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Stabilization of Expansive Clay Soil Using Pulverized Ceramic Waste, Cement Kiln Dust, and Alkali Activation: Material Characterization and Swell Analysis

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Abstract

Expansive clay soils present major geotechnical challenges because of their excessive swell-shrink behavior, which leads to pavement heaving, differential settlement, cracking of foundations, and deterioration of transportation infrastructure. Cement kiln dust (CKD) was incorporated as the calcium-rich alkali activator that supplies $Ca(OH)_2$ on hydration, thereby triggering pozzolanic reactions with the reactive silica and alumina of the pulverized ceramic waste (PCW) to form cementitious and geopolymeric gels within the soil matrix. Conventional stabilization methods based on cement and lime have proven effective; however, their environmental impacts and high carbon emissions have intensified the search for sustainable stabilization alternatives. This study investigated the stabilization of expansive clay soil using pulverized ceramic waste (PCW) and alkali activator through material characterization, consistency evaluation, and swell analysis. Laboratory investigations included particle size distribution, specific gravity, Atterberg limits, free swell index (FSI), X-ray diffraction (XRD), and X-ray fluorescence (XRF) analyses. Stabilization was performed using varying replacement levels of ceramic waste and cement kiln dust (CKD), alongside alkali activation. The untreated expansive clay soil exhibited high plasticity and severe swelling characteristics, with a liquid limit of 89.68%, plasticity index of 67.47%, and free swell index of 193.75%, confirming its highly expansive nature. XRD and XRF analyses revealed significant silica-, alumina-, and calcium-bearing phases within the stabilization materials, indicating strong geopolymerization and pozzolanic potential. The incorporation of ceramic waste and CKD significantly improved the consistency and swell behavior of the soil. The liquid limit decreased to 48.50%, while the plasticity index and free swell index reduced to 15% and 12%, respectively, at the optimum combined stabilization of 25% CW and 15% CKD. These improvements were attributed to flocculation, cation exchange, cementitious bonding, and geopolymeric gel formation within the soil matrix. The study demonstrates that pulverized ceramic waste and alkali activation can effectively reduce the expansiveness and moisture susceptibility of problematic clay soils. The combined stabilization approach offers a sustainable and environmentally friendly alternative for expansive soil treatment while simultaneously promoting beneficial reuse of ceramic waste materials in geotechnical engineering applications.

Keywords

Alkali Activation, Atterberg Limits, Cement Kiln Dust, Expansive Clay Soil, Free Swell Index, Geopolymer Stabilization, Geotechnical Engineering, Pozzolanic Reactions, Pulverized Ceramic Waste, Sustainable Soil Stabilization

1. Introduction

Expansive clay is one of the most problematic geomaterials found in geotechnical engineering practice due to the marked shrink-swell behavior associated with the seasonal variation of soil moisture [1]. These soils swell when wet and shrink when dry, causing substantial volume changes that cause pavement heaving, foundation cracking, differential settlement, and deterioration of engineering structures [1]. Challenges posed by expansive clay soils are especially significant in developing countries where the rapid growth of urban areas and construction of infrastructure is increasingly reaching areas overlying expansive clay deposits.

Expansive soils are characterized by active clay minerals and weak soil fabric, resulting in high plasticity, excessive compressibility, low bearing capacity, and poor durability under cyclic environmental conditions. These engineering deficiencies are mainly attributed to these factors [2]. These undesirable characteristics make untreated expansive soils unfit for use as pavement subgrades and foundation materials without stabilization treatment. As such, many stabilization methods have been developed to enhance the engineering properties of expansive clay soils.

Cement and lime are generally added to the soil to improve the strength of the soil and reduce plasticity, which is the traditional method of stabilization. However, the manufacturing of traditional stabilizers has high energy consumption and high CO2 emissions, which are related to environmental issues of sustainability [3]. With the growing concern for the environment and sustainable construction criteria, recent studies have been conducted on the use of industrial by-products, agricultural residues, and construction and demolition waste as environmentally friendly alternatives for soil stabilization [4].

The construction and demolition waste materials are of significant interest due to their substantial silica and alumina contents, which create pozzolanic reactions when stabilized in soil. The concrete wastes from the demolition of buildings, floor tiles, sanitary materials, and the pottery sector are a major source of landfill and environmental pollution [5]. The reuse of these types of waste materials in geotechnical applications would not only help in reducing the environmental burden, but also help in sustainable resource utilization and circular economy practices.

Past investigations have shown that waste from ceramics can be used as an effective modifier of the geotechnical characteristics of problematic soils. Sabat [6] reported that the incorporation of ceramic dust markedly decreases the plasticity properties of expansive soil, but increases the strength properties and the dimensional stability. Likewise, Cabalar *et al.* [7] noted that the addition of waste ceramic tiles resulted in better performance of pavement subgrade in soil stabilization applications. Also, the study on tropical residual soils showed that ceramic tile dust decreased the plasticity index and increased unconfined compressive strength, which confirmed that ceramic waste is a good sustainable soil stabilizer [8].

Reactive silica and alumina content play significant roles in the effectiveness of ceramic waste stabilization, which can be reacted pozzolanic and geopolymeric by introducing appropriate alkali activators. Alkali activation has become a promising sustainable stabilization method since alkali activation can give rise to cementitious compounds that can improve soil structure and durability [9]. Alkali activators enhance dissolution of the aluminosilicate materials and formation of binding gels like calcium silicate hydrate (C-S-H) and sodium alumino-silicate hydrate (N-A-S-H), which enhances the strength of the soil and reduces the swell potential [10].

A number of investigations regarding geopolymer and alkali-activated stabilization have been carried out recently, and significant improvements in the expansive clay behavior have been reported. Murmu *et al.* [11] reported that alkali-activated fly ash geopolymer stabilized expansive clay had a significant reduction in free swell ratio (FSR) and improvement in unconfined compressive strength (UCS). Similarly, the durability and ductility of stabilized soils were improved by the use of alkali-activated palm oil fuel ash (POFA) as a binder by Abdeldjouad *et al.* [12] using a geopolymeric bonding mechanism. Luo *et al.* [13] also noted that the mechanical and microstructural characteristics of silty clay soils were significantly enhanced by metakaolin-based geopolymer stabilization by the formation of dense cementitious matrices.

While many studies have been devoted to the stabilization of ceramic waste individually, and other studies have focused on the stabilization of expansive clay individually by alkali activator, limited studies have been conducted on the combined use of pulverized ceramic waste and alkali activator for the stabilization of expansive clay. CKD functions in this system as the primary alkali activator, providing the calcium hydroxide necessary to initiate pozzolanic and geopolymeric reactions with the aluminosilicate-rich PCW. In addition, most of the past research has been concerned with strength properties, and relatively few studies have investigated the consistency limits and swell properties of expansive clay stabilized with a ceramic-based geopolymeric system. Thus, the present study aims to study the stabilization of expansive clay soil with the use of pulverized ceramic waste and alkali activator. This study specifically tested the properties of the materials, namely expansive clay soil, pulverized ceramic waste, and alkali activator, and investigated the effect of these materials on the consistency characteristics and swell behavior of the stabilized soil. It is hoped that the results will help to promote sustainable geotechnical engineering by the beneficial use of ceramic waste materials in the stabilization of expansive soils.

2. Literature Review

2.1. Expansive Clay Soil and Its Engineering Challenges

Expansive clay soils are characterized by excessive swelling and shrinkage resulting from seasonal moisture fluctuations and mineralogical activity within clay matrices [1]. These volumetric changes induce pavement heaving, cracking of foundations, and differential settlement of engineering structures. The engineering behavior of expansive soils is mainly influenced by the presence of highly active clay minerals, poor drainage conditions, and moisture sensitivity, which collectively contribute to high plasticity, low bearing capacity, and poor long-term durability [2].

The increasing global demand for infrastructure development has intensified the need for sustainable stabilization approaches capable of improving the mechanical and volumetric behavior of problematic soils. Conventional stabilizers such as lime and cement have historically been effective in improving expansive soils through cation exchange and pozzolanic reactions. However, their production is associated with high carbon emissions, energy consumption, and environmental degradation [3]. Consequently, recent studies have shifted toward the utilization of industrial wastes, agricultural residues, and geopolymeric binders as environmentally sustainable stabilization alternatives [4].

