I. J. Engineering and Manufacturing, **2023, 2, 1-8**
Published Online on April 8, 2023 by MECS Press (http://www.mecs-press.org/)
DOI: 10.5815/ijem.2023.02.01

A Review on Stabilization of Soft Soils with Geopolymerization of Industrial Wastes

Tadesse A. Wassie*
Department of Civil Engineering, Institute of Graduate Studies, Ondokuz Mayis University, Samsun, Türkiye
Email: tadegeo68@yahoo.com
ORCID iD: https://orcid.org/0000-0003-1827-2461
*Corresponding Author

Gökhan Demir
Department of Civil Engineering, Faculty of Engineering, Ondokuz Mayis University, Samsun, Türkiye
Email: gokhandemir61@gmail.com
ORCID iD: https://orcid.org/0000-0002-3734-1496

Received: 03 January, 2023; Revised: 29 January, 2023; Accepted: 05 March, 2023; Published: 08 April, 2023

Abstract: Geopolymers are inorganic aluminosilicate polymers that solidify into ceramic-like substances at temperatures close to ambient. The elements in silicate oxide (SiO_2) and aluminum oxide (Al_2O_3) are essential for the hardening of geopolymers because they combine with other elements to create N-A-S-H formation, which gives the material its distinctive strength. Geopolymers based on industrial wastes are increasingly being used to stabilize soft soils. Fly ash, GGBS, metakaolin, glass powders, and others are a few of the industrial wastes that aid in synthesizing geopolymers. Several experimental studies were carried out to determine the mechanical strength, durability, and microstructure improvement of soft soils stabilized with geopolymers. Some of the experiments include X-ray diffraction (XRD), scanning electron microscopy (SEM), unconfined compression testing (UCS), and durability testing. The main objective of this review was to assess the different types of binders, binder ratios, alkali activator types, alkali activator concentrations, and other parameters used in synthesizing geopolymers. The binder's proportion varies between 5% and 30% of the soil's dry weight. Researchers commonly use sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) solution for the alkali activator. Since the unconfined compression test is one of the quickest and least expensive ways to determine shear strength, most researchers were used to measure stabilized soils' mechanical strength. This paper highlights the most frequently used industrial wastes used to synthesize geopolymers. The review enables researchers to acquire essential and complementary inputs for future research.

Index Terms: Geopolymers, Strength, Microstructure, Durability, Unconfined Compressive Strength

1. Introduction

Soil stabilization helps to improve the strength parameters and increases the bearing capacity. Stabilization may be applied in parking areas, site development projects, airports, and roadways. Industrial byproducts include ground-granulated blast furnace slag, fly ash, metakaolin, and conventional stabilizers that help treat soft soils.

Nowadays, the geopolymerization of industrial wastes for soil stabilization is more popular than conventional soil stabilizers. The excessive power used to produce traditional stabilizers leads to alternate cementitious binders [1]. Compared to Portland cement, the geopolymerization process is a reasonably green option. While both techniques produce a cementitious product that can bind aggregates to form a material with high compressive strength, the production of Portland cement is associated with considerable energy consumption and a significant carbon footprint[2]. Geopolymers, including fly ash, slag, and metakaolin, are being used as innovative substitute binders by activating a precursor in an alkali solution. The alkaline activator dissolves silicon and aluminum from silica and alumina-rich materials, creating geopolymers [3]. Alkali activation of aluminosilicate-rich materials results in the formation of alumino-silicates that are covalently linked [4]. An aluminosilicates-rich source (metakaolin, fly ash), an alkali-metal cation source (such as NaOH, KOH, or $Ca(OH)_2$), an additional amount of silica (if needed), and water are required for the synthesis of geopolymers. These components are combined in predetermined ratios to create a slurry that hardens into a geopolymer when allowed to cure. The dissolved aluminosilicates species in an aqueous solution undergo overlapping polycondensation processes that lead to their subsequent polymerization, gelation, and hardness as the slurry changes into the hardened geopolymer[5].

Some researchers stabilized the soft soils based on the deep soil mixing method. The deep mixing (DM) method involves mixing in situ soil with a hardening agent (cement, lime, slag, or other binders) at depths. Deep mixing can be accomplished by a wet or dry method. A dry approach uses the binder in a powder form, whereas a wet method uses it in a slurry form. The deep mixing Columns have a wide range of uses in soft soils, including the following: (1) support of superstructures, such as buildings, walls, embankments, and the like; (2) waterfront and marine applications, such as quay walls, wharf structures, and breakwaters; (3) stabilization of slopes; (4) lateral support; (5) containment of water and pollutant; (6) liquefaction mitigation; and (7) vibration reduction[6]. The binder content significantly influences the strength development of deep mixed columns. The recommended amount of binders is between 20 and 25 %, which varies depending on the kind of soil, particularly soils with greater clay content [7].

The objective of this study was to briefly review previous works on stabilizing soft soils using industrial waste-based geopolymers. The study provides baseline knowledge on the most widely utilized alkali activators, aluminosilicate-rich binders, and other parameters in synthesizing geopolymers for future researchers.

