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Synergistic Effects of Gypsum and Cement on the Geotechnical Properties of Clay Soils: Experimental Evaluation of CBR, UCS, and Compaction Characteristics

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ABSTRACT

Expansive clay soils are widely recognized as problematic subgrade materials due to their high plasticity, low strength, and pronounced swelling–shrinkage behavior. This study investigates the synergistic effect of gypsum and cement as stabilizing agents for clay soils. Laboratory tests were conducted on 96 soil specimens, with stabilizer contents of 1%, 3%, and 5% (by dry weight) and curing periods of 1, 7, and 14 days. Standard tests, including Atterberg limits, compaction, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS), were performed according to ASTM/SNI standards. Results demonstrate that the combined use of gypsum and cement significantly reduces the plasticity index from 41.54% to 8.35% and increases CBR from 1.99% to 23.65% after 14 days of curing. UCS values also improved, reaching a peak of 1.84 MPa under optimum stabilization conditions (5% additive, 14 days curing). These improvements are attributed to cation exchange and pozzolanic reactions that form calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) phases, enhancing soil particle bonding and reducing voids. The findings indicate that combined gypsum–cement stabilization is not only effective in improving mechanical properties but also modifies the soil classification from high plasticity clay (CH) to low plasticity clay (OL). This research contributes practical guidelines for road subgrade improvement and advances the scientific understanding of chemical–mineral interactions in soil stabilization.

Keywords : Expansive Clay, Soil Stabilization, Gypsum, Cement, California Bearing Ratio, Unconfined Compressive Strength

INTRODUCTION

Soil is one of the most essential components in civil engineering structures, particularly in subgrade layers that support pavements, embankments, and foundations. The strength and stability of soil directly determines the serviceability and durability of construction. However, in many regions, especially in Indonesia, clay soils are commonly found and often present significant geotechnical challenges. High plasticity, low permeability, and considerable swelling–shrinkage behavior make clay soils unsuitable for subgrade materials unless proper stabilization techniques are applied.

Soil stabilization has long been adopted as a solution to enhance the engineering properties of problematic soils. Various additives such as lime, cement, fly ash, and agricultural by-products have been utilized to improve shear strength, reduce plasticity, and increase bearing capacity. Among the various evaluation parameters, the California Bearing Ratio (CBR) is widely recognized as a key indicator to assess the effectiveness of soil stabilization, as it directly relates to the thickness design of road pavement layers.

A number of studies have reported the effectiveness of cement and lime in enhancing the geotechnical properties of clay soils. For example [1] [2] demonstrated that the use of cement or gypsum waste improved the plasticity index and CBR values of clay soils. Nevertheless, the majority of these studies were limited to a single stabilizing agent or conducted as a simple comparison between two different additives, without examining the synergistic effects that may arise from combining them [3].

Despite the promising outcomes, little attention has been given to the combined use of gypsum and cement for clay stabilization. Previous works have rarely explored how the interaction between these two additives influences both physical and mechanical properties of clay soils [4]. Moreover, the curing process—whether the soil is compacted before curing or cured before compaction—has often been overlooked, even though it may affect significantly the strength development and long-term performance of stabilized soils [5].

Field investigations in several subgrade sections around Medan, North Sumatra, revealed that many road segments constructed on natural clay soils have experienced early structural failures such as rutting, surface cracking, and uneven settlement within less than two years of service life. Laboratory analyses of representative soil samples indicated a liquid limit (LL) of 41.54%, plasticity index (PI) of 18.73%, and California Bearing Ratio (CBR) of only 1.99%, classifying the soil as high-plasticity clay (CH) under the Unified Soil Classification System (USCS). These geotechnical characteristics indicate that the soil possesses high compressibility, low shear strength, and significant volume change potential during wetting–drying cycles. Such behavior causes loss of bearing capacity and deformation of the pavement layer, leading to premature structural distress. The data highlight the necessity of developing a reliable stabilization method capable of improving soil strength, reducing plasticity, and enhancing long-term subgrade durability, particularly under tropical climatic conditions.

