

INVESTIGATING STABILISATION OF EXPANSIVE SOILS USING EGGSHELL POWDER AS AN ECO-FRIENDLY ADDITIVE

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ABSTRACT

Expansive soils, characterized by shrink-swell behavior due to clay minerals, present significant challenges in engineering applications like road pavements and waste containment. To mitigate these issues, eggshell powder (ESP) geopolymer was used as a stabilizing agent. This study, conducted in two phases, first assessed the natural soil properties, including specific gravity, Atterberg limits, particle size distribution, compaction characteristics, and volumetric shrinkage strain (VSS) at varying molding water contents. The second phase involved incorporating ESP at varying percentages (0%, 2.5%, 5%, 7.5%, and 10%) to evaluate its stabilization effectiveness. The soil was classified as A-7-5 (AASHTO) and CL (USCS) with a specific gravity of 2.59, a liquid limit of 45.05%, and a plastic limit of 32.9%. ESP addition reduced the specific gravity to 2.44 at 7.5%, while the plasticity index increased. The optimum moisture content (OMC) decreased from 20% (natural soil) to 17% at 7.5% ESP, and maximum dry density increased from 1.66 Mg/m³ to 1.705 Mg/m³ at 10% ESP. VSS significantly decreased with higher ESP percentages, achieving the allowable threshold of 4%. Statistical analysis confirmed that ESP significantly improved soil properties. The calcium carbonate in ESP decomposes into calcium oxide, which reacts with silica to form calcium silicate, enhancing soil stability. An ESP content of 7.5% was identified as optimal for mitigating volumetric shrinkage, making the soil suitable for waste containment. This study recommends ESP as a sustainable soil stabilizer for structurally unstable soils. Incorporating ESP by professionals improves soil properties while addressing environmental challenges of eggshell waste disposal sustainably.

Keywords: Stabilization, Eggshell, Expansive Soils, Eco-Friendly, Additive.

1. INTRODUCTION

Expansive clayey soils exhibit complex behaviors when subjected to variations in moisture, often experiencing significant volume changes (Zada et al., 2021). These soils are notorious for their hazardous characteristics due to their inherent tendency to undergo volumetric changes in response to fluctuations in moisture content. This property leads to widespread issues, including long-term costs associated with correcting and restoring structures built on such soils, which pose a global challenge (Blayi et al., 2020). Studies have highlighted the financial losses, historical cases, infrastructure maintenance expenses, and critical failures linked to expansive soils (Abbey et al., 2021; Obianyo et al., 2020). Alarming, the inevitability of unintended

settlements and progressive damages on these soils is exacerbated by the rapid growth of the global population (Abbey et al., 2021; Obianyo et al., 2020; Areias et al., 2020). Soil improvement has become a common method to address these challenges, particularly in enhancing the performance of pavement layers and road subgrades. This approach involves modifying onsite materials to improve their properties and resolve issues arising from soil instability (Modarres and Nosoudy, 2015; Sharma et al., 2018). The process is widely used to enhance the geotechnical and environmental characteristics of clayey soils. Expansive soils, due to their swelling and shrinking properties, absorb water and swell during the rainy season and shrink during dry periods, leading to cracking and settlement in subgrade layers as a result of repeated wetting and drying cycles. To address this issue, an experimental study was conducted to stabilize expansive soils using eggshells, a waste material, aiming to improve their strength and swelling/shrinkage properties (Modarres & Nosoudy, 2015). This stabilization method seeks to make expansive soils more suitable for use as subgrade material in highway construction (Sharma et al., 2018). The study analyzed changes in the physical and engineering properties of the soil after mixing it with varying proportions of eggshells (Pandya, 2014).

The production of eggshell powder involves zero emission of CO₂, unlike lime, where heating is carried out at temperatures up to 750°C (Nur et al., 2019). Therefore, incorporating eggshell powder in soil improvement processes renders the overall stabilization procedure cost-effective, sustainable, and environmentally friendly. Given the substantial volume of waste generated annually nationwide, which not only poses disposal challenges but also contributes to environmental contamination and health risks, utilizing such refuse and industrial waste, along with their by-products, as alternatives to construction materials can significantly contribute to environmental preservation and mitigate their adverse impacts on the environment. This study aims to evaluate the volumetric shrinkage of expansive soils through treatment with eggshell powder-geopolymer while the objective is to determine the index properties of natural and modified expansive soil.