2. Materials and Methods

Stabilization is mostly done for soils that have poor bearing capacity, high compressibility, low shear strength, and high swelling potential. Most researchers work on stabilizing fine-grained soils with high or low plasticity. The binder materials are traditional stabilizers, industrial waste products, or a combination of traditional stabilizers and industrial waste-based geopolymers. The most commonly used traditional stabilizers are lime and cement. These stabilizers are high in Cao, which aids in cementing soil particles. In other words, the industrial wastes include fly ash, metakaolin, ground granulated blast furnace slag, glass powder, olivine, and sewage sludge. The usage of an alkali activator is essential during the geopolymerization process and the strength, cost, and availability, the alkali activators can be either sodium- or potassium-based activators.

2.1. Soft Soils

These types of soils contain a high fraction of silty and clayey soils. Their unique characteristics, including their high water content, high void ratio, high compressibility, low shear strength, low permeability, and unique structural features, necessitate careful consideration in the study, construction, and maintenance of geotechnical structures built on them. For many urban districts that are situated on such soils, it is challenging to carry out large-scale development of high-speed transportation systems, high-rise structures, and underground operations.

2.2. Fly ash (FA)

Burning pulverized coal in electric generating power plants produces fly ash, a fine powder. Fly ash is the residue resulting from the coal's mineral impurities fusing together as they exit the combustion chamber, then cooling and hardening. Fly ash is a pozzolana, a substance made of alumina and siliceous material that makes cement when combined with water. Fly ash creates a substance that resembles Portland cement when combined with lime and water. This qualifies fly ash as a key component in various building materials, including hollow blocks, mosaic tiles, and blended cement.

2.3. Metakaolin

Metakaolin (MK), $A_{l2}Si_2O_7$, is a mainly amorphous dehydration product of kaolinite, $A_{l2}(OH)_4Si_2O_5$, which exhibits significant pozzolanic activity. The two primary chemical constituents are alumina ($A_{l2}O_3$, 14.5-47.43%) and silica (SiO_2, 44.4-73%). Metakaolin is a crucial ingredient, particularly when used with low calcium based alkali activator precursors[8].

$$\mathrm{Al_2Si_2O_5\,(OH)_4 \;\rightarrow Al_2O_3 \cdot 2SiO_2 + 2H_2O} \quad (1)$$

2.4. Ground granulated blast furnace slag (GGBS)

An iron byproduct produced in a blast furnace is called ground granulated blast-furnace slag, or GGBFS. Mostly silicate and aluminosilicates of molten calcium that had to be periodically removed from the blast furnace constitute this material. It is mostly composed of the oxides of calcium (CaO), silica (SiO_2), alumina (Al_2O_3), and magnesium (MgO), with traces of a few other minor oxides.

2.5. Alkali activators

The geopolymerization reaction occurs during the alkali-activation process and is principally caused by a chemical reaction between dissolved silicate and alumina species in an extremely alkaline environment. The two most common alkali activators researchers use in the geopolymerization process are NaOH and Na_2SiO_3.

2.6. Sample Preparation

Since there is no standard method for preparing the geopolymer mix, researchers use various techniques. The liquid limit setting will adjust the soil's moisture content to create soft soil with initial water content. This method is used for deep soil mixing purposes. The binders are combined for a predetermined amount of time after the soil has been moist for 24 hours, followed by adding the alkali activators and further mixing for a predetermined amount of time. To prepare the samples, the soft Bangkok clay, fly ash, and cement are mixed for two minutes. The alkali activators are then added, and the mixture should be mixed for about three minutes[9].

The alkali activators and binders were mixed in the second method, and then the prepared slurry was added to the soft soil. Before producing the geopolymer specimens, the geopolymer slurry and soft soil were mixed thoroughly for a predetermined time.

The dried clay was blended with water to create a liquid limit state, and after curing in tide containers for at least 24 hours, it was mixed with the geopolymer slurry that had already been prepared[10]. Geopolymerization is influenced by the ratio of binder materials, type of materials, alkali activators, the concentration of activators (molarity), and curing time. Several researchers utilized UCS and other laboratory tests to analyze stabilized samples' strength and microstructure improvement.

3. Literature Review

3.1. Fly Ash

Burning pulverized coal in electric power plants produces fine powder, fly ash. It is a term for the residue that results from the coal's mineral impurities fusing as they exit the combustion chamber, then cooling and hardening. Fly ash contains aluminous and siliceous materials which makes cement when in contact with water. It comes into Class C and Class F categories. In contrast to Class C, which has a high calcium level and less than 2% carbon content, Class F typically has a low calcium content and less than 5% carbon content.

Suksiripattanapong et al.[9] investigated the improvement of fly ash-based geopolymer and cement-stabilized soft Bangkok clay. Using a scanning electron microscope (SEM), the morphology of cement, fly ash, and soft Bangkok clay was investigated. Findings revealed that the unconfined compressive strength of soft Bangkok clay, cement, and FA geopolymer increased as the cement content increased while declining as the NS: NH ratios decreased.

