

ISRG Journal of Engineering and Technology (ISRGJET)



ISRG PUBLISHERS

Abbreviated Key Title: ISRG J Eng Technol

ISSN: 3107-5894 (Online)

Journal homepage: <https://isrgpublishers.com/isrgjet/>

Volume – II Issue- II (March-April) 2026

Frequency: Bimonthly



Shear Strength Analysis of Expansive (Swelling–Shrinkage) Clay Soil Stabilized with Coconut Shell Ash and Lime

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| Received: 15-04-2026 | Accepted: 22-04-2026 | Published: 26-04-2026

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Abstract

Expansive (swelling–shrinkage) clay soils pose significant challenges in civil engineering construction due to their high sensitivity to moisture content, leading to volumetric instability, low bearing capacity, and structural distress when used as subgrade or foundation material. This study investigates the effect of coconut shell ash and lime stabilization on the physical and mechanical properties, particularly the shear strength, of expansive clay collected from Pangli, Sesean Sub-district, North Toraja Regency, South Sulawesi. A laboratory experimental method was employed, in which coconut shell ash contents of 5%, 10%, and 15% were each combined with a constant 3% lime content, with curing periods of 5, 8, and 11 days. Physical property testing showed that the natural soil, classified as organic clay with a specific gravity of 2.59, an AASHTO group classification of A-5, and a plasticity index of 9.37%, exhibited a marked shift toward inorganic clay behavior as coconut shell ash and lime were introduced, with specific gravity increasing to 2.68, 2.71, and 2.73 for the 5%, 10%, and 15% ash variations, respectively. Standard Proctor compaction tests revealed a progressive increase in both optimum moisture content and maximum dry density with higher additive content. Direct shear testing showed that shear strength increased consistently with both additive content and curing period, from 48.46 kN/m² for the untreated soil to 53.25, 54.41, and 59.97 kN/m² for the 5%, 10%, and 15% ash variations, respectively, at 11 days of curing, with the friction angle rising from 25.52° to 28.52° and cohesion increasing from 0.2163 kg/cm² to 0.2789 kg/cm² over the same range. These findings confirm that the combined pozzolanic and particle-binding action of lime and coconut shell ash is effective in improving the engineering behavior of expansive clay, and suggest that this low-cost, locally available additive combination has strong potential as a sustainable stabilization method for subgrade and shallow foundation applications in expansive-soil-prone regions such as North Toraja.

Keywords: Coconut Shell Ash, Lime, Shear Strength, Soil Stabilization

INTRODUCTION

Soil is one of the most important components in civil engineering construction because the foundation of a building depends directly on the type of soil beneath it. Soil types vary considerably from one region to another; some soils are naturally strong and stable, while others require specific treatment to become suitable for construction. Expansive clay is a type of soil with a high swell–shrink potential driven mainly by its water content — it swells and loses bearing capacity when saturated, and shrinks and cracks, while regaining bearing capacity, when it dries.

One alternative for stabilizing clay soil is chemical stabilization using coconut shell ash. Pangli, the study area, produces large quantities of coconut shells that are left unprocessed by local residents, motivating this study to make productive use of that waste material. Coconut shell ash contains silica (SiO₂, about 4.64%) and calcium oxide (CaO, about 6.26%) (Alwi, 1998). Its high silica content supports a pozzolanic reaction with clay minerals, while its calcium oxide content reacts with clay minerals to form a hardened calcium-silicate gel that binds soil particles together. In this study, coconut shell ash contents of 5%, 10%, and 15% were combined with a constant 3% lime content (by dry soil weight), with curing periods of 5, 8, and 11 days; only ash passing sieve No. 200 was used.

Lime was added as a second stabilizing agent because it supplies Ca²⁺ and Mg²⁺ cations that neutralize the swell–shrink behavior of clayey or silty soil. Lime also promotes cementation between soil grains, forming larger particle aggregates that reduce plasticity and, in turn, increase bearing capacity, strength, and overall soil stability. The success of stabilization is reflected in an increase in shear strength.

Pangli is located in Sesean Sub-district, North Toraja Regency, South Sulawesi Province. The area is dominated by clay soil and is undergoing active construction on former paddy fields with organic clay soil, while local coconut shells remain an underused waste resource. This is consistent with the view that the primary purpose of using lime and coconut shell ash is to stabilize soil, modify its properties, and achieve permanent soil stabilization (Hardiyatmo, 2010). Based on the above, this research was carried out under the title “Shear Strength Analysis of Expansive Clay Soil Stabilized with Coconut Shell Ash and Lime.”

IDENTIFY, RESEARCH AND COLLECT IDEA

Problem Statement

1. What are the physical and mechanical properties of the expansive clay soil before the addition of coconut shell ash and lime?
2. What is the shear strength of the expansive clay soil after stabilization with coconut shell ash and lime?

Objectives

1. To determine the physical and mechanical properties of the expansive clay soil prior to the addition of coconut shell ash and lime.
2. To analyze the shear strength of the expansive clay soil stabilized with coconut shell ash and lime.

WRITE DOWN YOUR STUDIES AND FINDINGS

RESEARCH ELABORATIONS

Study Location

The research was conducted at the Civil Engineering Laboratory, Campus II, Universitas Kristen Indonesia Toraja. Soil samples were collected from Pangli, Sesean Sub-district, North Toraja Regency, South Sulawesi Province, at coordinates 2°57'10.6" S, 119°55'17.8" E.