Recent review studies have shown that non-traditional stabilizers, including fly ash, slag, ceramic waste, rice husk ash, waste glass powder, and quarry dust, can substantially improve the engineering performance of expansive soils while simultaneously reducing environmental pollution and waste disposal challenges [14]. Geopolymerization-based stabilization has particularly gained attention because of its ability to generate cementitious gels capable of forming dense and durable soil matrices through alkali activation processes [15] [16].

2.2. Stabilization Using Ceramic Waste Materials

The amount of ceramic waste produced during construction and demolition is significant, and most of that waste is being sent to landfills, even though it has a high silica and alumina content [5]. The use of ceramic waste for geotechnical purposes has the double advantage of waste recycling and soil improvement, in addition to the environmental benefits. The pozzolanic nature of pulverized ceramic waste can provide further stabilization of soil by particle bonding and by microstructural densification [6].

Sabat [6] has studied the stabilization of expansive soil by waste ceramic dust, and found significant decreases in plasticity characteristics and an increase in strength and dimensional stability of the soil. The study showed that the inclusion of ceramic dust influenced the clay matrix and also suggested better particle packing, thus reducing the swell potential. In the same way, Cabalar *et al.* [7] found that waste ceramic tiles have a significant effect on the subgrade performance of problematic soils, especially influencing the compaction and deformation behavior.

The study of tropical residual soils also confirmed the suitability of ceramic waste as a soil stabilizer. In fact, Chong *et al.* [8] noted that ceramic tile dust reduced plasticity index and increased unconfined compressive strength as a result of increased interparticle bonding and decreased moisture sensitivity. The study also revealed that the finer particles of the ceramic increased the pozzolanic reactivity due to the higher surface area available to react chemically.

Other industrial wastes rich in silica have been used as stabilizers and have proved to be effective. Granite dust was also reported to significantly improve the geotechnical and microstructural characteristics of expansive soils by decreasing the swelling characteristics and increasing the California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) values by Abdelkader *et al.* [17]. Their microstructural analyses revealed that the soil became stabilized by changes in soil structure and the development of tighter matrices.

2.3. Geopolymerization and Alkali Activation in Soil Stabilization

Due to its reduced environmental impacts and excellent durability properties, geopolymer stabilization has become an alternative to the traditional cementitious stabilization [9]. Geopolymerisation is a process that entails dissolution of aluminosilicate materials under alkaline conditions, and their polycondensation reaction to form binding gels such as Ca-S-H (calcium silicate hydrate), Ca-A-S-H (calcium aluminosilicate hydrate), and Na-A-S-H (sodium aluminosilicate hydrate) [10].

However, the geopolymerization process is highly influenced by the composition of the precursors, alkali activator concentration, curing conditions, and silica-alumina availability. The review conducted by Rojas *et al.* [14] shows that geopolymeric stabilization, which is also considered a method of stabilization process, brings benefits to the performance of soil due to the reduction of porosity and the formation of denser cementitious structures that improve the compressive strength and durability of the soil. The review also concluded that the alkali activators used most frequently are sodium hydroxide and sodium silicate, as they help in dissolving silica and alumina species required for gel formation.

Murmu *et al.* [11] showed that the use of alkali-activated fly ash geopolymer improved the mechanical properties of expansive clay by reducing the free swell ratio and enhancing the compressive strength. In the same way, Luo *et al.* [13] revealed that the geopolymer stabilization of silty clay using metakaolin generated a dense cementitious matrix, which improved the microstructural and mechanical properties of the clay.

The performance of alkali-activated stabilization has also been good when agricultural wastes are used as precursors. Abdeldjouad *et al.* [12] found that using alkali-activated palm oil fuel ash in stabilized soils resulted in an improvement in the strength and ductility of the soils due to geopolymeric bonding mechanisms. Recent research on rice husk ash-based geopolymer showed good enhancement in the tensile and compressive strength related to the formation of the sodium aluminosilicate hydrate (N-A-S-H) gels [15]. The study also highlighted the importance of alkali activator concentration, sodium silicate-to-sodium hydroxide ratio, and curing conditions on the geopolymerization efficiency and mechanical performance.

2.4. Swell Behavior and Alkali-Induced Stabilization Mechanisms

Chemical interactions in the clay matrix are very influential on the swell behavior of expansive soils. In alkali activation, the clay mineralogy is changed, and secondary cementitious compounds are formed, which results in a decrease in moisture sensitivity and volumetric instability [10]. However, excessive alkali concentration can also cause undesirable mineralogical changes and over-swelling under certain conditions.

The swelling behavior of alkali-treated kaolinitic clays with fly ash and ground granulated blast furnace slag (GGBFS) was studied by Sruthi *et al.* [16]. It was reported that alkali-transformed soils suffered from serious swelling as a result of the physicochemical reactions of the clay minerals with the alkali solutions. However, the addition of fly ash and GGBFS significantly decreased the swelling properties by stabilization reactions and the development of calcium-aluminum-silicate compounds.

Microstructural analysis by X-ray diffraction (XRD), scanning electron microscopy (SEM), and thermogravimetric analysis (TGA) showed that the stabilization decreased the void spaces and increased the soil density by cementitious product formation. The same observations were made on other geopolymer studies in which the presence of C-S-H and N-A-S-H gels led to low swelling potentials and high durability [11] [13].

2.5. Combined Stabilization Using Pulverized Ceramic Waste and Alkali Activators

Recently, this mixture of pulverized ceramic waste and alkali activators has emerged as a potential sustainable solution for stabilization of problematic soils due to the synergistic effect between the aluminosilicate precursors and alkaline solutions. The pulverized ceramic waste contains high amounts of silica (SiO_2) and alumina (Al_2O_3), which are geopolymeric precursor materials that can take part in pozzolanic and geopolymerization reactions in alkaline environments [5] [6]. On addition of alkali activators like sodium hydroxide and sodium silicate, dissolution of silica and alumina species takes place, and then a polycondensation reaction forms stable cementitious gels, and soil is improved [9] [10].

The stabilization mechanism of combined geopolymeric systems includes the formation of calcium silicate hydrate (C-S-H), calcium aluminosilicate hydrate (C-A-S-H), and sodium aluminosilicate hydrate (N-A-S-H) gels, which can link soil particles to reduce pore spaces in the clay matrix [14]. Rojas *et al.* [14] showed that the geopolymerization produces dense cementitious structures that reduce the porosity, moisture susceptibility, and volumetric instability of the clay soils, which significantly improve the engineering behavior of these soils. The study also found that fine aluminosilicate particles are more reactive, attributed to the higher surface area and dissolution of fine particles in alkaline conditions.

It has been demonstrated in earlier research that the ceramic waste can be responsible for the reduction in plasticity and swell behavior independently due to the particle replacement effect and pozzolanic activity [6]-[8]. In the same way, alkali-activated systems with fly ash, slag, metakaolin, and rice husk ash have shown significant results with respect to the compressive strength, tensile strength, and durability of expansive soils [11]-[13] [15]. Murmu [11] reported that alkali-activated fly ash geopolymer was found to be very effective in reducing the free swell ratio and improving the compressive strength of expansive clay soil due to the formation of geopolymeric gel. Luo *et al.* [13] also demonstrated that alkali activation leads to the formation of dense microstructures, which can improve soil stiffness and durability.

Significant reduction in swelling behavior has also been reported when alkali activators are mixed with waste materials that are rich in aluminosilicates. According to Sruthi *et al.* [16], the use of fly ash and ground granulated blast furnace slag (GGBFS) in alkali-treated kaolinitic clays produced a significant decrease in the swelling due to the formation of calcium-aluminum-silicate compounds and denser microstructural arrangements. Microstructural studies based on XRD and SEM revealed that geopolymeric stabilization led to the reduction of void spaces in the clay and to a change in the morphology of the clay, forming stable reaction products.

