressive strength of soil at 14 days of curing at 60°C (room temperature) compared to 1,000°C
2	[3]	Laboratory testing of clay soil stabilization with palm bunch ash and cement	UCS	Addition of oil palm bunch ash and cement increases the free compressive strength value of soil
3	[46]	Laboratory testing of clay soil stabilization with palm bunch ash	Maximum dry weight, optimum moisture content, CBR, and UCS	The maximum dry weight, optimum moisture content, CBR, and free compressive strength of soil increased with the addition of palm bunch ash with 14 days of curing
4	[25]	Laboratory testing of soft soil stabilization with palm bunch ash and fiber	Soil shear strength	Increasing the shear strength of soil with the addition of oil palm bunch ash and fiber within 14 days of curing
5	[24]	Laboratory testing of soft soil stabilization with palm bunch ash and lime	CBR	The pozzolan used was classified F, which contains almost no silica and alumina, so it was combined with 5% lime for pozzolanic reaction. Stabilization of 3% oil palm bunch ash and 5% lime increased the CBR value of the soil
6	[48]	Laboratory testing of clay soil stabilization with palm bunch ash and cement	Soil shear strength	There was an increase in the cohesion value of the soil and the shear strength value of the soil also increased with 20% palm bunch ash and 10% cement
7	[49]	Laboratory testing of clay soil stabilization with palm bunch ash and cement	CBR	Stabilization of soil with oil palm bunch ash and cement improves soil CBR value
8	[50]	Laboratory testing of clay soil stabilization with palm bunch ash and cement	Physical properties of soil and soil CBR	The addition of oil palm bunch ash changed the soil consistency limit by lowering the PI value. There was an increase in the CBR value of the subgrade at 7 days burial
9	[51]	Laboratory testing of clay soil stabilization with palm bunch ash	Soil shear strength	There is an increase in the shear strength of soil with the addition of oil palm bunch ash around 50–60% both the cohesion value and the angle of friction
10	[52]	Laboratory testing of clay soil stabilization with palm bunch ash	UCS	Oil palm bunch ash increases soil strength
11	[53]	Laboratory testing of clay soil stabilization with palm bunch ash	UCS and Soil shear strength	Soil shear strength and soil strength increase with the addition of palm bunch ash at 7 and 28 days of curing
12	[54]	Laboratory testing of clay soil stabilization with palm bunch ash	UCS	There was an increase in soil strength and a decrease in PI values with the addition of palm bunch ash and fly ash

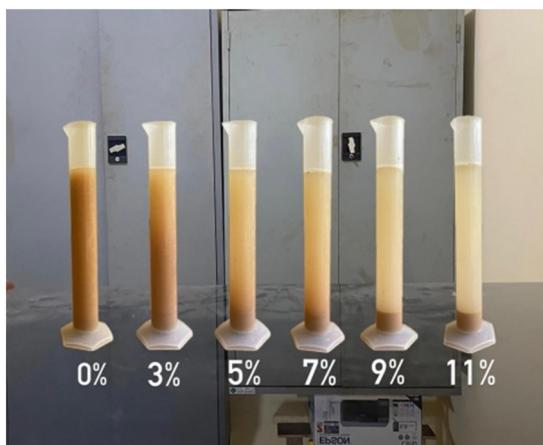


Figure 1: Precipitation processes due to lime addition.

cation exchange that occurs in the absorbed water layer results in a decrease in soil plasticity so that the soil has a good bearing capacity, and is good for use as a subgrade or foundation [10,66,67]. The amount of lime required as stabilizers varies between 2 and 10% by weight of the soil. The greater the PI value, the greater the amount of lime required [10].

3.2 Stabilization effect of lime on clay soil

Clay minerals partially react with lime, where lime pozzolan is stimulated by cation exchange [1]. The percentage of lime content applied depends on the clay mineral content. Increased lime content results in increased soil strength and reduced deformation [1,68]. The results of laboratory testing of clay stabilization with lime are shown in Table 6.