This study aims to investigate the effects of gypsum and cement combination on the stabilization of clay soils. Specifically, the objectives are: (1) to determine the optimum proportion of gypsum and cement for improving clay properties, (2) to evaluate the influence of curing duration on CBR values, and (3) to compare the performance of different curing–compaction sequences. These objectives are expected to provide a more comprehensive understanding of how combined stabilizers and curing methods affect soil improvement.

The novelty of this study lies in the simultaneous application of gypsum and cement with varied proportions and curing times, along with the comparative analysis of two curing–compaction treatments. Unlike previous studies that mainly investigated single additives or overlooked curing sequences, this research introduces a new perspective on optimizing soil stabilization techniques. Furthermore, the study focuses on local clay soils from North Sumatra, providing valuable context-specific insights that have not been widely reported in the literature.

The findings of this research are expected to contribute both scientifically and practically. From a scientific standpoint, it advances the understanding of chemical interactions between gypsum, cement, and clay minerals, as well as their implications on soil mechanics parameters. From a practical perspective, the results may serve as a guideline for engineers and practitioners in selecting more efficient, economical, and sustainable stabilization methods for road construction in regions with expansive clay soils. Hence, this research provides a novel contribution to the development of soil improvement strategies in civil engineering practice.

METHOD

Experimental Design

The study consisted of two stages [6], [7], [8], [9], [10]:

1. Testing of natural soil to determine its basic physical and engineering properties.
2. Stabilized soil testing, where clay was mixed with gypsum and cement at proportions of 1%, 3%, and 5% (by dry weight of soil). Each mixture was subjected to curing periods of 1, 7, and 14 days.

Samples and Test Program

A total of 45 samples of natural soil were prepared for baseline testing, which included water content, specific gravity, sieve and hydrometer analysis, Atterberg limits, standard Proctor compaction, California Bearing Ratio (CBR), and Unconfined Compression Strength (UCS) [11].

For stabilized soil, 51 samples were prepared with different gypsum–cement contents and curing times [12][13].

Testing Standards and Methods

All laboratory tests were performed according to the Indonesian National Standard (SNI), which follows ASTM equivalents. The testing program included [2], [14], [15], [16]:

a. Basic soil properties: water content (SNI 03-1965-1990), liquid limit (SNI 03-1967-1990), plastic limit (SNI 03-1966-1990), sieve analysis (SNI 03-1968-1990), specific gravity (SNI 03-1996-1990), and hydrometer analysis (SNI 03-3423-1994).
b. Engineering properties: standard Proctor compaction (ASTM D698), CBR laboratory test (SNI 03-1744-1989), and Unconfined Compression Strength (UCS, SNI 03-3638-1994).

Sample Preparation and Curing Procedure

Soil samples were oven-dried, pulverized, and passed through a 4.75 mm sieve prior to testing. The predetermined percentages of gypsum and cement were added to the dry soil, followed by the addition of water at the optimum moisture content. The mixture was homogenized and compacted according to the Proctor method [17].

Curing was conducted at room temperature for 1, 7, and 14 days. During curing, the samples were sealed in plastic wrapping to minimize moisture loss and allow proper chemical reactions between soil, gypsum, and cement.

Data Analysis

The experimental results were analyzed to evaluate the effect of gypsum and cement stabilization on [18], [19]:

1. Plasticity characteristics, assessed through changes in Atterberg limits.
2. Soil bearing capacity, assessed by CBR values.
3. Strength improvement, assessed through UCS testing.

Comparative analysis was carried out between untreated and stabilized soil at different additive percentages and curing times to identify the optimum stabilization condition.

RESULTS

Water Content Test Results

Testing of the basic properties and engineering properties of both native soil samples was completed, and one soil sample with lower plasticity and CBR values was selected. This sample was then used as the basis for planning the mixing of native soil with lime as a stabilizing agent.