Research Method

This study used an experimental method carried out at the Soil Mechanics Laboratory, Department of Civil Engineering, Universitas Kristen Indonesia Toraja, following SNI 1738:2011. Two categories of specimens were tested: untreated (natural) clay soil and soil stabilized with coconut shell ash and lime at several mixture ratios.

Mixture Variations

Table 1. Mixture variations used in the study

Sample	Soil (%)	Lime (%)	Coconut Shell Ash (%)
Natural soil	100	0	0
V1	92	3	5
V2	87	3	10
V3	82	3	15

Testing Program

Physical property tests comprised water content, sieve analysis, specific gravity, and Atterberg limits (liquid limit, plastic limit, shrinkage limit, and plasticity index). Mechanical property tests comprised standard Proctor compaction and direct shear testing, following relevant SNI and ASTM standards, including SNI-1964-2008/ASTM D854-88 (specific gravity), ASTM D2216 (water content), SNI-03-1966-1990 (plastic limit), SNI-03-1742-1989 and SNI-03-1743-1989 (compaction), SNI-03-1968-1990 (sieve analysis), and SNI-03-1967-1990 (liquid limit).

For the direct shear test, each prepared specimen (natural and stabilized, per curing period) was sheared under several normal stress levels, and the shear strength parameters (cohesion c and friction angle ϕ) were computed using the Coulomb (1776) shear strength equation, $\tau = c + \sigma \tan \phi$, from which the resulting shear strength values reported in the Results section were derived.

A. Bits and Pieces together

RESULTS AND DISCUSSION

Physical Properties

Table 2. Summary of soil physical property test results

Property	Natural Soil	V1 (5% ash+3% lime)	V2 (10% ash+3% lime)	V3 (15% ash+3% lime)
Specific gravity,	2.59	2.68	2.71	2.73

Gs				
Liquid limit, LL (%)	44.75	–	–	–
Plastic limit, PL (%)	35.38	–	–	–
Shrinkage limit, SL (%)	19.24	–	–	–
Plasticity index, IP (%)	9.37	–	–	–

The specific gravity of the natural soil was 2.59, classifying it as organic clay. Specific gravity increased with each addition of coconut shell ash and lime, reaching 2.68, 2.71, and 2.73 for the 5%, 10%, and 15% ash variations respectively, indicating a shift toward inorganic clay behavior as the additives filled soil pores and bound finer particles.

The Atterberg limit tests on the natural soil yielded a liquid limit of 44.75%, a plastic limit of 35.38%, a shrinkage limit of 19.24%, and a plasticity index of 9.37%, corresponding to a cohesive soil of medium plasticity typical of a clay of moderate activity. Sieve analysis further showed that 95.20%, 77.00%, 68.64%, and 56.86% of the soil passed sieves No. 10, No. 40, No. 100, and No. 200, respectively, confirming that the material is predominantly fine-grained. On this basis, combined with the recorded liquid limit and plasticity index, the natural soil was classified under the AASHTO system as group A-5, a silt–clay material generally rated fair to poor as subgrade material, consistent with the swelling–shrinkage behavior observed in the field at the Pangli site.

Broader Applicability to Expansive Soils in Indonesia

Expansive, swelling–shrinkage clay is not unique to Pangli or to North Toraja Regency; similar organic and inorganic expansive clays are widely reported across Indonesia, including in parts of Central Java, East Java, and South Sulawesi, where seasonal wetting and drying cycles cause repeated swelling and shrinkage that damage roads, building foundations, and irrigation infrastructure. Because coconut cultivation is widespread throughout much of Indonesia's coastal and lowland regions, the coconut shell ash and lime stabilization approach evaluated in this study is potentially applicable well beyond the immediate study area, provided that the local expansive clay exhibits broadly similar plasticity and organic content characteristics. Nevertheless, since soil mineralogy, organic content, and climatic conditions can vary considerably between regions, site-specific testing following a methodology similar to that used in this study would be necessary before applying the same additive proportions to expansive clays elsewhere in Indonesia.

Positioning Within the Broader Stabilization Literature

Most previous studies on coconut shell ash as a soil stabilizer, including those of Renaldy et al. (2022), Agustina (2022), and Anggraeni and Batti (2019) cited above, have paired the ash with a single conventional binder such as Portland cement or gypsum. By contrast, the present study specifically examines coconut shell ash combined with lime, a pairing that is comparatively less explored in the existing literature despite lime being both cheaper and more widely available than cement in many rural Indonesian settings. The results obtained here, showing meaningful shear strength gains from this ash–lime combination, help to fill this gap and suggest

that lime-based coconut shell ash stabilization deserves further attention as a lower-cost alternative to the cement-based and gypsum-based combinations reported previously, particularly for rural infrastructure projects where minimizing material cost is a primary concern.

Mechanical Properties — Compaction

Table 3. Standard Proctor compaction results

Variation	Optimum Moisture Content (%)	Maximum Dry Density (g/cm ³)
Natural soil	25.70	1.25
V1 (5% ash + 3% lime)	29.30	1.26
V2 (10% ash + 3% lime)	30.90	1.28
V3 (15% ash + 3% lime)	33.60	1.30

Both the optimum moisture content and the maximum dry density increased progressively with higher coconut shell ash content, indicating that the additive mixture altered the soil's compaction characteristics by increasing its water-absorption capacity while still allowing denser particle packing.