In the construction industry, soils with low geotechnical properties will usually be changed or improved using the stabilization measures (Nwonu, 2021). These soils are known as problem soils. They are characterized as expansive and collapsible soils (Bolarinwa & Ola, 2016). Expansive soils are problematic due to the performance of their clay mineral constituents, which make them exhibit the shrink-swell characteristics. The shrink-swell behaviors make expansive soils inappropriate for some engineering applications (such as roads pavement) in their natural form (Bolarinwa & Ola, 2016; Nwonu & Ikeagwuani, 2021). In an attempt to make them more feasible for construction purposes, numerous materials and techniques have been used to stabilize the soil (Ikeagwuani & Nwonu 2019). Some of the structurally unstable soil included residual lateritic soils, the black cotton soils (BCS) which occur widely in the north-eastern part of Nigeria and the Sokoto soft clay shale (attapulgitic) in the north-western Nigeria (Ayininuola et al., 2018). Expansive soils demonstrate significant shrinkage and swelling characteristics, leading to the development of surface cracks. When the soil is dry, these cracks can widen to over 50mm, closing completely when the soil is wet, resulting in an uneven soil surface due to irregular swelling and heaving (Attah et al., 2021). Due to the cohesive and impervious nature of expansive soil, it may be considered for use as a liner and cover in landfills. Unfortunately, the clay liner is susceptible to leachate attack, resulting in an increase in its hydraulic conductivity (Bowders et al., 1985; Madsen & Mitchell, 2005). This underscores the need for an enhanced clay liner with the ability to mitigate the impact of leachate on a barrier system while maintaining low permeability (Tawfik et al., 2019).

Soil improvement is a technique employed to enhance soil properties through the incorporation and blending of various materials. This process aims to elevate the dry unit weight, bearing capacity, and volume stability of in situ subsoils, sands, and other waste materials, ultimately fortifying road surfaces and other geotechnical applications. The initial soil stabilization tests were conducted in the United States in 1904, with cement introduced as a stabilizer for street construction in Sarasota, FL, in 1915 (ACI, 2005). Lime was incorporated into short stretches of highway in 1924 to accommodate the increasing traffic volume (Wang, 2002). Conventional stabilizers generally utilize pozzolanic reactions and cation exchange processes to alter and stabilize soil properties. (Little & Nair, 2009). Pozzolanic reactions involve the chemical interaction of siliceous and aluminous materials with calcium hydroxide at moderate temperatures, resulting in the formation of cementitious compounds. Conversely, cation exchange occurs when the soil can exchange free cations present in specific locations (Firoozi, Firoozi et al., 2017).

The eggshell, constituting the outer protective layer of a hard-shelled egg, serves as a natural source of Calcium Carbonate. Comprising approximately 11% of the total egg weight, the eggshell contains calcium carbonate (94%), calcium phosphate (1%), magnesium carbonate (1%), and organic substances (4%) (Mittal et al., 2016; Kristl et al., 2019). In its fresh state, the eggshell is composed of 90-97% calcium carbonate, which decreases to about 60-65% in the dry state (Kristl et al., 2019). The disposal of eggshells poses an environmental hazard, and various methods are employed, with 26.6% utilized as fertilizer, 21.1% as animal feed ingredients, 26.3% discarded in municipal dumps, and 15.8% employed in other ways (Mittal et al., 2016). Due to the attraction of vermin caused by eggshells and their attached membranes, many landfills are reluctant to accept eggshell waste. However, eggshell powder, which shares a chemical composition similar to lime, serves as an excellent alternative to commercially produced lime and can be effectively used as a reinforcing material. Predominantly composed of calcium and magnesium carbonate (lime) (Umar et al., 2022).

2. MATERIAL AND METHODS

The method employed in this study involves a systematic approach to investigating the use of eggshell powder (ESP) as a stabilizer for expansive soils. The eggshell sample used for this study was obtained from a tea shop and house-to-house kitchen waste collection in Jos, Plateau state, Nigeria. The eggshells were dried, ground into fine powder, and sieved through a 425 mm sieve. The percentage of Eggshell Powder on the volumetric shrinkage for 30 days Plate I.