Odeh and Al-rkaby [11] conducted durability, microstructures, and strength assessment of coal-fired fly ash-based geopolymer improved clay soil. Coal-fired fly ash was employed as a soil stabilizer, and sodium hydroxide and sodium silicate were used as alkali activators. Alkali activator to fly ash (AC/FA) ratios were 0.4, 0.6, and 0.8. Fly ash was added in samples at a ratio of 10, 15, and 20% by dry weight of the soil. The researchers concluded that geopolymers based on fly ash are effective stabilizers and that samples treated with geopolymers exhibit strong resilience to chlorination and acidic environments.

Abbas et al.[12] carried out experimental studies on stabilizing expansive soil with fly ash-based geopolymers. Alkali activates to binders ratios of 0.5, 0.75, and 1 was used to stabilize the expansive soil, while activator concentrations of 8, 10, and 12 molarity were used. It can be inferred that employing fly ash as a geopolymer instead of cement to stabilize expansive soils is more environmentally safe.

Abdullah and Shahin [10] studied the performance of clay soil stabilized by fly ash-based geopolymers. Unconfined compression tests and durability were used to evaluate the geomechanical properties. Activator/ (slag + Fly Ash) was altered in the ratio of 0.5, 0.75, and 1.0, and the geopolymer was added in the proportions of 10, 20, and 30% to the dry weight of the soil. The authors conclude that geopolymer-treated clay remarkably improved strength and durability properties.

Khasib et al. [13] investigated microstructural behavior, and strength development of POFA-based geopolymer stabilized soil. The proportion of POFA ranges from 10 to 40 % of the soil's dry weight. To investigate the mechanical characteristics of the stabilized soil, direct shear tests and unconfined compression strength tests were carried out. The authors conclude that the properties of soil were successfully improved by the developed geopolymer, which used POFA as a source material and NaOH and Na_2SiO_3 as alkali activators.

Abbas et al.[14] studied the stabilization of soft clay using FA-based geopolymer. Energy dispersive spectroscopy "EDS" and XRD examinations allowed for identifying the elemental composition and mineralogical content. The analysis revealed that the Fly Ash based stabilizers are good alternatives to Portland cement stabilizers.

Abdullah et al.[15] analyzed the geomechanical behavior of fly ash and granulated slag-based geopolymer-stabilized clay soils. Two natural clay samples with low and high plasticity and kaolin clay (CH) were used as soil samples in the experiment. The geopolymer was synthesized using fixed weight ratios of 20% slag/fly-ash and 40% activator/ (fly-ash + slag). Consolidated undrained (CU) triaxial compression tests and unconfined compressive strength (UCS) tests were performed in the lab. The authors conclude that the clay soil was successfully stabilized based on the UCS and triaxial test results.

Arulrajah et al.[7] conducted a soft marine clay improvement using slag and FA-based geopolymers. The Liquid contained 30% NaOH and 70% Na_2SiO_3, whereas the NaOH solution with a molarity of 8 was formed. The stabilized FA and S were prepared in the proportion of 10, 20, and 30 % of the dry mass of the soil. The initial moisture content of the soil sample before mixing with the binders was chosen to be in the limits of 0.75, 1.0, and 1.25 LL. The result shows that the combination of Fly ash and Slag binders considerably improved the strength and stiffness of the soft clay.

Ridtirud et al. [16] conducted a comparative study on cement and geopolymer-based treated soil. The lateritic soil was stabilized using conventional cement and Fly Ash class C to test the compressive strength. The geopolymer was prepared in quantities of 1.5, 3, 5, 7, 10, 15, and 25% of the dry weight of the soil, while the cement was added in quantities of 2-8%. In conclusion, geopolymer can be used in place of cement to stabilize lateritic soil.

Trinh and Thi Bui [17] studied how the amount of clay and binder in soft soil treated with FA-based geopolymer affected the compressive strength of the soil. FA was used in the proportion of 5 to 20% of the dry weight of the soil, while activator/FA ratio was taken 0.5. The author concludes that the strength of geopolymer-soil is significantly influenced by the content of clay and geopolymer.

Cristelo et al.[18] examined the effects of cement and FA-based geopolymer to stabilize soft soil. A sandy clay soil with low plasticity was considered in the laboratory experiment. Fly ash was taken into account in the stabilization process at a ratio of 20, 30, and 40% to the total weight of solids. The authors conclude that FA-based geopolymers can be used as an alternative for stabilization.

3.2. GGBS (Slag)

Slag is a cementitious substance that is a byproduct of the iron-making blast furnaces, is mostly utilized in concrete. It mostly comprises silicate and aluminosilicates of melted calcium that had to be periodically removed from the blast furnace.

Miraki et al.[19] investigated the stabilization of clay soil using slag and alkali-activated volcanic ash. Numerous VA/GGBS and L/S ratios, curing times, and curing conditions were employed during the stabilization process. According to the authors, volcanic ash and slag that has been alkali activated significantly and favorably affect clay soils.