The concentration of alkali activator and precursor composition also proved to be significant factors that influence the stabilization efficiency of rice husk ash geopolymer systems. Erhiferhi *et al.* [15] indicated that the ratio of sodium silicate to sodium hydroxide and the concentration of the activator had significant effects on the development of the tensile strength of geopolymer-stabilized deltaic clay soils. This study was based on the results that the strength improvement was due to the increased geopolymerization and production of sodium aluminosilicate hydrate (N-A-S-H) gels, which can bind soil particles for improving dimensional stability.

However, there are very few studies that have focused on the stabilization of expansive clay soil with pulverized ceramic waste and with alkali activator. Previous investigations have either been directed to the stabilization of ceramic wastes alone or to alkali-activated stabilization systems with the use of fly ash, slag, or agricultural ashes. Thus, there is limited information on the effect of pulverized ceramic waste and alkali activators on the consistency properties, swelling properties, and stabilization mechanisms of expansive soils. This gap indicates that the need for the geopolymeric interaction between the pulverized ceramic waste and alkali activators for sustainable expansive soil stabilization applications is still to be investigated.

2.6. Research Gap

Previous research has confirmed the beneficial effect of ceramic waste, industrial by-products, and geopolymeric stabilizers on improving the properties of expansive soil [6]-[13]. However, most of the studies carried out so far have focused on strength enhancement, compaction characteristics, and compressive behavior, and limited studies have been conducted on the combined effect of pulverized ceramic waste and alkali activators on consistency characteristics and swell behavior. While the geopolymer stabilization mechanisms are well studied for fly ash, slag, and rice husk ash, limited research has been done regarding the use of pulverized ceramic waste as a geopolymer precursor in expansive clay stabilization systems. The mechanisms of the interaction between ceramic wastes and the alkali activators, especially the aspects of consistency limits and the mechanism of swell reduction, are not well enough known.

Therefore, the aim of the present study is to assess the material characterization, consistency behavior, and swell characteristics of expansive clay stabilized with pulverized ceramic waste and alkali activator. The study aimed to promote sustainable geotechnical engineering by encouraging the use of ceramic waste materials in a beneficial manner for expansive soil stabilization.

3. Research Methodology

3.1. Materials

3.1.1. Expansive Clay Soil

The expansive clay soil used in this study was obtained from the Konza area of Machakos County, Kenya (approximately 60 km southeast of Nairobi; GPS: ~1.75˚S, 37.15˚E), a locality characterized by heavily expansive black cotton soil subgrade. Disturbed samples were collected from five sampling pits at depths ranging from 1.0 m to 1.5 m below the natural ground surface; equal-mass sub-samples from each pit were combined into a single composite sample for all subsequent laboratory characterization tests. Disturbed soil samples were collected from depths ranging between 1.0 m and 1.5 m below the natural ground surface in order to minimize the influence of organic matter and surface contamination. The collected soil was sealed in airtight polyethylene bags immediately after sampling to preserve its natural moisture condition prior to laboratory preparation.

In the laboratory, the soil samples were air-dried under room temperature conditions for 72 h and subsequently pulverized using a wooden mallet to disaggregate soil lumps without altering the natural soil mineralogy. The pulverized soil was then sieved through a 4.75 mm sieve in accordance with BS 1377 and ASTM D6913 procedures to remove oversized particles and obtain a uniform material suitable for laboratory testing.

3.1.2. Pulverized Ceramic Waste

Waste ceramic materials were obtained from discarded floor and wall tiles collected from construction and demolition sites. The ceramic wastes were thoroughly washed with clean water to eliminate dust, adhered mortar, and other contaminants that could interfere with pozzolanic reactions. The cleaned ceramic wastes were oven-dried at 105˚C ± 5˚C for 24 h to remove residual moisture prior to pulverization.

The dried ceramic materials were mechanically crushed using a jaw crusher, followed by grinding in a Los Angeles abrasion machine until a fine powder was obtained. The pulverized ceramic waste (PCW) was subsequently sieved through a 75 μm sieve to obtain fine powder suitable for geopolymerization and pozzolanic stabilization. The particle size selected was intended to maximize specific surface area and enhance the dissolution of silica and alumina during alkali activation.

3.1.3. Alkali Activator

The alkali activator used in this study consisted of sodium hydroxide (NaOH) solution and sodium silicate (Na_2SiO_3) solution. The alkali activator comprised a combination of 10 M sodium hydroxide (NaOH) solution and commercial sodium silicate (Na_2SiO_3) solution mixed at a sodium silicate-to-NaOH mass ratio of 2.5:1. The activator solution was prepared 24 h before specimen mixing to allow the exothermic dissolution to stabilize. Cement kiln dust (CKD) was incorporated as a supplementary calcium-rich binder at replacement levels of 5%, 10%, and 15% by dry weight of soil. The activator solution was added at a liquid-to-binder ratio of 0.45 by mass of total binder (PCW + CKD). Distilled water was subsequently added as necessary to bring each mixture to its respective optimum moisture content prior to compaction.

3.2. Experimental Design

The study adopted an experimental laboratory research design involving material characterization, consistency analysis, and swell evaluation of expansive clay soil stabilized using pulverized ceramic waste and alkali activator. The investigation was structured into three major phases:

1) Characterization of the expansive clay soil, pulverized ceramic waste, and alkali activator.

2) Evaluation of consistency characteristics of stabilized expansive clay soil.

3) Assessment of the swell behavior of stabilized expansive clay soil.

The stabilization program involved partial replacement of expansive clay soil with pulverized ceramic waste at varying percentages by dry weight of soil. The selected replacement levels consisted of 0%, 5%, 10%, 15%, 20%, and 25% PCW. Analytical-grade sodium hydroxide pellets were dissolved in distilled water to prepare the desired molarity concentration. The prepared NaOH solution was allowed to cool and equilibrate for 24 h before use because of the exothermic nature of the dissolution process.

Commercial-grade sodium silicate solution was then mixed with the sodium hydroxide solution at predetermined proportions to form the alkaline activator. The activator solution was prepared immediately prior to specimen mixing to maintain chemical stability and ensure adequate geopolymerization efficiency. The alkali activator was incorporated at a constant activator-to-binder ratio established through preliminary trials and literature recommendations.

3.3. Material Characterization

3.3.1. Physical Properties of Expansive Clay Soil

The physical properties of the untreated expansive clay soil were determined in accordance with BS 1377 and ASTM testing procedures. The tests conducted included:

- Natural moisture content
- Specific gravity
- Particle size distribution
- Atterberg limits
- Free swell index

Natural moisture content was determined using the oven-drying method at 105˚C ± 5˚C for 24 h. Specific gravity was determined using a pycnometer apparatus. Particle size distribution analysis involved both sieve analysis and hydrometer analysis to establish the soil gradation and percentage of clay-sized particles.

Atterberg limits comprising liquid limit, plastic limit, and plasticity index were determined using the Casagrande apparatus and rolling thread methods. Free swell index tests were conducted to evaluate the swelling potential of the untreated expansive clay soil.

3.3.2. Chemical and Mineralogical Characterization

Chemical characterization of the pulverized ceramic waste and expansive clay soil was conducted using X-ray fluorescence (XRF) analysis to determine the major oxide compositions, including SiO_2, Al_2O_3, CaO, Fe_2O_3, MgO, and Na_2O. The oxide composition was used to assess the suitability of the materials for geopolymerization and pozzolanic stabilization.

Mineralogical analysis was performed using X-ray diffraction (XRD) to identify dominant clay minerals and crystalline phases present in the soil and ceramic waste. The analysis facilitated understanding of the stabilization mechanisms and geopolymeric interactions occurring within the treated soil matrix.

Microstructural characterization was conducted using scanning electron microscopy (SEM) to evaluate morphological changes induced by stabilization. SEM images were used to examine particle arrangement, pore structure, and formation of geopolymeric gels within the stabilized specimens.

3.4. Preparation of Stabilized Soil Specimens

The required quantities of expansive clay soil and pulverized ceramic waste were measured based on dry weight proportions. Dry mixing was initially performed to achieve uniform distribution of the ceramic waste within the soil matrix. The alkali activator solution was then gradually added while mixing continuously to ensure homogeneity.

