



Research Article

Stabilisation of expansive soil by geo-polymerisation of industrial wastes - Fly ash

Aishwarya GAYATRI^{1,*}, P K PRADHAN², P K PARHI³

¹Department of Civil Engineering, Odisha University of Technology and Research Bhubaneswar, Odisha, 751029, India

²Retired, Department of Civil Engineering, Veer Surendra Sai University of Technology, Burla, Odisha, 768018, India

³Department of Civil Engineering, Institute of Technical Education and Research (ITER), Siksha 'O' Anusandhan (SOA) University, Bhubaneswar, Odisha, 751030, India

ARTICLE INFO

Article history

Received: 06 May 2025

Revised: 01 July 2025

Accepted: 19 August 2025

Keywords:

Alkali-Activated Fly Ash;
Expansive Soil; Stabilisation; Un-
Confined Compressive Strength

ABSTRACT

Due to their tendency to cause structural damage such as fractures and foundation failure, expansive soils, which have high volume changes with changing moisture levels, are a serious concern for civil engineers. This research examines fly ash, an industrial waste, as a replacement binder for conventional cementations resources in the field of sustainable soil stabilization. Class F fly ash of various Li/S ratios and NaOH concentrations (10, 12.5, and 15M) and Na₂SiO₃ concentrations were used to treat an expansive clay (Bhubaneswar, India). The resulting unconfined compressive strengths of 81 mixtures were tested after 3, 7, and 28 days of curing. The optimized mixture (4.8 MPa after 28 days curing, more than two times that of the untreated soil) showed uncfs increases with curing time and was optimized with a 12.5M NaOH concentration and 1.25 Li/S ration, before over-activation effects decreased the strength. Confocusing on recycling cost-effective, sustainable geopolymers like fly ash will ultimately reduce the construction industry's effects on the environment, because of its reduction in costs and carbon emissions relative to lime or cement, as shown by economic and environmental analyses and microstructural examinations respectively. This study provides an economically viable, green solution for problematic soils through systematically optimizing the parameters of geo-polymerization in expansive soil stabilization. It also presents quantitative evidence for the utilization of binders from industrial waste in geotechnical applications.

Cite this article as: Gayatri A, Pradhan PK, Parhi PK. Stabilisation of expansive soil by geo-polymerisation of industrial wastes - Fly ash. Sigma J Eng Nat Sci 2026;44(4):2415–2432.

INTRODUCTION

Background of the Study

Expansive soil (ES), often known as swelling soil, describes to soils that undergo significant volume changes. Considerably so when the moisture content varies. Clay and

other minerals that captivate water and enlarge are found in expansive soil. However, in dry conditions, soil will contract or shrink. A significant risk factor for construction projects is the characteristics of ES soils. According to [1], these kinds of soils can be found in both arid and semi-arid regions of the planet. The Deccan lava tract (Deccan

*Corresponding author.

*E-mail address: aishwaryagayatri24@gmail.com

This paper was recommended for publication in revised form by
Editor-in-Chief Ahmet Selim Dalkilic



Trap), which includes portions of Andhra Pradesh, Madhya Pradesh, Maharashtra, Odisha, and Gujarat within the sub-continent, is also home to expansive soil (ES) soils. The valleys of the Tapi, Krishna Godavari, and Narmada rivers also have expansive soils. Deep black soil covers the western portion of the Deccan Plateau in the catchment areas of the Godavari and Krishna rivers. Rock formations like basalt and traps weather to produce this kind of soil. These soils are rich in lime, magnesia, alumina, and iron, according to studies. However, they are deficient in phosphorus, organic matter, and nitrogen. The mainstream of the clay minerals found are Montmorillonite, which has several singular qualities. For example, the soil's color varies from chestnut brown to black. Additionally, a particularly high percentage of clay is frequently found in expansive soil. Bentonite soil is known for very high development and it is also highly dispersive. In the situation of ES, free swelling ranges from ten to fifteen times greater than the actual volume.

Every year, damage to pipelines, roads, buildings and structures due to ES is very large compared to damage caused by hurricanes, tornadoes, earthquakes and flood combinations. However, the vulnerabilities associated with ES, such as low strength in construction, increase over time and occasionally cause life-threatening damage (Vinod, Fayaz, Vismaya, & Kumar, 2022) [2]. ESs have severe impacts on the world economy and still have gained very limited attention. Maximum of the damage and losses caused by ES are not due to an absence of suitable engineering solutions but rather to the non-recognition of swelling soils (Fig. 1).

The stabilisation of soil is a procedure applied to increase the engineering properties of the soil, increasing its suitability and stability for construction [3]. Some common methods include mechanical, chemical, electrochemical and geo-synthetic stabilisation (She, Lu, Duan, Yao, & Liu, 2020). Major stabilisation methods can be categorised

into chemical and physical techniques (F. Zhang, Zhang, & Hong, 2019). Physical methods refer to using physical mechanisms to manipulate the soil's nature for better results. This can be achieved through the processes of compaction and drainage system [4]. Compaction can be done in a number of ways like compaction, vibro-compaction, and rolling to increase strength and density of the soil. Drainage is an effective method of removing excess water in the soil through the use of channels, pipes, and pumps so that the soil does not swell or shrink due to the water. Then again, compaction results in increased water resistance of the soil. Chemical additives refer to cement, fly ash (FA) and lime that are mixed with the soil to alter its inherent characteristics [5]. The additives chemically interact with soil particles to increase their cohesion and stability while the soil's plasticity is reduced.

Currently, geopolymer technology type is the most prevailing and widely accepted technology among the many other conventional ones. A geopolymer is First and foremost made up of ceramic, inorganic, or alumina silicate material capable of forming long-lasting, non-crystalline, and covalently bonded connections [6]. Basically, geopolymer is the product of the joint reactions of SiO_2 and Al_2O_3 polymerization calls for high rate of chemical reaction of silicon-alumina mineral structure under alkaline conditions [7, 8]. Minerals result in 3D polymeric chains and a ring structure with Si-O-Al-O bonds (Z. Zhang, Wang, & Provis, 2012). Geopolymer binding agents have exceptional durability and mechanical/physical characteristics. Such characteristics may be acquired through the application of secondary materials (IW, for example slag or FA) [9]. Geopolymetisation of industrial waste such as FA consists of the transformation of FA, which is an output product of burning coal in power plants, into a geopolymer agent. Extracting geopolymers from waste materials will not only be an effective way of solving the issues related



Figure 1. Shrink-swell soil (ES).

to the accumulation of wastes and the use of raw materials but also will be a step forward towards the environment. Geopolymers owing to their unique properties have a potential to lessen the release of CO_2 to the atmosphere (Syed, GuhaRay, Avinash, & Kar, 2020).

Industrial solid waste's natural pozzolanic feature makes these solids viable geopolymers for soil stabilization [10]. One of the primary causes of important environmental degradation that needs management is the unregulated generation and disposal of industrial waste (IW). To address the issue, new technologies are being employed in a more creative manner to locate the IWs. Chemical stabilization that eliminates both the hard soil matrix and the soil that is not dissolved in water is the highly efficient. Polymer stabilization has many advantages over chemical and physical stabilization.

. This model comprises N-A-S-H and (N, C)-A-S-H models. Low-calcium precursors such as Class F fly ash are frequently employed in the alkali-activation systems to form the N-A-S-H (sodium aluminosilicate hydrate) gel. Because of the occurrence of sodium ions, which serve as charge balancers, this polymer makes up a three-dimensional structure composed of silicon-aluminum tetrahedra. This material can be used effectively to stabilize expansive soils because of its excellent chemical stability and water resistance. Conversely, inclusion of calcium-containing materials, such as Class C fly ash or slag, creates the (N,C)-A-S-H (sodium/calcium aluminosilicate hydrate) gel. Calcium ions cause both the calcium-based and sodium-based binding phases to be present together, which can enhance water stability and accelerate setting and early strength. It is necessary to make a differentiation between these types of gels as it will enable geopolymer mixtures to be specifically designed for the chemistry of the industrial waste used and soil mineralogy. It can be said that the formation of N-A-S-H gel in the present study can be made possible by using Class F fly ash and sodium activators and thereby, increase the long-term durability and strength of stabilized expansive soils.

In this study, geopolymers composed only of industrial solid wastes, including alkali-activated fly ash (AAFA), have been used to stabilize expansive soils [11]. Extending on existing research, this research attempts to optimize mix design to increase the UCS at different curing times (CT), through different mix design of NaOH and Na_2SiO_3 activator concentrations. In contrast to other research efforts, the present research makes a complete geotechnical and chemical characterization of fly ash and comparing effectiveness of AAFA and conventional cement-based stabilizers [12]. In this study, valuable information is provided for the industry through microstructural analysis and the mention of benefits both economical and environmental [13, 14]. Considering the engineering problems faced across the globe by expansive soils, whose expansion and contraction as a result of water content affects infrastructures

adversely, this becomes very relevant. Not only does it satisfy the current need for cost-effective, waste-utilization methods for regions where there is excess industrial waste material, but it also demonstrates the superiority of geopolymer stabilization methods over traditional ones.

The objectives of the research study are as follows:

- Overview of the destruction caused by the ES.
- To evaluate the alternative cementitious material for the stabilisation of ES.
- To assess the ability of AAFA to stabilise ES in the region.
- To analyse the GT properties and chemical properties of FA.
- To assess the compressive strength of the ES FA mixture.
- To recommend cost-effective AAFA for the stabilisation of ES to achieve a sustainable environment.

The research questions are as follows:

- 1) What is the destruction caused by the ES in construction?
- 2) How can ES be stabilised via AAFA?
- 3) How do the GT and chemical properties of FA influence the compressive strength of ES FA mixtures?

