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Mechanical Performance of Cement–Additive Stabilized Soils With Different Plasticity Indices for Road Subbase Applications

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ABSTRACT

This research presents a laboratory study of the mechanical efficiency of engineering processes for cement-stabilized soils with varying plasticity indices in road subbase applications. Soils with low, medium, and high plasticity were selected from areas of selection in Papua Province, Indonesia. The soils were stabilized by a fixed composition with 10% ordinary Portland cement supplemented with 2% chemical additive, and the engineering performance of these mixes was assessed using Atterberg limits and compaction characteristics, unconfined compressive strength (UCS), and the California Bearing Ratio (CBR) test. All mechanical tests were performed after 7 days of curing to characterise early strength development. The findings suggest that the soil plasticity index, which serves as the engineering classification parameter, relates to differences in UCS and CBR performance after identical stabilization. Lower-plasticity index soils showed high UCS and CBR results across a large group of tests. In contrast, higher-level soils exhibited minimal initial performance but significant performance recovery after stabilization. The stabilized soil mixtures attained UCS and CBR values that complied with the basic performance standards in the Indonesian General Specifications (Bina Marga) for lower subbase layers. This work establishes that the performance of cement–additive stabilized soils depends on plasticity level, underscoring the importance of considering the plasticity index in preliminary soil characterization for pavement design. It is not well established under the conditions of laboratory-scale experiments and early curing, and requires investigation for both long-term performance and field performance.

Keywords: *Soil Stabilization; Cement; Chemical Additive; Plasticity Index; UCS; CBR; Road Subbase.*

1. Introduction (Tnr Font 11, Bold)

Subgrade and subbase material quality is a significant factor controlling the performance of road infrastructure, especially in areas with fine-grained soils (with moderately to highly plastic properties). They tend to have very poor bearing capacity, high compressibility, and significant sensitivity to moisture variations, leading to premature pavement damage such as rutting, cracking, and differential settlement [1–3]. In several tropical areas, such as Indonesia, soil does not meet minimum engineering standards, specifically for pavement foundation layers, and it is often required by some engineering projects to remediate the basic foundations before a building is constructed in the region. Moreover, to achieve high-performance conditions, soil preparation by the pavement man or man was required to prepare subgrade and subbase soil-type-based materials, which was recommended. Cement stabilization is widely reported to improve soil properties, including strength and stiffness, but soil characteristics strongly influence its efficiency under treatment [4,6].

Among soil properties, the plasticity index (PI) is commonly used as an engineering classification parameter to model mechanical response owing to the synergistic effects of clay content, mineralogy, and soil consistency [2,5]. Soils with varying plasticity levels have previously been shown to react differently to cement and additive stabilization, as indicated as variations in unconfined compressive strength (UCS) and California Bearing Ratio (CBR) [6,7,12,13]. However,

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the development of strength in stabilized soils not only relies on PI but also on clay mineral composition, particle size distribution, and soil fabric [1,7,11]. Hence, PI should be considered an index-based soil behaviour outcome rather than a direct mechanistic control variable in cement–stabilized soils.

However, comprehensive soil–cement stabilization research is still scarce, and studies comparing the mechanical properties of cement–additive stabilized soils with different plasticity indices to the same fraction composition of the mixture (i.e., soil composition and uniformity) in the laboratory are few. In particular, the early-age strength behavior, such as UCS and CBR performance after a short curing period, is the focus of very few studies, which openly acknowledge the limited applicability of laboratory-scale testing and the lack of long-term durability assessment [8,10]. Thus, this work presents a comparative laboratory study of cement–additive stabilized soils with different plasticity indices, including their mechanical properties as soon after initial curing. The analysis in this study is confined to testing soil–cement mixtures stabilized with selected additives in vitro. The mechanical properties evaluated include UCS and CBR, which are vital engineering parameters for assessing the appropriateness of subgrade and subbase materials in pavement design. This study is not concerned with long-term field performance, durability under cyclic wetting and drying conditions, or economic feasibility considerations. We aim to explore the differences in the UCS and CBR performance of additive-stabilized soil–cement mixtures at varying soil plasticity levels. The results are anticipated to provide index-based insight into soil performance for use in preliminary pavement material selection and stabilization planning. Still, they are not predictive of longer-term pavement performance.