Plate I: Dried eggshell

The Characterization of ESP involves processes of collection of eggshell waste, followed by cleaning to remove organic matter. Drying and grinding the eggshells to produce fine ESP particles. Characterization of ESP to determine its physical, chemical, and mineralogical properties, such as particle size distribution, specific surface area, and chemical composition. ESP was mixed with the base material (soil) in varying percentages to evaluate its effects. Common percentages used were 0%, 2.5%, 5%, 7.5%, and 10% Table 1. ESP was thoroughly blended with the base material to ensure homogeneity. Water content was adjusted as necessary to facilitate proper mixing and achieve desired consistency. The eggshell sample used for this study was obtained from a tea shop and house-to-house kitchen waste collection in Jos, Plateau State, Nigeria. The eggshells were dried and grinded into fine powder and sieved through a sieve 425mm.

%	0	2.5	5	7.5	10
OMC -2	8.543	9.275	7.824	7.149	7.985
OMC	15.280	6.854	8.197	2.679	6.607
OMC+2	20.661	9.981	11.219	9.292	8.056

Table 1: Percentage of Eggshell Powder on Volumetric Shrinkage for 30 Days

2.1 Expansive soil

The soil sample used for this study (undisturbed sample) was obtained from university of Jos permanent site, at Latitude 9.96557° or 9° 57' 56" North and longitude 8.88338° or 8° 53' 0" East, Jos, Plateau state Nigeria (Mapcarta, 2024). The topsoil was excavated to a depth of about 0.5m before obtaining soil samples in sacks and were sealed in plastic bags and put in sacks to avoid loss of moisture during transportation. The soil sample was then air-dried, pulverized and then sieved through several standard sieves for different types of tests with the largest sieve been BS No. 4 sieve (4.76 mm aperture) as seen on Plate II.



Plate II: Soil sample

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2.2 Natural Moisture Content

In carrying the natural moisture content test, BS 1377-2 (2022) was used to carry out the test. Taking the weight of cleaned containers was performed to the nearest 0.01g (m_1). The fresh soil sample was obtained, crumbled and placed loosely in the containers. The containers + soil samples were weighed together as (m_2). The container was kept in the oven and dried at about 110°C for 24hrs. The container + dry soil samples were then removed from the oven then weighed to nearest 0.01g as (m_3). The natural moisture content as obtained from the site was calculated taking the average of the three oven dried samples given by the expression;

$$w = \frac{m_2 - m_3}{m_3 - m_1} \times 100$$

Where:

W = Moisture content (%).

m_1 = Mass of container (g).

m_2 = Mass of container + wet soil (g).

m_3 = Mass of container + dry soil (g).

2.3 Specific gravity

The specific gravity of the soil was determined in accordance with BS 1377-2 (2022) Test (B) for fine-grained soils. Density bottle with the stopper weighed w_1 . Some quantity of the soil was transferred into the bottle to fill about one third ($\frac{1}{3}$) of the bottle and was weighed w_2 . Sufficient tap water was added gradually and was stirred gently to remove air bubbles before placing the stopper. The stopper was then inserted and then weighed w_3 . The bottle was then cleaned completely filled with distilled water and the stopper inserted, then weighed as w_4 . The specific gravity was then calculated using the equation.

$$G_s = \frac{w_2 - w_1}{(w_4 - w_1) - (w_3 - w_2)}$$

Where,

G_s = Specific gravity

w_1 = Weight of the empty bottle (g)

w_2 = Weight of the bottle + soil (g)

w_3 = Weight of the bottle + water (g)

w_4 = Weight of the bottle + soil + water full (g)

2.4 Wet sieve analysis

The particle size analysis was carried out in accordance with BS 1377-2 (2022) Part 2. 200 g of the soil sample was weighed, wet sieve to remove clay and silt particles using BS No 200 sieve (0.075 mm aperture) under tap water. Washing was done carefully to avoid damage to the sieve. After washing, the sample retained was dried in an oven set to 105°C for 24 hours. After drying the standard BS sieves were arranged in descending order of sieve size. The oven-dried samples were transferred individually into the sieves then shaken for at least 10 minutes manually. After sieving, the mass retained on each sieve was weighed. The percentages

passing each sieve size was calculated and plotted on a semi-log graph; percentage passing against sieve sizes. The same process was repeated for the remaining percentages of the admixtures.