Despite numerous studies on FA stabilization of soils, supreme previous research has attentive on a limited number of mix proportions or has examined the effects of FA and activator concentrations in isolation, often using fewer than 20 combinations and rarely exploring the full interaction between multiple variables. The rationale behind the test of 81 unique mixture combinations in the current research is to conduct a systematic analysis on the influence of NaOH concentration, FA content, and activator/ash ratio on geotechnical characteristics of expansive soil. It is evident that such an extensive experimental design addresses a very important research issue by allowing for establishing optimum mix parameters and obtaining an extensive set of data related to their synergic impact, which is not covered in any previous studies. The novelty of such a study is due to its complexity.

The paper is organized: Section 1 introduces and thoroughly explains the stabilisation of ES through the geopolymerisation of IW FA. It also outlines the significance of the research. Section 2 then looks over the literature relevant to this study. The study Materials and Methods are described in Section 3. In Section 4, there is a detailed discussion of the results, and recommendations for further research are also provided.

Literature Review

There is an inherent probability of ES causing serious challenges and problems in engineering due to its attributes (Zada et al., 2023). Previous research on the challenges caused by ES performance was highlighted in [15]. The method frequently exhibits shrink-swell features. In actuality, this method, which modifies the natural characteristics of soil, cannot replicate the natural world. The act of converting a natural soil into a building material is called

soil stabilization. From an engineering perspective, stability using processes and additions has historically improved the inherent qualities of soil. Chemical, microstructural, economic, and waste material reuse aspects were all covered by these advancements. The soil stabilization procedure was altered by standardization, geoenvironmental consideration, and stabilization progression optimization. Exploratory methods and predictive models were considered components of the soil stabilization process. To adequately stabilize natural soils, surface optimization, design optimization, and optimization techniques of all dimensions were employed. This evolution enabled to optimize pre and post construction operations to protect ESs from damages.

Fibers used to increase the strength of the soil is one of the aspects of mechanical soil stabilization. On the other hand, chemical soil stabilization involves adding different kinds of chemical compounds such as lime and cement into the soil [16,17]. In addition, the effects of the use of natural fiber and recycled ash on the strength and durability of engineered soils were investigated in an original research paper. Soil stabilization is usually a result of adding chemical compounds. Bottom ash and natural fibre have been cited in literature as materials that play an important role in achieving soil stabilization. These two materials are also used as reinforcements against tensile cracks in the soil. Hence, the mechanical, chemical, and swelling properties of soil stabilization by engineered soil (ES) will first be examined. Stabilization of engineered soil (ES) with bottom ash percentages of 5%, 10%, 15%, and 20% has been well documented. The natural fibre reinforcements to be used for ES stabilization include 0.25%, 0.50%, and 1.00% of coir fibers. The CT period is 28 days.

This study has evaluated the durability of stabilised soil through the mechanical and chemical properties before and after the 2nd, 4th, 6th, 8th, and 10th days of freeze-thaw cycle test (FTC). Stabilisation of the ES using BA decreases the swelling pressure and controls the plastic behaviour. The increase in the quantity of BA exponentially results in the increase of electrical conductivity, pH, and calcite content of the ES soil. It also increases tensile strength and compressive strength of the soil. CF-reinforced specimen had very small mechanical strength losses during the FTC. It also had relatively higher tensile strength. Proposed mechanisms of BA and CF to stabilise ES are discussed. It has decided that both the BA and CF stabilise ES efficiently, and they can be used for road pavements.

The reason behind glass being non-biodegradable is its inert property, and glass powder produces more friction compared to clay [18]. The prevailing study [19] presents a new method of using waste glass powder (WGP) to enhance the ES. In this case, ES is expandable, meaning that it will reduce its strength when wetted or shrunk. This results in volume change. In this study, ES used in the construction industry creates problems all over the world. These problems affect civil engineering projects such as embankments,

railways, highways and roadways. To strengthen ES, one must use other materials such as WGP. They were ground and incorporated into the soil samples in various percentages, including 2.5, 5, 10, 15 and 25%, based on the dry weight of the soil. Various tests were performed on treated and untreated ES with different percentages of WGP. Moreover, they include free swelling, compaction, Atterberg limits, and California-Bearing Ratio. The results of the tests show that the presence of WGP in the ES improves the consistency and shear strength of the soil sample. Furthermore, adding fifteen percent of WGP reduces the thickness of the sub-base to sixty-three percent.

A conventional study (Vijayan & Parthiban, 2020) explained the use of solid waste in ES as a stabilizing material to reinforce ES. They possess common characteristics such as unexpected shrinkage and swelling, high compressibility, weak transfer system, and low permeability. The rate of failure mechanism such as the failure of subgrade and excess settlement rate is quite fast. ES is more susceptible to such characteristics compared to other soils. It becomes hard to build up infrastructures with these kinds of soil by civil engineers. The technological advancement of the current world leads to effluents that cannot be controlled. Production and removal of solid waste become critical issues in every nation. The industries producing construction materials become highly involved in solid wastes. Several studies have been undertaken in order to produce novel construction materials at a large scale. Prevailing studies tried to evaluate different forms of solid waste to stabilize soils. Presence or absence of lime in the stabilization process will create room for utilization of solid waste for GT purposes.

A prevailing study [20] explained the use of calcium-based stabilizers (CSMs) for stabilizing ES. The properties of CSMs have been thoroughly discussed. They are capable of improving various soil properties by triggering carbonation, cationic exchange, flocculation, and hydration. Incorporating CSMs in soil stabilization for construction has its pros and cons. The physical and chemical transformations of soils have been elucidated in detail. Using X-ray fluorescence technology the impact of adding CSMs to soils has been investigated. SEM images have shown that chemical reactions at a microscopic level are occurring between CSMs and soils. Because, it is recommended to use CSMs in GT construction projects by ES.

Per authors, lime is an excellent stabilizer for ES, which can also be mixed with the FA waste material for stabilizing soils and enhancing their properties [21]. Besides, as an old method, FA and lime can be combined for soil stabilization resulting in pollution free and sustainable environment [22]. ES soils have fragile physical properties that not only create difficulties in the handling and disposal of these soils but also present a range of challenges. Some of the physical properties that influence the handling and disposal of soils include their shrinkability, swellability, and the bearing capacity of the soil.

These are some of the factors that cause shrink-swell behavior of soil, So making it unsuitable for construction. Engineering properties can be enhanced through both physical and chemical processes. The process makes it feasible to use the soil for construction purposes. Mixing is usually used to improve the properties of soil. Research was conducted on the individual as well as blended mixtures such as FA and lime. It focused on evaluating the GT properties of ES. Different proportions of lime and FA were added to find the best proportion to stabilise ES. The results showed that FA and lime reduced plasticity and liquid limit, swell index and increased the dry weight and strength of soil-admixture. The flocculated structure with pores was found in the soil and was responsible for decreasing moisture contents and plasticity index. There was an increase in dry weight resulting in higher soil-admixture strength than ES.

The research by (Baldovino et al., 2021) and others focused on glass powder waste as a geopolymer material for soil stabilization. They wanted to reduce landfill waste and move away from regular binders such as cement and lime. Different levels of GP were tested at 5 percent 15 percent and 30 percent along with a set amount of 5 percent lime. This was to check the effects on how strong the compacted soil became. Results showed better mechanical properties and improved microstructure as the glass powder increased. Performance was linked to a new volumetric binder index. It seems this points to good long term uses for glass waste in stabilization efforts. After seven days the mixes did not reach subbase levels yet after ninety days they were all suitable for earthwork. Some of the strength gains felt more noticeable at higher GP amounts but I am not totally sure how that lines up with every mixture tested.

In connection with the development of eco-friendly, mechanochemically activated geopolymeric stabilizers and comparison of them with traditionally activated ones, the authors of , [23] have achieved great success in the field of soil stabilization process. In addition, their work examines the effect of different GGBS contents on the mechanical and durability properties of soil stabilization process, particularly on sulfate corrosion resistance. As compared to CAG samples, MAG samples revealed better resistance to magnesium sulfate corrosion and higher UCS, by 12–45%. Moreover, such soils have managed to retain up to 93% of their strength under the influence of sulfate solutions over the period of 60 days, taking into consideration mass loss, ultrasonic pulse velocity, and FTIR spectroscopy tests. The conclusion is that mechanochemical activation, as well as an increase in the quantity of GGBS, increases the sulfate resistance and UCS of geopolymer binders that allow using the stabilized soil in severe conditions.

Significance of accounting for the influence of Fluid Structure Interaction has been emphasized in terms of earthquakes due to recent improvements in understanding of seismic behavior of fluid storage tanks. In order to examine the influence of earthquakes on fluid storage tanks, [24] applied finite element analysis, proving itself very useful in

modeling of reservoirs. Taking into account variations in physical parameters and fill factors, the influence of two-way coupling of the structure and the contents of reservoir has been considered. It should be mentioned that contrary to assumptions about designing of reservoirs, the highest influence of seismic activity was noticed not in case of 100 percent fill factor, but in terms of partial fill factor. Also, seismic retrofitting has been recognized as being critical both for partial and full fill factors, especially when water level is 10 percent below the height of reservoir.

However, adequate investigation work on the use of AAFA stabilized with industrial wastes is yet to be done despite the numerous studies done on the stabilization of expansive soil using different chemical and industrial waste amendments. This has been mainly due to the fact that variation has been made in the dosage level of the activator and the proportion of FA used. In addition, there is yet no adequate comparative work carried out on the performance of geopolymers vis-a-vis conventional binders such as cement or lime.

Research Gap

As has been observed previously, due to the swelling and shrinkage characteristics of the soil in case of ES, a process of stabilization is necessary and as a consequence, chemical stabilization with the use of FA, lime, and cement will improve the performance of ES. However, research regarding the optimal dosage of AAFA in the mix design process, the quantity of the activator and curing conditions is minimal. The sustainability issues along with cost benefits of using AAFA in ES stabilization are still unexplored. To address this, the present work involves systematic laboratory testing to evaluate AAFA performance versus other conventional stabilizers and to assess sustainability and cost feasibility of AAFA-stabilized soils. As the availability of the related literatures, it has been identified that various materials are used for the stabilization of ES.