2. Materials and Methods

2.1. Materials

a. Soil Samples
Three categories of natural soils were employed in this research, identified according to the Unified Soil Classification System (USCS) and AASHTO specifications. The selected soils were intended to represent varying levels of plasticity: low plasticity with PI values less than 10, medium plasticity with PI ranging from 10 to 20, and high plasticity with PI equal to or greater than 20.

b. Cement
Ordinary Portland Cement (OPC) Type I, in accordance with ASTM C150 specifications, was used as the primary stabilizing agent. Cement content was varied at 10% by dry weight of soil.

c. Additives
Chemical additive: A proprietary soil conditioner (Diva Soil) used at a dosage of 2% by dry soil weight.

d. Water
Distilled water was used for sample preparation to eliminate the influence of impurities on soil–cement hydration.

2.2. Experimental Design

The experimental program consisted of preparing soil–cement mixtures with and without additives for each soil type. The mix proportions included:

a. Natural soil (control sample)
b. Soil + 10% cement
c. Soil + 10% cement + 2% Diva Soil

Specimens were prepared according to ASTM D1633 for Unconfined Compressive Strength (UCS) and ASTM D1883 for California Bearing Ratio (CBR) tests. The curing period was set at 7 days to evaluate strength development over time.

2.3. Testing Procedures

a. Atterberg Limits and Soil Classification

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Plasticity index (PI) was determined using Atterberg limits tests (ASTM D4318) to classify the soils and confirm the plasticity range.

b. Compaction Test
Standard Proctor compaction (ASTM D698) was performed to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) for each mixture.

c. UCS Test
Cylindrical specimens (38 mm × 76 mm) were tested for unconfined compressive strength at 7 days using a loading rate of 1 mm/min.

d. CBR Test
Soaked CBR tests were performed on compacted specimens cured for 7 days. Penetration resistance was recorded at 2.5 mm and 5 mm penetrations.

2.4. Theoretical Consideration

The theoretical framework of this study is based on the interaction between cement hydration products and soil particles, which leads to the formation of cementitious bonds that enhance soil strength and stiffness. During hydration, cement reacts with water to form binding compounds that fill voids and improve interparticle bonding within the soil matrix. These processes contribute to increased resistance to deformation and enhanced load-bearing capacity. In addition, the incorporation of chemical additives is expected to modify soil behavior by reducing plasticity and improving particle arrangement through mechanisms such as particle flocculation and aggregation. These effects can enhance soil compactability and facilitate more effective stress transfer within the stabilized soil structure. Consequently, the improvement in unconfined compressive strength (UCS) and California Bearing Ratio (CBR) values observed in this study is interpreted as the combined effect of cementitious bonding and plasticity reduction under early curing conditions [1–3]. Detailed chemical and microstructural mechanisms were not explicitly investigated in this study.

3. Results and Discussions

3.1. Properties of Natural Soil

Natural soil samples were collected from three locations in Papua, representing diverse local soil conditions. This selection provided variations in soil plasticity, enabling a more comprehensive analysis of the effect of additive incorporation in soil–cement mixtures on unconfined compressive strength (UCS) and CBR values.

Table 1. The soil sample from T3 (Koya, Jayapura) exhibits the highest risk of volume change due to its high plasticity index (PI), making stabilization essential. The soil from T1 (Kebun Coklat, Merauke) exhibits medium plasticity and still requires stabilization to ensure reliable subgrade performance. Meanwhile, the soil from T2 (Kampung Samaya, Merauke) is relatively more stable in terms of plasticity; however, treatment is still necessary, as its liquid limit (LL) remains high.

Table 1. Soil Sample from 3 Different Areas

Atterberg Limit Parameters	Unit	T1 (Chocolate Farm, Merauke)	T2 (Samaya Village, Merauke)	T3 (Koya, Jayapura)
Shrinkage Limit (SL)	%	15.31	16.58	10.26
Liquid Limit (LL)	%	41.93	36.67	35.46
Platic Limit (PL)	%	28.89	28.51	14.54
Plasticity Index (IP)	%	13.04	8.16	20.92

3.2. California Bearing Ratio (CBR)

This test was conducted to determine the California Bearing Ratio (CBR) of natural soil compacted in the laboratory at a specified moisture content and cured for 7 days.
The data indicate that the addition of 10% cement and 2% Diva Soil significantly increased the CBR values at all compaction levels (number of blows). At the standard penetration of 0.1 inch, the CBR

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value increased from approximately 47.5% at 10 blows to 87.5% at 56 blows, while at the 0.2 inch penetration, it increased from 55.0% to 98.3%. This finding indicates that the combination of chemical stabilization and increased compaction energy is associated with improved soil bearing capacity. The increase in CBR values places the stabilized soil in the very good subgrade material category for road pavement construction, in accordance with Bina Marga specifications, which generally require a minimum CBR of 6–10% depending on the road class.

