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Cement Stabilization of a Tropical Expansive Clay: Effect on Plasticity and Shear Strength

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Abstract
The Expansive clay soils, prevalent throughout the central and southern regions of Trinidad, present a significant geotechnical hazard that compromises the integrity and lifespan of civil infrastructure. These soils are highly plastic and undergo considerable volumetric changes with moisture fluctuations, leading to structural damage. This investigation provides a quantitative evaluation of the effectiveness of Ordinary Portland Cement (OPC) as a stabilizing agent for these problematic soils. Samples of expansive clay from the Couva area in central Trinidad were systematically treated with low dosages of cement at 0% (control), 1%, 3%, 5%, 7%, 9%, and 11% by dry soil weight. The impact of cement stabilization on the soil's geotechnical properties was assessed through laboratory tests focused on plasticity and shear strength. Plasticity changes were measured using Atterberg Limits tests (ASTM D4318), while shear strength improvements were evaluated through Unconfined Compressive Strength (UCS) tests (ASTM D2166) on specimens cured for 7 and 28 days. The UCS samples were all prepared at optimum water content and maximum dry density, as determined by the standard Proctor test. The results indicate a dose-response relationship. The addition of cement consistently reduced the Plasticity Index (PI), which dropped from 35 in the untreated soil to 3.00 at 11% cement content. Meanwhile, the 28-day UCS increased significantly, from 0.294 MPa for the control to 4.547 MPa at 11% cement content, a strength increase of over 1400%. This study shows that low-dose cement stabilization effectively improves the engineering properties of Trinidadian expansive clays, providing quantified, locally calibrated parameters to guide ground improvement strategies for more durable infrastructure.

Keywords: *Trinidad, expansive clay, cement stabilization, plasticity index, shear strength, unconfined compressive strength.*

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I. INTRODUCTION

The island of Trinidad has complex geology that gives rise to significant geotechnical challenges in the central and southern regions. These areas are extensively underlain by formations of expansive clay soils, which constitute a primary source of risk for civil engineering work [1], [2]. The inherent problematic nature of these soils is linked to Trinidad's tropical climate, characterised by a wet and dry season, and is also prevalent in the C2-177 Talparo Clays (soil series name) found at the studied site in Couva. This Clay soil type is known to be over-consolidated, highly plastic, and potentially expansive[3]. Therefore, this cyclical variation in precipitation drives significant changes in the soil's moisture content, triggering a damaging shrink-swell behaviour [2]. This causes volumetric instability, resulting in severe structural damage to foundations, walls, and pavement.

There exist traditional mitigation approaches such as soil replacement, moisture control barriers, and chemical stabilization[4]. Among these, cement stabilization stands out as a widely recognized technique due to its ability to improve the strength and stiffness of weak soils with relative ease of application [5]. That is, when mixed with clayey materials, cement initiates hydration and pozzolanic reactions that form cementitious compounds that bind particles together [6]. This increases particle density, refines pore structure, and reduces compressibility. Over time, the stabilized matrix exhibits enhanced load-bearing capacity and reduced susceptibility to seasonal volume change. Despite these advantages, large-scale application of cement stabilization must weigh the cost implications, environmental impact, and project-specific soil variability[7]. Not all clay soils respond identically to the exact cement dosage. A lack of methodological uniformity in prior research means findings are not always directly transferable between projects or geographic areas. For instance, differences in mineralogy, grain size distribution, or initial moisture content influence reaction kinetics during stabilization. Even compaction methods, whether tapping for more friable black sandy clay or hammer tamping for denser yellow clay, can alter final UCS values in test samples [8].

