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Sustainable Soil Improvement: Soft Clay Stabilization Using Rice Husk Ash and Waste Spent Catalyst RCC 15

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ABSTRACT

This study explores the chemical stabilization of soft clay soil to enhance its bearing capacity and improve its performance under structural loads. A fixed proportion of Rice Husk Ash (RHA) at 6% by weight was combined with varying amounts of spent catalyst RCC 15 (5%, 7%, 9%, and 11%) as stabilizing agents. The experimental program included the characterization of soil index properties, followed by engineering tests with emphasis on Unconfined Compressive Strength (UCS), Atterberg limits, compaction characteristics, and California Bearing Ratio (CBR). The Atterberg limit tests indicated a consistent reduction in the plasticity index (PI) with increasing RCC content, reflecting improved soil stability. Compaction results showed an increase in Maximum Dry Density (MDD) and a decrease in Optimum Moisture Content (OMC), with the highest MDD (13.29 kN/m³) and an OMC of 25.67% achieved at 6% RHA and 11% RCC. UCS values increased progressively, reaching a maximum of 1.822 kg/cm² with the same mixture. CBR results further supported these findings, with unsoaked values increasing from 4.75% to 6.60%, and soaked values from 3.30% to 6.20%. The combined use of RHA and RCC 15 significantly improves the geotechnical properties of soft clay, highlighting its potential as a sustainable and effective construction material.

Keywords: Soft Clay Stabilization, Rice Husk Ash, Spent Catalyst RCC 15, Compressive Strength, California Bearing Ratio

1. INTRODUCTION

Soil is a fundamental component in construction, especially in foundation engineering [1], as it must have sufficient strength to support the loads of superstructures built upon it[2]. However, soils at many construction sites often exhibit limitations, including low permeability, high plasticity index, and low compressibility[3]. These unfavorable properties can compromise infrastructure stability and potentially lead to structural failures. Thus, improving soil engineering characteristics through stabilization is critical [4]. Stabilization of soil is a widely used civil engineering technique designed to modify and enhance the mechanical and physical properties of soft soil to make it more sustainable for construction purposes [5]. This process generally involves the addition of specific materials to increase soil bearing capacity, reduce plasticity, and improve compaction characteristics[6]. Stabilization is especially important in soils with low strength, high plasticity, excessive swelling potential, or inadequate gradation[7]. Increasing the percentage of stabilization materials leads to improved soil performance. in previous research, adding emulsified asphalt and marble powder ash increases soil bearing capacity, provided the composition is properly adjusted to requirements [8].

A sustainable and efficient material for soil stabilization is Rice Husk Ash (RHA), waste product derived from rice milling[9]. Rice Husk Ash (RHA) is rich in SiO_2 (silica) and possesses pozzolanic properties, enabling it to react with calcium hydroxide in the presence of moisture to form calcium silicate hydrates (C-S-H), which contribute to increased soil strength. Numerous studies have shown that incorporating RHA can significantly enhance the compressive strength and reduce the swelling potential of clayey soils, making it an ideal stabilizing agent[10]. Another innovative material gaining attention in soil stabilization is the Spent RCC 15 Catalyst, a byproduct of petroleum refining industries by PT. Pertamina [11]. RCC 15 is rich in silica, ferrous compounds, and alumina, which also possess pozzolanic properties. The combined use of RHA and RCC 15 in stabilizing soft clay soils offers an environmentally friendly approach, as both materials are industrial byproducts [11]. This strategy not only minimizes waste but also enhances the load-bearing capacity of soil, reduces settlement, and improves its overall engineering properties.

Recent international studies support the application of these pozzolanic materials in soil stabilization[12]. Research has indicated that adding rice husk ash (RHA) can increase the unconfined compressive strength (UCS) of soft soil by up to 50%[5]. Furthermore, incorporating catalysts such as RCC 15 improves durability and resistance to environmental factors, including moisture fluctuations. Additionally, the use of these materials helps mitigate the environmental impact associated with conventional soil stabilization methods, such as cement or lime, which are energy-intensive and contribute to carbon emissions[13]. In conclusion, the combined application of Rice Husk Ash and Spent RCC 15 Catalyst offers a promising and sustainable approach to improving the geotechnical properties of weak soils. This method not only enhances soil structural performance but also promotes industrial waste recycling, aligning with global efforts toward more sustainable construction practices[14].