The increase in strength of clay soil occurs due to the reduction in plasticity and pozzolanic reaction in lime processing, which results in considerable hardening as seen in the magnitude of the resilience modulus [11]. There is a 20-fold increase in the modulus of resistance of montmorillonite clay when mixed with lime.

Table 5: Chemical content of lime based on literature

Oxide	K ₂ O	CaO	SiO ₂	V ₂ O ₅	Cr ₂ O ₃	MnO	Fe ₂ O ₃
Conc (%) [63]	0.02	66.3	<0.03	<0.01	<0.03	0.01	0.1
Conc (%) [15]	—	61.62	2.55	—	—	—	0.66
Conc (%) [23]	0.07	71.58	2.13	0.01	—	0.01	0.23
Conc (%) [5]	0.03	95.03	0	0	—	0.60	0.08
Conc (%) [28]	0	93.35	0	—	—	—	—
Conc (%) [64]	—	56.1	1.38	—	—	0.13	0.12
Conc (%) [65]	—	63.60	4.11	—	—	—	2.70

The National Lime Association recommends that PI values > 10% can be stabilized with lime. Based on the AASTHO classification of soil types A-4, A-5, A-6, A-7, A-2-6, and A-2-7 are suitable for stabilization with lime [71–73]. The process of flat particles and large particles in the clay sample produces a lot of particle bundles and forms a compact structure [23]. Lime-stabilized clay soil forms a white cement gel and Ca(OH)₂ in the soil pore space when water is added [23]. Filling the pores between particles with lime results in a decrease in PI and an increase in compressive strength [10,23].

4 Stabilization of clay soil with fly ash

Fly ash is a finely graded material measuring 0.01–100 microns, which is produced from burning coal in power plants. It is finer than ordinary Portland cement consisting of silica and alumina and CaO, Fe₂O₃, TiO₂, K₂O, MnO, Na₂O, and SO₃ [1,74,75]. The main constituents of fly ash are silica and alumina. Fly ash class C has high calcium and is environmentally friendly for stabilizing clay soils, it can be used as an alternative to chemical additives such as cement and lime. The use of fly ash in clay stabilization can improve the physical and mechanical properties of clay soils. Highly plastic clay soil has a high sensitivity to calcium, so the addition of fly ash can reduce the liquid limit and shrinkage potential of clay soil [74]. Over the past few decades, fly ash has been called a problematic waste because it pollutes agricultural land. Fly ash is ranked as the fifth largest source of raw materials and waste that can be used for alternative infrastructure and geotechnical development [9].

Fly ash is low in calcium and rich in aluminosilicate and is commonly used for geopolymer synthesis [76,77]. For decades, fly ash has been labeled as a problematic solid waste due to its conventional disposal method from thermal power plants and mills [78]. The type of class of fly ash based on ASTM C618-17-2019 [39] depends on the chemical composition and properties of the coal burned. Class C fly ash contains a lot of lime, CaO > 20%, and the sum of SiO₂ + Al₂O₃ + Fe₂O₃ > 50%. Class F fly ash contains little lime, CaO < 10%, and the sum of SiO₂ + Al₂O₃ + Fe₂O₃ > 70% [20,74]. Class F fly ash has pozzolanic properties while class C fly ash has pozzolanic properties and cement [74]. A conceptual microstructure model showing the stabilization mechanism of fly ash geopolymers is shown in Figure 2.