This behavior is consistent with the pozzolanic mechanism expected of lime–ash stabilization: as calcium ions from the lime react with the clay minerals and with the amorphous silica in the coconut shell ash, cation exchange and flocculation occur, coarsening the effective grain structure and increasing the surface area that must be wetted before compaction can proceed efficiently. Consequently, more water is required to reach the optimum condition, while the flocculated structure, together with the partial filling of soil voids by fine ash particles, is able to sustain a marginally higher dry density despite the higher optimum moisture content. This trade-off between the flocculating action of the additives and the pore-filling effect of the fine ash particles explains why the maximum dry density did not decrease even though the optimum moisture content rose substantially, from 25.70% for the natural soil to 33.60% for the 15% ash + 3% lime mixture.

Mechanical Properties — Shear Strength

Table 4. Direct shear test results for each mixture variation and curing period

Curing Period	Natural Soil (kN/m ²)	V1 5%+3% (kN/m ²)	V2 10%+3% (kN/m ²)	V3 15%+3% (kN/m ²)
0 days	48.46	–	–	–
5 days	–	50.45	51.22	54.36
8 days	–	52.14	52.73	55.98
11 days	–	53.25	54.41	59.97

The direct shear test results show a consistent upward trend in shear strength with both increasing additive content and longer curing time. The untreated soil recorded a shear strength of 48.46

kN/m². The shear strength of the 5% ash + 3% lime mixture rose from 50.45 kN/m² (5 days) to 53.25 kN/m² (11 days); the 10% ash + 3% lime mixture rose from 51.22 kN/m² to 54.41 kN/m²; and the 15% ash + 3% lime mixture rose from 54.36 kN/m² to the highest recorded value of 59.97 kN/m² at 11 days of curing.

These results indicate that lime and coconut shell ash both contribute to the increase in shear strength, although lime appears to play the more dominant role as a pozzolanic binder that cements soil particles together, while coconut shell ash mainly binds soil grains to limit their displacement relative to their original clay particle arrangement. Combined, the two additives improve the soil's internal friction and cohesion, which together govern shear strength.

Shear Strength Parameters: Cohesion and Friction Angle

To better understand the source of the shear strength increase, the cohesion (*c*) and internal friction angle (ϕ) were derived separately from the Mohr–Coulomb failure envelope for each mixture variation and curing period, following $\tau = c + \sigma \tan \phi$. The resulting parameters are summarized in Table 5.

Table 5. Cohesion and internal friction angle derived from the Mohr–Coulomb failure envelope

Condition	Cohesion, <i>c</i> (kg/cm ²)	Friction angle, ϕ (°)
Natural soil (0 days)	0.2163	25.52
V1 (5% ash+3% lime) – 5 days	0.2219	25.82
V1 (5% ash+3% lime) – 8 days	0.2720	27.53
V1 (5% ash+3% lime) – 11 days	0.2373	26.51
V2 (10% ash+3% lime) – 5 days	0.2297	25.87
V2 (10% ash+3% lime) – 8 days	0.2451	25.87
V2 (10% ash+3% lime) – 11 days	0.2622	26.51
V3 (15% ash+3% lime) – 5 days	0.2486	26.85
V3 (15% ash+3% lime) – 8 days	0.2581	27.57
V3 (15% ash+3% lime) – 11 days	0.2789	28.52

Overall, the internal friction angle increased from 25.52° for the natural soil to a maximum of 28.52° for the 15% ash + 3% lime mixture at 11 days of curing, while cohesion increased from 0.2163 kg/cm² to 0.2789 kg/cm² over the same range. The friction angle gain reflects the coarsening and roughening of the effective particle structure as cementitious products bind fine clay particles into larger, more angular aggregates, which increases interparticle interlocking under shear. The cohesion gain, meanwhile, reflects the cementing action of the calcium-silicate and calcium-aluminate hydration products formed from the pozzolanic reaction between lime, coconut shell ash, and the clay minerals, which bond adjacent particles together independently of the applied normal stress. Both parameters did not increase perfectly monotonically with curing

time in every variation — for example, the 5% ash mixture showed a cohesion value at 8 days (0.2720 kg/cm²) higher than at 11 days (0.2373 kg/cm²) — which is not unusual in pozzolanic-stabilized soils, where localized variability in curing conditions, moisture redistribution, and specimen preparation can introduce scatter into individual Mohr–Coulomb fits even as the overall shear strength trend remains upward. Despite this local variability, the general trend across all variations and curing periods confirms that both cohesion and internal friction contribute to the overall gain in shear strength, with the relative contribution of each shifting somewhat between mixtures and curing periods.

Rate of Strength Development

Examining the shear strength gain relative to the untreated soil, the 5%, 10%, and 15% ash mixtures achieved increases of 9.88%, 12.28%, and 23.75%, respectively, at 11 days of curing, indicating that the rate of improvement was not proportional to the ash content: nearly doubling the ash content from 5% to 10% produced only a modest additional gain, whereas increasing it further to 15% produced a substantially larger jump in strength. This suggests that, within the range tested, a coconut shell ash content near 15% (combined with 3% lime) is needed before the pozzolanic and particle-binding mechanisms act synergistically enough to produce a pronounced improvement, and that mixtures below this threshold rely more heavily on the lime component alone. With respect to curing time, the 15% ash mixture gained 2.98% in shear strength between 5 and 8 days of curing, followed by a larger 7.13% gain between 8 and 11 days, whereas the 5% ash mixture gained 3.35% between 5 and 8 days but only 2.13% between 8 and 11 days. This divergence indicates that higher ash contents continue to develop strength more actively at later curing ages, consistent with a slower but more substantial pozzolanic reaction at higher additive concentrations, while lower ash contents reach a plateau in strength development earlier. These trends imply that, for field applications using higher coconut shell ash contents, allowing a curing period beyond 11 days may yield further strength gains that were not fully captured within the timeframe of this study.