Distilled water was added where necessary to achieve the optimum moisture content corresponding to maximum dry density. The resulting mixture was sealed in airtight polyethylene bags and allowed to equilibrate for 24 h to facilitate moisture distribution and initial geopolymerization reactions.

3.5. Consistency Limit Tests

Consistency characteristics of the stabilized soil mixtures were evaluated through liquid limit, plastic limit, and plasticity index tests conducted in accordance with ASTM D4318 and BS 1377 procedures. The tests were performed on untreated soil and all stabilized mixtures to assess the influence of pulverized ceramic waste and alkali activation on soil plasticity behavior.

The liquid limit was determined using the Casagrande cup method, while the plastic limit was obtained by rolling soil threads to a diameter of 3 mm. Plasticity index values were subsequently computed as the difference between the liquid limit and plastic limit.

3.6. Swell Tests

3.6.1. Free Swell Index Test

The free swell index test was conducted to evaluate the swelling characteristics of untreated and stabilized expansive clay soils. Oven-dried soil passing through a 425 μm sieve was poured separately into graduated cylinders containing distilled water and kerosene. The swell index was computed based on the difference in sediment volumes.

3.6.2. Curing Procedure

Prepared stabilized specimens were sealed in polyethylene wraps immediately after compaction to minimize moisture loss during curing. The specimens were cured under controlled laboratory temperature conditions of 25˚C ± 2˚C for curing periods of 7, 14, and 28 days.

The curing process was intended to facilitate geopolymerization and pozzolanic reactions between the aluminosilicate-rich ceramic waste and alkali activator. Following curing, specimens were subjected to consistency and swell tests.

3.7. Data Analysis

Experimental results were analyzed using descriptive and comparative statistical techniques. Mean values and percentage variations were computed for all measured parameters. The influence of pulverized ceramic waste content on consistency characteristics and swell behavior was evaluated using trend analysis and graphical representation.

3.8. Reliability and Quality Control

All laboratory tests were conducted in triplicate to ensure repeatability and reliability of results. Calibration of testing equipment was performed prior to experimentation in accordance with laboratory quality assurance procedures. Standardized testing protocols specified in ASTM and BS standards were strictly followed throughout the experimental program to ensure accuracy and reproducibility of findings.

4. Results

4.1. Materials Characteristics

4.1.1. Particle Distribution

These were the results of a Particle Size Distribution (PSD) test carried out on an expansive soil sample using standard sieve analysis. The purpose was to assess the gradation characteristics and determine the proportion of fine and coarse particles, and is presented in **Figure 1**.

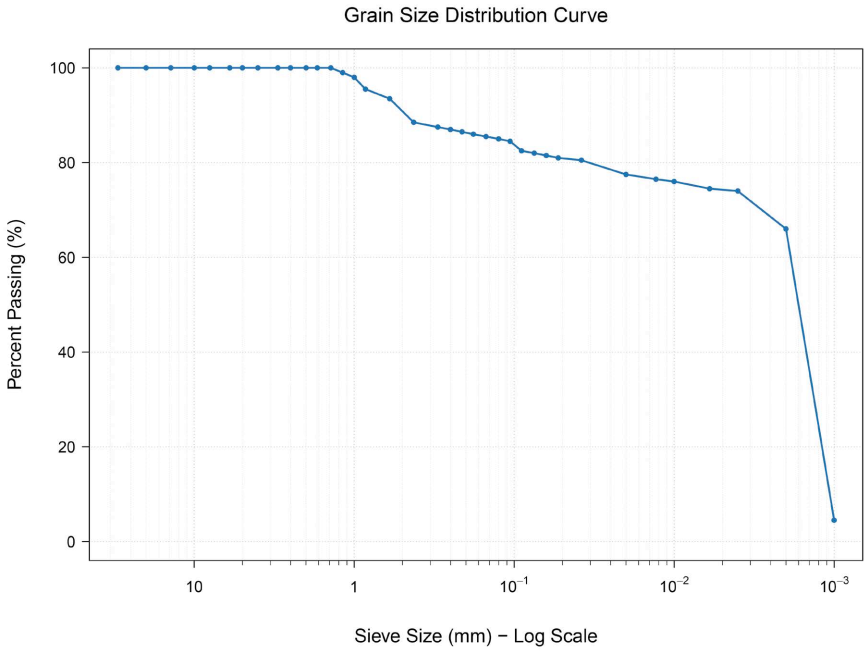

Figure 1. Particle size distribution curve.

Figure 1 indicates that the soil sample shows 100% passing for all coarse and medium gravel sizes (>4.75 mm), indicating an absence of gravel. Approximately 86.84% of the material passes the 0.075 mm sieve, classifying it as a fine-grained soil. The curve suggests the soil is well-graded with a smooth transition from coarse to fine particles. The steep slope in the fine region implies a relatively narrow distribution of fine particles, likely silt or clay. Based on the Unified Soil Classification System (USCS), Soils with more than 50% passing the No. 200 sieve (0.075 mm) are classified as fine-grained. Given 86.84% passing the 0.075 mm sieve, this soil is classified as highly plastic clay (CH).

4.1.2. Specific Gravity

The specific gravity of expansive clay soil was tested in a pycnometer following the testing procedures outlined in BS 1377. Specific gravity values were measured in the range of 2.10 to 2.41, with the average value being 2.26 at the laboratory temperature of 20˚C. The values obtained are within the typical range as determined for highly plastic clay soils, and suggest that the soil is dominated by aluminosilicate clay minerals as the predominant mineral within the soil matrix. Specific gravity values are relatively low as compared with quartz-dominated soils, which typically have specific gravities of about 2.65, indicating the presence of low-density clay minerals, such as montmorillonite and kaolinite. The moisture absorption and surface activity of these minerals generally render them associated with expansive soils. The specific gravity characteristics observed are thus in agreement with the expansive nature of the soil investigated and help in its classification as black cotton soil.

The lower densities of expansive clay minerals are related to their layered crystalline structure and relatively high void ratio, which gives them an increase in water affinity and volumetric instability. The mineralogical composition and physicochemical properties of expansive soils containing montmorillonitic clay minerals usually result in lower specific gravity values, which are reported by Kavur *et al.* [18]. The results obtained thus indicate that the mineralogical properties of the investigated soil are linked to high swelling and shrinkage characteristics, and thus the soil needs to be stabilized before being used in engineering applications.

4.1.3. Atterberg Limits for Untreated Expansive Soil

The untreated expansive clay soil had a liquid limit (LL) of 89.68%, a plastic limit (PL) of 22.21%, and a plasticity index (PI) of 67.47%. The Atterberg limit values obtained show that the soil is very plastic and also highly sensitive to moisture. Based on typical soil classification schemes, soils with a liquid limit > 50% and high plasticity indices are typically classified as highly plastic expansive clays.

The very high liquid limit is an indication of the soil's ability to retain water, which is a characteristic of soils containing active clay minerals like montmorillonite. Likewise, a higher plasticity index represents a broad range of moisture conditions where the soil is plastic and deformable, and therefore is highly sensitive to swelling and shrinkage due to changes in the environment. These are the properties of black cotton soils and are in agreement with the properties of expansive soil behavior reported in earlier studies [1] [18].

The high plastic property of the soil investigated indicates that the soil is not very engineering suitable in its untreated state. Soils with high LL and PI values are recognized as expansive soils that can experience excessive volumetric instability, causing pavement heaving, differential settlement, shrinkage cracks, and distress in foundations and transportation infrastructure. As stated by Kavur *et al.* [18], when moisture enters the expansive soils, they expand considerably physically and chemically due to the hydration of the active clay minerals and rearrangement of the internal structure of the soil. Thus, the results obtained validate the expansive behavior of the soil and the need for its stabilization to enhance its engineering properties and dimensional stability.