Table 6: Overview of research results stabilization of clay with lime

No.	Author	Testing model	Parameters researched	Research results
1	[12]	Laboratory testing of stabilization of clay soil with lime	Index properties and shear strength of soil	The addition of lime variation increases the specific gravity and optimum moisture content of clay soil. The addition of lime to clay soil can increase the shear strength value of the soil
2	[6]	Laboratory testing of clay stabilization with lime, cement, and fly ash	CBR	There is an increase in the CBR value of soil with the addition of lime, cement, and fly ash
3	[5]	Laboratory testing of pH variation in clay stabilization with lime	Soil shear strength	The shear strength parameter of clay soil increases with the addition of lime at high pH 9 and low pH 3
4	[4]	Laboratory testing of stabilization of clay soil with lime and plastic fiber on clay soil	UCS, split tensile strength, and CBR	The addition of lime can increase the compressive and tensile strength of soil. The role of fibers in soil stabilization with lime becomes more significant
5	[22]	Laboratory testing of the effect of temperature and curing time on reactivity and stabilization strength of limestone soil	UCS	Lime stabilization is applicable at lower temperatures when drying time is increased and thermal protection is provided
6	[56]	Laboratory testing of soil stabilization with lime and fiber	Soil shear strength and UCS	There was an increase in friction angle and cohesion values with the addition of lime and fiber. There is an increase in soil strength with the addition of these stabilizers
7	[57]	Laboratory testing of soil stabilization with lime and fiber	UCS	There is an increase in soil strength with the addition of lime and fiber
8	[58]	Laboratory testing of soil stabilization with lime and fiber	UCS	There was a high increase in soil stabilization with lime and fiber with a maximum curing time of 90 days
9	[69]	Laboratory testing of soil stabilization with lime	Soil shear strength	The longer treatment process on lime-stabilized soil, namely, 28, 90, and 180 days, increased the cohesion value and shear angle
10	[8]	Laboratory testing of soil stabilization with lime	CBR and UCS	There was a significant decrease in soil plasticity and maximum dry density increased due to the addition of lime to the clay soil. The CBR value and compressive strength of the soil increased due to the mixture of lime with clay Lime and bagasse ash combined at the optimal ratio of 4:1, the CBR results of stabilization of clay soil increased
11	[70]	Laboratory testing of soil stabilization with lime and bagasse ash	CBR	Increase in soil strength with lime and cement mixture and brine addition
12	[16]	Laboratory testing of clay stabilization with lime and cement in the presence of salt water	UCS	

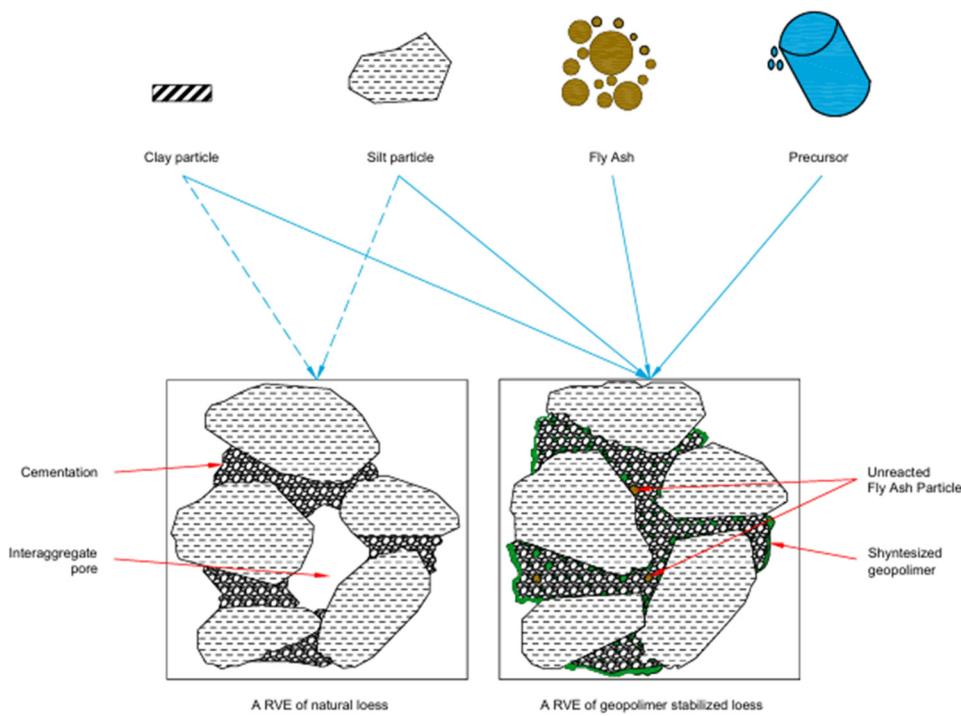


Figure 2: Conceptual microstructure model of fly ash geopolymer stabilization.