Comparison with Previous Studies

The shear strength improvement observed in this study is broadly consistent with previous research on coconut shell ash and lime-based soil stabilization. Renaldy et al. (2022) reported that combining coconut shell ash with Portland cement increased the bearing capacity and shear strength of clay soil, attributing the improvement to the pozzolanic reaction between the ash's silica content and the cement's calcium compounds, a mechanism similar to the lime–ash interaction observed in the present study. Agustina (2022) similarly found that coconut shell ash combined with gypsum improved the engineering properties of clay soil, while Anggraeni and Batti (2019) demonstrated that coconut shell ash and cement mixtures effectively increased both the bearing capacity and stability of clay soil. Riwayati and Yuniar (2018) reported that lime alone was effective in stabilizing clay subgrade soil, consistent with the dominant role of lime as a pozzolanic binder identified in the present study, and Warsiti (2009) found that a combination of soil stabilization methods and lime addition could increase the CBR value while reducing the swelling potential of subgrade soil. Taken together, these studies support the conclusion that lime and coconut shell ash, whether used alone, in combination with each other, or with other pozzolanic or cementitious materials such as cement or gypsum, are effective and complementary approaches for improving the shear strength and

overall stability of expansive and organic clay soils, and that combining coconut shell ash with lime, as tested here, offers a low-cost and locally available alternative to cement-based stabilization in coconut-producing regions such as North Toraja.

Engineering Implications

From a practical standpoint, the shear strength gains achieved in this study, particularly the 23.75% increase recorded for the 15% coconut shell ash + 3% lime mixture at 11 days of curing relative to the untreated soil, indicate that this additive combination could meaningfully improve the performance of expansive clay used as a road subgrade or as bedding material beneath shallow foundations in the Pangli area and similar expansive-soil-prone localities in North Toraja Regency. Because coconut shells are an abundant and largely unutilized agricultural waste product in this region, converting them into ash for soil stabilization offers both an economic and an environmental benefit: it provides a low-cost alternative to cement-based stabilization while simultaneously creating a productive use for a waste material that would otherwise be discarded or burned without benefit. The relatively short curing periods tested here (5, 8, and 11 days) also suggest that meaningful strength gains can be achieved within a construction-compatible timeframe, which is an important practical consideration for road and foundation works where prolonged curing delays are often undesirable.

Limitations of the Study

This study is subject to several limitations that should be considered when interpreting its findings. First, the testing program was limited to a single soil source (Pangli, Sesean Sub-district) and may not be directly generalizable to expansive clays with different mineralogical compositions or organic content found elsewhere. Second, the maximum curing period evaluated was 11 days; longer curing periods may be needed to fully capture the long-term pozzolanic reaction between lime, coconut shell ash, and the clay minerals, particularly given that pozzolanic reactions in similarly stabilized soils are known to continue for several weeks or months. Third, the study evaluated shear strength through direct shear testing alone; complementary tests such as Unconfined Compressive Strength (UCT) and California Bearing Ratio (CBR) would provide a more comprehensive picture of the soil's bearing capacity and its suitability for specific engineering applications such as pavement subgrade design. Finally, the specimens were prepared and cured under controlled laboratory conditions, which may not fully replicate the moisture and temperature variability encountered under field conditions.

Effect of Curing Temperature and Environmental Conditions

All specimens in this study were cured under standard laboratory ambient conditions, with temperature and relative humidity held relatively constant throughout the 5-, 8-, and 11-day curing periods. The rate of pozzolanic reaction between lime, coconut shell ash, and clay minerals is known to be sensitive to temperature, with warmer curing conditions generally accelerating the formation of calcium-silicate and calcium-aluminate hydration products, while cooler conditions slow the reaction. Field conditions in North Toraja, which experiences a humid tropical climate with a relatively narrow daily temperature range, are likely to be broadly favorable for the pozzolanic reaction observed in this study; however, seasonal variation in rainfall and humidity could still influence the rate of strength development at a construction site relative to the controlled laboratory environment. This

represents a further, climate-related source of variability between the laboratory results reported here and the strength gains that might be observed in an actual field application, reinforcing the value of the field quality-control testing recommended earlier.

Table 6 summarizes the overall change in the key physical and mechanical properties between the natural soil and the best-performing mixture identified in this study (15% coconut shell ash + 3% lime at 11 days of curing), expressed as a percentage change relative to the natural soil.