Table 1. Water Content Test Results

Testing	Variation (1%,3%, 5 %)x (1,7,14 day)	Number of Test Objects
Liquid Limit Testing	3x3x1 sample	9 samples
Plastic Limit Testing	3x3x1 sample	9 samples
Compaction Testing	3x5 samples	15 samples
CBR Testing	3x3 sample	9 samples
Laboratory Testing	3x3x1 sample	9 samples

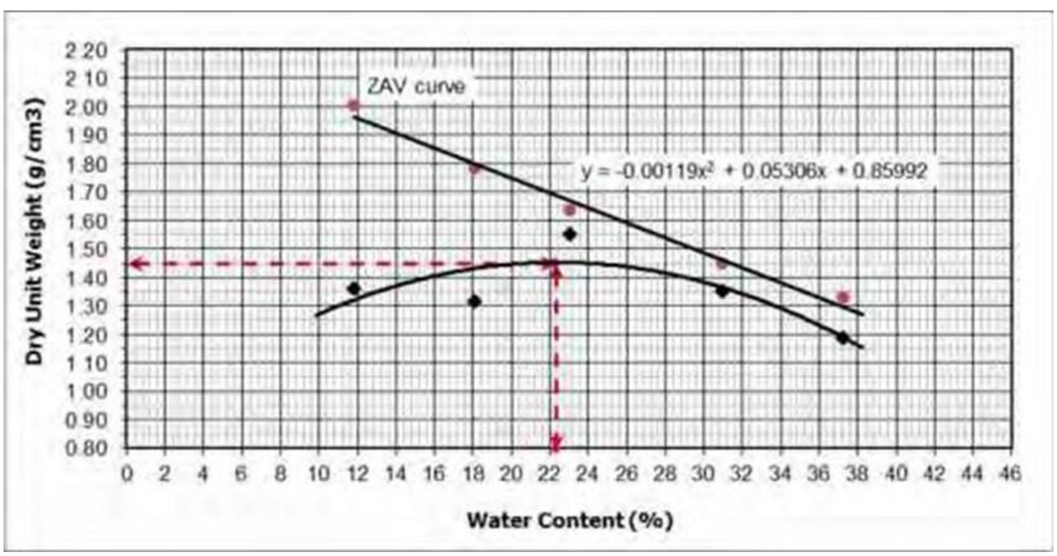

Figure 1. The Relationship Between Water Content and Dry Unit Weight

The figure shows the relationship between water content (%) and dry unit weight (g/cm^3) obtained through soil compaction testing. The resulting curve exhibits a parabolic trend, with peak values representing the maximum dry unit weight (γdmax) and optimum moisture content (OMC).

The graph also displays the Zero Air Void (ZAV) curve, which serves as the theoretical maximum dry unit weight of soil without air voids. A comparison of the laboratory test results with the ZAV curve shows that the compaction results are below this theoretical limit, indicating the presence of air voids in the soil sample. This is a normal condition in soil compaction, as achieving a zero air void condition is nearly impossible in the field.

Technically, the obtained γdmax and OMC values can be used as basic parameters in earthwork planning, particularly for road and embankment construction. The γdmax value provides an overview of the maximum achievable density, while the OMC serves as a reference for the water content that must be maintained for optimal compaction. Thus, these results indicate that the test soil has quite good bearing capacity potential when compacted at a water content of around 22%.