Clay particles are the main component that usually clump together to form clay aggregates that provide load-bearing capacity. Due to the special features of the loess formation process, we are characterized by the formation of open metastable structures and their mechanical properties depend on cementation/suction between particles [79]. The cementation bond and suction capacity of loess soils will decrease and eventually lead to collapse behavior when the loess is wetted or subjected to increased applied pressure [79].

The benefits of fly ash are as follows [1].

1. Drying agent

A large amount of water is absorbed by fly ash during the hydration process and can be used as a curing agent for moist soils, especially if rapid curing is desired.

2. Control of volume instability

Can reduce soil volume instability and reduce soil shrinkage expansion properties.

3. Strength improvement

The cement compounds and pozzolanic reactions of fly ash provide a cementing bond to the soil that increases its strength.

Table 7: Fly ash chemical content based on literature

Composition	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	K ₂ O	CaO	MgO	Na ₂ O	LOI	SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃
Conc (%) [79]	52.06	20.54	5.5	0.69	14.07	3.29	0.94	0.1	78.1
Conc (%) [80]	51.11	25.56	12.48	0.70	4.30	1.45	0.77	0.57	89.15
Conc (%) [74]	48.20	22.30	5.30	1.20	15.80	1.20	1.50	—	75.80
Conc (%) [81]	36.00	16.80	17.64	1.83	26.73	—	—	—	70.44
Conc (%) [82]	66.88	25.12	2.41	1.83	1.69	—	—	—	94.41
Conc (%) [83]	50.2	22.5	5.17	—	20.3	0.51	—	—	77.87
Conc (%) [84]	59.40	33.99	1.21	0.64	27.68	0.42	—	0.21	94.6
Conc (%) [85]	49.72	15.15	9.30	2.00	13.1	2.97	2.37	1.00	74.17
Conc (%) [78]	45.00	30.00	10.00	4.00	30.00	6.00	2.00	0	85.00
Conc (%) [86]	58.8	21.1	1.1	2.4	3.4	1.1	0.4	3.4	81.00
Conc (%) [87]	54.9	25.8	6.9	—	9.7	1.8	—	6.0	87.6
Conc (%) [65]	40.60	19.06	5.34	—	24.00	2.00	—	6.00	65.00

Table 8: Overview of research results stabilization of clay soil with fly ash

No.	Author	Testing model	Parameters researched	Research results
1	[80]	Laboratory testing of clay stabilization with fly ash	UCS	Stabilization of clay soil with fly ash increases the compressive strength value of the soil
2	[74]	Laboratory testing of clay stabilization with fly ash to improve soil-bearing capacity	Maximum dry weight, optimum moisture content, CBR, and UCS	Maximum dry weight decreases with the addition of fly ash, there is an increase in CBR value and compressive strength of clay soil at 7% fly ash
3	[79]	Laboratory testing of clay stabilization with fly ash	UCS	Stabilization of clay soil with fly ash increases the compressive strength value of the soil and increases the Young's modulus value
4	[86]	Laboratory testing of stabilization of clay soil with fly ash and lime	Maximum dry weight and optimum moisture content	High sulfate in fly ash reduces its effective role. The high LOI of coarse fly ash increases the optimum moisture content value and decreases the maximum dry weight
5	[85]	Laboratory testing of clay stabilization with fly ash and fiber	UCS	The fly ash content of the soil affects the stress and strain. The strength is significantly affected by the addition as well as the length and number of fibers provided. The addition of fly ash and fiber increases the strength of clay soil
6	[90]	Laboratory testing of cyclic behavior of fly ash stabilized clay soil	Stress and strain, soil modulus	Fly ash improves the cyclic performance of clay soils such as the achievable strain of the soil, the number of load cycles, and the cyclic shear modulus. Fly ash is required to maintain durability against applied loading
7	[77]	Laboratory testing of stabilization of clay soil with fly ash and slag	UCS	The addition of fly ash and slag increased the strength of the soil, proving an alternative to traditional cement or lime binders
8	[91]	Laboratory testing of clay stabilization with fly ash and bottom ash	UCS	The soil strength value increases with the curing time. The addition of fly ash and bottom ash increases the soil strength values
9	[92]	Laboratory testing of clay stabilization with fly ash	UCS	Loamy soil containing 10% fly ash increases the free compressive strength of the soil
10	[93]	Laboratory testing of stabilization of clay soil with fly ash and lime	UCS	Addition of fly ash and lime increases soil strength after 7 days and 28 days of curing
11	[94]	Laboratory testing of clay stabilization with fly ash	Atterberg limits and UCS	The addition of fly ash can reduce the PI and specific gravity of clay soil. The strength of clay soil increases with the addition of fly ash
12	[95]	Laboratory testing of clay stabilization with fly ash	UCS	The addition of fly ash improves the physical and mechanical properties of clay soil and increases the strength of clay soil, so fly ash is recommended for stabilization of clay soil