2. MATERIAL

2.1 Soft Clay

Clay soil is defined as soil composed of particles smaller than 0.002 mm, characterized by its plasticity when mixed with water[15]. This property arises from the unique mineralogical composition of clay, which primarily consists of structural units known as Alumina Octahedra and Silica Tetrahedra[16]. These fundamental units form layered arrangements that influence the soil's physical and chemical behavior. The high surface area of clay particles, combined with their charged surfaces, allows them to attract and retain significant amounts of water. When moisture is introduced, water molecules interact with the clay minerals, leading to the formation of hydration layers. This interaction affects the soil's plasticity, cohesion, and swelling potential. The extent of these changes depends on the type of clay minerals present, such as kaolinite, montmorillonite, or illite[17]. Montmorillonite, for instance, exhibits a high swelling capacity due to its expansive structure, making it more sensitive to moisture changes than kaolinite, which is more stable and less plastic. These mineral-water interactions are crucial in determining the engineering properties of clay soils, such as shear strength, compressibility, and permeability. In civil engineering, understanding these characteristics is essential for designing stable foundations and choosing suitable soil stabilization techniques. Proper moisture control, the use of additives such as lime or cement, and careful geotechnical assessments are common strategies employed to mitigate the challenges posed by clay soils in construction projects[18].

In this study, the type of clay soil used is classified as soft clay, which is commonly encountered in areas with poor natural drainage and high organic content. Soft clay typically exhibits low shear strength, high water content, and high compressibility, leading to excessive settlement when subjected to structural loads. It often demonstrates a high plasticity index (PI), low unconfined compressive strength (UCS), and low California Bearing Ratio (CBR), making it inadequate for construction purposes without treatment. The mechanical behavior of soft clay is significantly affected by changes in moisture content, which further compromises its stability. Therefore, improving the engineering properties of soft clay through stabilization methods is critical to ensure the safety and durability of infrastructure built on such problematic soils.

2.2 Spent Catalyst RCC 15

Spent Catalyst RCC (Residuum Catalytic Cracking) 15 is a byproduct produced during the kerosene distillation process at PT. Pertamina RU VI in Balongan, West Java. This waste material possesses pozzolanic properties, making it a valuable resource for construction applications[19]. It comprises various components, including alumina, silica oxide, iron, and other elements that enhance its reactivity when mixed with water and calcium hydroxide [11].

Figure 1 Spent Catalyst RCC 15

Table 1 Chemical Elements of Spent Catalyst RCC 15

Type	Characteristic (%)
$Si0_2$	47.13
Al_2o_3	45.34
Fe_2O_3	0.61
CaO	0.16
Na_2O	0.45
MgO	0.26

The chemical composition of Spent Catalyst RCC 15, as detailed in Table 1, underscores its potential benefits for soil stabilization and various engineering applications. The pozzolanic materials present in RCC 15 can enhance the strength and durability of soil and concrete mixtures, contributing to more sustainable and efficient construction practices. In summary, Spent Catalyst RCC 15 represents a promising solution for improving construction materials while promoting waste recycling within the industry.

2.3 Rice Husk Ash

Authors Rice husk, a byproduct of the rice milling process, accounts for approximately 20% of the total weight of rice and yields ash with a silica content exceeding 90% when burned[16]. This silica-rich Rice Husk Ash (RHA) exhibits pozzolanic properties, allowing it to react with calcium hydroxide to form beneficial compounds such as calcium silicate hydrate (C-S-H)[20]. Visually gray in color, RHA functions as a filler in construction applications, effectively occupying voids between coarse aggregates to enhance density and reduce permeability, which ultimately improves the durability of mixtures[21].
Agricultural waste, such as rice husk ash (RHA), is commonly utilized in chemical soil stabilization techniques due to its abundance[22]. In addition, the Philippines' top rice-producing provinces produce about 9 million tons of rice annually. This large-scale production is accompanied by a significant amount of rice husk ash waste, which poses both an environmental challenge and an opportunity for potential reuse in various applications[10]. The potential of RHA in the field of soil stabilization is significant. The chemical elemets of Rice Husk Ash can be seen in Table 2.