There is hardly any literature available of the industrial waste AAFA used as one of the stabilizers for ES. So far no assessment has been done of the engineering characteristics of ES by applying AAFA as its stabilizer. That means the present investigation is an appreciable work in the investigation of AAFA and its influence on ES. The evaluation is done by using different proportions of alkali to activate AAFA. The Un-Idenpened Compressive Strengths (USCS) is determined to evaluate the bonding effects.

The novelties of the research study are as follows. A detailed examination of the influence of different types of alkaline activators and curing techniques on the mechanical properties of these soils can contribute to the improvement of the process of geopolymerization. Moreover, it emphasizes the benefits that this novel sustainable technology offers over conventional technologies that involve stabilization by means of cement or lime stabilization. Parameters of geopolymerization and soil properties can be employed in order to develop a standard approach for different engineering applications.

MATERIALS AND METHODS

Material Characterisation

ES

The ES for this current study is gathered from Lingipur Nuagaon, plotno S -60, Bhubaneswar. The soils obtained from above the first 500 mm layer of the soil profile were collected using distribution sampling technique and analyzed in the lab. Partial vacuum packaging was done for the soils samples for storage while the moisture content determination was done through the polythene bag. The drying, grinding, and sieving process for the samples was done to get samples with sizes less than 4.75 mm.

Geotechnical properties of the soil sample aspects show that AAFA in relation to geopolymers stabilization of ES is compliant with ASTTM standard [25]. According to the soil classification, the ES soil falls under the category

of compressible clay CH and satisfies the IS: 1498 criteria. Several tests were conducted on the virgin soil VS giving ES.

Table 1 demonstrates the GT possessions of the ES. The soil classification, liquid and plastic limits and UCS are evaluated for ES. The ES grain size analysis (from Table 1) revealed that 63% (clay and silt) of the VSs passed through the 75 IS sieve. This illustrates that the experimental ES was a fine-grained soil with a significant surface area. The ES being assessed as an outcome is very plastic. The variance-free swell index (DFS) of the ES is presented in Table 1. 80% has a particular gravity (G) of 2.66, a maximum dry density (MDD), a natural moisture content (NMC) of 6.11% and a perfect moisture content (OMC) of 23.51%. The ES's plastic and liquid limits are 27% and 72%, respectively. In accordance with ASTM D2487 [26], the soil is characterised as clay with high CH.

Furthermore, Figure 2 provides a visual representation of the GSDs for the ES. The aforementioned graph displays a

Table 1. GT Properties of ES

S.NO	PARTICULARS	TEST RESULTS
1	SOIL CLASSIFICATION(USCS)	CH
2	LIQUID LIMIT (%)	72
3	PLASTICLIMIT (%)	27
4	PLASTICITY INDEX (%)	45
5	OPTIMUMMOISTURE CONTENT (%)	23.51
6	MAXIMUM DRY DENSITY(g\cc)	1.62
7	DIFFERENTIALFREE SWELL (%)	80
8	SPECIFIC GRAVITY	2.66
9	UCS (kg/cm ²)	1.99
10	GRAIN SIZE DISTRIBUTION (GSD) GRAVEL($\geq 2000 \mu\text{m}$)	0
	SAND (75-20000 μ)	37
	SILT(2-75 μm)	63

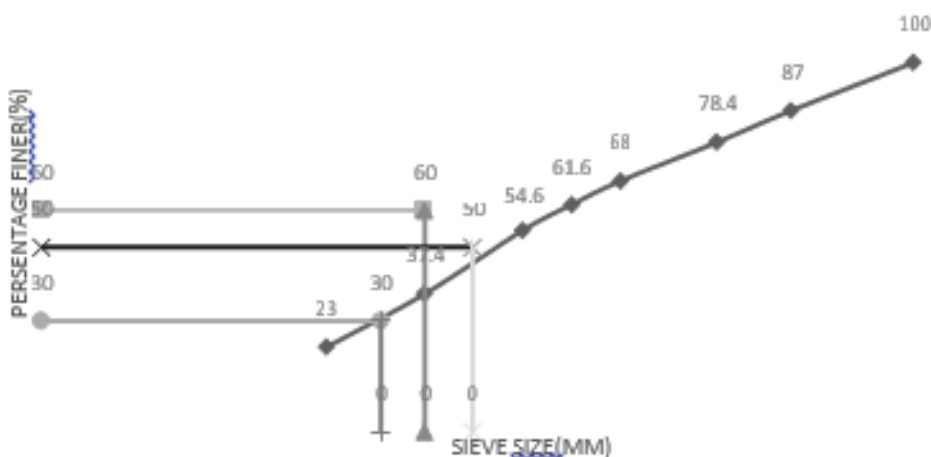


Figure 2. Grain size distribution of expansive soil.

particle size distribution curve with sieve sizes on the x-axis and the cumulative proportion of particles smaller than the corresponding sieve size on the y-axis. For instance, 60% of the material is smaller with a sieve size of 60 mm. The steeper slope of the curve, particularly in the middle ranges between 20 and 60 mm, indicates that the material has a wide dispersion of particle sizes. A substance with a wide variety of particle sizes is indicated by a steep slope, whereas more homogeneity would be indicated by a more gradual curve.

A Jeol-840-A model scanning electron microscope (SEM) organised with the help of an electronic dispersive X-ray (EDX) analyser was used to scrutinise the particle chemistry and individual morphology. The mineralogy of the materials used was examined via X-ray diffraction (XRD) on a Rich-Siefert X-ray diffractometer with a Ni filter and a copper target (Fig. 3) and (Table 2).

This XRD pattern likely corresponds to a crystalline material or compound, possibly a mineral or an engineered material. The high peak at around 500 (2 θ) is indicative of a primary phase, while the smaller peaks at other angles suggest secondary phases or impurities in the sample. The results of the X-ray diffraction technique indicate the presence of crystals in the sample, thereby showing the nature of the phases involved. The major peak, collected with extra negligible peaks, can help in identifying certain materials and their crystal structures by matching them to standard database patterns.

Table 2. Mineralogical composition of the expansive soil

Minerals	Interlayer Bonding
Kaolinite	Hydrogen; Strong
Montmorillonite	Oxygen-oxygen; Very weak
Illite	K ions; Strong
Vermiculite	Weak
Chlorite	Strong

Table 2 provides the information on the type of bonding present between layers in various minerals. The presence of hydrogen and potassium ions in kaolinite and illite, respectively, makes them have strong interlayer bonding. Chlorite also has strong bonding. On the other hand, montmorillonite possesses very weak oxygen-oxygen bonds while those of vermiculite are weak.

FLYASH

The FA used in this case study has been obtained from the captive power plant of JinDAL ALUMINIUM LIMITED located at Angul of state Odisha in India, where the content of calcium is low (Class F). The properties of GT of FA are mentioned in Table 3 below. Graphical depiction of GSD and XRD of FA has been presented in Figures 4 and 5, respectively.

Table 3 shows essential data for FA. It possesses liquid limit of 24.46% and it is non-plastic in nature, hence does not have plasticity index. Its optimum moisture content is 12.6% while maximum dry density is 1.45 g/cc. FA does not possess any free swell which means that it swells very little when exposed to water. Its specific gravity value is 2.20. When it comes to grain size distribution, FA is made up of 5% sand, 90% silt and 5% clay.

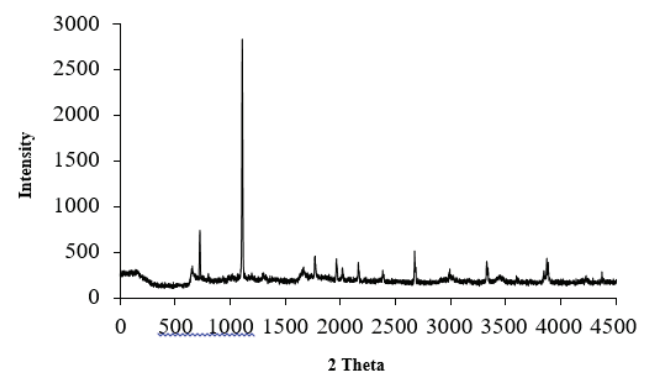


Figure 3. XRD analysis of the expansive soil.

Table 3. Geotechnical properties of flyash

S.NO	PARTICULARS	FLYASH
1	LIQUID LIMIT (%)	24.46
2	PLASTICLIMIT (%)	NON-PLASTIC
3	PLASTICITY INDEX (%)	-
4	OPTIMUM MOISTURE CONTENT (%)	12.6
5	MAXIMUM DRY DENSITY(g\cc)	1.45
6	DIFFERENTIALFREE SWELL (%)	0
7	SPECIFIC GRAVITY	2.20
9	GSD GRAVEL($\geq 2000 \mu\text{m}$)	0%
	SAND (75-20000 μ)	5%
	SILT (2-75 μm)	90%
	CLAY ($\leq 2 \mu\text{m}$)	5%

Figure 4 below is a grain size distribution curve, just like sieve analysis curve. X axis is the sieve size measured in millimeters from 0.01mm to 10mm, while Y axis denotes the percentage of material finer than the sieve size. Data points indicated on this curve are joined by a line showing the percentage of finer material in relation to the sieve size. At first, at sieve size of 60mm, there is 0% of finer material, meaning there are no particles smaller than this sieve size. There is a marked jump in finer material up to 63mm then it slowly rises. Up to sieve size of 63mm to 100mm, percentage of finer materials is very much indicating presence of high percentage of finer material. Sharp bends especially from sieve size of 63mm to 69mm indicate changes in particle size distribution or material phase.

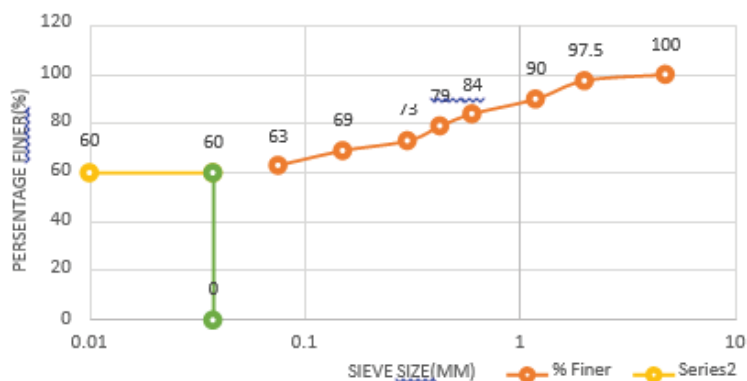


Figure 4. Grain size distribution of fly ash.