Previous investigations have demonstrated that UCS tends to increase with higher cement percentages until an optimal point is reached[5], [9]. However, using excessive cement may unnecessarily raise costs without proportionate performance gains, as there is often a decrease in return on strength improvement beyond an optimal dosage[10], [11]. Moreover, the handling characteristics and achievable compaction densities can vary depending on water content at mixing, a factor closely tied to the Atterberg limits of both untreated and treated soils[6] . Cement-stabilised clays also face long-term performance questions under environmental loading conditions such as wetting-drying cycles or freeze-thaw exposures[12]. While these are less pronounced in tropical climates like Trinidad's compared with temperate zones, seasonal rainfall variation still induces alternating saturation states in subgrades beneath pavements or shallow foundations. Such cyclic processes could degrade particle bonding over time unless carefully addressed during material design[12]. Alternative stabilisation agents, such as lime or fly ash, have shown merit elsewhere but require broader comparative studies under identical site conditions before replacing or reducing cement usage [11]. Polyurethane grouts offer rapid strengthening but are generally more suited to targeted remediation than large-area ground improvement because of cost considerations. Microbially induced calcite precipitation (MICP), while promising from a sustainability standpoint due to potential use of saline water for calcium ion sources, currently suffers from slower reaction rates compared with cement hydration [13].

Given this backdrop, the current research is motivated by two interlinked needs: first, to better quantify how low-dose cement applications, from around 1% up toward mid-range levels near 11%, alter both plasticity and shear-related properties of locally sourced expansive clay; second, to provide engineering practitioners with data-driven guidelines on dosage optimization for typical construction scenarios within Trinidad. A well-defined link between incremental reductions in Plasticity Index (PI) and simultaneous improvements in UCS would offer not only cost efficiency but also improved material performance predictions for designs spanning road subgrades to shallow foundation beds. Establishing such relationships requires controlled laboratory investigations that focus on standard geotechnical parameters: Atterberg limits for assessing shifts in consistency range, and UCS measurements across systematically varied cement letdowns. By capturing these variations methodically and tying them back to real-world site conditions identified through grain size analysis and classification, the study endeavors to address the persistent uncertainty surrounding low-percentage stabilization thresholds in expansive tropical clays. Furthermore, outcomes from this investigation could directly inform localized construction specifications rather than relying solely on generalized international norms. Most prior research focuses on high-bentonite clays in temperate zones, which differ significantly from the iron-rich, high-plasticity residual tropical Talparo clay studied here. This aligns with both cost-saving objectives within public infrastructure budgets and strategies aimed at extending the lifecycle performance of structures subject to fluctuating loads over long operation periods.

II. LITERATURE WORK

The Cement stabilization of clay soils has long been utilized as an effective method to enhance the mechanical performance of problematic expansive clays for structural applications. In their natural state expansive clays often exhibit high plasticity and poor load-bearing properties in their natural state, with strength behavior heavily influenced by mineral composition, water content, and particle packing. The microstructural interactions between clay minerals and stabilizers play a central role in performance improvements. When cement is introduced into these systems, hydration reactions release calcium hydroxide, which subsequently participates in pozzolanic reactions with the reactive silica and alumina phases in the clay.

The primary mechanism of cement stabilisation in clay soils begins with the hydration of cement particles when mixed with soil and water. When cement is mixed with soil and water, hydration of the cement particles occurs, forming calcium-silicate-hydrate (C-S-H) and calcium-aluminate-hydrate (C-A-H) gels. These compounds coat and bind soil aggregates, providing an immediate increase in strength [6].

The hydration process also releases calcium hydroxide ($Ca(OH)_2$), which raises the soil's pH. This high-pH environment facilitates crucial secondary reactions that contribute to long-term performance. First, cation exchange and flocculation occur, where calcium ions ($Ca^{2}+$) from the cement displace weaker cations on the clay surfaces, causing the clay particles to aggregate into larger, more stable clusters. This structural change reduces the soil's affinity for water and lowers its plasticity [14]. Second, long-term pozzolanic reactions take place, where the calcium hydroxide reacts with the silica and alumina inherent in the clay minerals to form additional, stable C-S-H and C-A-H compounds. This process further cements the soil matrix, contributing to a time-dependent increase in strength and stiffness [15].

Studies have consistently demonstrated the efficacy of cement treatments and how they significantly improve UCS and reduce PI of expansive clays, with strength gains being proportional to cement content and curing time[6], Research by Dash & Hussain [14] highlighted that even small percentages of cement can cause a marked reduction in the PI of high-plasticity soils. The performance of stabilised soil is strongly linked to curing conditions, with extended curing periods (e.g., 28 days versus 7 days) allowing for more complete pozzolanic reactions, resulting in substantially higher ultimate strength [6]. This paper builds upon this established body of work by applying these principles to a specific Trinidadian expansive clay in the Couva Area, providing locally relevant data within the practical 1–11% cement content window.