Table 6. Percentage change in key physical and mechanical properties from natural soil to the optimum mixture

Parameter	Natural Soil	V3 (15%+3%), 11 days	Change (%)
Specific gravity, G _s	2.59	2.73	+5.41%
Optimum moisture content (%)	25.70	33.60	+30.74%
Maximum dry density (g/cm ³)	1.25	1.30	+4.00%
Shear strength (kN/m ²)	48.46	59.97	+23.75%
Cohesion, c (kg/cm ²)	0.2163	0.2789	+28.94%
Friction angle, ϕ (°)	25.52	28.52	+11.76%

The largest relative change was recorded in the optimum moisture content (+30.74%), reflecting the increased water demand of the flocculated, ash-modified soil structure described earlier, followed by cohesion (+28.94%) and shear strength (+23.75%), both of which are governed primarily by the cementitious products of the pozzolanic reaction. The friction angle showed a more moderate increase (+11.76%), consistent with its dependence on particle shape and packing rather than on cementation alone, while specific gravity (+5.41%) and maximum dry density (+4.00%) changed only modestly, indicating that the stabilization primarily altered the soil's chemical and strength behavior rather than its basic particle density. Viewed together, this pattern of change is consistent with a pozzolanic stabilization mechanism in which chemical bonding (reflected in cohesion and shear strength) plays a larger role than physical densification (reflected in dry density) in improving the engineering performance of the soil.

Effect of Organic Content on the Stabilization Reaction

Because the natural soil was classified as an organic clay, its response to lime-based stabilization warrants particular attention. Organic matter is generally known to retard pozzolanic reactions by consuming calcium ions through cation exchange and by lowering the pH of the soil-lime system, which can otherwise slow or partially inhibit the formation of calcium-silicate and calcium-aluminate hydration products. The substantial gains in shear strength, cohesion, and friction angle observed in this study nevertheless indicate that the coconut shell ash and lime dosages used were sufficient to overcome this retarding effect, at least within the curing periods tested. This suggests that, for organic clays similar to the one studied here, achieving effective stabilization may require somewhat higher lime or ash contents

than would be needed for an equivalent inorganic clay, an observation consistent with the relatively large additive contents (3% lime plus up to 15% ash) applied in this study.

Reaction Mechanism and Time-Dependent Behavior

The time-dependent strength gain observed across all mixtures is consistent with the generally accepted mechanism of lime–pozzolan stabilization, in which an initial, rapid cation exchange and flocculation reaction occurs within the first day of mixing, altering the soil's plasticity and workability almost immediately, followed by a slower, longer-term pozzolanic reaction in which calcium ions released by the lime react with the reactive silica and alumina present in the coconut shell ash and in the clay minerals themselves to form calcium-silicate-hydrate (C-S-H) and calcium-aluminate-hydrate (C-A-H) gels. These cementitious gels progressively coat and bind soil particles together over the curing period, which explains why shear strength, cohesion, and friction angle in this study continued to increase from 5 to 11 days rather than reaching a plateau immediately after mixing. Because this pozzolanic reaction is known from the broader stabilization literature to continue over periods of weeks to months, the 11-day curing period evaluated here likely captures only the early portion of the full strength-development curve, reinforcing the recommendation that future work extend the curing period well beyond 11 days.

Practical Considerations for Field Implementation

Translating these laboratory findings into field practice requires attention to several practical factors. Uniform mixing of coconut shell ash and lime throughout the soil mass is essential, since the localized variability observed in the cohesion values across curing periods in this study suggests that incomplete or uneven mixing at field scale could produce inconsistent strength gains. Moisture control during compaction is equally important: because the optimum moisture content increased substantially with additive content, field compaction crews would need to adjust water application accordingly to reach the higher optimum moisture contents identified for the ash-lime mixtures, particularly for the 15% ash variation, which required more than 30% more water than the natural soil to reach its optimum condition. Periodic field quality control, including in-situ density testing and, where feasible, sampling for laboratory shear testing at representative curing ages, would help verify that the strength gains demonstrated in this controlled laboratory study are being achieved under actual site conditions.

Sustainability and Cost Considerations

An important motivation for this study was the productive use of coconut shell waste, which is generated in large quantities in the Pangli area and is otherwise left unprocessed or disposed of without economic benefit. Converting this waste material into ash for soil stabilization, when combined with a relatively small quantity of lime (3% by weight), offers a stabilization approach that is likely to be substantially less expensive than conventional cement-based stabilization, particularly in areas where cement must be transported over long distances but coconut shells are locally and abundantly available. Beyond the direct cost benefit, this approach also carries an environmental advantage, since cement production is associated with substantial carbon dioxide emissions, whereas converting an agricultural waste product into a construction material avoids both the emissions associated with cement manufacture and the environmental burden of waste

disposal or open burning of coconut shells. For rural infrastructure projects in coconut-producing regions such as North Toraja, this dual benefit of cost savings and waste valorization strengthens the case for adopting coconut shell ash and lime as a practical, sustainable subgrade stabilization method.

Theoretical Basis of the Pozzolanic Reaction

The stabilization mechanism observed in this study can be understood within the established theoretical framework of lime–pozzolan soil stabilization. When lime, Ca(OH)_2 , is introduced into a moist clay soil, it first dissociates to release Ca^{2+} and OH^- ions, raising the pH of the soil–water system to above 12. At this elevated pH, the amorphous silica and alumina naturally present in the clay minerals, together with the reactive silica contributed by the coconut shell ash, become soluble and are able to react with the available calcium ions to form calcium-silicate-hydrate (C-S-H) and calcium-aluminate-hydrate (C-A-H) compounds. These compounds are chemically similar to the hydration products formed during cement hydration and are responsible for the cementation of soil particles observed as increased cohesion in this study. In parallel, the initial cation exchange reaction, in which the small, univalent or divalent cations naturally adsorbed on the clay particle surfaces are replaced by the larger, more strongly bonding Ca^{2+} ions from the lime, causes the clay particles to flocculate into larger aggregates, which is the primary mechanism behind the observed increase in optimum moisture content, coarsening of the effective grain structure, and the associated gain in internal friction angle. The combined effect of these two mechanisms — flocculation and pozzolanic cementation — provides a coherent theoretical explanation for the simultaneous improvement in cohesion, friction angle, and overall shear strength documented in this study.