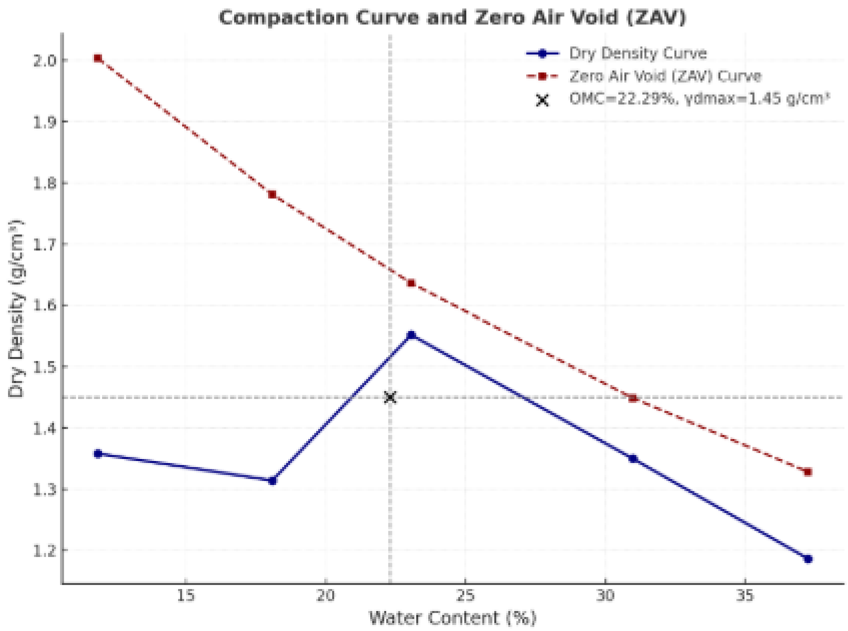

Figure 2. Compaction Curva and Zero Air Void

The compaction test results graph shows the relationship between water content and dry unit weight of the soil with a typical parabolic curve that reaches an optimum point at a water content of 22.29% with a maximum dry unit weight (γdmax) of 1.45 g/cm^3. This value indicates that at this condition the soil reaches its maximum density, so that the optimum water content becomes an important reference in field work to obtain the best compaction quality. The Zero Air Void (ZAV) curve shown is above the laboratory test results, confirming that full compaction conditions without air voids cannot be achieved practically. Thus, these results indicate that the characteristics of the test soil are good enough to be used as embankment material, as long as compaction is carried out at a water content close to the optimum.

Soil Specific Gravity Test Results

The purpose of this test is to determine the ratio between the bulk density of soil and the weight of water in the same volume at a certain temperature. The specific gravity (Gs) value of soil is very important because it is the basis for analyzing the physical properties of the soil, such as the relationship between water content, dry unit weight, and degree of saturation. This Gs data is used in calculations in compaction tests to determine the relationship between water content and maximum dry unit weight, as well as in the CBR (California Bearing Ratio) test to assess the bearing capacity of the soil.

Table 2. Soil Specific Gravity Testing

Specific Gravity, Gs		1	2	3
Depth	[m]			
Determination No				
Pycnometer No		2	3	6
Heavy Pycnometer	[gram]	67.40	67.42	72.18
Heavy Pycnometer + dry soil	[gram]	80.94	81.14	85.40
Heavy Pycnometer + land	[gram]	175.19	174.37	177.09
Dry + water				
Weight of Pycnometer + water	[gram]	166.79	165.83	168.90
Temperature (T)	[° C]	28.00	28.00	28.00
Density of Water at T, (Gt)	[gr/cm3]	0.9963	0.9963	0.9963
Specific Gravity of Soil (Gs)		2.62	2.64	2.62

Based on the results of soil specific gravity testing at different depths using a pycnometer, Gs values of 2.62; 2.64; and 2.62 were obtained at a test temperature of 28 °C with a water density of 0.9963 gr/cm^3. This value indicates the consistency of the characteristics of the minerals that make up the soil, which are generally in the range of 2.60–2.70, so it can be categorized as normal fine-grained mineral soil. The existence of a relatively uniform Gs value indicates the homogeneity of the soil sample with regard to the specific gravity parameters of solid particles, so this data is valid to be used as a basis for calculations in compaction analysis and CBR tests. Thus, the results of this specific gravity test provide an important contribution in understanding the physical properties of the soil that directly affect the bearing capacity and stability of the construction above it.