By correlating these geotechnical PIs with empirical UCS data across various curing stages and dosage regimes, engineers can robustly calibrate design specifications tailored specifically for local problem soils while balancing economy against performance metrics. Ultimately, literature suggests that while dosages above certain thresholds yield diminishing strength returns relative to cost input, the combined effects on PI reduction and shear property enhancement justify targeted low-to-mid-range applications of cement, potentially augmented by supplementary materials, to achieve predictable engineering outcomes in expansive tropical clays like those encountered in Trinidad [6].

III. METHODOLOGY

The expansive clay shown in Figure 1 was sourced from Couva, Trinidad (10°24′37.2″N, 61°24′58.8″W), located near the Couva Children’s Hospital, chosen to represent typical high-plasticity soils encountered in central Trinidad. Sampling followed a randomized block approach to minimize bias from local heterogeneity and to capture variations in mineral composition and particle size distribution. Each bulk sample was air-sealed after collection to maintain natural moisture levels until preliminary characterization tests could be conducted. Initial laboratory procedures included standard classification tests, such as particle size distribution analysis using sieve analysis, hydrometer methods, and Atterberg limits testing performed according to ASTM D4318. These data established baseline properties, including liquid limit (LL), plastic limit (PL), and plasticity index (PI), which are particularly sensitive indicators of expansive potential and anticipated response to chemical stabilization. All cement-stabilized samples were prepared by weight-based blending of OPC into air-dried, pulverized clay at target dosages ranging from 1% to 11% by dry mass of soil. Water was added during mixing to bring each batch close to its previously determined OMC. A mechanical mixer ensured uniform distribution of cement throughout the soil matrix while minimizing clumping or segregation. After mixing, specimens for UCS testing were statically compacted in cylindrical molds to dimensions conforming to ASTM D2166 standards. The compaction process itself may have varied slightly between batches due to differences in workability at higher cement contents, a factor that can influence resulting densities and must be accounted for when interpreting strength data.

Immediately after molding, each specimen was sealed in a plastic wrap and placed in a controlled-curing environment with constant humidity to simulate field protection against rapid moisture loss. Curing periods of 7 days and 28 days were selected based on prior research, which showed that early strength gains are largely driven by hydration reactions within the first week, with continued gains over longer durations being more strongly linked to pozzolanic activity. For UCS testing, samples were removed from curing conditions at their target ages, unwrapped, and tested under strain-controlled loading until peak axial stress was reached. Load readings were recorded continuously to generate stress-strain curves, from which peak strength values were extracted. Untreated control specimens of similar dimensions and compaction state were tested alongside treated samples for direct comparison. To complement strength evaluation, Atterberg limit testing was repeated on portions of stabilized material that had been cured under identical conditions but not molded into UCS specimens. This allowed assessment of PI reduction associated with incremental cement content increases under otherwise identical treatment protocols. Microstructural insights from earlier studies guided the interpretation framework for this study. Moisture control throughout sample preparation proved critical because insufficient water availability during hydration can hinder complete binder reaction. Literature suggests the water mass should be at least 0.20 times that of added cement to ensure full hydration. Consequently, all mixing protocols incorporated checks against this ratio during batching workflows[16]. Deviations below this threshold risk competition between binder phases and clay particles for available moisture, potentially delaying strength development.

(a) (b) (c)

Fig. 1. Expansive soil (a) In-Situ Soil (b) Prepared soil with added cement for the Atterberg Limits (c) Compacted and tested UCS sample