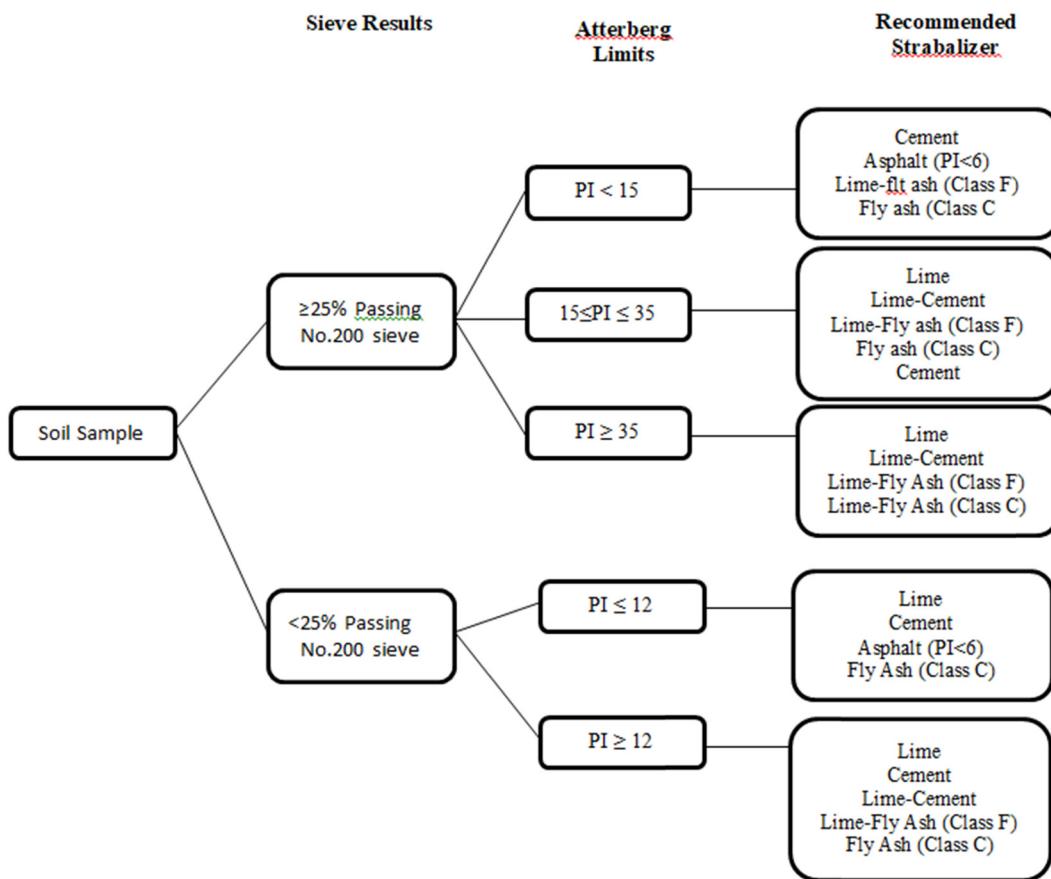


Figure 3: Stabilizer selection recommendations based on soil physical properties [9].

4.1 Fly ash chemical content

The chemical content of fly ash is shown in Table 7.