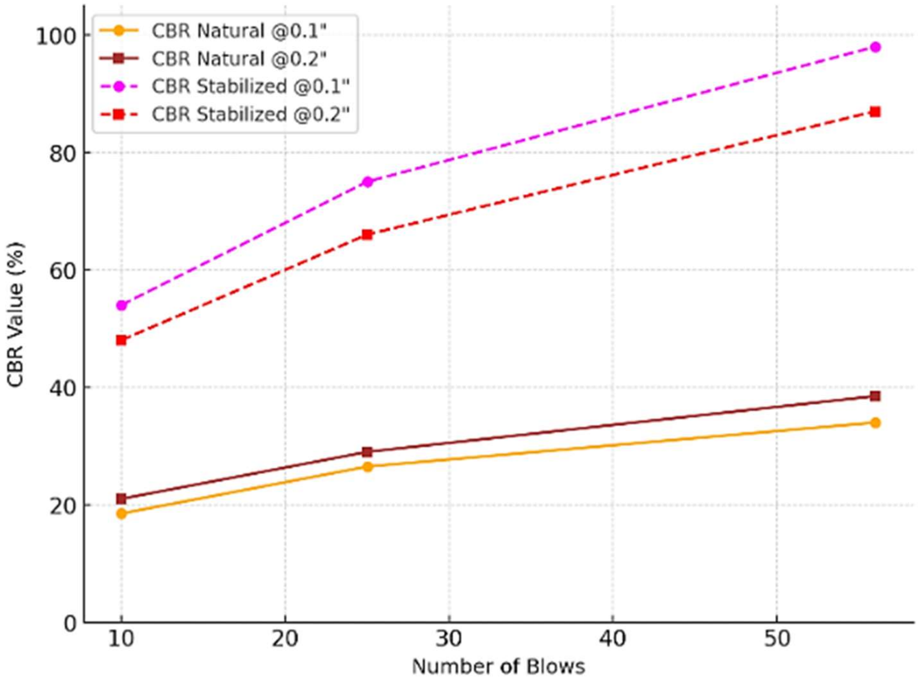

Figure 1. The caption is adjusted to align with the graphic's width for consistency**.**

CBR values after stabilization (10% cement + 2% Diva Soil) at two penetration levels (0.1" and 0.2") with respect to the number of blows. A significant increase in CBR is observed with increasing number of blows, indicating the effectiveness of the combined stabilization and compaction.

At location T2, the CBR value of the natural soil was slightly lower compared to T1. At a penetration of 0.1 inch, the CBR value increased from 17.1% at 10 blows to 25.6% at 25 blows, and then to 33.4% at 56 blows. At a penetration of 0.2 inch, the CBR values were recorded at 20.7%, 28.7%, and 37.0% for the same number of blows. The relatively low initial values are associated with the soil texture, which is predominantly silt with moderate plasticity. Although the CBR values show a fairly consistent increase with compaction energy, they remain at levels that require stabilization treatment to be considered reliable as a road subgrade layer.