Data collection protocols also emphasized replicability; triplicate specimens at each cement percentage level were prepared and tested so that mean values could be computed alongside measures of variability. Statistical analysis included plotting UCS versus cement content for both curing times, tracking changes in PI across dosage steps, and examining any non-linearities indicative of diminishing returns past certain thresholds. This multi-tiered methodology ensured that insights derived here would remain directly translatable into local geotechnical practice while allowing critical comparison back to established performance benchmarks.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The effectiveness of cement stabilization in altering the geotechnical properties of Trinidadian expansive clay is shown in the linked results for plasticity, shear strength, and ultimate bearing capacity. The following sections highlight the main findings from each test, showing how the soil shifts from a problematic, high-plasticity material to a strong, durable one. The classification and compaction results for the natural soil provide critical insights into its geotechnical properties. The gradation analysis indicated a high clay content (65.6%), classifying the soil as mainly fine-grained. The Atterberg limits further supported this, with LL of 51% and PI of 35%, indicating the soil is highly plastic. These properties, along with an optimum moisture content (OMC) of 18.2% and a maximum dry density (MDD) of 1695 kg/m³, show that the soil is very unsuitable for construction without stabilization. These initial results highlight the need for stabilization to enhance the soil's load-bearing capacity and resistance to environmental changes.

Figure 2 shows a complete view of how the soil changes by plotting the LL, PL, and the resulting PI against the cement content used. A sharp, consistent drop in the Liquid Limit (LL) is observed, decreasing from 51% to 22%, while the Plastic Limit (PL) remains relatively stable or shows a slight increase (16% to 19%). A significant drop in the Plasticity Index is observed, decreasing from 35% in the untreated soil to 3% at 11% cement. This significant decrease demonstrates that cement stabilisation is highly effective at reducing soil's expansive behaviour, turning it from a high-risk to a low-risk material for construction. The reduction in plasticity occurs because the chemical composition of the clay particles changes as cement is added, promoting cation exchange and pozzolanic reactions. The cementitious compounds form a coat and bond the clay particles, lowering their water affinity and making the structure more stable. It was observed that at higher cement contents, the samples become slightly more granular and brittle, making it harder to get consistent Atterberg limit values and suggesting that over-treatment may be happening.

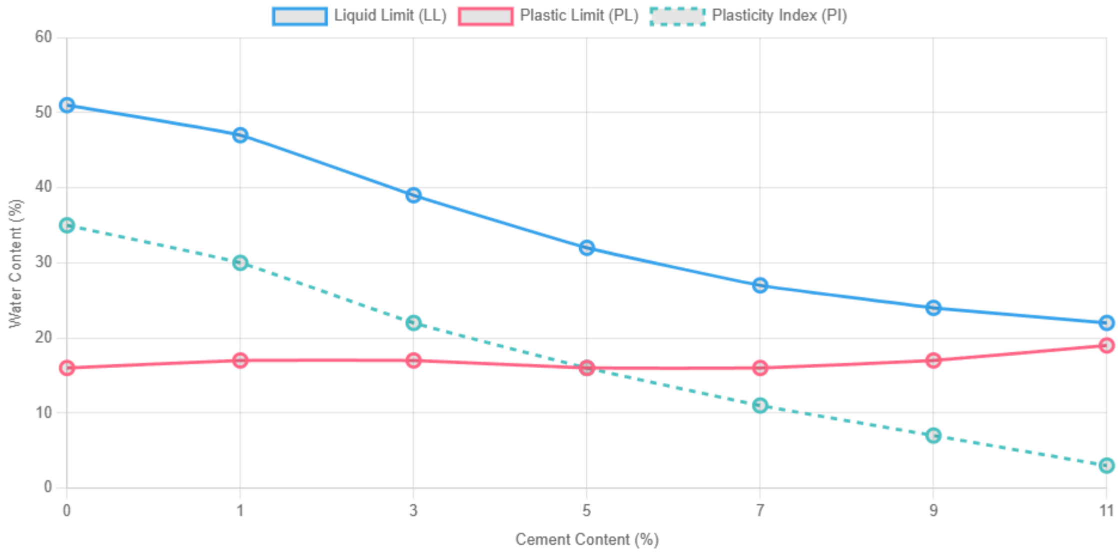

Fig. 2. Effect of Cement content on Atterberg Limits.

Figure 3 highlights the most important result of the Atterberg Limits testing: the decrease in the PI. The PI directly reflects a soil's shrink-swell potential, which is the main engineering challenge this study addresses. The graph shows a strong, nearly linear inverse relationship between cement content and plasticity. The PI drops from 35% in the natural or controlled clay sample to just 3% with 11% cement, indicating low plasticity. This significant 90% reduction proves that cement stabilisation is highly effective at reducing soil's expansive behaviour, turning it from a high-risk to a low-risk construction material.