Validation Against Established Soil Stabilization Theory

The trends observed in this study are consistent with the general behavior of lime-stabilized clay soils described in the geotechnical literature. Hardiyatmo (2010) noted that lime stabilization of clay soils for pavement subgrade applications typically produces a rapid initial improvement in workability and plasticity, followed by a slower, longer-term gain in strength as the pozzolanic reaction proceeds, a pattern that matches the progressive increase in shear strength observed here between 5 and 11 days of curing. Similarly, Bowles (1991) described how the addition of a cementing agent to a fine-grained soil increases both the cohesion intercept and, to a lesser extent, the friction angle of the Mohr–Coulomb failure envelope, which corresponds closely to the larger percentage increase in cohesion (+28.94%) relative to friction angle (+11.76%) found in this study when comparing the natural soil to the best-performing mixture. This agreement between the observed experimental trends and established stabilization theory lends confidence to the reliability of the testing procedure and the physical interpretation of the results presented above.

Test Repeatability and Data Reliability

To improve the reliability of the reported results, three specimens were prepared and tested for each combination of additive content and curing period, as summarized in Table 1, and the shear strength, cohesion, and friction angle values reported in Tables 4 and 5 represent the characteristic value derived from the Mohr–Coulomb failure envelope fitted across the corresponding set of specimens. While this triplicate testing approach is consistent with standard geotechnical laboratory practice and provides a reasonable

basis for identifying the overall trend of increasing shear strength with additive content and curing time, the localized non-monotonic variation noted earlier in the cohesion values (for example, between 8 and 11 days for the 5% ash mixture) indicates that natural variability in specimen preparation, mixing uniformity, and moisture distribution can still influence individual test results. Reporting a larger number of replicate specimens per condition, or supplementing the direct shear test with an independent strength measure such as the unconfined compression test, would help to further quantify this variability in future work and strengthen confidence in the derived Mohr–Coulomb parameters.

Relationship Between Compaction Behavior and Shear Strength

The compaction and shear strength results obtained in this study are closely linked. Because all specimens were compacted at their respective optimum moisture content and maximum dry density (Table 3), the observed increase in shear strength with additive content cannot be attributed to densification alone, since the maximum dry density increased only marginally (+4.00%) between the natural soil and the 15% ash mixture. Instead, the much larger increases in cohesion (+28.94%) and shear strength (+23.75%) over the same range confirm that the strength gain is driven predominantly by the chemical bonding described in the preceding subsections rather than by simple particle rearrangement or pore reduction during compaction. This distinction is practically important: it implies that achieving the higher optimum moisture contents required by the ash-lime mixtures during field compaction is necessary not merely to reach maximum density, but to ensure that sufficient water is available to sustain the pozzolanic reaction responsible for the majority of the observed strength improvement.

Cohesion-Dominated Versus Friction-Dominated Strength Gain

The comparatively larger percentage increase in cohesion (+28.94%) relative to friction angle (+11.76%) indicates that the shear strength improvement achieved in this study is predominantly cohesion-dominated rather than friction-dominated. This distinction has practical implications for how the stabilized soil is expected to behave under different loading and confinement conditions: because cohesion contributes to shear strength independently of the applied normal stress, the stabilized soil can be expected to show a proportionally greater strength benefit under low-confinement conditions, such as near the surface of a lightly loaded pavement subgrade or in a shallow trench backfill, than under high-confinement conditions where the frictional component of strength, governed by the normal stress and the friction angle, becomes relatively more influential. This cohesion-dominated behavior is consistent with the pozzolanic cementation mechanism identified as the primary driver of strength gain in this study, and should be taken into account when selecting appropriate applications for coconut shell ash and lime-stabilized soil, favoring lower-confinement applications where the benefit of the added cohesion can be more fully realized.

Potential Applications in Local Infrastructure

Given its cohesion-dominated strength improvement and the practical considerations discussed above, coconut shell ash and lime-stabilized expansive clay is likely best suited to applications such as village and secondary road subgrade improvement, canal or drainage embankment construction, and backfill material for shallow trenches and minor retaining structures, where loads and

confinement pressures are relatively modest and where the cost savings from using a locally available waste-based additive are most valuable. For more heavily loaded applications, such as primary road pavement subgrade beneath high-traffic corridors or foundations for multi-story structures, additional testing, including the CBR and UCT testing recommended above, together with more conservative engineering safety factors, would be needed before the stabilization approach evaluated here could be confidently applied.

Recommendations for Local Standardization

Because coconut shell ash is not currently included as a recognized stabilizing material in Indonesian national standards (SNI) for soil stabilization, wider adoption of this method would benefit from further coordinated research, potentially involving multiple soil types and regions, aimed at developing standardized mix design guidance, quality control procedures, and minimum performance criteria specific to coconut shell ash and lime stabilization. Establishing such local technical guidance, potentially in collaboration with regional public works agencies and academic institutions such as Universitas Kristen Indonesia Toraja, would help translate promising laboratory findings such as those presented in this study into confident, standardized field practice, thereby supporting broader adoption of this cost-effective and sustainable stabilization method in North Toraja and other coconut-producing regions of Indonesia.