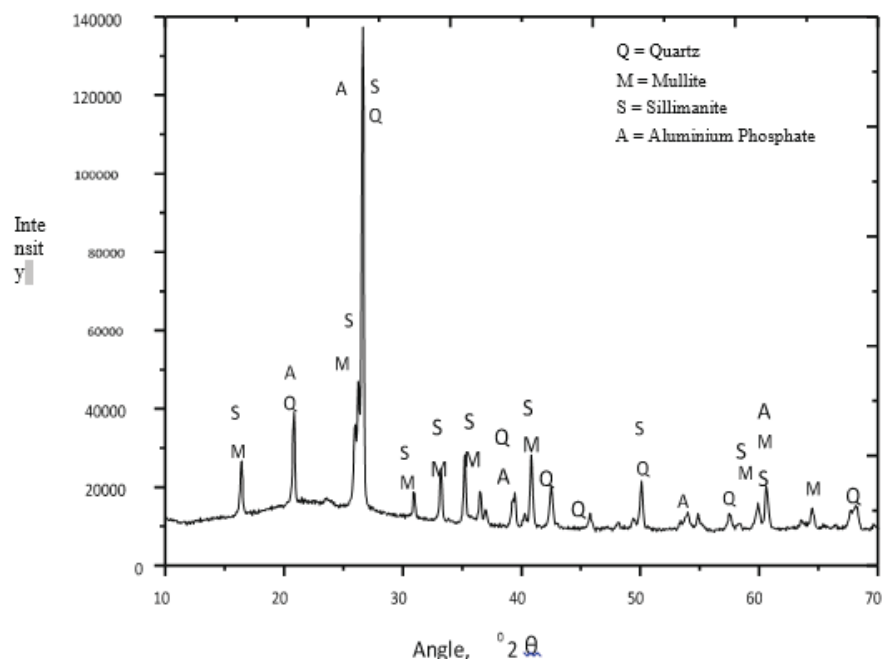


Figure 5. XRD pattern of fly ash.

X-ray diffraction pattern indicates the existence of various minerals like quartz, mullet, sillimanite, and aluminium phosphate in the given sample. This is mainly due to really every mineral produces its own unique pattern of peaks due to the distinct atomic arrangements. By way of illustration, quartz produces a very distinctive peak at 26.6° whereas mullite and sillimanite produce their characteristic peaks marked as “M” and “S” respectively. Besides these, silli(man)ite has another peak in the range of 25-27°. Aluminium phosphate peaks are indicated as “A”. Generally, peaks signify the number of atoms in a particular crystal plane. This is the principle behind determining the relative amounts of minerals in a given sample. Crystals with high symmetry will produce only a few peaks whereas crystals with low symmetry contribute to various peaks. The XRD method uses 2 values.

Table 4. Chemical properties of FA

SL NO	PARAMETER	% BY MASS
1	SiO ₂	51.57
2	Al ₂ O ₃	22.57
3	Fe ₂ O ₃	14.91
4	CaO	4.82
5	SO ₃	0.99
6	Ignition loss	3.56
7	Na ₂ + K ₂ O	0.68
8	MgO	1.74

The Table 4 presents the chemical composition of a material, likely FA, in terms of percentage by mass. The main constituents of the sample comprise silicon dioxide (SiO₂) which makes up 51.57%, aluminium oxide (Al₂O₃), which accounts for 22.57%, and iron oxide (Fe₂O₃) which makes up 14.91%. On the other hand, the quantity of CaO

is 4.82% and SO₃ is 0.99%. The loss on ignition, accounting for the volatiles, is 3.56%. In addition, Na₂.

The parameters of fly ash/alkaline activator ratios and NaOH molarities used in this experiment were selected by the authors based on previous research findings. These earlier studies pointed out that fly ash/alkaline activator ratios and NaOH molarities are very important factors which affect quite a bit the process of geopolymerization and this way the properties of the final geopolymeric product. Actually, the interval of fly ash/activator ratios between 1.5 and 2.5 as well as NaOH molarities from 8 M to 14 M were normally considered as a good range for obtaining maximum fly ash geopolymers compressive strength and workability. For example, BURDUHOS-NERGIS et al. (2025) have identified that the best fly ash/activator ratio to achieve the highest compressive strength of class F FA geopolymers is 2.0. So, the present research work has been planned to assess the influence of changing the ratios within these intervals research says data mentioned above (Table 5).

Table 5. Nomenclature of AAFA samples

Sample designation	Hydroxide concentration	FA content (%)	Activator to sol	Activator/FA ratio
S1	10 M	20	15	0.75
S2		30	15	0.50
S3		40	15	0.38
S4		20	20	1.00
S5		30	20	0.67
S6		40	20	0.50
S7		20	25	1.25
S8		30	25	0.83
S9		40	25	0.63
S10	12.5 M	20	15	0.75
S11		30	15	0.50
S12		40	15	0.38
S13		20	20	1.00
S14		30	20	0.67
S15		40	20	0.50
S16		20	25	1.25
S17		30	25	0.83
S18		40	25	0.63
S19	15 M	20	15	0.75
S20		30	15	0.50
S21		40	15	0.38
S22		20	20	1.00
S23		30	20	0.67
S24		40	20	0.50
S25		20	25	1.25
S26		30	25	0.83
S27		40	25	0.63

Sample Preparation and Testing

Another part of the experiment is an analysis of the influence of FA/soil ratio (dry weight) on the strength properties [27]. In particular, the following percentage of FA was selected; 20%, 30% and 40%, i.e., ratios or percentages of soils/ash corresponding to 0.25, 0.43 and 0.67, respectively, according to the percentage of solids containing FA and soil. In addition, higher percentages of activator/solid were considered at 0.15, 0.2 and 0.25 for all FA mixtures to assess the influence of activator on the improvement of strength.

The research conducted by [28] included analysis of UCS in samples treated with 10 M, 12 M and 15 M AAFA having soil ratios/ash values of 0.25, 0.43 and 0.67, respectively, at various ash/activator ratios.

After first homogenising the FA and soil, the activator was included in the mixture. In accordance with (Terashi & Kitazume, 2011), the samples were blended in a mechanical mixer for 3 minutes and subsequently cast into 100 mm high and 50 mm diameter moulds through tapping the moulds on the counter of the lab [28]. Using laboratory tests, the amount of water added to each mix was adjusted to reach that ideal moisture content. Each mixture uses a specific amount of water as specified in Table 6.

All samples were prepared and tested under controlled laboratory conditions. After mixing, the specimens were cast into 100 mm high and 50 mm diameter molds, then cured at room temperature (approximately $25 \pm 2^\circ\text{C}$) and relative humidity of 50–60% for the specified curing durations of 3, 7, and 28 days, as described previously. For all the designs, the tests for three replicates were carried out to determine consistency. In addition, the procedures for mixing, molding, curing, and UCS test followed strictly according to ASTM guidelines.

The percentage usage of FA of 40, 30, and 20% based on the total mixed dry mass were considered. To compare with the actual amount of FA, these percentage rates are taken into consideration.

The Table 5 outlines various samples (S1 to S27) with different hydroxide concentrations, FA content, activator to solution ratios, and activator to FA ratios. Hydroxide concentration

is 10 M, 12.5 M, and 15 M. FA content is 20%, 30%, and 40%. Activator to solution ratio ranges between 15 to 25 while activator to FA ratio is 0.375, 0.75, and 1.25. For example, S1, S10, and S19 sample series have 20% FA content and activator to FA ratio of 0.75. This enables an effective analysis of various effects of these factors on the samples properties.

It is clear that the choice of these high molarity solutions of NaOH was done according to their capacity to improve FA particles dissolution necessary for high compressive strength geopolymer. The ratio of sodium hydroxide to sodium silicate in these samples was optimized after several preliminary tests. These were done to get a proper balance between workability and compressive strength of the samples. In order to get optimal geopolymerization conditions, high molarity NaOH solutions and optimized sodium silicate to sodium hydroxide ratio were applied to get effective activation of FA.

The Table 6 presents a series of samples (A1 to A9) with varying water to solid ratios and FA contents. Water to solid ratio can be taken at either 15%, 20%, or 25%. Content of FA can vary from 20% to 40%. Water to FA ratio will also vary liable on the situation; for instance, ratios such as 0.75 for A1, 0.5 for A2, and 1.25 for A7. Such an arrangement will make it easier to observe and analyze how varying water and FA ratios affect the performance of the mixtures. In this case, mixture A4 has water to FA ratio of 1.0 and mixture A6 of 0.5.

If the FA content is relatively higher (for instance, 40%), due to ball-bearing effect reducing water requirement, then water to solid ratio should be 15%. If a combination requires some degree of moisture in order to ensure its easy handling, a water to solid ratio of 20% could be appropriate especially for cases when FA percentage content is moderate (for instance, 30%). Where FA content percentage is relatively lower (say 20%) or when the mixtures have high amount of activators requiring water for reduced viscosity, ratio can be 25%.

To ensure accuracy and reliability, all experimental measurements and procedures in this work were conducted strictly according to the ASTM and IS standards. The reproducibility and validity of results are ensured by

Table 6. Nomenclature of different types of mixtures

SAMPLE	WATER TO SOLID (%)	FA CONTENT (%)	WATER/FA RATIO
A1	15	20	0.75
A2	15	30	0.50
A3	15	40	0.38
A4	20	20	1.00
A5	20	30	0.67
A6	20	40	0.50
A7	25	20	1.25
A8	25	30	0.83
A9	25	40	0.63

the application of specified test procedures (e.g., ASTM D2487 and IS 1498 for soil classification and other appropriate ASTM and IS methods for geotechnical and chemical characterization). The primary basis of methodological correctness lies in following these internationally accepted standards; model validation was done without any independent or external experimental data.