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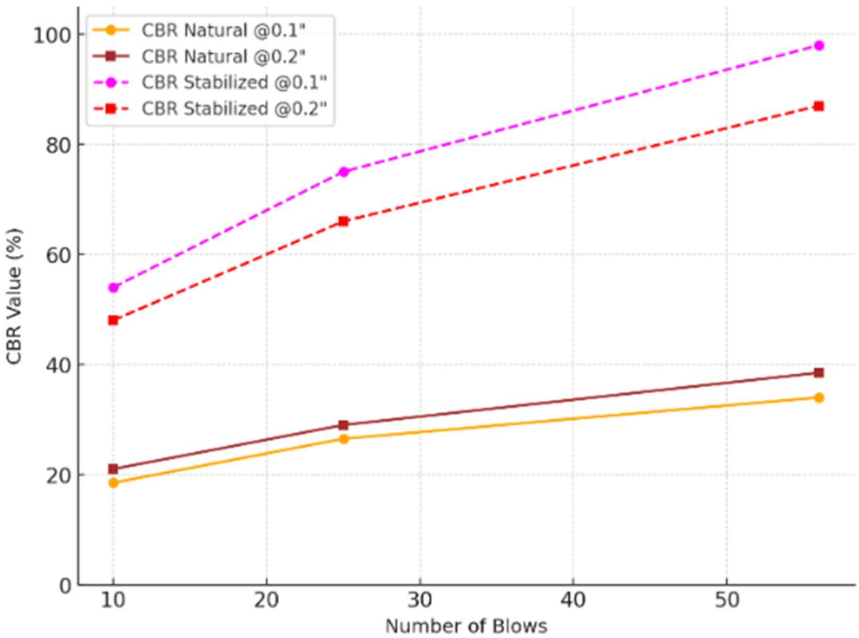

Figure 2. Graph of CBR Value vs. Number of Blows for Soil T2

The calculation results show that the natural soil T2 has CBR values that gradually increase with the number of blows, from 17.1% at 10 blows to 33.4% at 56 blows under a standard penetration of 0.1 inch, and from 20.7% to 37.0% at a penetration of 0.2 inch. However, these values are still within the medium category, which generally requires further treatment to meet subgrade soil requirements. After stabilization with a combination of 10% cement and 2% Diva Soil, the CBR values increased significantly at all compaction levels. At 0.1 inch penetration, the CBR values rose to 45.0%, 64.0%, and 82.5% at 10, 25, and 56 blows, respectively. Similarly, at 0.2 inch penetration, the CBR values increased to 51.7%, 71.7%, and 92.5%.

The CBR test results on the natural soil T3 show relatively low values, both in terms of the number of blows and penetration. At a standard penetration of 0.1 inch, the CBR value increased from 2.53% at 10 blows to 4.60% at 56 blows, whereas at a 0.2-inch penetration, the CBR value rose only from 2.10% to 3.82% at the same number of blows. These values are far below the general standard for road subgrade soils, which typically require a minimum CBR of 6–10%, indicating that the silty clay soil at this location has very limited bearing capacity. In terms of load carried, at 0.1-inch penetration, soil T3 sustained about 25.3 lbs at 10 blows, increasing to 46.0 lbs at 56 blows. Similarly, at 0.2 inch penetration, the load increased only from 31.5 lbs to 57.3 lbs, which is significantly lower than the standard CBR test loads (1000 lbs for 0.1 inch and 1500 lbs for 0.2 inch).

The low CBR values and load capacity are closely related to the characteristics of soil T3, which is dominated by plastic silt (PI ~20.9%) and has a fine-grained particle size distribution, making the soil prone to deformation under loading. This confirms that the natural soil in Koya, Jayapura, requires stabilization, either through intensive compaction or the addition of binding materials such as cement and additives, to be used as an adequate road subgrade.

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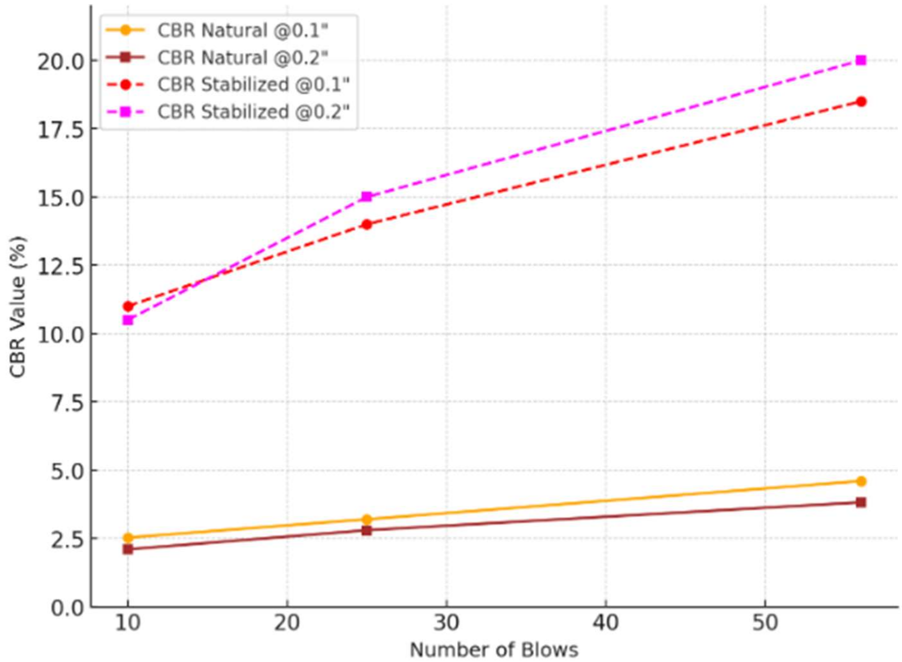