2.5 Atterberg limits

Atterberg limits tests include the determination of the liquid limit, plastic limit and the plasticity index for the natural soil and the modified soils. They were also conducted in accordance with Test 1(A) BS 1377-2 (2022) Part 2 for the natural soil and BS 1377-2 (2022) for the modified soils.

2.6 Liquid limit

The soil sample for liquid limit (LL) test was air-dried and 200g of the material passed through BS No. 40 sieve (425mm aperture), was obtained and thoroughly mixed with water to form a homogeneous paste on a flat glass plate. A portion of the paste was then placed in the cup of the Casagrande apparatus, leveled off parallel to the base and divided by drawing the grooving tool along the diameter through the centre of the hinge. The cup was raised and allowed to drop repeatedly by rotating the crank until the two sections of soil met at the base of the groove. The number of blows at which that occurs is recorded and a little quantity of the soil was taken and its moisture content determined. The test was conducted across a range of moisture contents, evenly distributed from drier to wetter conditions. The values of the moisture content (determined) and the corresponding number of blows was then plotted on a semi-logarithmic graph and the liquid limit was determined as the moisture content corresponding to 25 blows. This same procedure was then repeated for each of the modified soil.

2.7 Plastic Limit

A portion of the expansive soil used for the liquid limit test was retained for the determination of plastic limit (PL). The ball of the natural soil / treated soil was moulded between the fingers and rolled between the palms of the hand until it dried sufficiently. After the liquid limit test has been determined, small portions of the soil paste were taken and then tried to roll into a 3mm thread. The moisture content at which the soil can be rolled into a thread of 3 mm without crumbling is the plastic limit of the soil. A portion of the rolled soil thread was then put into the oven for moisture content determination. This experiment procedure was repeated three times in order to get the average moisture content which corresponds to the plastic limit. The same procedure was repeated for all modified soil.

2.8 Plasticity index

Plasticity index (PI) is the numerical difference between the liquid limit (LL) and plastic limit (PL) given as

$$PI = LL - PL$$

Where; PI = plasticity index (%)

LL = liquid limit (%)

PL = plastic limit (%)

2.3 Compaction

A Compaction test was carried out in accordance with BS 1377-2 (2022) using British Standard light (BSL) compaction energy. Soil sample was dried in open air, then sieved using 4.75mm sieve. The mould used was weighed without the base and collar. The dimensions of the mould were recorded, and subsequently the volume of the mould. The inside of the mould with collar was lubricated using oil to be able to remove the soil easily after the compaction. 3 kg of the soil/soil-admixtures sample was mixed thoroughly with 12 % of water (and the water was added at 3 % for each of the compaction). The sample was then compacted into the 1000 cm³ (of mass m¹); in three layers of approximately equal mass with each layer receiving 27 blows of 2.5 kg rammer. The material was dropped from a height of 300 mm, with the blows evenly distributed across the surface of each layer. After compaction, the collar was removed, and the compacted sample was leveled at the top of the mold using a straight edge. The mold containing the leveled sample was then weighed to the nearest 1 g, denoted as m². Three small samples were then taken from the compacted soil for the determination of moisture content. The sample was then removed from the mould, crushed and additional water added (3 %) and the same procedure was repeated until the weight of the mould + soil decreased with respect to the previous one. For each sample, the water content in the soil was obtained by oven-drying it for 24hours. The same procedure was repeated for all modified soils. six set of samples were taken for moisture content determination.

The corresponding values of moisture content at maximum dry densities (MDD), obtained from the graph of dry density against moisture contents gives the optimum moisture contents (OMC).