RESULTS AND DISCUSSION

UCS of the Expansive Soil and Fly Ash Mixture

Figure 6 shows the UCS values for all the FA-treated samples at 3, 7 and 28 days after curing. The results clearly

establish that, likened with the other mixes, Mix A5 offers greater 3-day strength. However, compared with the other mixes, Mix A1 provides more strength after 7 and 28 days of curing. The strength of mix A9 after 3, 7 and 28 days of curing is the lowest.

A total of 81 samples were investigated utilising different ratios of activator and FA. In Figures 7, 8 and 9, the deviations in the UCS values of the combinations formed with 10, 12.5 and 15 M solutions, unlike CT, are illustrated.

Figure 7 shows that the UCS combination activated with 10 M solution decreases as the FA concentration increases and that the strength increases as the curing duration increases. This clearly shows that mix S5 has greater

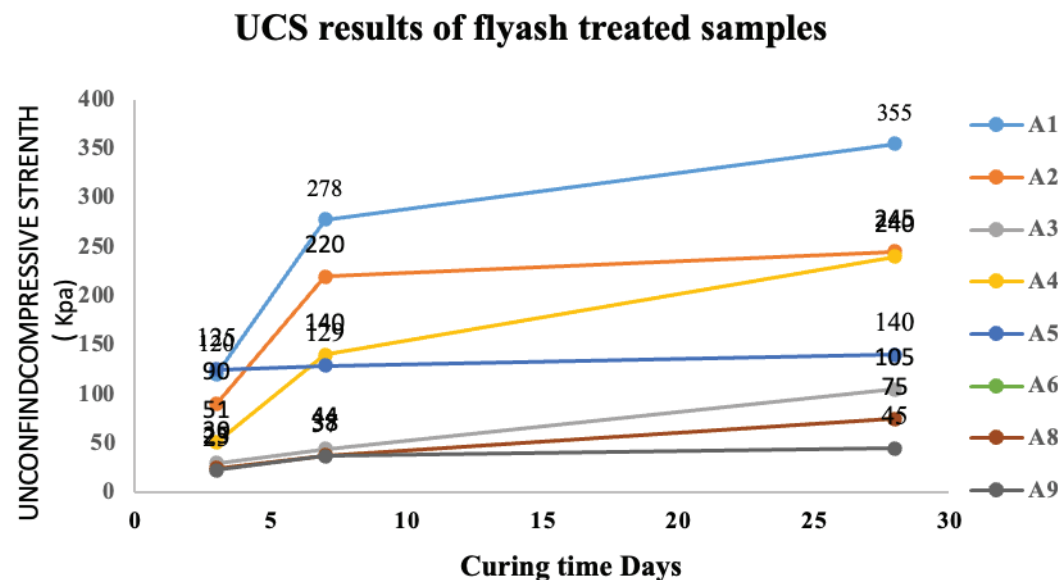


Figure 6. UCSs of the geopolymerised FA-treated samples.

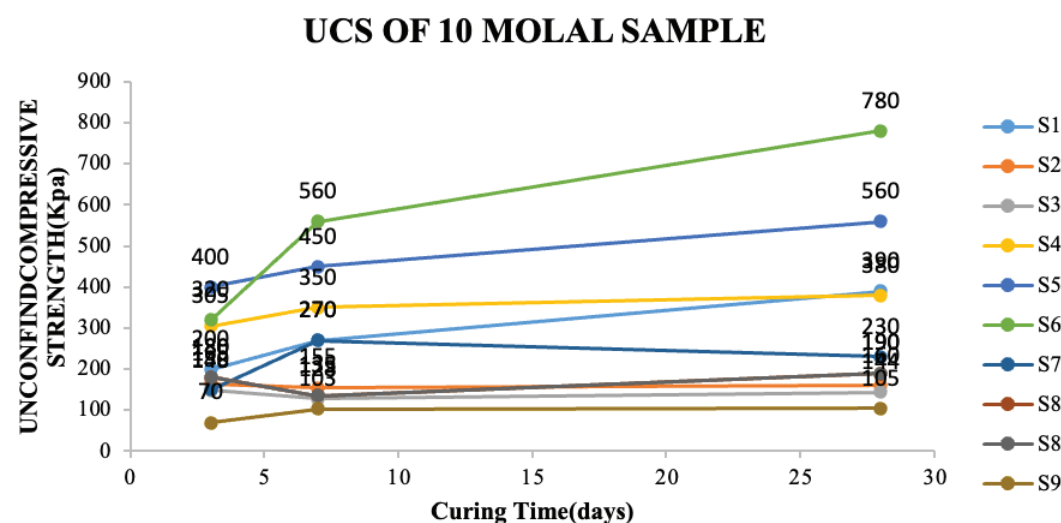


Figure 7. UCS of the 10 M sample.

strength after 3 days, although mix S6 has greater strength after 7 and 28 days. Mix S9 has the lowest strength at 3 and 7 days, whereas mix S8 has the lowest strength at 28 days. Similarly, Figure 7 also shows the results for a 12.5 M solution. Compared with S16, S12 has a stronger formulation for the 3-, 7- and 28-day formulations. Mix S18 presented the lowest strength after 3 days, whereas mix S11 presented the lowest strength after 7 days. Figure 9 shows that, for the 15 M solution, mix S19 has greater strength after 28 days of formulation, and mixes S25, S26 and S27 have the lowest strength after 3 and 7 days.

Mix S5 attained the highest strength among the 81 mixtures after 3 days of curing, and Mix S24 obtained the highest strength after 7 days of CT. In terms of strength, mix

S12 outperforms all the other mixes and excels well. This may be related to the amount of period essential for the nucleation process to occur, at the time when the byproduct of the raw silica with alumina dissolution formed prior to precipitation.

Effect of activator / Ash ratio

Figure 9 shows the different UCS values observed after a period of three curing days using various combinations of different activator concentrations: 10M, 12.5M, and 15M of NaOH, and FA contents, which range from 20, to 30, and 40%. High FA was found to give the best results with the activator to ash ratio in the range of 0.3 to 0.5.

Figure 10 shows some irregular patterns, which might be ascribed to interactions involving concentrations of the

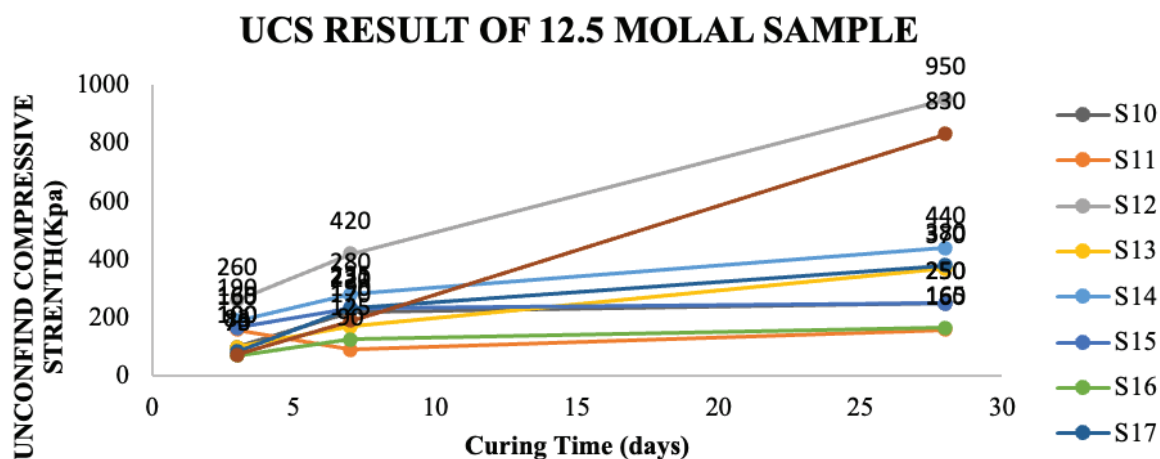


Figure 8. UCS of the 12.5 M sample.

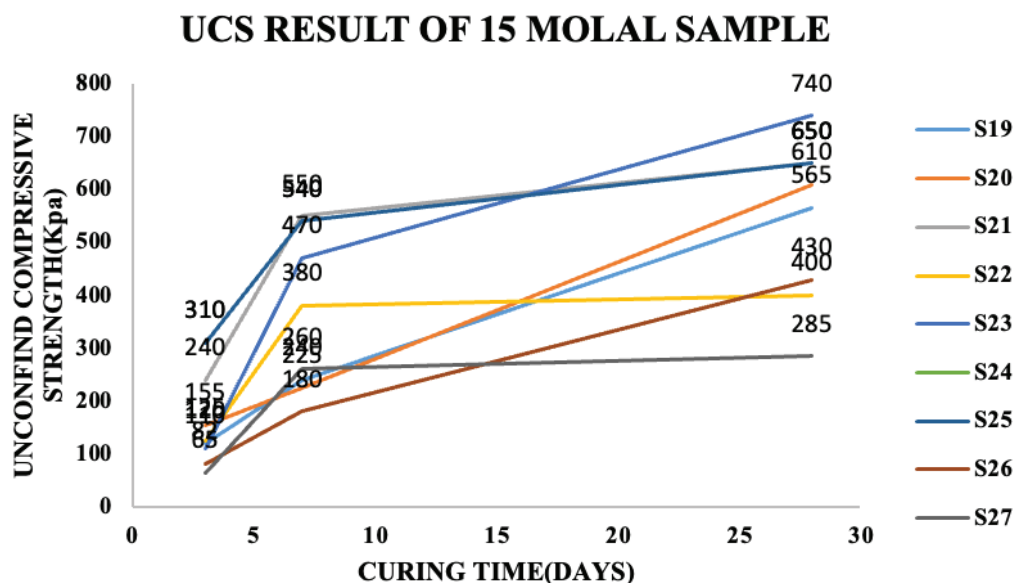


Figure 9. UCS of the 15 M sample.