4.1.4. Free Swell Index of Untreated Expansive Soil

The untreated expansive clay soil had a value of 193.75% FSI, which is an extremely high swelling potential. Soils with FSI values of less than 50% are generally regarded as being of low expansiveness, and those with FSI values greater than 100% are classified as highly expansive soils. Thus, the result obtained corroborates the high expansiveness of the soil studied and its high susceptibility to moisture-induced volume change due to moisture. This high swell potential could be explained by the high percentage of active clay minerals having expansive lattice structures and high-water absorption capacity, such as the montmorillonite. Hydration of exchangeable cations in the interlayer space of clay minerals produces a physicochemical swelling and a significant volume increase when it comes in contact with water. Upon drying, loss of water in the drying process causes shrinkage, desiccation cracking, and hence repeated shrink-swell cycles, which have a negative effect on engineering constructions.

The swelling characteristics observed in these soils are typical of black cotton soils and contribute to the poor engineering performance of expansive clay deposits. Generally, higher FSI values are indicative of soils with low bearing capacity, high compressibility, pavement heaving, differential settlement, and foundation and transportation structural instability. As reported by Das *et al.* [19], expansive soils containing montmorillonite minerals exhibit a strong swelling phenomenon due to the effect of water absorbed between the particles and the diffuse double-layer expansion.

The high swell index result from this study indicates that it correlates with the Atterberg limit results, in which high liquid limit and plasticity index have been obtained. Thus, the results of the combined tests verify that the soil investigated is severely expansive and should be stabilized before it can be used in engineering applications such as pavements, embankments, and shallow foundations.

4.1.5. XRD

X-ray diffraction (XRD) analysis was conducted on three representative samples designated as Sample A, Sample B, and Sample C in order to determine their mineralogical compositions and crystalline phases. In all XRD and XRF analyses, Sample A represents the untreated expansive clay soil, Sample B represents cement kiln dust (CKD), and Sample C represents pulverized ceramic waste (PCW). This designation is maintained consistently throughout Tables 1-6 and the accompanying discussion.

Sample A

The mineralogical composition of Sample A (expansive clay soil), as presented in Table 1, is dominated by Moganite (94.4%), a monoclinic silica polymorph, with a minor phase of Filipstadite (5.6%), a complex iron-magnesium-antimony oxide. The high Moganite content indicates substantial reactive silica within the soil matrix, which can participate in pozzolanic reactions when combined with calcium-bearing activators. The low concentration of Filipstadite reflects minor iron-bearing accessory mineralogy. XRD patterns were collected using a Bruker D6 Phaser diffractometer (Cu Kα radiation, 2θ range 5˚ - 70˚), and phase identification was performed using the DIFFRAC.EVA software suite with reference to the ICDD PDF-4+ crystal database; only phases achieving a figure-of-merit match quality score ≥70% were reported.

Table 1. XRD Sample A profile.

Compound Name	Formula	Phase Type	Concentration (%)	Crystal System	Space Group (No.)	Density (g/cm³)
Filipstadite	$Fe_{24\cdot 97}Mg_{35\cdot 53}O_{108}Sb_{20\cdot 496}$	Complex Oxide	5.6%	Cubic	F d −3 m:2 (227)	4.940
Moganite	O_2Si	Silica	94.4%	Monoclinic	I 1 2/a 1 (15)	2.620

The presence of Sodium Alum suggests active ionic constituents and soluble aluminosulfate phases within the sample. Such phases may contribute to cation exchange reactions during stabilization and enhance chemical interaction between soil particles and alkali activators. The occurrence of scandium and oxynitride phases further reflects mineralogical diversity and indicates the presence of trace metallic and nitrogen-bearing compounds within the material matrix.

Sample B

Sample B, as presented in Table 2, exhibited a mineralogical composition dominated by calcite (54.8%), with secondary phases comprising Clinomimetite (32.0%) and Galaxite (13.2%). The predominance of calcite indicates a carbonate-rich composition and suggests the presence of calcium-bearing minerals capable of contributing to cementitious stabilization reactions. Calcite plays a significant role in stabilization processes because calcium ions enhance flocculation and agglomeration of clay particles while promoting the formation of calcium silicate hydrate (C-S-H) compounds under reactive conditions. The high calcite content, therefore, suggests that Sample B possesses considerable potential for improving soil structure and reducing plasticity characteristics. Galaxite, identified as a manganese-aluminum spinel oxide, indicates the occurrence of transition metal oxides that may influence mineral stability and chemical durability. The presence of clinomimetite, an arsenate mineral, reflects complex geochemical interactions and suggests mineralogical evolution associated with carbonate or metal-rich environments.

Table 2. XRD Sample B profile.

Compound Name	Formula	Phase Type	Concentration (%)	Crystal System	Space Group (No.)	Density (g/cm³)
Calcite	$CCaO_3$	Carbonate	54.8%	Hexagonal	R −3 c:H (167)	2.710
Galaxite	$Al_{2.11}Mn_{0.89}O_4$	Spinel-type Oxide	13.2%	Cubic	F d −3 m:2 (227)	4.120
Clinomimetite	$As_3ClO_{12}Pb_5$	Arsenate	32.0%	Monoclinic	P 1 1 21/b (14)	7.370

Sample C

Sample C, as presented in **Table 3**, was dominated by Moganite (94.4%), with minor occurrence of Filipstadite (5.6%). The exceptionally high concentration of Moganite confirms that the sample is highly silica-rich and possesses substantial geopolymerization potential. The abundance of silica-bearing phases is advantageous in stabilization applications because reactive silica contributes significantly to the formation of geopolymeric and pozzolanic reaction products under alkaline environments. The dominance of Moganite therefore indicates that Sample C may exhibit excellent compatibility with alkali activators and may contribute to improved strength development and reduced swell potential in stabilized expansive soils. The presence of Filipstadite, a complex iron-magnesium-antimony oxide, indicates additional mineralogical complexity and suggests possible igneous or volcanic influence in the material origin. Such mineral assemblages are commonly associated with highly crystalline silica-rich geological formations.

Table 3. XRD Sample C profile.

Compound Name	Formula	Phase Type	Concentration (%)	Crystal System	Space Group (No.)	Density (g/cm³)
Filipstadite	$Fe_{24.97}Mg_{35.53}O_{108}Sb_{20.496}$	Complex Oxide	5.6%	Cubic	F d −3 m:2 (227)	4.940
Moganite	O_2Si	Silica	94.4%	Monoclinic	I 1 2/a 1 (15)	2.620

The XRD results collectively indicate that the investigated samples possess substantial quantities of silica-bearing and calcium-bearing mineral phases, which are highly favorable for stabilization and geopolymerization processes. Samples A and

C demonstrated high reactive silica contents, while Sample B exhibited dominant carbonate phases capable of contributing calcium ions during stabilization. The mineralogical compositions, therefore, suggest strong potential for chemical interaction, pozzolanic reactivity, and enhanced stabilization performance when combined with alkali activators in expansive soil treatment applications.

4.1.6. XRF

X-ray fluorescence (XRF) analysis was conducted on Samples A, B, and C to determine their elemental oxide compositions and evaluate their chemical suitability for stabilization applications. Sample codes are as defined in Section 4.1.5.

Sample A

Sample A, as presented in Table 4, was predominantly composed of silicon dioxide (SiO_2), accounting for 52.214% of the total oxide composition, followed by ferric oxide (Fe_2O_3) at 30.568%. Additional oxides identified included potassium oxide (K_2O) at 9.153%, calcium oxide (CaO) at 4.354%, and titanium dioxide (TiO_2) at 1.599%, alongside minor quantities of MnO, ZrO_2, SO_3, SrO, CuO, and NbO.

Table 4. XRF Sample A results.

Analyte (Oxide)	Result (%)
SiO_2	52.214
Fe_2O_3	30.568
K_2O	9.153
CaO	4.354
TiO_2	1.599
MnO	1.339
ZrO_2	0.401
SO_3	0.120
SrO	0.100
CuO	0.090
NbO	0.061

The high silica content indicates that Sample A is silica-rich and possesses substantial pozzolanic and geopolymeric potential. Silica plays a critical role in stabilization because reactive SiO_2 participates in the formation of cementitious compounds such as calcium silicate hydrate (C-S-H) and sodium aluminosilicate hydrate (N-A-S-H) under alkaline conditions. The abundance of silica, therefore, suggests that the material may significantly contribute to strength enhancement and reduction of swell characteristics in stabilized expansive soils.