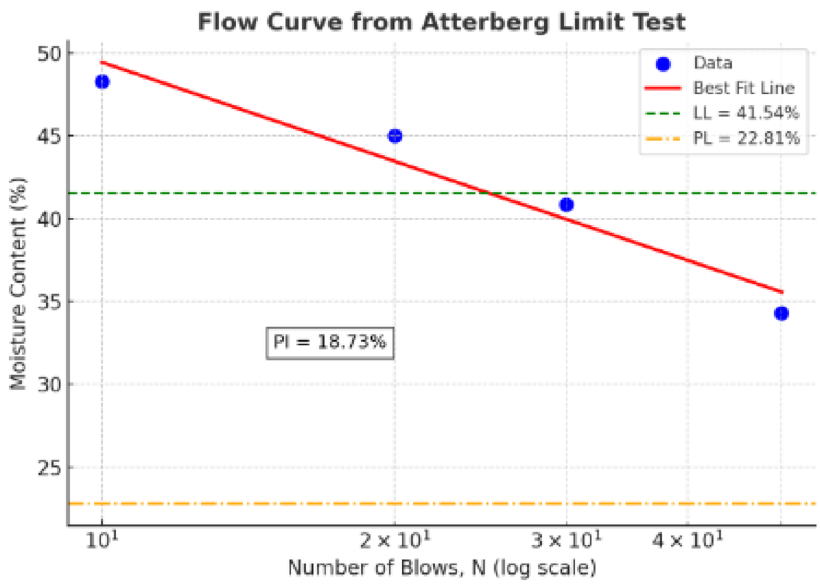

Figure 3. Liquid Limit testing

Liquid Limit testing using the Casagrande method produces a relationship curve between water content and the number of impacts as shown in Figure 1. The test data are plotted in a semi-log scale, where the horizontal axis represents the number of impacts (N) in a logarithmic scale, while the vertical axis shows the water content (%). Linear regression of the test data produces a Liquid Limit (LL) value of 41.54% at 25 impacts. Meanwhile, the Plastic Limit (PL) value is obtained at 22.81%, so the plasticity index (PI) is calculated at 18.73%.

High LL and PI values indicate that the soil has moderate to high plasticity, according to the Atterberg classification. This condition indicates the dominance of clay fractions with significant clay mineral activity, so that the soil is cohesive and sensitive to changes in water content. Geotechnically, soil with moderate to high plasticity has the potential to experience large volume changes (swelling and shrinkage), which have implications for the stability of the base soil layer (subgrade) and the bearing capacity of the foundation. This finding is consistent with previous research stating that PI values > 17% generally indicate moderate expansive behavior (Chen, 1988; Seed et al., 2001). Therefore, in planning construction on this soil, a soil improvement strategy or the use of adequate pavement layers is required to reduce the impact of deformation due to moisture variations.

Engineering Inspection of Real Land Properties

The standard proctor test aims to determine the relationship between water content and soil density by compacting the soil in a cylinder of a certain size using a mold, the soil sample passes through a sieve. The purpose of the standard proctor test is to find the maximum density value and optimum water content of a soil sample.

Table 4. The Compaction Test Results

Item	Unit	Symbol	1	2	3	4	5
Mold weight	g	Wm	3600	3600	3600	3600	3600
Weight of solid soil + mold	g	Wcm	5000	5030	5360	5230	5100
Cup No.	-	-	C-1	C-2	C-3	C-4	C-5
Cup weight	g	Mc	13.80	13.80	13.80	13.80	13.80
Weight of wet soil + cup	g	Mcm	155.40	158.70	132.00	146.60	168.60
Weight of dry soil + cup	g	Mnm	140.42	136.51	109.86	115.06	126.59
Water content	%	w	11.83	18.08	23.05	30.97	37.25
Soil density	g/cm^3	γd	1,358	1,314	1,552	1,350	1,186
Zero Air Void (ZAV) curve	g/cm^3	γz	2,004	1,781	1,636	1,449	1,328

Based on the compaction test results in the table, it can be seen that the water content (w) increased from 11.83% to 37.25%, while the soil unit weight (γd) fluctuated with the highest value of 1.552 g/cm^3 at a water content of 23.05%. This indicates that the optimum water content (OMC) is around 23%, with a maximum dry unit weight (MDD) of 1.552 g/cm^3. After passing the OMC, the dry unit weight value decreases again as the water content increases due to excess water filling the soil pores, thereby reducing the density. The Zero Air Void (ZAV) curve shows the theoretical limit of soil density at fully saturated conditions, where all pores are filled with water. These results are consistent with the theory of soil compaction, namely the existence of a parabolic relationship between water content and dry unit weight.