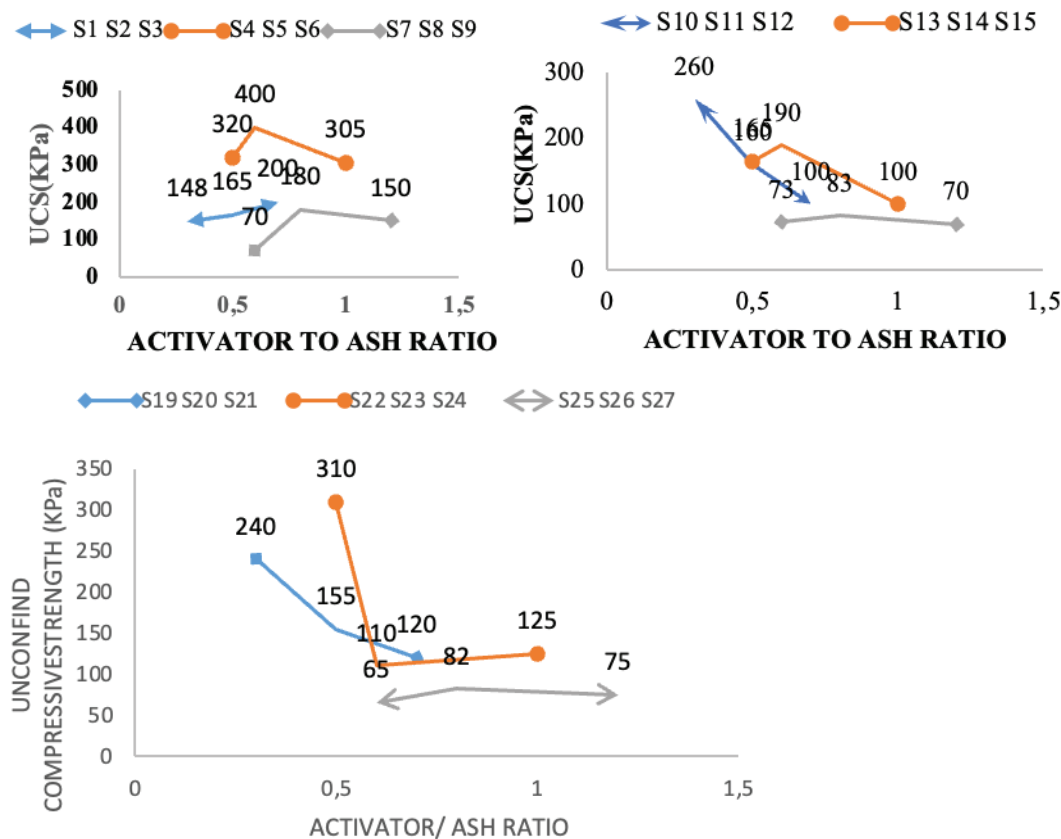


Figure 10. Three days of curing of the 10, 12.5 and 15 M samples.

activator, activator to ash ratio, and FA content. For instance, some concentrations of the activator require different optimal activator-to-ash ratios for maximum strength, which may lead to strength variations. This variability arises due to FA properties that differ from one another and also to specific geopolymerization conditions, like CT and temperature. Interactions among activator dosage, activator ash ratio, and fly ash behavior are largely responsible for the irregular trends seen in Figure 10's UCS results within three days of curing. Changes in any of these factors might result in over-activation or poor geopolymerization, affecting the formation of strength. In addition, as some blends improve stronger binding, while others worsen matrix quality, the variability is caused by variations in fly ash's chemistry, particle size, and reactivity. This makes the outcome of strength tests biased, thus stressing the significance of optimizing mixture characteristics in order to obtain consistent geopolymer performance.

The variations in the UCS of the samples after 7 days of curing with *activator / ash ratio* at 10, 12.5 and 15 M NaOH and 20, 30 and 40% FAC are represented in Figure 11. The samples containing more FAC had the ability to attain greater strength under these conditions, which paralleled an *activator / ash ratio* of 0.3--0.5. The maximal strength of S6 was observed after the curing period of seven days.

High strength was obtained in those samples having high FA concentration, even after curing periods that did not exceed three days. This could be explained by the fact that the developed amorphous aluminosilicate gel was immature and would continue to develop for long periods of time. Generally, under the condition of using CT where higher strengths are required, the samples having high FA concentration would demonstrate increased strengths after longer curing periods. However, deviating from the optimum conditions would result in weak samples. Thus, for example, samples S4-6 with increased strengths depending on FA concentration were possibly affected by the more efficient activation process or different activator:ash ratios, whereas S1-3 and S7-9 with decreasing strengths could be the results of poor activation processes or other activator:ash ratios.

The reason for the wavy declining and increasing pattern for 12.5 M and 15 M samples could be attributed to the over-activation processes, which could result in excess dissolution of silica and alumina leading to the weakening of the geopolymer matrix. Moreover, the difference in reactivity of FA and pore structures could increase the effect. Therefore, one can conclude that the major factors affecting geopolymerization and thus the strength of expansive soil were the chemical composition (reactive silica and alumina concentrations), grain size, and the FA content. The

development of geopolymer gels depended on reactivity and fineness of fly ash.

Figure 11 shows the dependence of the UCS of the samples cured for 7 days on the activator to ash ratio varying from different molarities of NaOH solution (10M, 12.5M, and 15M) and various amounts of fly ash (20%, 30% and

40%). The results show that samples with higher fly ash concentration, especially in the ratio between 0.3 and 0.5, are likely to have higher UCS values because they undergo better geopolymerization process. In addition, it is evident from the results that there are optimum strength ratios, failure of which leads to irregular strength values. This figure

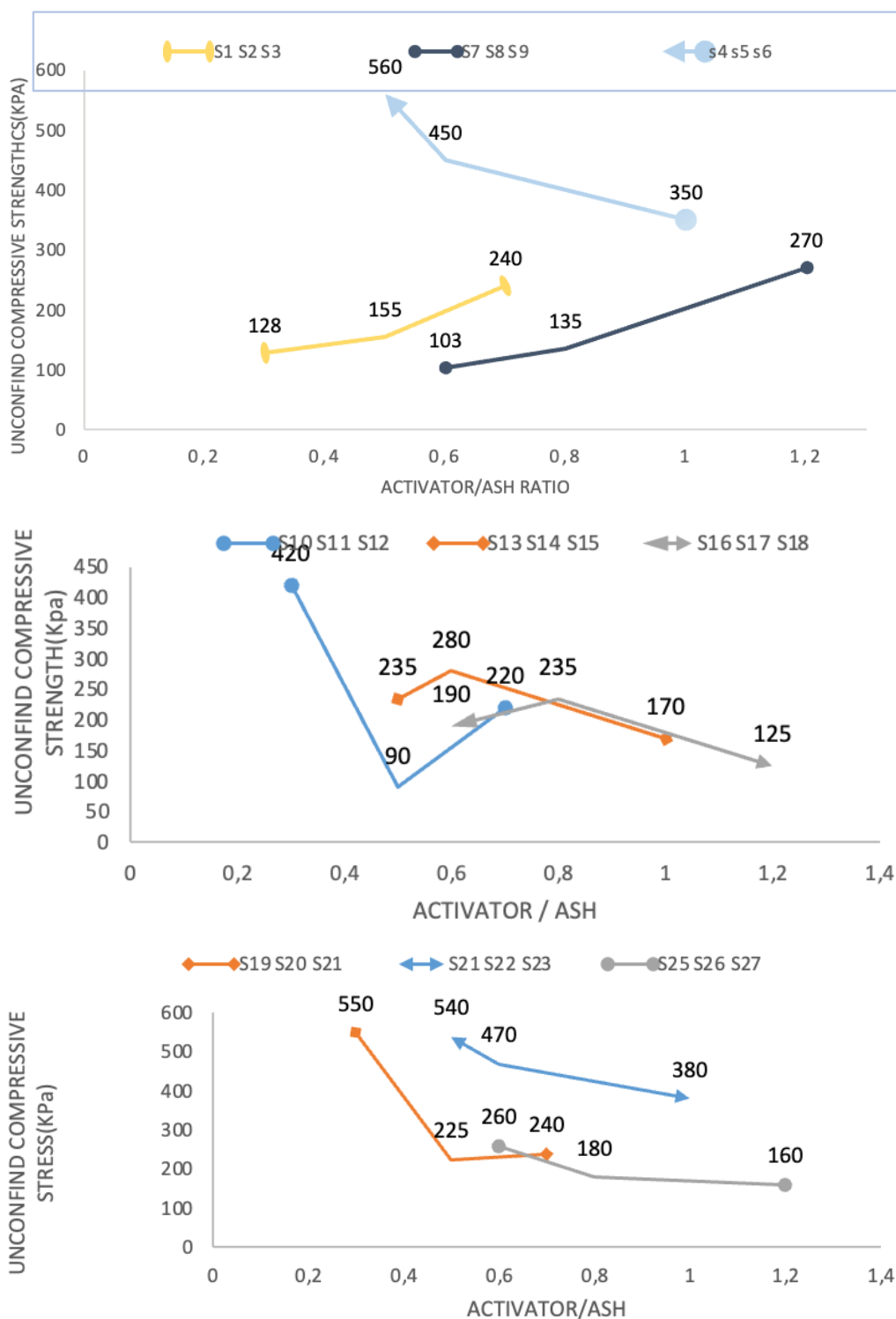


Figure 11. Seven Days of Curing of the 10 M, 12.5 M and 15 M Samples.

underscores the importance of balancing activator concentration and fly ash content to maximize mechanical strength in geopolymer-based stabilization of expansive soils.

In the current situation, samples with ash ratios ranging from 0.3 to 0.625 can achieve the maximum strength, and sample S12 displays this determined strength. Additionally, the samples formed with 12.5 M NaOH show superior strength to the other samples over the curing period of 28 days. With the exception of an initial stage, all the curing phases experience the supreme strength at a lower *activator / ash ratio*, which suggests that such an effort is cost efficient [28].