The elevated ferric oxide concentration further indicates the presence of iron-rich mineral phases commonly associated with ceramic waste materials and aluminosilicate-rich geological formations. Iron oxides may contribute to stabilization through densification of the soil matrix and enhancement of chemical bonding reactions. The relatively high potassium oxide content suggests the occurrence of feldspathic minerals or potassium-bearing ceramic constituents, which are commonly found in fired clay products and ceramic materials. The moderate calcium oxide content indicates the presence of limited calcium-bearing compounds capable of supporting secondary pozzolanic reactions. Minor oxide constituents such as titanium dioxide, manganese oxide, and zirconium oxide likely represent accessory minerals and trace elemental inclusions within the material matrix.

Sample B

The XRF results for Sample B, as presented in **Table 5**, revealed a dominant calcium oxide (CaO) concentration of 80.059%, with secondary oxides including ferric oxide (Fe_2O_3) at 8.061%, silicon dioxide (SiO_2) at 6.567%, and potassium oxide (K_2O) at 4.363%. Minor quantities of titanium dioxide, manganese oxide, strontium oxide, bromine, and zirconium oxide were also detected.

Table 5. XRF Sample B results.

Analyte (Oxide)	Result (%)
CaO	80.059
Fe_2O_3	8.061
SiO_2	6.567
K_2O	4.363
TiO_2	0.474
MnO_2	0.206
SrO	0.155
Br	0.076
ZrO_2	0.038
CaO	80.059
Fe_2O_3	8.061

The exceptionally high calcium oxide content indicates that Sample B is strongly calcareous in nature and likely originates from calcium-rich industrial materials such as lime-based products or cement kiln dust. Calcium oxide is a critical component in stabilization because it facilitates cation exchange, flocculation, agglomeration, and pozzolanic reactions within expansive clay soils.

The dominance of CaO suggests that Sample B possesses substantial chemical stabilization potential through the formation of calcium silicate hydrate (C-S-H) compounds when combined with silica-rich materials. The coexistence of moderate ferric oxide and silica contents further supports the likelihood of secondary cementitious reactions and matrix densification during stabilization. The relatively low silica content compared to Sample A indicates that Sample B primarily functions as a calcium-rich activator rather than a silica precursor. Trace oxides such as SrO, Br, and ZrO_2 likely represent residual mineral inclusions or impurities associated with industrial processing.

Sample C

Sample C, as presented in **Table 6**, was characterized by high concentrations of silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3), accounting for 41.865% and 30.548%, respectively. Additional oxides included potassium oxide (K_2O) at 14.866%, calcium oxide (CaO) at 5.091%, ferric oxide (Fe_2O_3) at 4.902%, and smaller quantities of ZrO_2, TiO_2, ZnO, SrO, and Rb_2O. The combined silica and alumina content exceeding 70% indicates that Sample C is highly aluminosilicate-rich and therefore possesses excellent geopolymerization potential. Aluminosilicate materials are essential in geopolymer stabilization because they provide the reactive species necessary for the formation of durable geopolymeric gels under alkaline conditions.

Table 6. XRF Sample C results.

Analyte (Oxide)	Result (%)
SiO_2	41.865
Al_2O_3	30.548
K_2O	14.866
CaO	5.091
Fe_2O_3	4.902
ZrO_2	1.214
TiO_2	1.094
ZnO	0.302
SrO	0.084
Rb_2O	0.033
SiO_2	41.865

The elevated potassium oxide content suggests the presence of feldspar minerals and potassium-bearing ceramic constituents commonly associated with fired clay and ceramic products. Potassium-bearing compounds may influence alkali activation reactions and contribute to enhanced dissolution of silica and alumina during geopolymerization. The moderate calcium oxide concentration indicates the potential for supplementary pozzolanic reactions, while ferric oxide contributes additional mineralogical complexity and possible enhancement of matrix densification. Minor oxides, including zirconium oxide and titanium dioxide, likely represent accessory mineral phases within the material.

The XRF results collectively demonstrated that Samples A and C are rich in silica and aluminosilicate compounds, while Sample B is dominated by calcium oxide. This complementary chemical composition suggests strong compatibility for combined stabilization applications involving geopolymerization and pozzolanic reactions. The high reactive silica and alumina contents of Samples A and

C, together with the calcium-rich composition of Sample B, indicate substantial potential for the formation of cementitious and geopolymeric products capable of improving the consistency characteristics and swell behavior of expansive clay soils.

4.2. Consistency and Swell Properties

Liquid Limit

The liquid limit (LL) represents the moisture content at which soil transitions from a plastic state to a liquid state and serves as an important indicator of soil consistency and moisture susceptibility. Figure 2 indicates that the untreated expansive clay soil exhibited a very high liquid limit of 89.68%, confirming the highly plastic and expansive nature of the investigated soil. Such elevated liquid limit values are characteristic of montmorillonite-rich expansive soils and indicate substantial water adsorption capacity, high compressibility, and poor engineering performance under fluctuating moisture conditions.

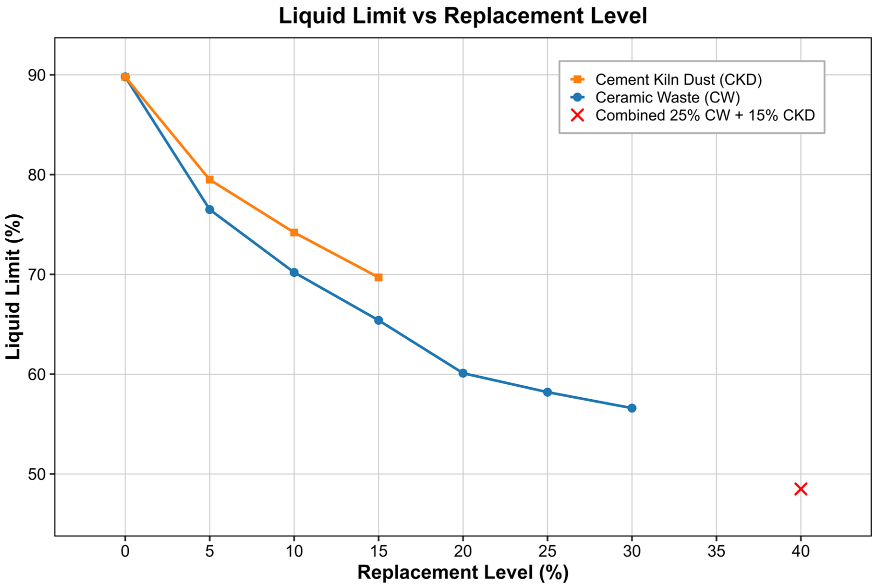

Figure 2. Liquid limit vs. replacement level.

The incorporation of ceramic waste (CW) resulted in a progressive and significant reduction in liquid limit values with increasing stabilizer content. The LL decreased consistently from 89.68% for the untreated soil to 56.54% at 30% CW replacement. The observed reduction indicates that ceramic waste effectively decreased the moisture sensitivity and plastic behavior of the expansive clay soil. The improvement may be attributed to cation exchange, flocculation, and agglomeration processes occurring between clay particles and the silica-rich ceramic waste, which altered the soil structure and reduced its capacity to retain absorbed water.

The reduction in liquid limit further suggests that the addition of ceramic waste promoted the replacement of active clay fractions with comparatively non-plastic particles, thereby reducing the thickness of the diffuse double layer surrounding clay minerals. Similar observations were reported by Sabat [6], who noted that ceramic dust stabilization substantially reduced the liquid limit and plasticity characteristics of expansive soils because of pozzolanic interactions and improved particle packing.

In comparison, cement kiln dust (CKD)-stabilized specimens exhibited a relatively slower reduction in liquid limit values. The LL decreased from 79.50% at 5% CKD to 69.70% at 15% CKD, indicating that although CKD contributed to consistency improvement, its influence on moisture sensitivity reduction was less pronounced than that of ceramic waste. The reduction associated with CKD stabilization may be attributed to the high calcium oxide content of CKD, which promotes cation exchange and flocculation of clay particles through lime-like stabilization mechanisms.