Figure 3. Graph of CBR Value vs. Number of Blows for Soil T3

The test results show that stabilization using 10% cement and 2% Diva Soil significantly improved the CBR value of soil T3 at all compaction levels. At a standard penetration of 0.1 inch, the CBR value increased from the original 4.60% to 18.4% at 56 blows, while at a penetration of 0.2 inch, the CBR value rose from 3.82% to 19.9%. This is equivalent to more than a fourfold increase compared to the initial natural soil condition. A similar improvement is evident in the soil's load-bearing capacity. After stabilization, at 56 blows, the soil sustained loads of 184 lbs at 0.1 inch penetration and 299 lbs at 0.2 inch penetration, which are much higher than the initial loads of only 46.0 lbs and 57.3 lbs under the unstabilized condition. This indicates that the combination of cement and Diva Soil stabilization not only enhances the bonding strength between soil particles but also significantly improves the bearing capacity of the silty clay soil in Koya, Jayapura, which was previously categorized as very low. With this increase in CBR value, soil T3 becomes much more suitable for use as a subgrade layer in road pavement after stabilization treatment.

3.3. Unconfined Compressive Strength (UCS)

In the Unconfined Strength Test (UCS), both the natural soil and the soil mixed with 2% Diva + 10% Cement were tested. A total of 3 samples were examined after a 7-day curing period, in accordance with SNI-03-6887-2002.

Soil T1 has a UCS value of 10.5 kg/cm², which is technically categorized as medium strength but is still insufficient for direct use without additional stabilization. Meanwhile, soil T3 has the lowest UCS value, 9.3 kg/cm², indicating weak bearing capacity and the need for significant engineering intervention, such as mixing with cement or other additives, to improve its strength.

In contrast, soil T2 has an average UCS value of 15.4 kg/cm². This value meets the minimum requirement for the lower subbase layer (14.0 kg/cm²), indicating that, technically, this soil has the potential to be used directly for lower subbase construction. However, additional tests such as CBR and plasticity characteristics are still necessary to ensure overall technical feasibility. Nevertheless, for use as an upper subbase layer, soil T2 still does not meet the minimum standard, as it has not reached the UCS value of 21.0 kg/cm². Overall, this analysis shows that among the three soil types tested, only soil T2 demonstrated the best mechanical performance in the UCS test. Soils T1 and T3 require stabilization treatment.

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Table 2. The Unconfined Compressive Strength (UCS) test was conducted on three types of natural soil, namely T1, T2, and T3, to evaluate the initial bearing capacity of each soil before stabilization efforts or utilization as a base material for road pavement foundation layers. The test results showed that the average UCS values for soil T1, T2, and T3 were 10.5 kg/cm², 15.4 kg/cm², and 9.3 kg/cm², respectively.

Table 2. Average UCS

Soil Type	Sample 1 (kg/cm²)	Sample 2 (kg/cm²)	Sample 3 (kg/cm²)	Average UCS (kg/cm²)
T1 – Original Soil	10.3	10.5	10.7	10.5
T2 – Original Soil	15.2	15.4	15.6	15.4
T3 – Original Soil	9.1	9.4	9.4	9.3

The results of the Unconfined Compressive Strength (UCS) tests on soils T1, T2, and T3 indicate varying bearing capacities. Soil T1 shows a UCS value of 20.8 kg/cm², which is considered moderate and close to the Bina Marga lower subbase requirement. Soil T2 records the highest UCS at 24.4 kg/cm², exceeding the minimum standards and indicating very good performance. Soil T3, with a UCS of 21.3 kg/cm² after stabilization, also meets the required criteria, although its natural condition was initially much weaker. Table 3 presents the unconfined compressive strength (UCS) values of stabilized soils after 7 days of curing under identical mixture proportions

Tabel 3. Unconfined Compressive Strength (UCS) values of soils stabilized with 10% Ordinary Portland Cement and 2% chemical additive after a curing period of 7 days, representing early-age mechanical performance under laboratory conditions.