The Figure 12, indicates the compressive strength development of various samples after 28 days of curing, highlighting the influence of different activator molarities, fly ash contents, and ratios on long-term strength performance. These figures demonstrate how optimal combination of such parameters will help increase geopolymerization and strength gain through time.

Besides, geopolymerization offers a range of benefits from economic and environmental points of view in

comparison to conventional technologies of soil stabilization like cementing or lime stabilization. With the use of waste products as raw materials, the cost of materials is minimized and the disposal problem is solved. Furthermore, unlike ordinary binders, geopolymers are durable and produce less carbon dioxide. While being both economical and environmentally-friendly, geopolymeric cements face also the challenge related to availability of raw materials and standard testing regimes. In turn, conventional methods of soil stabilization like cement or lime stabilization may seem to have more expensive and environmentally harmful consequences.

From the above analysis, the ideal properties that would lead to the maximum UCS are; 12.5 M NaOH, activator to ash ratio of 0.3–0.5, and fly ash content of 30–40%. Using such parameters, S12 mix gave the maximum UCS at 28 days, hence demonstrating the significance of regulating fly ash content and activator concentrations.

Curing duration plays a significant part in the strength development, and the most strength gains were recorded

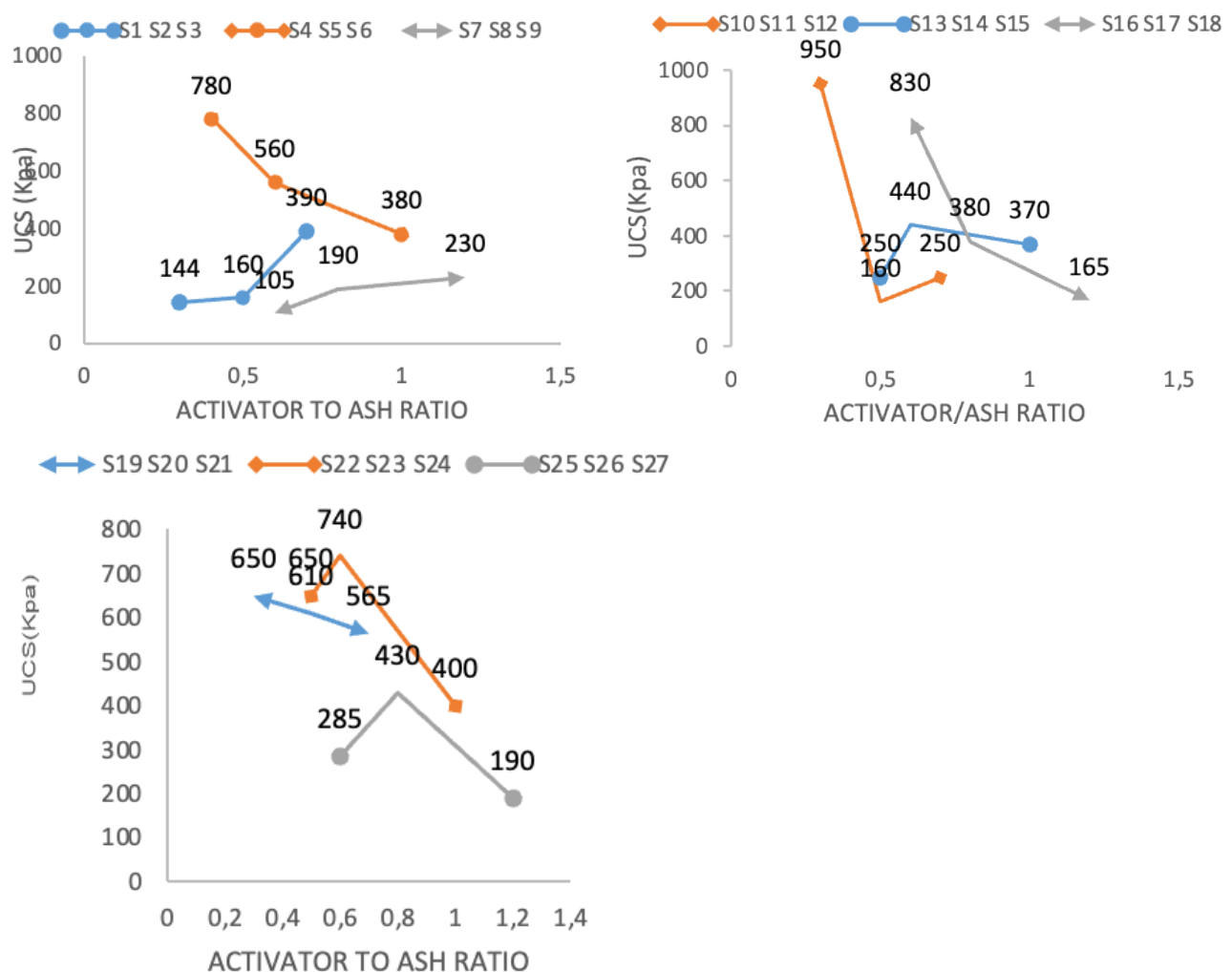


Figure 12. Twenty-eight days of curing of the 10, 12.5 and 15 M samples.

at 28 days. Significance of adequate curing of the geopolymerization to attain optimal strength development can be demonstrated by the fact that almost all mixes achieved their maximum UCS values at 28 days.

Retrofit Proposal Based on the Results

It is recommended that the present expansive soil foundation/subgrade can be improved through in-situ blending of 30–40 percent of Class F FA with soil and activation with a 12.5M NaOH solution, using an activator-to-ash ratio of 0.3 to 0.5, with compaction and curing for a period of not less than 28 days. This relies on the improved UCS and durability with the best FA geopolymer formulations observed. It is recommended that this customized geopolymer-stabilized mix be applied to the surface or used in place of the top layer of soil for structural elements such as retaining walls or shallow foundations to enhance bearing capacity and reduce swelling damage. The latest research shows that the repair method with geopolymers is more effective in enhancing the durability and load bearing capacity of a structure than the traditional methods using cement mortar. Besides addressing the technical drawbacks of ES technology, this method is also seen as environmentally friendly.

Limitations of the Study

Even so, despite Truth is this mentioned study has proved FA as an effective geopolymer stabilizer for ES, what comes next concerns should be given attention. Firstly, it is difficult to generalize the results shown because they are based solely on the laboratory test and with FA which is sourced only from a particular source; and Because of this the variations in properties of FA from other sources or production processes might not have been reflected. When it comes to estimating field stability, limited it is in the study as well as no comparison results with standard stabilizers (for instance cement lime etc.) and no long-term stability test (sulfate attack, heating-cooling cycles, wetting-drying etc) have been presented. Also, the economic and eco-profile of the process of the geopolymerization with FA as a stabilizer has not been evaluated, as well as possible environmental risk and potential of heavy metal leaching from FA.

Furthermore, the feasibility and practicability of geopolymer stabilization in question remain undefined due to the lack of any tests performed in field conditions during the study. Thus, in order to demonstrate that this innovative technique of soil treatment and its eco-panel can work, additional investigations will be required. Whether the findings from this experiment can be extrapolated to other sites should be verified considering different soils characteristics including, but not limited to, mineralogical composition, plasticity and the presence of organic material in soil as well as weather conditions like temperature, relative humidity and rainfall intensity. Soils containing higher levels of montmorillonite clay minerals or regions with wide temperatures ranges allowing the occurrence of freeze-thaw cycles can behave differently when geopolymerized

using FA. Factors influencing the efficiency of FA as an alkaline activator include, among others, coal composition and combustion technologies. An initial sensitivity analysis indicates that reduced contents of either calcium or amorphous materials in FA will lower efficiency of geopolymer formation and strength development, whereas increased impurity levels in the ash may affect durability.

Future Recommendations

To comprehensively assess the performance and longevity of soil stabilization by using AAFA, it is imperative to further investigate the durability of soils exposed to the actual conditions of the field environment including seasonal moisture changes, freeze-thaw, and wet-dry cycles. Besides that, results obtained with these new stabilizers should be compared with those achieved with traditional ones (e.g. cement lime) to evaluate mechanical differences and economic implications of the process. Determining the potential effects of adding various mineral kinds to soils in conjunction with climatic changes would be beneficial. However, we must first evaluate the leaching of heavy metals, leaching causes, and modifications in order to determine how much different ashes may affect the method's outcomes. In the meanwhile, we could consider conducting a feasibility study to ascertain the costs associated with purchasing fly ash and turning it into geopolymers. We will have the opportunity to cooperate with geopolymers in the construction of various infrastructures through pilot studies conducted under the agreements formed between industry, contractors, and local government agencies. To support that using geopolymer is a way to reduce greenhouse gas emissions in the construction industry, one of the aspects that needs thorough investigation is the carbon footprint connected with this method. That's the reason we need to look at alkali-activated fly ash side by side with other building materials such as lime and cement.

Building on the research by (Tiwari, Satyam, & Puppala, 2021), who also found enhancement in strength and reduction of swelling through the use of natural fibers and recycled ash, the current paper based on AAFA also hold the promise for almost double the UCS value of natural soil and the shrink-swell capacity can be almost completely controlled over such soil. But, in sharp contrast to (Tiwari, Satyam, & Puppala, 2021) who have examined mainly the combined effect of fibers and ash, the present research brings to light the significance of optimum AAFA composition not only fly ash level but also the activator/fly ash ratio in final strength of the samples.

In the present paper, AAFA stabilization is shown to result in a UCS that is at least equal to or even surpasses that which was achieved by soil treated with WGP in the work of (Blayi, Sherwani, Ibrahim, Faraj, & Daraei, 2020), Mostly at elevated CT. Although (Blayi Sherwani Ibrahim, Faraj, & Daraei, 2020) identified 15% WGP as the best percentage to enhance the engineering properties of soil, this investigation reveals that soil stabilized with 30–40% FA, an activator/ash ratio of 0.3–0.5 and 12.5M NaOH at 28days

exhibits very high UCS. Because of this, while AAFA and WGP are both effective soil stabilizers, FA geopolymerization can be further optimized.