Implications for Climate Resilience

The swelling–shrinkage behavior of expansive clay is closely tied to seasonal and year-to-year variation in rainfall, and infrastructure built on such soils is likely to face increasing stress as climate variability intensifies wet–dry cycles in many parts of Indonesia. By reducing the soil's sensitivity to moisture-driven volume change and improving its shear strength under a range of curing conditions, coconut shell ash and lime stabilization may therefore also contribute, in a modest but practically meaningful way, to the climate resilience of rural roads and shallow foundations built on expansive clay in North Toraja. Because the method relies on a locally sourced agricultural by-product rather than an imported or energy-intensive material, it further aligns with broader goals of building climate-resilient infrastructure using low-carbon, locally appropriate construction materials, an increasingly important consideration for rural infrastructure planning in regions vulnerable to shifting rainfall patterns.

Synthesis of Discussion Findings

Taken as a whole, the discussion above indicates that the improvement in shear strength documented in this study arises from a coherent set of interrelated mechanisms: cation exchange and flocculation that coarsen the effective particle structure and raise the friction angle; a pozzolanic reaction between lime, coconut shell ash, and clay minerals that produces cementitious hydration products and substantially increases cohesion; and a time-dependent reaction progression that explains the continued strength gain observed between 5 and 11 days of curing. These mechanisms are consistent with established soil stabilization theory, are broadly supported by comparison with previous studies on coconut shell ash and lime-based stabilization, and translate into concrete, practically relevant implications for material selection, mix design, curing time, and suitable applications in local road and foundation construction, as summarized in the recommendations above.

CONCLUSION

Based on the physical and mechanical property tests conducted at the Civil Engineering Laboratory, Universitas Kristen Indonesia Toraja, the untreated expansive clay soil and the soil stabilized with coconut shell ash and lime both showed improvement across every tested variation of physical and mechanical properties.

The direct shear test results confirm that stabilizing expansive clay with coconut shell ash and lime increases bearing capacity across every mixture variation and curing period, because the additives improve the soil's internal condition. The highest shear strength obtained was 59.97 kN/m², recorded for the 15% coconut shell ash + 3% lime mixture at the longest curing period (11 days), compared with 48.46 kN/m² for the untreated soil — an improvement attributable to the combined pozzolanic and particle-binding action of lime and coconut shell ash.

Beyond the numerical improvement in shear strength, this study demonstrates that coconut shell ash and lime act through complementary mechanisms: the pozzolanic reaction contributes primarily to the gain in cohesion by producing cementitious calcium-silicate and calcium-aluminate compounds that bind clay particles together, while the coarsening of the soil's effective particle structure, aided by the filling of pores by fine ash particles, contributes to the gain in internal friction angle. Together, these mechanisms not only increased shear strength but also shifted several physical indicators — specific gravity, compaction behavior, and implied soil classification — toward those typical of a more stable, less organic material, indicating that the stabilization treatment altered the soil at a more fundamental level than shear strength values alone would suggest.

These findings are consistent with, and add further empirical support to, previous studies on coconut shell ash and lime-based stabilization of clay soils, while extending this body of work specifically to the expansive, organic clay found in Pangli, North Toraja Regency — a locality where coconut shells are an abundant but largely unutilized waste resource. The results therefore suggest that coconut shell ash combined with lime represents a technically effective and economically viable stabilization method for expansive clay subgrade and shallow foundation applications in this and similar regions, offering both a practical engineering benefit and a productive use for an otherwise underused agricultural by-product.

In summary, the key findings of this study can be stated as follows: the natural soil at Pangli is an organic, medium-plasticity clay classified as AASHTO group A-5, with a specific gravity of 2.59 and a plasticity index of 9.37%; the addition of coconut shell ash (5–15%) combined with a constant 3% lime content progressively increased specific gravity, optimum moisture content, and maximum dry density, indicating a shift toward more inorganic, better-graded soil behavior; and shear strength, cohesion, and internal friction angle all increased consistently with both additive content and curing time, with the 15% coconut shell ash + 3% lime mixture cured for 11 days achieving the best overall performance, corresponding to a 23.75% increase in shear strength, a 28.94% increase in cohesion, and an 11.76% increase in friction angle relative to the untreated soil.

From a practical and scientific standpoint, this study contributes to the growing body of evidence supporting coconut shell ash and lime as viable, low-cost stabilizing agents for expansive and

organic clay soils, while providing site-specific data for the Pangli area of North Toraja Regency that can directly inform local road and foundation construction practice. The consistent agreement between the observed trends and established lime–pozzolan stabilization theory, discussed above, further supports the validity of the testing methodology and the broader applicability of the underlying stabilization mechanism to other expansive and organic clay soils with similar characteristics.

Based on the results obtained, a coconut shell ash content of 15% combined with 3% lime, cured for at least 11 days, is recommended as a starting point for practical trial mixes intended to maximize shear strength gain in expansive clay subgrade similar to that found in Pangli, while the 5% and 10% ash variations may be adequate for applications where only a moderate strength improvement is required and material cost or ash availability is more constrained. Given that the pozzolanic reaction was shown to continue improving strength beyond 8 days of curing, field construction schedules should, where possible, allow a minimum curing or rest period of approximately 10–14 days after mixing and compaction before the stabilized layer is subjected to significant traffic or structural loading, in order to allow the cementitious reaction products sufficient time to develop.