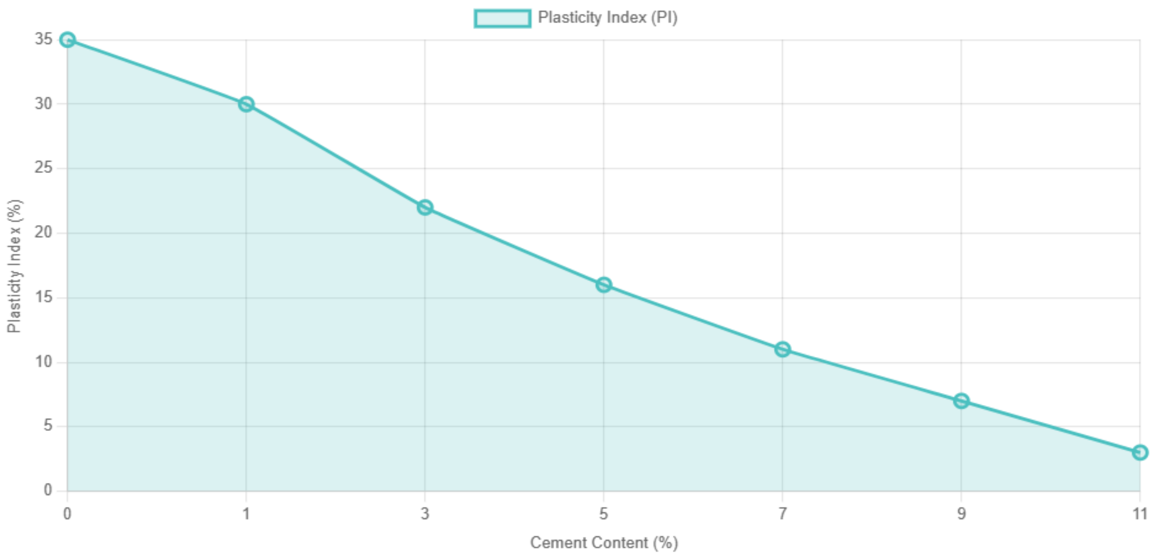

Fig. 3. Reduction in Plasticity Index (PI) vs. Cement Content.

Figure 4 shows a significant increase in shear strength and ultimate bearing capacity as cement content rises. There is a clear, positive relationship: as cement content increases, the UCS and the ultimate bearing capacity also increase sharply. The 28-day UCS grows from 0.294 MPa in untreated soil to a peak of 4.547 MPa at 11% cement content. This is about 1446.6% increase. Similarly, the ultimate bearing capacity rises from 1.083 MPa in the untreated sample to a maximum of 16.744 MPa at 11% cement. This improvement mainly results from the formation of calcium-silicate-hydrate (C-S-H) and calcium-aluminate-hydrate (C-A-H) gels, which bond flocculated soil particles.