The presence of silica in fly ash reacts with Ca^{2+} ions of lime to reduce the Ca^{2+} concentration. Since ettringite requires more Ca^{2+} ions, there is a reduction in the Ca^{2+} concentration, which tends to reduce the possibility of ettringite formation so that the swelling of sulfate is

reduced [1]. Fly ash with high sulfate content can be beneficial to the total sulfate potential of lime-treated clay soils, which can exacerbate ettringite formation and swelling. Thus, fly ash can be a crucial factor for the selection of materials to limit sulfate in shrinkage expansion of lime-treated expansive soils [86].

Particles finer than 10 mm will tend to show better pozzolanic reactivity. Clay stabilized with fly ash having

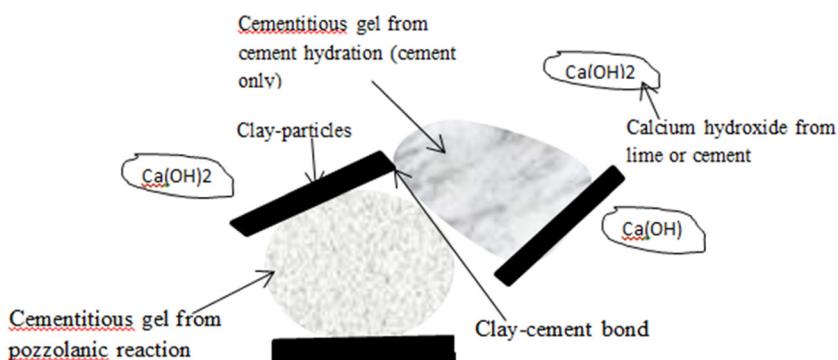


Figure 4: Mechanism of strength development due to pozzolanic reaction [106].

a higher CaO/SiO_2 , $\text{CaO}/\text{Al}_2\text{O}_3$ than $\text{CaO}/(\text{SiO}_2/\text{Al}_2\text{O}_3)$ ratio experiences higher pozzolanic activity as well as better engineering properties [87,88].

4.2 Stabilization effect of fly ash on clay soil

Fly ash increases the bearing capacity of clay soils and improves their physical and mechanical properties. Clay soils have a high sensitivity to calcium, so the addition of fly ash significantly lowers the liquid limit value and reduces the shrinkage expansion properties of the soil [1,89]. The results of laboratory testing of clay stabilization with fly ash are shown in Table 8.

Research related to the stabilization of clay soil with fly ash has been widely studied. Laboratory studies improved the physical and mechanical properties of the soil. Significant improvement occurs depending on the chemical content of fly ash and the length of curing, as shown in Figure 3.

Scanning electron microscope (SEM) technique coupled with energy dispersive X-ray (EDX) is the best and most widely used method to identify the morphology (microstructure) and constituents of fly ash particles [74]. SEM-EDX analysis was used to describe the microstructure of the sample [74].

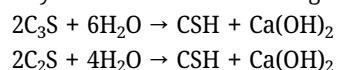
silicate (C2S), tricalcium aluminate (C3A), and tetra calcium aluminoferrate (C4AF). For C is CaO , S is SiO_2 , F is Fe_2O_3 , and H is H_2O [1]. Cement has been widely used for stabilizers in clay soils as subgrade soils [100]. For stabilization of clay soil with cement, the cement content is larger than 20% [26]. Portland cement is a construction material that is often used in the construction world. But its manufacture causes wastage of energy because it requires a temperature of 1,450–1,550°C and has other properties that have an impact on the environment [76].