Table 3. Unconfined Compressive Strength (UCS) values of soils stabilized

Soil Type	Specimen 1 (kg/cm²)	Specimen 2 (kg/cm²)	Specimen 3 (kg/cm²)	Average UCS (kg/cm²)
T1 – Stabilized Soil	20.5	20.8	21.1	**20.8**
T2 – Stabilized Soil	24.1	24.4	24.7	**24.4**
T3 – Stabilized Soil	21.0	21.3	21.6	**21.3**

Table 3 summarizes the unconfined compressive strength (UCS) values of the stabilized soils after 7 days of curing. The results show that all stabilized soil types experienced a clear increase in UCS compared to their natural conditions, indicating the effectiveness of cement–additive stabilization in enhancing early-age mechanical performance. Under identical mixture proportions, soils with lower plasticity indices exhibited higher average UCS values. In comparison, soils with higher plasticity indices achieved lower initial strength but still satisfied the minimum UCS requirements for lower subbase applications specified in the Indonesian General Specifications (Bina Marga). These findings are illustrated in the following graph.

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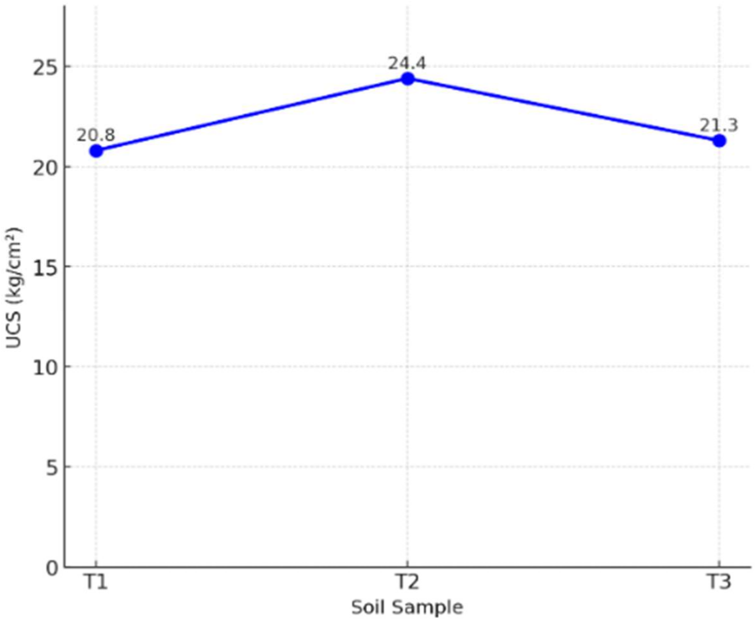

Figure 4. Unconfined Compressive Strength (UCS) of Soils T1, T2, and T3

The graph shows that soil T2 achieved the highest UCS value (24.4 kg/cm²), exceeding the minimum requirement for both lower and upper subbase layers. Soil T1 recorded 20.8 kg/cm², which meets the lower subbase requirement but falls slightly below the standard for the upper subbase. Soil T3, with 21.3 kg/cm² after stabilization, reached the threshold for the upper subbase, confirming the effectiveness of stabilization treatment.

3.4 Mechanical Performance of Stabilized Soils across Different Plasticity Index Ranges

The mechanical response of the stabilized soils was assessed through unconfined compressive strength (UCS) and California Bearing Ratio (CBR) values obtained after early curing under identical mixture proportions. Stabilized soils have been found to exhibit varying strength and bearing capacity within the plasticity index (PI) range. Soils with low PI were generally found to exhibit higher UCS and CBR, whereas soils with high PI showed lower initial performance but demonstrated considerable strength and bearing capacity improvements with cement–additive stabilization. The differences observed in this study suggest that soil plasticity, under the same stabilization scheme, is related to strength differences. All stabilized soil mixtures in this study also met the minimum UCS and CBR requirements for the lower subbase applications, as outlined in the Indonesian General Specifications (Bina Marga). This indicates that cement–additive stabilization is applicable for early mechanical performance improvement across different soil plasticity characteristics, provided that suitable compaction and mixture control has been exercised.