Sahoo and Singh [20] studied expansive soil's strength and durability properties stabilized with geopolymers and conventional stabilizers. The slag proportion was varied from 5 to 20% and activated by sodium hydroxide having different molarity. The researchers conclude that in comparison to traditional stabilizers, soil stabilized with geopolymers is stronger and more durable.

Fakhrabadi et al.[21] investigated the durability, physical properties, and microstructure of geopolymers synthesized from copper slag which stabilized clayey-sandy soil. The soil sample comprised 80% poorly graded sandy soil and 20% highly plastic clay soil (CH). The copper slag was used in the ratios of 0, 10, and 15 % of the dry weight of the soil, and the ratios of binder to the solution were 1:1. The authors indicated that copper slag effectively stabilized the clay-sand soil.

Noolu et al. [22] studied the slag-based geopolymer's strength and durability characteristics for stabilizing expansive soil. Slag was added to the soil in amounts of 10, 20, and 40% of the dry weight of the soil. The findings of the UCS test show that stabilizing black cotton soil with GGBS greatly enhances its strength properties.

Abdila et al.[23] analyzed mechanical properties of soil stabilized with FA and Slag based geopolymers. The treatment and untreated samples were subjected to chemical analysis (XRD) and morphology (SEM) testing. The researchers conducted numerous laboratory experiments to characterize the raw materials before the stabilization process began. It can be concluded that using slag and FA-based geopolymer for soil treatment has increased the soil's strength properties.

Yaghoubi et al. [3] studied how environments affected the geopolymer-based stabilized clay's strength characteristics. The silty clay soil with high plasticity was recovered from about 4 m and stabilized with slag and FA. The combined proportion of slag and FA varied from 10 to 30 % of the dry weight of the soil. The properties of the stabilized soil were investigated using UCS, SEM, and XRD tests. The authors draw that increasing the liquid/ (Fly ash + slag) ratio, mixing duration, and fly ash + slag ratio will enhance the unconfined compressive strength value.

3.3. Metakaolin

The mineral kaolinite, found in kaolin clay, makes metakaolin. Metakaolin decreases greenhouse gas emissions related to the production of Portland cement and is also used to replace 5 to 20 percent of the Portland cement in a mixture. Metakaolin is an aluminosilicate substance with various percentages of alumina (40–45%) and silica (50–55%) [21].

Noolu et al. [22] performed laboratory research on the microstructure, and mechanical characteristics of metakaolin-based geopolymer stabilized silty clay. Experimental tests, including UCS, SEM, and EDS were performed to study the characteristics of silty clay soil stabilized by metakaolin-based geopolymer. The findings revealed that metakaolin-based geopolymer effectively improves silty clay soil.

Samuel et al.[4] examined the volume change of expansive soil and strength enhancement utilizing geopolymer-based stabilizer. Metakaolin was used in ratios of 4, 10, and 15% by the dry weight of the soil. The result shows that both geopolymer-treated soils showed a considerable decrease in shrinkage and swelling and raising in UCS values after only seven days of curing.

Abdulkareem and Abbas [26] performed stabilization utilizing metakaolin-based geopolymer, with MK making up 8 to 14% of the dry weight of the soil. The sodium hydroxide to sodium silicate alkaline activator ratio was two, and the SEM testing apparatus was utilized to evaluate the improvement of treated samples. The authors revealed that the metakaolin-based geopolymers successfully stabilize the soft soil.

Wang et al. [27] conducted laboratory studies on geopolymer-stabilized soil's strength and material ratio performance. In the stabilization process, the appropriate mixing ratio of metakaolin was determined, and the strength performance of treated soil was examined. The metakaolin ratio added to the soil was varied from 6 to 12% of the dry weight of the soil and that of the activators were varied from 3-11%. According to laboratory findings, the quantities of alkali activator and Mk enhance the geopolymer-improved soil's unconfined compression strength at first, afterward decreasing.

Khadka et al.[28] carried out research on the strength and swell/shrink behavior of geopolymer stabilized highly plastic clay. To determine the fundamental characteristics, the laboratory analysis of the high plasticity clay (CH) was done using various laboratory experiments. A proportion of 3 to 15% of the dry weight of the soil sample was used to prepare the stabilized sample. The authors verified that one-dimensional swell tests showed that FA geopolymer-treated materials significantly reduced swell behavior, whereas MK-treated soil showed negligible improvement in swell behavior.

Zhang et al.[29] studies on the stabilization of sulfate-rich soils using calcium-free geopolymers. To evaluate the mechanical strength and swelling potential, a metakaolin with a ratio of 8 and 13% of the dry weight of the soil was utilized. The clay soil was additionally stabilized with cement and lime. SEM, XRD, and EDX tests were conducted after unconfined compression and swelling tests to evaluate the microstructure and mineralogical composition of the stabilized soil. The results indicate that geopolymers without calcium are suitable stabilizers for sulfate-rich soils.