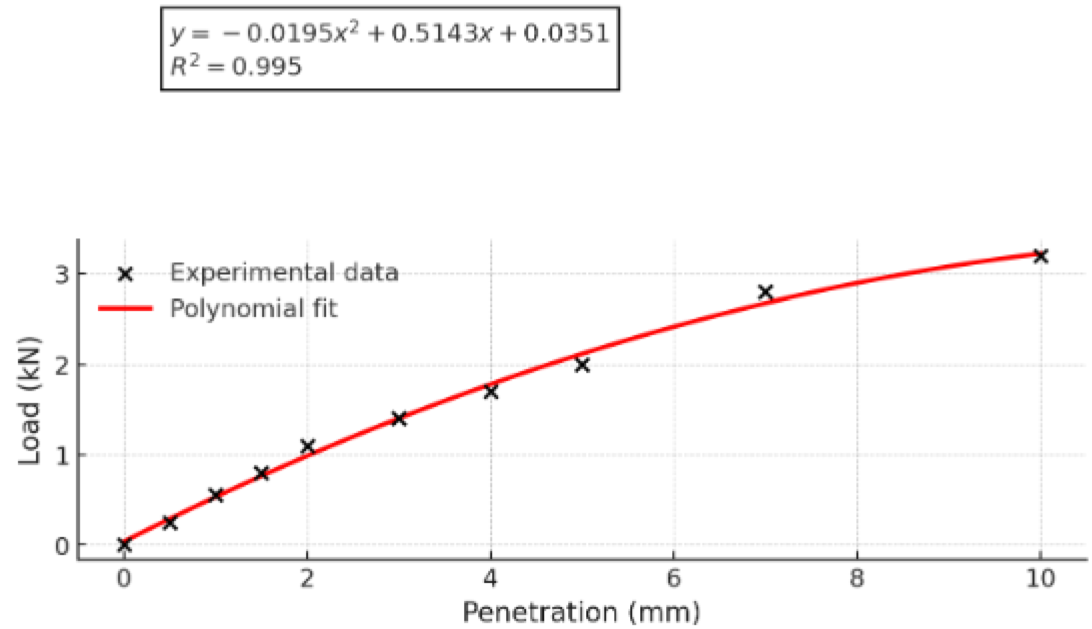

Figure 4. The Relationship Between Penetration and Load With Experimental Test

The CBR graph shows the relationship between penetration and load with experimental test data presented using second-order polynomial regression. The regression equation obtained is y = -0.0195x^2 + 0.5143x + 0.0351 with a coefficient of determination R^2 = 0.995, which indicates a very high level of model fit to the test data. This value indicates that the curve can accurately represent soil behavior in the CBR test. The load increases with penetration up to 10 mm, with a downward-curving curve that corresponds to the characteristics of the soil that experiences a decrease in the rate of load increase after passing a certain point. These results indicate that the soil bearing strength is quite good and can be used to evaluate the bearing capacity of the subgrade layer in pavement construction.