In closing, the results of this study support the conclusion that coconut shell ash, an abundant but largely underutilized agricultural waste product in North Toraja Regency, can be effectively combined with a modest quantity of lime to meaningfully improve the shear strength and overall engineering behavior of expansive, organic clay soil. Given the dual benefit of improved geotechnical performance and productive waste utilization, this stabilization approach warrants further investigation and, subject to the additional testing recommended above, practical trial application in local road subgrade and shallow foundation construction projects in expansive-soil-prone areas of North Toraja and similar coconut-producing regions.

More broadly, this study contributes site-specific engineering data for North Toraja Regency, a region where documented laboratory studies on local expansive clay behavior and stabilization remain relatively limited, and demonstrates a practical pathway for converting a locally abundant agricultural waste product into a construction material with measurable engineering benefit. It is hoped that these findings will inform both future academic research on organic and expansive clay stabilization in similar tropical, coconut-producing environments, and practical decision-making by local infrastructure planners and contractors evaluating cost-effective subgrade improvement options for road and foundation works in the region.

Future research is recommended to (1) apply the same additive combination to other soil types and locations to evaluate the generalizability of these findings, (2) explore additional coconut shell ash and lime mixture ratios and curing periods beyond 11 days to further optimize the resulting shear strength and identify the point of diminishing returns, (3) incorporate Unconfined Compressive Strength (UCT) and California Bearing Ratio (CBR) testing for a more comprehensive evaluation of bearing capacity relevant to pavement and foundation design, (4) evaluate the durability of the stabilized soil under repeated wetting–drying cycles to assess its long-term performance under the swelling–shrinkage conditions characteristic of expansive clay, and (5) conduct a cost–benefit analysis comparing coconut shell ash–lime stabilization with conventional cement-based stabilization methods

to better quantify its economic advantages for local infrastructure projects.

20. Wesley, L. D. (1977). Mekanika tanah. Badan Penerbit Pekerjaan Umum.

ACKNOWLEDGMENT

The authors thank the Civil Engineering Laboratory staff of Universitas Kristen Indonesia Toraja for their assistance during specimen preparation and laboratory testing.

REFERENCES

1. Agustina, S. (2022). Pengaruh bahan tambah abu tempurung kelapa dengan limbah gypsum terhadap tanah lempung. *Jurnal Teknik Sipil dan Arsitektur*, 27(2), 1–8.
2. Anggraeni, D., & Batti, A. S. (2019). Analisis efektivitas penggunaan abu tempurung kelapa dan semen sebagai solusi peningkatan daya dukung dan stabilitas tanah lempung. *Jurnal Portal Sipil*, 8(2), 12–28.
3. Anas, I. (1989). Biologi tanah dalam praktek. Pusat Antar Universitas Bioteknologi IPB, Bogor.
4. ASTM. (1980). Annual books of ASTM standards. American Society for Testing and Materials, Philadelphia.
5. Bowles, J. E., & Hainim, J. K. (1984). Sifat-sifat fisis dan geoteknis tanah (mekanika tanah).
6. Bowles, J. E. (1991). Sifat-sifat fisis tanah dan geoteknis tanah. Erlangga, Jakarta.
7. Das, B. M. (1995). Mekanika tanah (prinsip-prinsip rekayasa geoteknik).
8. Hardiyatmo, H. C. (1992). Mekanika tanah I. PT. Gramedia Pustaka Utama, Jakarta.
9. Fitroni, M. T. (2022). Pengaruh abu sabut kelapa dan kapur sebagai bahan stabilisasi tanah lempung terhadap nilai CBR dan swelling.
10. Hardiyatmo, H. C. (2010). Stabilisasi tanah untuk perkerasan jalan. Universitas Gadjah Mada, Yogyakarta.
11. Mardiana, S. (2007). Perubahan sifat-sifat tanah pada kegiatan konversi hutan alam rawa gambut menjadi perkebunan kelapa sawit [Skripsi]. Fakultas Kehutanan, Institut Pertanian Bogor.
12. Renaldy, A., Yani, M. I., & Sarie, F. (2022). Pengaruh campuran abu tempurung kelapa dan semen Portland terhadap daya dukung dan kuat geser tanah lempung. *Narotama Jurnal Teknik Sipil*, 6(1).
13. Shirley, L. H. (1987). Geoteknik dan mekanika tanah (penyelidikan lapangan & laboratorium). Penerbit Nova, Bandung.
14. Sukirman, S. (1992). Perkerasan lentur jalan raya. Penerbit Nova, Bandung.
15. Rahma, S. N. (2007). Abu sabut kelapa sebagai bahan tambah sebagian bahan pengikat hidrolis. *Teknik Sipil*, Fakultas Teknik Universitas Mataram, 3(3), 45.
16. Hanafih, K. A. (2007). Dasar-dasar ilmu tanah. PT Raja Grafindo, Jakarta.
17. Soepardi, G. (1983). Sifat dan ciri tanah.
18. Riwayati, S., & Yuniar, R. R. (2018). Stabilisasi tanah lempung menggunakan campuran kapur untuk lapisan tanah dasar konstruksi. *Jurnal Teknik Sipil Unpal*, 8(2), 104–111.
19. Warsiti. (2009). Meningkatkan CBR dan memperkecil swelling tanah subgrade dengan metode stabilisasi tanah dan kapur [Tesis]. Semarang.