3.4. Other Industrial Wastes

To stabilize soft soils, industrial wastes, including glass powder, olivine, and sewage sludge-based geopolymers, were utilized.

Ashiq et al.[30] conducted research to determine how industrial waste glass powder could enhance the Siwalik clay soil's engineering characteristics. The IWGP varies from 5 to 20 % to the dry weight of the soil for the determination of different engineering properties of the soil. The remolded samples and stabilized samples were prepared at OMC and MDD. The authors conclude that adding IWGP improves the unconfined compressive strength and CBR values.

Baldovino and Rose [31] examine soil stabilization based on recycled glass powder geopolymers. The authors analyzed the effects of adding GP in three different weight-based amounts 5%, 15%, and 30% on the durability and split tensile strength (qt) against wet-dry cycles. By dry weight of the soil, the proportions of GP were 5, 15, and 30%, while those of cement were 3, 6, and 9%. The findings demonstrated that GP is an eco-friendly binder that improves the mechanical properties of poor soils.

Dheyab et al.[32] studied geopolymer-based soil stabilization for economical and environmentally friendly projects. The morphology and mineralogical makeup of the treated soil samples were better characterized using SEM and XRD examinations, respectively. The olivine stabilization was utilized at 30% of the dry weight of the soil sample, while the molarities of the NaOH alkali activator were 4, 6, 8, 10, and 12. The authors proved that olivine-treated soils significantly improve and can replace the use of traditional soil stabilizers.

Harichane et al.[33] conducted stabilization of cohesive soil using natural pozzolana and lime. Two clayey samples classified as CH and CL were collected for the experimental tests from the depth of 4 and 5 m, respectively. Experimental studies on unconfined compressive strength, shear strength, compaction, and Atterberg limits were carried out following the examination of the mineralogical content of the soil and stabilizers. The outcome revealed that adding lime increases unconfined compressive strength, which is further improved when lime and natural pozzonana were combined. In contrast to naturally pozzolana stabilized soils, the maximum dry density of lime-stabilized soils decreases with increasing lime content. Furthermore, the plasticity index declines while the lime content increases.

Chen and Lin [34] conducted sewage sludge ash and cement stabilization of soft subgrade soil. Experiments were conducted on the triaxial compression test, UCS, CBR, pH values, Atterberg limits, and compaction test for the ISSA/cement soil specimens. The 4:1 fixed ratio of cement to ISSA was used to manufacture the additive. Then, a mixture of 0, 2, 4, 8, and 16% (by weight) was chosen for mixing with cohesive soil. According to the authors, the soft subgrade soil is efficiently improved, and its plasticity index decreases.

From Table 1 below, soft cohesive soils were stabilized with different types of geopolymers. As observed, sodium hydroxide and sodium silicate were commonly used to synthesize geopolymers. The molarity of sodium hydroxide ranges from 8 to 14 in most of the studies. Fig.1 shows the comparison of UCS values at 28 days curing time by several researchers.

Table 1. Summary of soil types, binders, alkali activators, and UCS values

References	Soil Type	Binder Type	Alkali activators(L)	L/B	NaOH Molar	Experiments	UCS Value@28days
[9]	Soft Bangkok Clay(CH)	Fly ash(F) Cement	NS/NH (50:50,70:30, 80:20)	0.6	8	UCS,SEM	4312kpa
[11]	Clay(CH)	Coal Fired Fly ash(C)	NS/NH(2)	0.4,0.6,0.8	10	UCS, SEM Durability	6.4Mpa
[12]	Expansive soil	Fly ash Cement	NS, NH	0.5,0.75,1	8,10,12	UCS	0.332Mpa
[10]	Clay(CH)	GGBFS,Fly ash(F)	NS/NH (2.33)	0.5,0.75,1	14	UCS, SEM Durability	1800kpa
[13]	Soil 1(CH) Soil 2(CL)	Palm Oil Fuel Ash (POFA)	NS/NH(2.5)	0.75	12	UCS, Direct Shear Test	4.18Mpa
[15]	Kaolin clay	Fly ash (F) and slag	NS/NH(70:30)	-	14	UCS, SEM Durability	8260kpa
[7]	Soft marine clay	Fly ash and slag	NS/NH(70:30)	1	8	UCS, flexural beam, SEM	1.034 MPa
[16]	Lateritic soil	Fly ash	NS/NH(1:1)	-	8	UCS	1716kpa
[17]	Clay, sand	Fly ash	NS/NH(2)	0.5	12	UCS	1.8Mpa
[19]	Clay(CL)	Volcanic ash, GGBS	NH	0.18,0.22,0.26	6	UCS,SEM	8.45Mpa
[20]	Expansive soil	GGBS	NH	-	2,6,8	UCS,SEM, Durability	-
[21]	Clayey - sand	Copper slag	NS/NH(70:30)	1	0,2,4,8, 11,15	UCS, SEM, Durability	1400kpa
[22]	Expansive soil(CH)	GGBS	NH	-	3,8,11	UCS Durability	-
[23]	Clay(CH)	Fly ash, GGBS	NS/NH(2)	0.3,0.4,0.5,0.6,1	10	UCS, SEM	-
[24]	Silty clay(CL)	Metakaolin	NS, NH	-	-	UCS, SEM	7Mpa
[26]	Soft soil	Metakaolin	NS/NH(0.5)	-	10	UCS, SEM	5.6Mpa
[27]		Metakaolin	CaO, $NaHCO_3$(1:1)		-	UCS, SEM	-