Figure 2 Rice Husk Ash

Table 2 Chemical Elements of Rice Husk Ash

Particulars	Properties
Color	Gray
Odour	Odouless
Shape-texture	Irregular
Specific gravity	2.18
Mean particle size (µm)	12.34
Appearance	Very fine
Passing #325(%)	96.6

Research has demonstrated RHA's effectiveness in soil stabilization and concrete production, highlighting its ability to ameliorate compressive strength, decrease plasticity, and improve the load-bearing capacity of weak soils[23]. Its fine particle size and high specific surface area enable RHA to act as a binder, facilitating better compaction and structural integrity[17,24]. Moreover, the utilization of RHA aligns with sustainable construction practices by decreasing dependence on traditional cement, thus reducing carbon emissions[25]. In summary, RHA is a valuable material that enhances the physical and mechanical properties of construction materials, supporting more environmentally friendly engineering solutions[26][27].

3. METHODS

Soil stabilization refers to a series of processes aimed at improving or modifying the properties of subsoil to make it more suitable for applications such as road construction and foundation support. The primary objective of stabilization is to enhance the soil's load-bearing capacity, resistance to compaction, strength, and overall performance. This can be achieved through various techniques, depending on the characteristics of the existing soil and project requirements. Mechanical stabilization is one common method that focuses on improving soil properties by altering its gradation. This is done by combining two or more types of natural soils to create a mixture with better engineering characteristics. The combination allows for an optimal balance of soil particle sizes, resulting in improved stability, compaction properties, and strength.

There are several approaches to soil stabilization, which can involve one or more of the following activities:

1. Adding inert materials: This method increases soil cohesion or enhances frictional resistance by blending materials such as sand or gravel.
2. Increasing soil density: Mechanical compaction methods are used to densify the soil, reducing void spaces and improving load-bearing capacity.
3. Incorporating chemical additives: Materials like cement, lime, and fly ash are introduced to induce physical and chemical reactions, leading to increased strength, reduced permeability, and improved durability.
4. Lowering the groundwater table: By controlling water levels, soil stability can be enhanced, especially in areas with high water tables.
5. Soil replacement: In cases where existing soil conditions are unsuitable, poor-quality soil is removed and replaced with more stable materials.

The choice of stabilization method depends on the geotechnical properties of the soil, environmental considerations, and the intended function of the stabilized layer. Proper implementation ensures long-term structural performance, making stabilization a critical step in civil engineering and construction projects. At this stage, an activity plan for the research is formulated. The research implementation involves several key phases, including information gathering and literature review, soft clay soil sampling in the field, preparation for laboratory testing, and data analysis of the stabilization test results. The research flow can be observed in the following Figure 3.