Waste materials utilization to improve soil characteristics and support sustainability was the major point of the studies by (Vijayan & Parthiban, 2020) and (Indiramma, Sudharani, & Needhidasan, 2020). In fact, the current findings are in agreement to previous research yet the major role of this paper is in extensive discussion of the effects of activator concentration and curing time. Besides that, the present work has been very successful in showing that geopolymers can exercise the functionalities of conventional binding agents or even exceed them but with Quite a bit lowered environmental impact. The outcomes presented by [29] and [30] are consistent with the present results as well since they have proven that the use of industrial waste-based geopolymers was an efficient and adequate solution for stabilization of difficult to treat soils (such as peat and high liquid limit sub-grade soils). Though these researches were done on different soil materials (POFA GGBFS brCDW), the findings related to the mechanical properties reported in these papers have great agreement with those of this work on the strength of ES stabilized by FA-based geopolymers. The essence of this paper is that it upholds the optimization of curing conditions and the activator/ash ratio.

Such findings align well with those of [23], whose work demonstrated that geopolymers activated by mechano-chemical treatment are more resistant to sulfate corrosion.

The contribution of the present paper to the literature is twofold: first by achieving the mix design optimization of the geopolymer stabilized ES second by the evaluation of geopolymerization for efficiency against conventional stabilization methods through a comparative study, and the last aspect of the paper is the focus on the manufacture of high-performance and environment friendly soils stabilized by industrial wastes. These points A lot add to the present literature.

CONCLUSION

This paper reviews the application of alkali-activated fly ash in stabilizing expansive soils. Such technology may have environmental impacts as well as construction-related impacts as well. For instance, some findings from this paper show that 12.5M concentration of sodium hydroxide is the most appropriate because it is cheaper and more environmentally friendly owing to minimal pollution sources. Moreover, sodium hydroxide can yield the highest value of Ultimate Compressive Strength (UCS). Consequently, after applying sodium hydroxide to the soil, it was measured to be 4.8MPa. Aside from that, this soil's UCS value is significantly greater than that of other unstabilized soils due to the technology's cost-effectiveness and environmental friendliness when their wastes are utilized. Because of this, engineers can use materials like fly ash for sustainable construction even in areas with poor soil. However, this is only possible in the Indian state of Odisha.

However, the results will vary significantly due to the various mineralogical compositions of soils and climates in different areas of the world. In actuality, the results were influenced by the fly ash quality and soil environmental variables, according to the sensitivity analysis. Because the quality of the stabilized fly ash can be readily evaluated and applied on site using deep soil mixing columns, jet grouting, and geosynthetic slope/embankment stabilization techniques, it is essential to do mixture design tests before beginning any work.

Practical Implications

The results from the study provide a feasible, sustainable, and affordable way to stabilize the expansive soil, which plays a vital appeal in the construction sector through building foundations, embankment, and road construction. Using fly ash, which is basically an industrial waste, to soil stabilization through alkali activation of fly ash only, is a reason why such a method is considered. Besides its main functions, it also contributes to reducing environmental effects of lime and cement application. This method suits well areas with abundant fly ash that ensures waste is used in the best way.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

REFERENCES

- [1] Jones LD, Jefferson I. Expansive soils. In: ICE Manual of Geotechnical Engineering, Volume 1: Geotechnical Engineering Principles, Problematic Soils and Site Investigation. 2012. p. 413–441.

- [2] Dungca JR, Galupino JG. Artificial neural network permeability modeling of soil blended with fly ash. *GEOMATE J* 2017;12:77–82. [\[CrossRef\]](#)
- [3] Mathew A, Sasikumar A. Performance of soft soil reinforced with bamboo and geonet. *Int Res J Eng Technol* 2017;4:464–369.
- [4] Ayyappan A, Palanikumar S, Kumar DD, Vinoth M. Influence of geopolymers in the stabilization of clay soil. *Int J Emerg Technol Eng Res* 2017;5:108–120.
- [5] Mahajan L, Kirange M, Bhagat S. Statistical exploration for enlargement of reformed water cement ratio law for fly ash concrete. *Sigma J Eng Nat Sci* 2025;43:269–281. [\[CrossRef\]](#)
- [6] Miao S, Shen Z, Wang X, Luo F, Huang X, Wei C. Stabilization of highly expansive black cotton soils by means of geopolymerization. *J Mater Civ Eng* 2017;29:04017170. [\[CrossRef\]](#)
- [7] Khadka SD, Jayawickrama PW, Senadheera S. Strength and shrink/swell behavior of highly plastic clay treated with geopolymer. *Transp Res Rec* 2018;2672:174–184. [\[CrossRef\]](#)
- [8] Kabay N, Miyan N. A comparative study on the physical and mechanical properties of alkali activated materials. *Sigma J Eng Nat Sci* 2020;38:649–658.
- [9] Parhi PS, Garanayak L, Mahamaya M, Das SK. Stabilization of an expansive soil using alkali activated fly ash based geopolymer. In: *Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology*. Springer; 2017. [\[CrossRef\]](#)
- [10] Parikshith M, Sekhar DC. Feasibility of flyash based geopolymer for soil stabilization. *Int J Innov Technol Explor Eng* 2019;9:4348–4351. [\[CrossRef\]](#)
- [11] Cengizler H, Koç M. The effect of marble waste in the production of low-temperature porous material from alkali-activated fly ash. *Sigma J Eng Nat Sci* 2024;42:1148–1159. [\[CrossRef\]](#)
- [12] Rosales J, Agrela F, Marcobal JR, Diaz-Lopez JL, Cuenca-Moyano GM, Caballero A, et al. Use of nanomaterials in the stabilization of expansive soils into a road real-scale application. *Materials* 2020;13:3058. [\[CrossRef\]](#)
- [13] Ghadir P, Ranjbar N. Clayey soil stabilization using geopolymer and Portland cement. *Constr Build Mater* 2018;188:361–371. [\[CrossRef\]](#)
- [14] Habibbeygi F, Nikraz H. Compression behaviour of highly expansive clays stabilised with a green stabiliser of magnesium chloride. *GEOMATE J* 2018;14:144–150. [\[CrossRef\]](#)
- [15] Ikeagwuani CC, Nwonu DC. Emerging trends in expansive soil stabilisation: A review. *J Rock Mech Geotech Eng* 2019;11:423–440. [\[CrossRef\]](#)
- [16] Dungca JR, Codilla II EET. Fly-ash-based geopolymer as stabilizer for silty sand embankment materials. *GEOMATE J* 2018;14:143–149. [\[CrossRef\]](#)
- [17] Estabragh A, Rafatjo H, Javadi A. Treatment of an expansive soil by mechanical and chemical techniques. *Geosynth Int* 2014;21:233–243. [\[CrossRef\]](#)
- [18] Arrieta Baldovino JdJ, dos Santos Izzo RL, da Silva ÉR, Rose J. Sustainable use of recycled-glass powder in soil stabilization. *J Mater Civ Eng* 2020;32:04020080. [\[CrossRef\]](#)
- [19] Blayi RA, Sherwani AFH, Ibrahim HH, Faraj RH, Daraei A. Strength improvement of expansive soil by utilizing waste glass powder. *Case Stud Constr Mater* 2020;13:e00427. [\[CrossRef\]](#)
- [20] Jalal FE, Xu Y, Jamhiri B, Memon SA. On the recent trends in expansive soil stabilization using calcium-based stabilizer materials (CSMs): A comprehensive review. *Adv Mater Sci Eng* 2020;2020:1510969. [\[CrossRef\]](#)
- [21] Andavan S, Pagadala VK. A study on soil stabilization by addition of fly ash and lime. *Mater Today Proc* 2020;22:1125–1129. [\[CrossRef\]](#)
- [22] Indiramma P, Sudharani C, Needhidasan S. Utilization of fly ash and lime to stabilize the expansive soil and to sustain pollution free environment—An experimental study. *Mater Today Proc* 2020;22:694–700. [\[CrossRef\]](#)
- [23] Hamid Abed M, Hamid Abed F, Aliraza Seyed Z, Sabbar Israa A, Canakci H, Kurdi NH, et al. Experimental feasibility study of using eco-and user-friendly mechanochemically activated slag/fly ash geopolymer for soil stabilization. *Clean Mater* 2024;11:100226. [\[CrossRef\]](#)
- [24] Tabatabaei Z, Fatehi-Nobar B. Numerical investigation of ground tanks for storage subjected near-fault earthquakes. *Pollack Period* 2021;17:75–80. [\[CrossRef\]](#)
- [25] Elseknidy MH, Salmiaton A, Nor Shafizah I, Mousa AH. A study on mechanical properties of concrete incorporating aluminum dross, fly ash, and quarry dust. *Sustainability* 2020;12:9230. [\[CrossRef\]](#)
- [26] Helmuth R. Some questions concerning ASTM standards and methods of testing fly ash for use with portland cement. *Cem Concr Aggreg* 1983;5:103–110. [\[CrossRef\]](#)
- [27] Niş A, Altundal MB. Mechanical strength degradation of slag and fly ash based geopolymer specimens exposed to sulfuric acid attack. *Sigma J Eng Nat Sci* 2019;37:917–926.
- [28] Cristelo N, Glendinning S, Fernandes L, Pinto AT. Effects of alkaline-activated fly ash and Portland cement on soft soil stabilisation. *Acta Geotech* 2013;8:395–405. [\[CrossRef\]](#)
- [29] Amaludin AE, Asrah H, Mohamad HM, bin Amaludin HZ, bin Amaludin NA. Physicochemical and microstructural characterization of Klias Peat, Lumadan POFA, and GGBFS for geopolymer based soil stabilization. *HighTech Innov J* 2023;4:327–348. [\[CrossRef\]](#)
- [30] Xie J, Zhang J, Cao Z, Blom J, Vuye C, Gu F. Feasibility of using building-related construction and demolition waste-derived geopolymer for subgrade soil stabilization. *J Clean Prod* 2024;450:142001. [\[CrossRef\]](#)