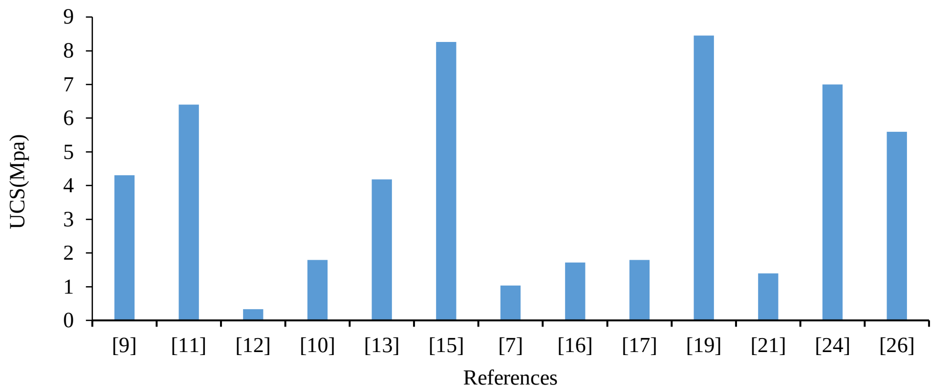

Fig. 1. UCS values at 28 days of curing time by various researchers

4. Conclusion

This study examines the stabilization of soft soils using geopolymers derived from industrial wastes. Fly ash, metakaolin, ground granulated blast furnace slag, and other industrial wastes were used to synthesize geopolymers. This research provides a critical evaluation of the literature on the use of geopolymers as a more environmentally friendly alternative binder for soil stabilization. The strength, microstructure and durability tests were conducted on the fly ash based geopolymers. The fly ash ratio ranged from 5 to 30 percent of the dry weight of the soil, while NaOH and Na_2SiO_3 were the two most often utilized alkali activators. The research revealed that improved samples had greater unconfined compressive strength and durability. The slag-based geopolymers stabilized expansive soils and soft clay soils. The slag was used in the range of 5 to 30 percent of the dry weight of the soil. Unconfined compressive strength tests, SEM, and XRD testing were used to study the stabilized soils. The slag-based geopolymers improved the unconfined compressive strength values and helped raise the black cotton soils' strength properties. Metakaolin-based geopolymers were used to stabilize expansive soils and weak soils. SEM, EDS, and UCS experiments were carried out to investigate the improvement of treated soils, which have a metakaolin ratio that varies from 4 to 20% of the dry weight of the soil. The enhanced unconfined compressive strength of the treated soils and reduced expansive soils' swelling and shrinkage are also evident.

References

[1] C. Phetchuay, S. Horpibulsuk, A. Arulrajah, C. Suksiripattanapong, and A. Udomchai, "Strength development in soft marine clay stabilized by fly ash and calcium carbide residue based geopolymer," *Appl. Clay Sci.*, vol. 127–128, pp. 134–142, 2016, doi: 10.1016/j.clay.2016.04.005.

[2] A. Arulrajah, T. Kua, C. Suksiripattanapong, and S. Horpibulsuk, "Stiffness and strength properties of spent coffee grounds-recycled glass geopolymers," *Road Mater. Pavement Des.*, vol. 0, no. 0, pp. 1–16, 2017, doi: 10.1080/14680629.2017.1408483.

[3] M. Yaghoubi, A. Arulrajah, M. Miri, S. Horpibulsuk, S. Darmawan, and J. Wang, "Impact of field conditions on the strength development of a geopolymer stabilized marine clay," *Appl. Clay Sci.*, no. June, pp. 1–10, 2018, doi: 10.1016/j.clay.2018.10.005.

[4] R. Samuel, A. J. Puppala, A. Banerjee, O. Huang, M. Radovic, and S. Chakraborty, "Improvement of Strength and Volume-Change Properties of Expansive Clays with Geopolymer Treatment," 2021, doi: 10.1177/03611981211001842.

[5] R. Samuel, A. J. Puppala, and M. Radovic, "Sustainability Benefits Assessment of Metakaolin-Based Geopolymer Treatment of High Plasticity Clay," pp. 1–14, 2020.

[6] J. Han, "Principles and Practices of Ground Improvement," New Jersey, 2015.

[7] A. Arulrajah, M. Yaghoubi, M. Miri, S. Horpibulsuk, M. Win, and M. Leong, "Evaluation of fly ash- and slag-based geopolymers for the improvement of a soft marine clay by deep soil mixing," *Soils Found.*, vol. 58, no. 6, pp. 1358–1370, 2018, doi: 10.1016/j.sandf.2018.07.005.