2.4 Volumetric shrinkage test

The volumetric shrinkage upon desiccation was measured by extruding compacted cylindrical specimens (fifteen in number) from the compaction mould and allowing the cylindrical specimens to dry on a laboratory table. The samples were prepared by compacting the soil samples using the British Standard Light (BSL). Three soil samples were extruded for natural soil and ESP concentration, (for 2.5% one sample was extruded each for OMC, OMC-2 and OMC+2 and the same was repeated for 5.0%, 7.5% and 10% ESP). After compaction the specimen were extruded from the mould using the extruding machine and the volumetric shrinkage of various specimens were observed for a period of time till there was no noticeable change in specimens from 0 up to 30 days, the height and diameter of the specimen was measured with the aid of a digital vernier caliper accurate to 0.01 mm. The volumes of each specimen were calculated using

$$V = \pi r^2 h$$

Where; v = volume (mm³), π = 3.142, r = radius (mm), h = height (mm).

The volumetric shrinkage strain (VSS) was calculated from the eq.

$$\text{volumetric shrinkage strain \%} = \frac{\text{initial volume} - \text{final volume}}{\text{initial volume}} \times 100$$

3. RESULTS AND DISCUSSION

The shrinkage values were taken at moulding water content of OMC -2, OMC and OMC+2. It was observed that the volumetric shrinkage of the soil (VSS) significantly decreased with increase in eggshell content Figure 1. Effect of ESP on volumetric shrinkage after 30 days. Details of the variable are given in table B4.7. The decrease in volume of the soil specimen was as a result of the rearrangement of the soil particles as it reacts with the mixed ESP.

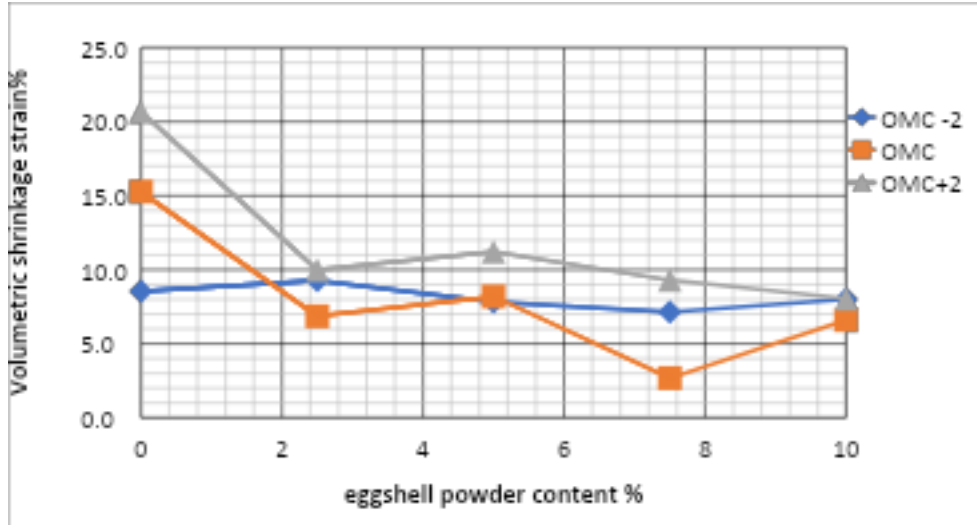


Figure 1: Effect of eggshell powder on volumetric shrinkage after 30 days

3.1 Effect of the moulding water content relative to optimum on volumetric shrinkage of the soil.

The variation of volumetric shrinkage strain with water content relative to optimum is shown in figure 2. In general, volumetric shrinkage strain increased as the molding water content exceeded the optimum moisture content (OMC) for the natural soil compacted within a range of -2% to +2% of the OMC. The Maximum permissible volumetric shrinkage strain value of 4% was recorded at moulding water content of 0 (OMC) treated with 7.5% eggshell powder. OMC+2 and OMC-2 moulding water content relative to optimum did not meet the regulatory maximum 4% volumetric shrinkage strain for all ESP mixture.