3.5. Index-Based Interpretation of UCS and CBR Variations

The differences in UCS and CBR coefficients reported here are reported from the perspective of plasticity index as an engineering classification parameter rather than a direct mechanistic variable. The plasticity index considers the contributions of clay content, soil consistency, and water sensitivity to compaction and early strength development in stabilized soil. Therefore, soils with lower PI values will be better candidates for increased particle rearrangement and bonding under cement stabilization, leading to higher UCS and CBR. However, the enhanced strength and properties of stabilized soils are not due solely to PI. The performance variations experienced for these soils' behavior may also be due to mineralogical composition, particle size distribution, soil fabric, etc. Since these considerations were not explicitly studied in this approach, the PI should be

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an index that allows comparison of soil performance under the same stabilization condition, rather than a single factor determining mechanical behavior under fixed loading control conditions.

3.6. Engineering Implications of Plasticity Index in Stabilized Soil Evaluation

This study highlights the practical application of the plasticity index as an initial screening parameter associated with stabilized soil assessment from an engineering perspective. The relationship between PI range and early-age UCS and CBR performance indicates that PI has the potential to serve as a preliminary characterization of the predicted response of soils to cement–additive stabilization under controlled laboratory conditions. With this information, engineers can now determine which stabilization approaches are applicable and when additional chemical treatment is indicated for higher-plasticity soils. However, PI-based evaluation should not replace comprehensive laboratory testing or detailed material characterization. The results described herein support decisions from the earliest stages, favoring different pavement materials rather than final materials, in any pavement design decision. In some critical applications, deeper investigative work is needed to assess the long-term strength development, durability characteristics, and soil mineralogy for future reliability.

3.7. Limitations of the Study and Implications for Future Research

Despite these results, some limitations need to be taken into account when interpreting the study. First, the study was based on a short curing time and a laboratory scale, which represent early-age strength development rather than long-term performance and durability under environmental loading. Second, only one cement and additive dosage was tested, so a functional link between stabilizer dosage, plasticity index, and mechanical performance could not be determined. Third, the mineralogical and microstructural properties of the soils were not investigated, which could affect the strengthening of such stabilized systems. Additional studies are suggested to overcome these limitations, including extending curing duration, assessing durability using wetting–drying cycles, and varying stabilizer content under different parameters. Moreover, mineralogical and microstructural studies would be more insightful into the mechanisms of strength development in stabilized soils with varying plasticity nature. These types of studies would increase our understanding of stabilized soil behavior and can lead to more complete pavement design.

4. Conclusion

Based on the laboratory experiments conducted in this study, the mechanical behaviour of cement–additive-stabilized soils varied across different ranges of soil plasticity index. For all proportions of the mixture and early curing conditions, soils with low plasticity indices exhibited good unconfined compressive strength (UCS) and California Bearing Ratio (CBR) values. In contrast, soils with higher plasticity indices showed low initial performance but improved significantly after stabilization. As the stability performance indicates, the use of the soil plasticity index as an engineering classification criterion is related to variations in the strength and bearing capacity of stabilized soils. Nevertheless, the variation experienced as a percentage of applied load in both test-based and experimental designs cannot be solely attributed to the plasticity index, as mineralogical composition and soil structure also contribute to the development of a strong load.

All stabilized soil mixtures tested in this work met the minimum UCS and CBR requirements of the Indonesian General Specifications (Bina Marga) for lower subbase applications with short curing time in the laboratory. The results demonstrate that cement-additive stabilization may improve the early-age mechanical performance of soils with differing plasticity when appropriate material selection and quality control are instituted. This investigation was specifically limited to laboratory-scale testing and early curing assessment. The findings, therefore, are recommended to complement preliminary pavement material characterization and stabilization designs, rather than to forecast long-term field performance and durability. Future studies using long curing times, durability testing, and mineralogical characterization should be used to enhance understanding of the stabilized behavior of soil.

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