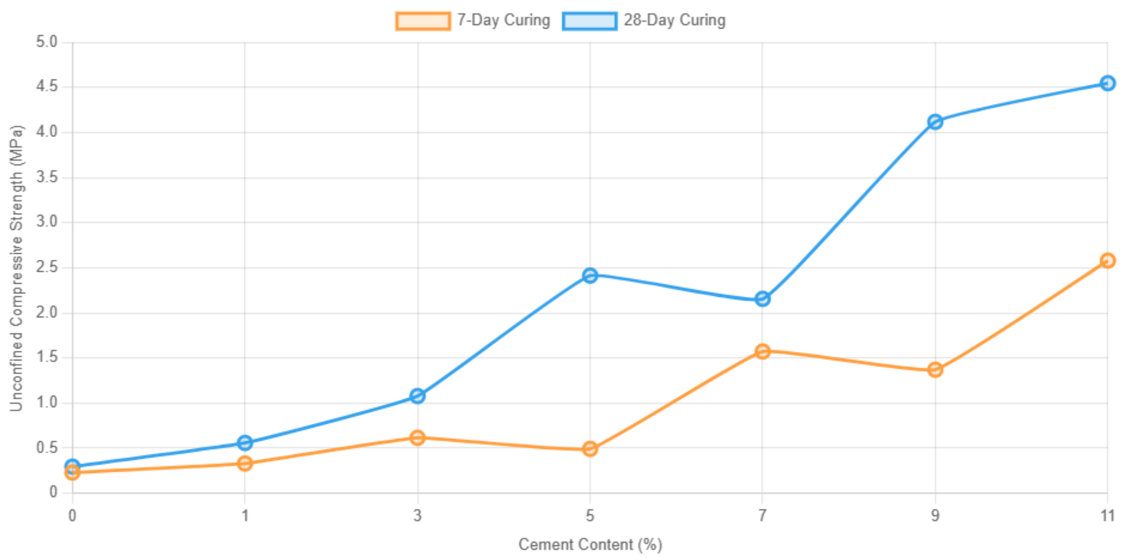

Fig. 4. Unconfined Compressive Strength (UCS) vs. Cement Content

The data clearly demonstrates that strength development depends on time, with 28-day strengths being significantly higher than 7-day values. This highlights how slower pozzolanic reactions contribute to long-term strength and durability. The specific calculation for the UCS increase at 11% cement content provides additional quantitative support for these findings. With an untreated soil UCS of 0.294 MPa and a 28-day UCS of 4.547 MPa at 11% cement, the percentage increase is calculated as:

$$\text{Percentage Increase} = [(UCS_{treated} - UCS_{untreated})/UCS_{untreated}] \times 100\%$$

The results show that the best cement content for stabilisation is between 8% and 11%. Within this range, the highest UCS and ultimate bearing capacity values were recorded, indicating maximum strength gain without the adverse effects of over-stabilisation. When cement content exceeds 11%, UCS values tend to fluctuate and may even decrease. The most rapid strength gain rate is typically observed between 7% and 9% cement content, indicating a threshold where cost-efficiency should be prioritized. This is probably due to soil over-stiffening, which can cause brittleness and microcracking under load, as seen in a sample with a higher cement content. Comparing the bearing capacity of the stabilised soils to commercial clay blocks provides a useful benchmark. The peak capacity of the stabilised soil (4.547 MPa) is similar to the compressive strength of lighter masonry products like Abel's Classic block (6.9 MPa). It should be noted that the ultimate bearing capacity of a shallow foundation is typically calculated using the UCS and is directly enhanced by the increased shear strength. This suggests that cement-stabilised clays are effective for use in subgrades and foundation layers, offering a cost-effective and structurally sound alternative to manufactured materials in suitable applications.

The relationship among these phenomena is synergistic. The initial reduction in plasticity and flocculation, which directly reduces swell potential, is essential for effective strength gain. By forming larger, more stable aggregates, these initial reactions improve soil structure, enabling the cementitious gel to form stronger bonds. Overall, the results confirm that low-dose cement stabilisation is a highly effective dual-purpose method for improving the geotechnical properties of this Trinidadian expansive clay.

V. CONCLUSION

This study examined how cement stabilization enhances the strength and bearing capacity of high-plasticity clay soils from central Trinidad. Based on detailed analysis of Atterberg limits and UCS tests, results showed that OPC is an effective stabilizer for these soils. An optimal cement content of 8-11% was identified for field use to maximize strength gains while preventing adverse effects such as brittleness and cracking. The addition of cement consistently improves the geotechnical properties of the expansive clay, reducing plasticity and significantly increasing UCS and ultimate bearing capacity. This transformation turns problematic soil into structurally suitable soil. The peak 28-day UCS of 4.547 MPa at 11% cement demonstrates the effectiveness of this range. Additionally, stabilization enhances the soil's load-bearing capacity to levels similar to those of commercial masonry products, with the highest capacity approaching 6.9 MPa, identical to Abel's Classic clay block, indicating its potential for structural use. The study also confirms that strength develops over time, with 28-day strengths exceeding 7-day values, highlighting the role of pozzolanic reactions in ensuring long-term durability and performance. Based on these results, cement stabilization is a recommended method for improving high-plasticity clay soils in Trinidad. Future research should focus on long-term durability, including cyclic wetting-and-drying tests and large-scale field trials that account for environmental and soil variability. It is also important to examine alternative stabilizer blends, such as lime and fly ash, and to assess how changes in water content affect stabilization effectiveness and the formation of shrinkage cracking.

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