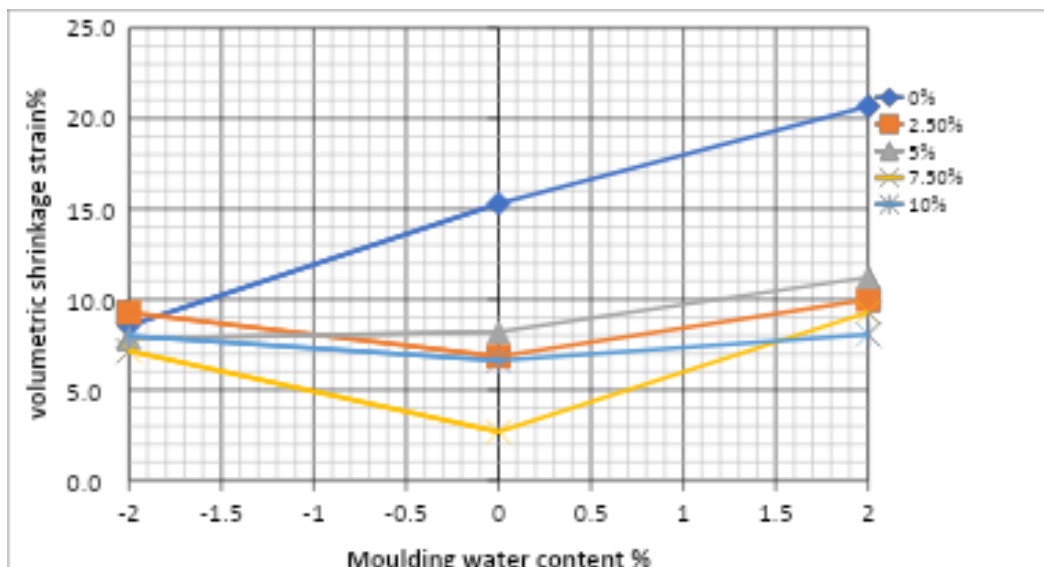


Figure 2: Effect of moulding water content on volumetric shrinkage

The two-way ANOVA shown in Table 2 indicates that the effect of the eggshell powder inclusion is statically significant ($F_{CAL} > F_{crit}$) and the addition of the moisture content is not statistically significant with respect to the volumetric shrinkage ($F_{CAL} < F_{crit}$). In addition to volumetric shrinkage, other properties analyzed after stabilization with eggshell powder (ESP) include: Shear Strength which evaluates the soil's resistance to shearing forces and its overall stability under load. Compaction Characteristics which Include maximum dry density (MDD) and optimum moisture content (OMC) to assess the soil's ability to achieve desired density. Plasticity Index which determines changes in the soil's plasticity and workability after stabilization. Unconfined Compressive Strength (UCS) which measures the soil's load-bearing capacity without lateral support.

Table 2: Two-way variance (ANOVA) for effect of eggshell powder on volumetric shrinkage

Property	Source of variance	Degree of Freedom	F_{CAL}	p-value	F_{crit}	Remark
Volumetric shrinkage	Eggshell powder	4	4.1346094	0.041754	3.83783	$F_{CAL} > F_{crit}$ SS
	Moisture content	2	3.1275494	0.099193	4.45897	$F_{CAL} < F_{crit}$ NS

SS- Statistically Significant, NS-Not significant

4. CONCLUSION

Based on the results obtained, it can be concluded that an eggshell powder (ESP) content of 7.5% effectively stabilizes the soil against volumetric shrinkage. This stabilization enhances the soil's ability to resist deformation and maintain its structural integrity under varying environmental conditions. Consequently, the treated soil exhibits improved performance characteristics, making it particularly suitable for applications in waste containment systems. By minimizing volumetric shrinkage, the risk of cracks or structural failures in waste containment liners is significantly reduced, thereby ensuring better containment of hazardous materials and preventing

environmental contamination. This finding underscores the potential of ESP as a sustainable and cost-effective soil stabilizer in geotechnical engineering applications.

5. RECOMMENDATIONS

This study recommends the utilization of eggshell waste as an efficient soil-stabilizing material. For practitioners, this implies a viable, cost-effective alternative to conventional stabilizers that enhances soil performance while addressing sustainability goals. By incorporating eggshell powder into soil stabilization practices, engineers, builders and other professionals can improve the engineering properties of the soil, reduce reliance on chemically produced stabilizers, and contribute to mitigating the environmental challenges associated with eggshell waste disposal. This approach offers a practical pathway to sustainable construction and environmental stewardship.

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