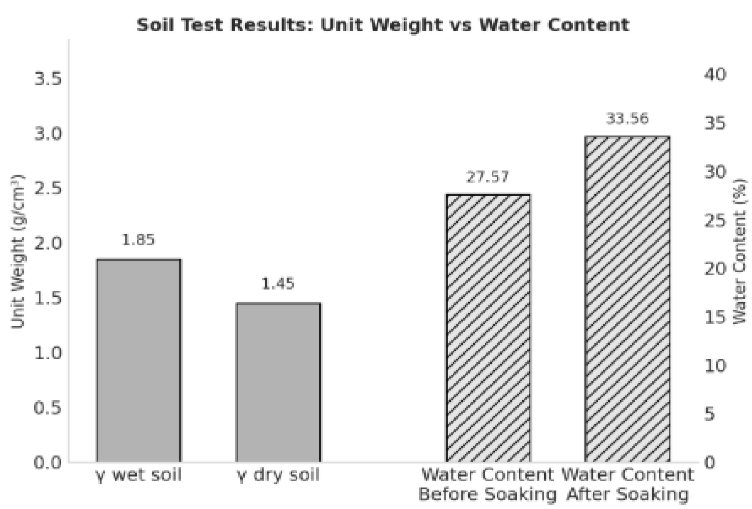

Figure 4. The Soil Test Result

Unconforming Compression Strength

The results of the UCS experiment with variations in the addition of 5% gypsum and cement with a curing time of 14 days can be seen in the table.

Table 5. The Compaction Test Results

t (minutes)	Deflection (mm)	Strain (%)	Proving Ring Reading (div)	Actual Load (kN)	Correction Factor	Area (cm^2)	q_u (kN/m^2)
0.5	3/3	0.3	20.0	0.028	1.0049	23.0	86.05
1	7/3	0.7	58.0	0.080	1.0141	23.0	140.73
2	13/3	1.3	110.0	0.152	1.0263	23.1	214.56
3	25/3	2.5	220.0	0.303	1.0544	23.2	383.65
5	35/3	3.5	325.0	0.449	1.0789	23.3	555.89
7	50/3	5.0	470.0	0.649	1.1093	23.4	849.37
10	75/3	7.5	725.0	1,001	1.1584	23.5	1309.72
15	100/3	10.0	930.0	1,283	1.2035	23.6	1630.73
20	125/3	12.5	1035.0	1,428	1.2240	23.7	1844.40
25	150/3	15.0	1010.0	1,393	1.2201	23.8	1805.09
30	175/3	17.5	865.0	1,193	1.2046	23.9	1508.61

Parameter	Value (g)
Mold + wet soil	312.8
Blank print	474.3
Wet ground	171.4
Cup + dry soil	132.8

Based on the results of the Unconfined Compression Test, the soil sample with a diameter of 4 cm and an initial length of 7.5 cm showed an increase in deviation stress as the strain increased until it reached a maximum value at a strain of approximately 12.5%. The highest unconfined compressive strength (qu) obtained was approximately 1844 kN/m^2, before experiencing a decrease in stress due to soil structure failure. This value reflects the characteristics of the soil which has a fairly high bearing capacity with significant plastic deformation. The wet and dry weight data indicate a relatively high initial water content, which contributes to progressive deformation behavior. In general, the stress-strain curve pattern obtained is in accordance with the characteristics of cohesive soil, where there is an increase in stress to a peak followed by weakening (strain softening). This finding is in line with the literature that saturated or near-saturated clay soils tend to show a clear maximum compressive strength and a decrease after passing a critical strain.

DISCUSSION

The results showed that the addition of gypsum and cement consistently increased the California Bearing Ratio (CBR) and unconfined compressive strength (UCS) of clay soil. The most significant increase was achieved with a 5% mixture with a curing time of 14 days, where the CBR value increased from 1.99% to 23.65% and the UCS increased from 0.201 kg/cm^2 to 0.703 kg/cm^2. These findings align with a recent study confirming the effectiveness of calcium-based additives in improving highly plasticized soils [20].

A decrease in the plasticity index (PI) was also identified as one of the dominant effects of the stabilization process. At a mixture content of 5%, the PI value decreased from 41.54% to 8.35%, indicating a shift in soil properties from high to low plasticity. This decrease in PI directly impacts the potential for soil shrinkage and swelling, as revealed by [21] [22] in their study on controlling soil expansivity with CaO-based additives.

From a mechanistic perspective, the increase in soil bearing capacity can be explained by two processes: (1) ion exchange between soil cations (Na^+, K^+) and Ca^{2+} from gypsum and cement that triggers particle flocculation, and (2) pozzolanic reactions that form calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) bonds. This phenomenon is consistent with the findings [23], [24]who emphasized the main role of pozzolanic reactions in strengthening the microstructure of clay soils. Curing time has been shown to play a significant role in the stabilization process. Samples cured for 14 days showed greater strength gains compared to those cured for 1 and 7 days. This is consistent with the research [25], [26], [27], who reported that hydration and pozzolanic reactions require time to achieve stable bonds, thus increasing soil bearing capacity with increasing curing time.