[8] M. Nodehi and V. M. Taghvaee, "Alkali-Activated Materials and Geopolymer: a Review of Common Precursors and Activators Addressing Circular Economy," *Circ. Econ. Sustain.*, vol. 2, no. 1, pp. 165–196, 2022, doi: 10.1007/s43615-021-00029-w.

[9] C. Suksiripattanapong, R. Sakdinakorn, S. Tiyasangthong, N. Wonglakorn, C. Phetchuay, and W. Tabyang, "Properties of soft Bangkok clay stabilized with cement and fly ash geopolymer for deep mixing application," *Case Stud. Constr. Mater.*, vol. 16, no. November 2021, p. e01081, 2022, doi: 10.1016/j.cscm.2022.e01081.

[10] H. H. Abdullah and M. A. Shahin, "Geomechanical Behaviour of Clay Stabilised with Fly-Ash-Based Geopolymer for Deep Mixing," *Geosciences*, 2022, doi: https://doi.org/10.3390/geosciences12050207.

[11] N. A. Odeh and A. H. J. Al-rkaby, "Strength , Durability , and Microstructures characterization of sustainable geopolymer improved clayey soil," *Case Stud. Constr. Mater.*, vol. 16, no. November 2021, p. e00988, 2022, doi: 10.1016/j.cscm.2022.e00988.

[12] R. Santhikala, K. Chandramouli, and N. Pannirselvam, "Stabilization of expansive soil using flyash based geopolymer," *Mater. Today Proc.*, vol. 68, pp. 110–114, 2022, doi: 10.1016/j.matpr.2022.07.006.

[13] I. A. Khasib, N. N. Nik Daud, and N. A. Mohd Nasir, "Strength Development and Microstructural Behavior of Soils Stabilized with Palm Oil Fuel Ash (POFA)-Based Geopolymer," 2021.

[14] J. M. Abbas, A. M. Ibrahim, and A. M. Shihab, "Investigation to some preliminary geotechnical properties of soft clay stabilized by fly ash based geopolymers," *Key Eng. Mater.*, vol. 857 KEM, pp. 259–265, 2020, doi: 10.4028/www.scientific.net/KEM.857.259.

[15] H. H. Abdullah, M. A. Shahin, and P. Sarker, "Use of Fly-Ash Geopolymer Incorporating Ground Granulated Slag for Stabilisation of Kaolin Clay Cured at Ambient Temperature," *Geotech. Geol. Eng.*, vol. 37, no. 2, pp. 721–740, 2019, doi: 10.1007/s10706-018-0644-2.

[16] C. Ridtirud, S. Leekongbub, and P. Chindaprasirt, "COMPRESSIVE STRENGTH OF SOIL CEMENT BASE MIXED WITH FLY ASH – BASED GEOPOLYMER," vol. 14, no. 46, 2018.

[17] S. H. Trinh and Q. anh Thi Bui, "Influencing of Clay and Binder Content on Compression Strength of Soft Soil Stabilized by Geopolymer Based Fly Ash," vol. 13, no. 10, pp. 7954–7958, 2018.

[18] N. Cristelo, S. Glendinning, L. Fernandes, and A. T. Pinto, "Effects of alkaline-activated fly ash and Portland cement on soft soil stabilisation," pp. 395–405, 2013, doi: 10.1007/s11440-012-0200-9.

[19] H. Miraki, N. Shariatmadari, P. Ghadir, S. Jahandari, and Z. Tao, "Clayey soil stabilization using alkali-activated volcanic ash and slag," *J. Rock Mech. Geotech. Eng.*, vol. 14, no. 2, pp. 576–591, 2022, doi: 10.1016/j.jrmge.2021.08.012.

[20] S. Sahoo and S. P. Singh, "Strength and durability properties of expansive soil treated with geopolymer and conventional stabilizers," *Constr. Build. Mater.*, vol. 328, no. January, p. 127078, 2022, doi: 10.1016/j.conbuildmat.2022.127078.

[21] A. Fakhrabadi, M. Ghadakpour, A. J. Choobbasti, and S. S. Kutanaei, "Evaluating the durability , microstructure and mechanical properties of a clayey-sandy soil stabilized with copper slag-based geopolymer against wetting-drying cycles," *Bull. Eng. Geol. Environ.*, pp. 5031–5051, 2021, doi: https://doi.org/10.1007/s10064-021-02228-z.

[22] V. Noolu, M. R. G, sudheer K. Reddy B, and R. V. Prasad Chavali, "Strength and durability characteristics of GGBS geopolymer stabilized black cotton soil," *Mater. Today Proc.*, vol. 43, pp. 2373–2376, 2021, doi: https://doi.org/10.1016/j.matpr.2021.01.939.