The comparatively superior performance of ceramic waste in reducing liquid limit may be associated with its high silica content and finer particle distribution, which enhanced pozzolanic reactivity and facilitated greater modification of the clay matrix. The interaction between reactive silica and calcium-bearing compounds likely contributed to the formation of secondary cementitious products capable of reducing water affinity within the soil structure.

The optimum combined stabilization mixture consisting of 25% CW and 15% CKD produced the most substantial reduction in liquid limit, decreasing the LL to 48.50%. This value represents a remarkable improvement compared to the untreated expansive soil and demonstrates the effectiveness of combined stabilization using ceramic waste and CKD. The significant reduction observed in the combined mix exceeded the improvements achieved by the individual additives at their respective optimum contents, indicating the occurrence of synergistic stabilization effects.

The enhanced performance of the combined mixture may be attributed to the interaction between the silica-rich ceramic waste and the calcium-rich CKD, which promoted extensive pozzolanic and cementitious reactions within the soil matrix. The combined stabilization mechanism likely enhanced particle bonding, reduced diffuse double-layer thickness, and generated denser soil fabric through the formation of calcium silicate hydrate (C-S-H) and other cementitious compounds. Consequently, the soil exhibited substantially lower water affinity and improved consistency behavior.

Plastic Limit

The plastic limit (PL) represents the moisture content at which soil transitions from a semi-solid state to a plastic state and serves as an important indicator of soil workability and plastic behavior. The untreated expansive clay soil exhibited a relatively low plastic limit, reflecting the high activity and moisture sensitivity commonly associated with expansive clay minerals. Following stabilization with ceramic waste (CW) and cement kiln dust (CKD), a progressive increase in plastic limit values was observed, indicating substantial improvement in soil consistency characteristics and reduction in clay activity.

Figure 3 indicates that for ceramic waste stabilization, the plastic limit increased steadily from 24.32% at 5% CW replacement to 35.02% at 30% CW replacement. The continuous increase in PL values demonstrates the effectiveness of ceramic waste in modifying the plastic behavior of the expansive clay soil. The improvement may be attributed to the replacement of highly active clay particles with comparatively non-plastic ceramic particles, resulting in reduced moisture sensitivity and improved particle arrangement within the soil matrix. The increase in plastic limit further suggests that ceramic waste promoted flocculation and agglomeration of clay particles through pozzolanic interactions, thereby reducing the thickness of the diffuse double layer surrounding expansive clay minerals. Similar observations were reported by Sabat [6], who noted that ceramic waste stabilization improved soil consistency characteristics by reducing clay activity and enhancing soil workability.

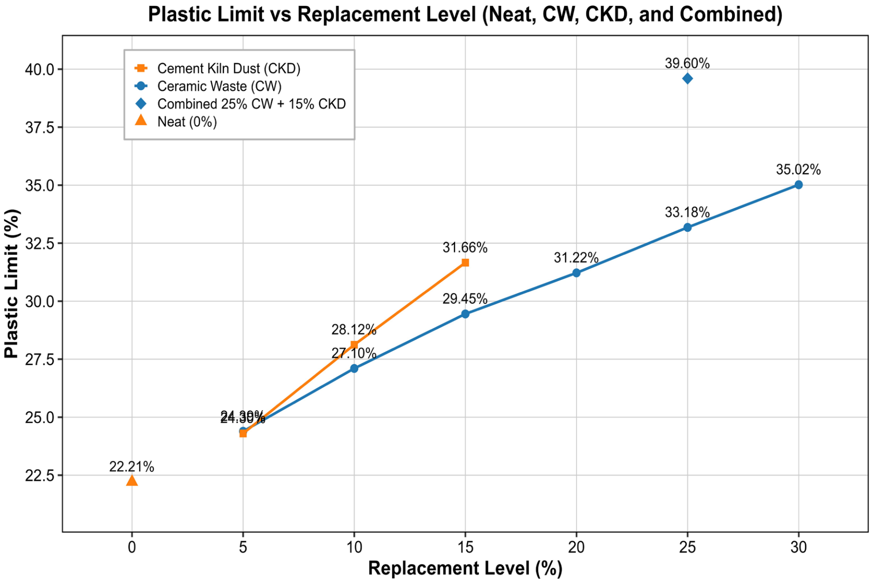

Figure 3. Comparative trend of plastic limit variation for CW and CKD.

In the case of CKD stabilization, the plastic limit increased from 24.29% at 5% CKD replacement to 31.66% at 15% CKD replacement. The increase observed with CKD stabilization may be associated with the high calcium oxide content of CKD, which promotes cation exchange, flocculation, and cementitious reactions within the expansive clay matrix. These reactions reduce the affinity of clay minerals for water and transform the soil structure into a more stable and aggregated form. Although both stabilizers improved plastic limit values, ceramic waste exhibited comparatively greater effectiveness in increasing the PL at higher replacement levels. This behavior may be associated with the high silica and alumina contents of ceramic waste, which contribute to enhanced pozzolanic reactivity and improved particle interlocking within the stabilized soil system.

The combined stabilization mixture consisting of 25% CW and 15% CKD produced the highest plastic limit value of 39.60%, representing the maximum improvement among all investigated mixtures. The substantial increase in PL indicates a strong synergistic interaction between ceramic waste and CKD during stabilization. The silica-rich ceramic waste likely enhanced pozzolanic activity and facilitated particle rearrangement, while the calcium-rich CKD accelerated cementitious bonding and promoted the formation of stable reaction products within the soil matrix. The combined stabilization mechanism, therefore, resulted in the development of a denser and more stable soil structure with significantly reduced plasticity and improved workability characteristics. The increase in plastic limit further indicates reduced moisture susceptibility and improved dimensional stability of the expansive clay soil following stabilization.

Plasticity Index

The plasticity index (PI), defined as the difference between the liquid limit and plastic limit, represents the moisture range over which soil remains plastic. It is one of the most important indicators used to evaluate the expansiveness, workability, and volumetric stability of clay soils. High PI values are generally associated with highly active expansive soils that exhibit significant swelling, shrinkage, and moisture sensitivity. Figure 4 indicates that the untreated expansive clay soil exhibited a very high plasticity index, confirming the presence of highly plastic clay minerals and severe expansive characteristics. Following stabilization with ceramic waste (CW), a substantial and progressive reduction in PI values was observed with increasing replacement levels. The plasticity index decreased continuously, reaching a minimum value of 20.97% at 30% CW replacement. This pronounced reduction demonstrates the effectiveness of ceramic waste in modifying the plastic behavior of expansive clay soil and improving its engineering suitability.

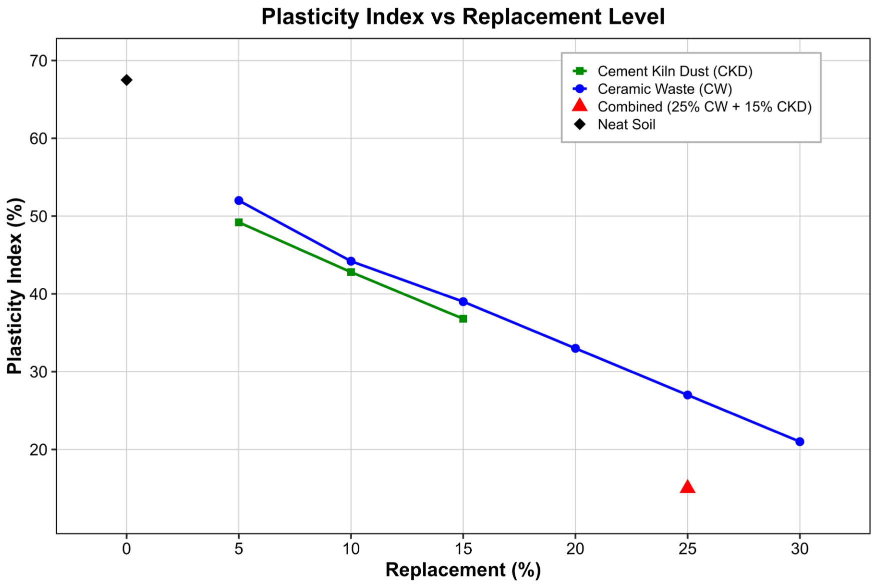

Figure 4. Plasticity index vs replacement level.