Cement stabilization is a mixture of cement, soil, and water to form a rigid and hard material when compacted, thus increasing the bearing capacity of the soil [101]. The use of cement as stabilization of clay soil improves the physical and mechanical properties of the soil, where observations show that the addition of cement reduces plasticity, liquid limit, and development potential of the soil significantly. Soil strength increases with the addition of cement to clay soil [96,102]. Stabilization of soil with cement is influenced by several factors [1]:

1. Cement ratio
2. Cement content
3. Burial period
4. Sulfate content and organic content

5.1 Chemical content of cement

Calcium silicate consists of silicate (C3S) and di-calcium silicate (C2S), resulting in a very analogous hydration [103]. Clay soil when mixed with cement and water, hydration will occur, calcium silicate releases calcium ions into the clay and forms the following compounds [104]:



5 Stabilization of clay with cement

Besides lime, most popular chemical additive used for soil stabilization is Portland cement. Portland cement has been used for about 100 years in various places [96–99]. Portland cement is a fine heterogeneous compound consisting of four different oxides, namely, silicate (C3S), di-calcium

Table 9: Chemical content of cement based on literature

Composition	SiO_2	Al_2O_3	Fe_2O_3	K_2O	CaO	MgO	Na_2O	LOI
Conc (%) [103]	20.18	4.41	2.40	0.14	65.66	0.66	0.06	2.50
Conc (%) [107]	21.7	7.5	2.9	—	54.7	1.7	—	3.4
Conc (%) [108]	39.41	11.63	3.35	1.21	36.35	5.52	0.32	0.02
Conc (%) [104]	19.66	5.48	3.72	—	62	2.87	—	3.55
Conc (%) [109]	21.60	4.13	4.57	0.56	64.44	1.06	0.11	0.76
Conc (%) [110]	30.32	11.83	3.24	1.09	50.90	1.60	0.69	—
Conc (%) [111]	21	5	4	1	65	1	—	4
Conc (%) [96]	21.60	4.13	4.57	0.56	64.44	1.06	0.11	0.76
Conc (%) [32]	20.59	4.90	3.21	0.90	63.80	0.90	0.05	2.48
Conc (%) [112]	21.60	4.13	4.57	0.56	64.44	1.06	0.11	0.76
Conc (%) [113]	18.30	4.68	2.32	0.57	66.80	1.59	0.28	0.21

Table 10: Overview of results research on stabilization of loamy soil with cement

No.	Author	Testing model	Parameters researched	Research results
1	[11]	Laboratory tests of stabilization of clay soil with cement on shrinkage expansion soil	UCS, liquid limit, and plasticity	The addition of cement resulted in increased strength and stiffness of the soil and reduced the shrinkage potential of the soil
2	[14]	Laboratory tests of stabilization of clay soil with cement on shrinkage expansion soil	UCS and plasticity	The addition of cement increases soil strength by a factor of 4–10 and decreases swelling potential by <1%
3	[26]	Laboratory tests of stabilization of clay soil with cement against strain and stress	UCS and soil modulus	The addition of cement increases soil strength and makes the strain modulus small due to addition of cement
4	[15]	Laboratory tests of stabilization of clay soil with cement and polypropylene fiber	UCS	There was an increase in soil strength with the addition of cement and polypropylene fiber
5	[16]	Laboratory tests of stabilization of clay soil with cement and polypropylene fiber	CBR	There is an increase in the strength of soil with the addition of cement and polypropylene fiber due to changes in the temperature in wet and dry conditions
6	[17]	Laboratory tests of stabilization of clay soil with cement and fly ash	UCS	There was an increase in the CBR value of cement-stabilized soil
7	[18]	Laboratory tests of stabilization of clay soil with cement and fly ash	CBR and UCS	There is an increase in soil strength due to the addition of cement and fly ash to the soil
8	[19]	Laboratory tests of stabilization of clay soil with cement and fiber mixture	CBR and UCS	Stabilization of clay with cement and fiber addition, very effective in increasing CBR value and soil strength
9	[120]	Testing laboratory stabilization of clay soil with cement	UCS	The compressive strength of soil increases with the addition of cement in clay soil within 7 days of curing
10	[121]	Testing laboratory stabilization of clay soil with cement	Permeability	Liquid limit and plastic limit decrease with the addition of cement. The permeability coefficient of stabilized soil at 2% cement increased about 14 times greater than that of the native soil
11	[122]	Laboratory tests of stabilization of clay soil with cement and sawdust ash	UCS	There is an increase in the strength value of cement and sawdust ash stabilized clay soil
12	[123]	Laboratory tests of clay stabilization with cement and gypsum	CBR and UCS	CBR value and compressive strength of soil increased with the addition of cement and gypsum within 28 days of curing