[23] S. R. Abdila *et al.*, "Evaluation on the Mechanical Properties of Ground Granulated Blast Slag (GGBS) and Fly Ash Stabilized Soil via," *Materials (Basel).*, pp. 1–19, 2021, doi: https://doi.org/10.3390/ma14112833.

[24] Y. Luo, J. Meng, D. Wang, L. Jiao, and G. Xue, "Experimental study on mechanical properties and microstructure of metakaolin based geopolymer stabilized silty clay," *Constr. Build. Mater.*, vol. 316, p. 125662, Jan. 2022, doi: 10.1016/J.CONBUILDMAT.2021.125662.

[25] Y. Luo, J. Meng, D. Wang, L. Jiao, and G. Xue, "Experimental study on mechanical properties and microstructure of metakaolin based geopolymer stabilized silty clay," *Constr. Build. Mater.*, vol. 316, no. November 2021, p. 125662, 2022, doi: 10.1016/j.conbuildmat.2021.125662.

[26] S. O. Abdulkareem and J. M. Abbas, "Effect of Adding Metakaolin Based Geopolymer to Improve Soft Clay under Different Conditions," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 856, no. 1, 2021, doi: 10.1088/1755-1315/856/1/012011.

[27] S. Wang, Q. Xue, Y. Zhu, G. Li, Z. Wu, and K. Zhao, "Experimental study on material ratio and strength performance of geopolymer-improved soil," *Constr. Build. Mater.*, no. xxxx, p. 120469, 2020, doi: 10.1016/j.conbuildmat.2020.120469.
[28] S. D. Khadka, P. W. Jayawickrama, and S. Senadheera, "Strength and Shrink / Swell Behavior of Highly Plastic Clay Treated with Geopolymer," pp. 1–11, 2018, doi: 10.1177/0361198118797214.
[29] M. Zhang, M. Zhao, G. Zhang, P. Nowak, A. Coen, and M. Tao, "Calcium-free geopolymer as a stabilizer for sulfate-rich soils," *Appl. Clay Sci.*, vol. 108, pp. 199–207, 2015, doi: 10.1016/j.clay.2015.02.029.
[30] S. Z. Ashiq, A. Akbar, K. Farooq, and H. Mujtaba, "Sustainable improvement in engineering behavior of Siwalik Clay using industrial waste glass powder as additive," *Case Stud. Constr. Mater.*, vol. 16, no. January, p. e00883, 2022, doi: 10.1016/j.cscm.2022.e00883.
[31] A. Baldovino and J. L. Rose, "Geopolymers Based on Recycled Glass Powder for Soil Stabilization," *Geotech Geol Eng*, vol. 0123456789, pp. 4013–4031, 2020, doi: 10.1007/s10706-020-01274-w.
[32] W. Dheyab, Z. T. Ismael, M. A. Hussein, and B. Bin Kim Huat, "SOIL STABILIZATION WITH GEOPOLYMERS FOR LOW COST AND ENVIRONMENTALLY FRIENDLY CONSTRUCTION," vol. 17, no. 63, pp. 271–280, 2019.
[33] K. Harichane, M. Ghrici, S. Kenai, and K. Grine, "Use of Natural Pozzolana and Lime for Stabilization of Cohesive Soils," *Geotech. Geol. Eng.*, vol. 29, no. 5, pp. 759–769, 2011, doi: 10.1007/s10706-011-9415-z.
[34] L. Chen and D. F. Lin, "Stabilization treatment of soft subgrade soil by sewage sludge ash and cement," *J. Hazard. Mater.*, vol. 162, no. 1, pp. 321–327, 2009, doi: 10.1016/j.jhazmat.2008.05.060.

Authors' Profiles

Tadesse A. Wassie was graduated his BSc degree in Water Resource Engineering from Bahir Dar University, Amhara, Ethiopia. He was also graduated M.Sc. in Geotechnical Engineering from Addis Ababa institute of Technology, Addis Ababa University ,Addis Ababa, Ethiopia. Currently, he is a Ph.D. student in the department of Civil Engineering, Institute of Graduate Studies, Ondokuz Mayis University, Samsun, Türkiye. His research interest in Ground Improvement, Foundation Engineering, soil Mechanics, Slope stability, and Infrastructure on problematic soils and rocks.

Dr. Gökhan Demir was graduated his BSc degree in Civil Engineering from Atatürk University, Türkiye. He was also graduated both his M.Sc. and Doctorate degree in Civil Engineering from Karadeniz Technical University, Türkiye. Currently working as an Associate Professor in the Department of Civil Engineering, Faculty of Engineering, Ondokuz Mayis University, Samsun, Türkiye. His research interest in Ground Improvement, Foundation Engineering, soil Mechanics, Slope stability, and Infrastructure on problematic soils and rocks

How to cite this paper: Tadesse A. Wassie, Gökhan Demir, "A Review on Stabilization of Soft Soils with Geopolymerization of Industrial Wastes", International Journal of Engineering and Manufacturing (IJEM), Vol.13, No.2, pp. 1-8, 2023. DOI:10.5815/ijem.2023.02.01