Based on soil classification, the original soil falls into the CH (high plasticity clay) category according to USCS and A-7-6 (19) according to AASHTO. However, after being stabilized with 5% gypsum and cement, the soil shifts to the OL (low plasticity organic clay) category according to the Unified Classification. This shift shows that the stabilization method used not only increases the bearing capacity but also changes the basic properties of the soil to be more suitable for use as a subgrade. Similar findings were reported by [28], [29], [30] in a study of subgrade stabilization in a road pavement project.

Standard Proctor test results show a decrease in maximum dry unit weight (MDD) with the addition of gypsum and cement, accompanied by an increase in optimum moisture content (OMC). This phenomenon indicates that stabilized soil absorbs water more readily, thus requiring more careful water content control in field practice. A similar observation was observed by[31] [32], [33], who stated that stabilization with calcium can modify the soil density-moisture relationship.

The increase in CBR values achieved in this study has important implications for planning road pavement thickness. With a CBR value >20% after stabilization, clay soil has the potential to be used as an adequate subgrade layer. A study by [34], [35] also showed that increasing CBR due to stabilization can reduce the required aggregate layer thickness, making it more economical in road construction.

From a construction safety perspective, it's important to note that the use of gypsum as an additive carries certain risks, such as its hygroscopic nature. Therefore, material handling procedures must adhere to safety standards as recommended by SNI and international practices [3], [36], [37]. This suggests that while laboratory results are promising, field application requires a thorough evaluation of climatic and drainage conditions.

The results of this study confirm that a combination of gypsum and cement at a 5% concentration with a 14-day curing period is the optimum condition for improving the stability of clay soil. These results reinforce recent literature that emphasizes the effectiveness of calcium-based additives in improving the geotechnical performance of problematic [38], [39], [40]. Thus, this study contributes to the development of more efficient, economical, and applicable soil stabilization methods in road construction.

RESEARCH IMPLICATIONS

The results of this study indicate that the addition of a combination of gypsum and cement to clay soil significantly increases the California Bearing Ratio (CBR) value, which was previously in the low range in its original condition, to more than 23-41% after curing for 14 days. This increase is in line with the findings of Nuril Mahda Rangkuti et al. (2019), who reported that the addition of 5% gypsum + cement with curing and compacting first treatment resulted in a CBR value of 41.54% in clay soil. Improvements can be explained by the hydration of cement and the effect of gypsum as a secondary reactant, which produces compounds such as calcium silicate hydrate (CSH), which strengthen the interparticle structure of the soil, reducing porosity and plasticity. These changes reduce the potential for plastic deformation and volumetric changes in the soil due to changes in water content, consistent with findings from the literature on clay soil stabilization with gypsum, cement, or other stabilizer combinations. For example, in studies using gypsum alone as a stabilizer for high-plasticity clay soils, the plasticity level decreased significantly as the gypsum percentage increased, although the increase in CBR was sometimes more moderate without the addition of catalysts or longer curing times.

CONCLUSION

This study proves that the combination of gypsum and cement is an effective stabilization method to improve the physical and mechanical properties of high-plasticity clay soil. The addition of 5% gypsum-cement mixture with a curing time of 14 days resulted in optimum conditions, with a significant increase in the CBR value (from 1.99% to 23.65%) and unconfined compressive strength (up to 1.84 MPa), as well as a decrease in the plasticity index from 41.54% to 8.35%. The improvement mechanism is controlled by ion exchange and pozzolanic reactions that produce stronger interparticle bonds through the formation of C–S–H and C–A–H. In addition to increasing the bearing capacity, this stabilization also changes the soil classification from CH to OL, making it more suitable for use as a subgrade material. Practically, these findings provide a scientific and technical basis for planning more efficient, economical, and sustainable road construction in areas with expansive clay soil distribution.

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