$\text{Ca}(\text{OH})_2$ formed during the hydration of silicate (C3S) and di-calcium silicate (C2S) decomposes into OH^- and Ca^{2+} , furthermore Ca^{2+} ions contribute to the soil flocculation. It also reacts with pozzolanic materials such as silica and alumina present in the soil [1,105]. As a result, cementitious components are formed (calcium aluminate hydrate [CAH] and calcium silicate hydrate [CSH]) that lead to the strengthening of inter-particle bonds thereby improving soil strength performance. Cementitious soil improvement is a mixture of crushed soil, cement, and water, which is then subjected to a compaction process that will produce a new material called soil-cement material. The reaction of cement with soil material and water will create a hardened compound that improves the strength of the soil and the technical properties of the soil become stronger and more resistant to water [1,106]. The increase in strength mechanism due to the cementitious compound of pozzolan is shown in Figure 4 [106].

The pozzolanic reaction takes place slowly over months or years, and can further strengthen the soil with reduced plasticity and increased gradation [106]. The chemical content of cement is shown in Table 9.

5.2 Stabilization effect of cement on clay soil

Cement can be mixed with all types of soil, but it is most suitable for granular soils with high fineness and medium-plasticity clay soils in cement stabilization [1]. Cement admixture is recommended in soils with PI values $<20\%$. Cement becomes difficult to mix with highly plastic clay soils as lumps will form, making mixing difficult [111]. Laboratory test results of stabilization of clay soil with cement are shown in Table 10.

Less cement is required for low-plasticity clays and high cement is required for high-plasticity clays [1]. In high plasticity soils, the liquid limit will continue to decrease up to 6% cement, while in low plasticity soils the liquid limit value increases [124]. Microstructure and mineralogy studies using SEM, EDX spectroscopy, and X-ray diffraction were conducted to see the mechanism of chemical reaction of clay with cement [96].

EDX results confirmed the presence of Si and Ca in selected areas providing qualitative evidence for the gel formation of C-S-H specimens. Cement-stabilized specimens indicate that sodium silicate has geopolymersized [92]. Stabilization of clay soil with cement effectively increases the shear strength and compressive strength of the soil in a relatively short period [125].

6 Conclusion

This article presented a literature review of clay stabilization with chemicals such as palm bunch ash, lime, fly ash, and cement. The conclusions obtained are as follows:

1. Chemical stabilization can increase the strength of clay soils. The stabilization process depends on the percentage of additives, clay mineralogy, and the length of curing.
2. Palm bunch ash has been successfully used in clay soil stabilization because it is rich in silica and low in lime (CaO). The addition of palm bunch ash increases soil strength. The classification of palm bunch ash based on its pozzolanic properties is class C and class F.
3. Lime is suitable for highly plastic soils such as expansive clays. Lime mixtures in clay soils show a considerable increase in strength due to the development of pozzolan, which shows the effect of cement on soil particles. Based on AASTHO classification of soil types, A-4, A-5, A-6, A-7, A-2-6, and A-2-7 are suitable for stabilization with lime.
4. Fly ash has a low calcium content, so it does not produce significant soil strength as with lime and cement. Clay soils have a high sensitivity to calcium, so the addition of fly ash significantly lowers the liquid limit value and reduces the shrinkage expansion properties of the soil.
5. Cement is suitable for granular soils with low plasticity. Cement admixture in expansive clay soils can reduce the shrinkage expansion properties of the soil. Cement admixtures are recommended in soils with PI values $<20\%$. Stabilization of soil with cement has higher strength when compared to lime. The strength is due to the formation of compounds due to the addition of cement.

As suggested, road construction on soft soil is one of the main problems faced by geotechnical engineers, one of the efforts to improve it is stabilization. Several stabilization techniques have their advantages and disadvantages. The selection of chemical stabilization methods must be considered so as not to impact the environment. This research can be a recommendation for engineers to choose the chemical stabilization method used.

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