The reduction in PI associated with CW stabilization may be attributed to several physicochemical mechanisms, including cation exchange, flocculation, agglomeration, and pozzolanic reactions. The incorporation of ceramic waste likely replaced part of the highly active clay fraction with comparatively non-plastic silica-rich particles, thereby reducing the soil's moisture affinity and plastic deformation capacity. Furthermore, the high silica and alumina contents of ceramic waste may have facilitated the formation of secondary cementitious compounds capable of enhancing soil particle bonding and reducing clay activity. CKD-stabilized soils exhibited a comparatively less pronounced reduction in plasticity index values. The PI decreased from 49.2% to 36.8% across the investigated CKD replacement range. Although CKD contributed to improvement in soil consistency characteristics through flocculation and cementitious stabilization mechanisms, its influence on plasticity reduction was less significant than that achieved using ceramic waste. The improvement observed with CKD stabilization may be associated with the high calcium oxide content of the material, which promotes cation exchange and aggregation of clay particles. The resulting reduction in diffuse double-layer thickness decreases the water adsorption capacity of expansive clay minerals and improves soil stability. However, the comparatively lower reduction in PI suggests that CKD alone may not sufficiently alter the clay matrix to the same extent as silica-rich ceramic waste. The observed results therefore indicate that ceramic waste is more effective than CKD in reducing the plasticity of expansive clay soils.

The combined optimum stabilization mixture consisting of 25% CW and 15% CKD produced the lowest plasticity index value of 15%, representing the greatest reduction among all stabilized mixtures. The substantial decrease in PI demonstrates a strong synergistic stabilization effect between ceramic waste and CKD. The combined system likely enhanced particle agglomeration, reduced clay activity, and promoted the formation of stable cementitious compounds capable of transforming the expansive clay matrix into a denser and less plastic structure. The synergistic interaction between the silica-rich ceramic waste and calcium-rich CKD may have accelerated pozzolanic and geopolymeric reactions, resulting in improved interparticle bonding and a significant reduction in moisture susceptibility. Consequently, the stabilized soil exhibited enhanced workability, lower swelling potential, and improved dimensional stability.

Free Swell Index

The Free Swell Index (FSI) test was conducted to evaluate the influence of ceramic waste (CW) and cement kiln dust (CKD) on the swelling characteristics and volumetric stability of the expansive clay soil. Free swell index is an important parameter used to assess the degree of expansiveness of clay soils and their susceptibility to moisture-induced volume changes. High FSI values are generally associated with active clay minerals, particularly montmorillonite, which exhibit significant water adsorption and expansion behavior.

Figure 5 indicates that the untreated expansive clay soil recorded a very high FSI value of 193.75%, confirming the severe expansive nature of the investigated soil. Such high swell values indicate substantial moisture sensitivity and explain the poor engineering performance commonly associated with black cotton soils, including pavement heaving, differential settlement, shrinkage cracking, and structural instability under seasonal moisture fluctuations. The incorporation of ceramic waste resulted in a substantial and progressive reduction in FSI values with increasing replacement levels. The FSI decreased continuously from 193.75% for the untreated soil to 20% at 30% CW replacement, representing an overall reduction of approximately 89.7%. The significant reduction demonstrates the effectiveness of ceramic waste in minimizing the swell potential and improving the dimensional stability of expansive clay soil.

Figure 5. Free swell index vs replacement level.

The observed improvement may be attributed to several stabilization mechanisms associated with ceramic waste incorporation. The replacement of active clay particles with comparatively non-expansive ceramic particles likely reduced the overall clay activity and moisture adsorption capacity of the soil matrix. Furthermore, the high silica and alumina contents of ceramic waste may have promoted pozzolanic reactions that enhanced particle bonding and generated denser soil structures with reduced pore spaces.

The reduction in FSI also suggests that ceramic waste contributed to the flocculation and agglomeration of clay particles, thereby limiting interparticle expansion upon water absorption. Similar observations have been reported in previous stabilization studies where silica-rich additives significantly reduced swell behavior through physicochemical modification and cementitious stabilization processes. Cement kiln dust stabilization also produced a noticeable reduction in free swell index values, although the rate of reduction was comparatively less pronounced than that observed for ceramic waste stabilization. The FSI decreased from 193.75% for the untreated soil to 55% at 15% CKD replacement, corresponding to an approximate reduction of 71.6%.

The improvement associated with CKD stabilization may be attributed to the high calcium oxide content of CKD, which promotes cation exchange, flocculation, and cementitious reactions within the expansive clay matrix. The calcium ions supplied by CKD replace exchangeable cations surrounding clay particles, thereby reducing diffuse double-layer thickness and minimizing moisture-induced expansion. In addition, the formation of calcium silicate hydrate (C-S-H) compounds likely contributed to increased soil aggregation and reduced swelling susceptibility. Although both stabilizers significantly improved the volumetric stability of the expansive soil, ceramic waste exhibited greater effectiveness in reducing swell potential at higher replacement levels. This superior performance may be associated with the enhanced pozzolanic reactivity and particle replacement effects provided by the silica-rich ceramic material.

The combined optimum stabilization mixture consisting of 25% CW and 15% CKD produced the most substantial reduction in free swell index, yielding an FSI value of 12%. This represents an overall reduction of approximately 93.8% compared to the untreated expansive soil. The remarkable improvement demonstrates the occurrence of strong synergistic stabilization effects between ceramic waste and CKD. The enhanced performance of the combined stabilization system may be attributed to the interaction between the silica-rich ceramic waste and the calcium-rich CKD, which collectively promoted extensive pozzolanic and cementitious reactions within the soil matrix. The combined stabilization mechanism likely enhanced particle rearrangement, reduced void spaces, minimized water absorption, and generated stronger interparticle bonding through the formation of cementitious compounds. The drastic reduction in FSI indicates that the stabilized soil exhibited substantially improved dimensional stability and significantly lower susceptibility to moisture-induced volumetric changes. Consequently, the combined use of ceramic waste and CKD demonstrates strong potential as an effective and sustainable stabilization approach for expansive clay soils intended for pavement subgrades, embankments, and foundation applications.

5. Conclusions

This study investigated the stabilization of expansive clay soil using pulverized ceramic waste and alkali activator through detailed material characterization, consistency analysis, and swell evaluation. The untreated expansive clay soil exhibited severe expansive characteristics, including high liquid limit, elevated plasticity index, and excessive free swell index, confirming its poor engineering suitability for pavement and foundation applications without stabilization treatment. Material characterization through XRD and XRF analyses demonstrated that the investigated stabilization materials possessed substantial silica, alumina-, and calcium-rich phases favorable for geopolymerization and pozzolanic stabilization. Samples rich in reactive silica and aluminosilicate compounds showed strong potential for cementitious reaction development, while calcium-rich materials enhanced flocculation and particle bonding within the expansive soil matrix.

The stabilization results revealed that both ceramic waste and cement kiln dust significantly improved the consistency characteristics and volumetric stability of the expansive clay soil. Increasing ceramic waste content progressively reduced the liquid limit, plasticity index, and free swell index while simultaneously increasing the plastic limit. The reductions observed indicate substantial improvement in moisture susceptibility, clay activity, and dimensional stability of the treated soil. Compared to CKD stabilization alone, ceramic waste demonstrated greater effectiveness in reducing plasticity and swell behavior because of its high reactive silica and alumina contents. However, the combined stabilization system consisting of 25% ceramic waste and 15% CKD produced the most significant improvement in engineering behavior. The optimum mixture reduced the liquid limit from 89.68% to 48.50%, lowered the plasticity index to 15%, and decreased the free swell index from 193.75% to 12%.

The superior performance of the combined stabilization system was attributed to synergistic physicochemical interactions between the silica-rich ceramic waste and calcium-rich CKD. The stabilization mechanisms involved cation exchange, flocculation, agglomeration, pozzolanic reactions, and geopolymeric gel formation, which collectively enhanced particle bonding, reduced diffuse double-layer thickness, minimized water absorption, and produced denser soil microstructures.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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