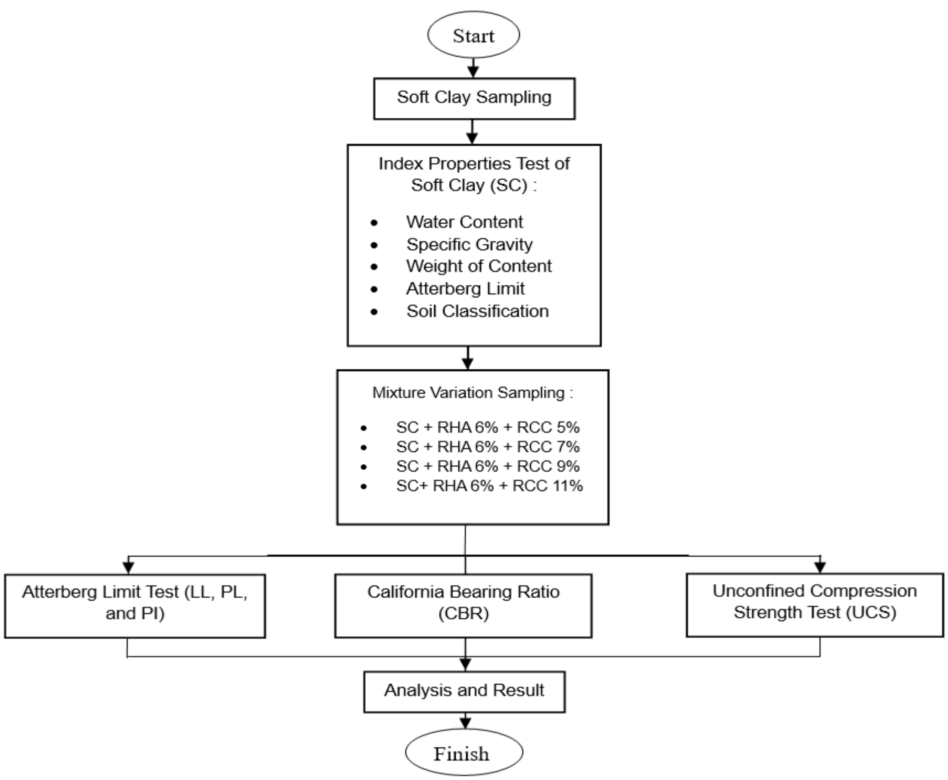

Figure 3 Research Flow Chart

In this study, soil samples were taken from the Cililin area, West Bandung Regency. Rice Husk Ash (RHA) and Spent Catalyst RCC 15 were used as stabilizers. Spent catalyst rcc 15 was obtained from PT. Pertamina RU VI Blongan, West Java, indonesia. The research was conducted at the Soil Mechanics Laboratory, Department of Civil Engineering, Bandung State University of Technology. The mixture content in this test consisted of 6% rice husk ash (RHA) and 5%, 7%, 9% and 11% spent catalys rcc 15 (RCC) from soft clay, followed by Atterberg Limit, California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) testing. The selection of 6% RHA was based on findings from previous studies which reported that this percentage provides optimal pozzolanic reactivity and strength gain for clayey soils without inducing excessive brittleness or diminishing workability [28]. Meanwhile, the RCC 15 variation from 5% to 11% was designed to explore the incremental effects of catalyst addition on soil performance. Prior research [11,18] suggests that up to 11% RCC still yields beneficial strength gains without resulting in particle agglomeration or uneven distribution, which could negatively affect mechanical properties.

4. RESULT AND DISCUSSIONS

The initial stage of this study involves collecting soft soil samples from Cililin, West Java. These soft soil samples will undergo index property testing, followed by stabilization with the addition of Rice Husk Ash (RHA) and Spent Catalyst RCC 15 (RCC) with 3 days of curing time. The mixture percentages used in this study are based on previous research, with RHA at 6%, and RCC 15 varied at 5%, 7%, 9%, and 11%. The purpose of index properties testing is to determine the specific gravity, water content, unit weight, and Atterberg limits. This test aims to identify the characteristics of the soft soil based on its classification according to AASHTO and USCS standards[29]. Table 3 presents the results of the soft soil's index properties. Based on the data from Table 3, the soil is classified as type A-7-6 according to AASHTO standards. Under the USCS classification, the soil is identified as CH, indicating it is an inorganic clay with high plasticity or expansive clay

Table 3 Index Properties of Soft Clay

Index Properties	Symbol	Unit	Value
Water Content	w	%	41.48
Specific Gravity	Gs	-	2.591
Weight of Content	γ	gr/cm^3	1.393
Liquid Limit	LL	%	59.38
Plastic Limit	PL	%	29.93
Plasticity Index	PI	%	29.45

4.1 Moisture Content and Density Relationship

Table 4 presents a summary of the compaction test results for each mixture proportion. The findings indicate enhance in the maximum dry density (MDD) and a decrease in the optimum moisture content (OMC) with the addition of Spent Catalyst RCC 15 to the mixture sample. A similar trend is observed when a constant 6% Rice Husk Ash (RHA) is incorporated into the specimens. Generally, the compaction curves for clay soils exhibit a bell-shaped pattern, as seen in the compaction test curve for soil and the soil mixture containing 11% spent catalyst RCC 15. Conversely, the introduction of RCC into the soil specimens resulted in a leftward shift of the compaction curves, a pattern typically associated with silt mixed with sand. This alteration in the compaction curve trends highlights the effectiveness of the admixtures used in the research[30]. A more detailed visualization of the curve comparisons is provided in Figure 4.

Figure 4 displays the moisture-density curves for each mixture, plotting MDD against varying moisture contents. As the RCC content increases from 5% to 11%, the peak of each curve shifts slightly higher, indicating that the MDD improves as RCC content rises. This leftward and upward shift of the compaction curves reflects a typical response for clay stabilized with pozzolanic materials like RHA and RCC[10]. The highest MDD is observed at the combination of 6% RHA with 11% RCC, supporting the conclusion that increased RCC contributes to greater dry density. In summary, Table 4 and Figure 4 demonstrate that the addition of rice husk ash waste (RHA) and RCC ameliorate the compaction characteristics of soft clay, with 6% RHA and 11% RCC yielding the best results in terms of lower OMC and higher MDD. This improvement is consistent with the pozzolanic reaction that contributes to soil densification and strength.

4.2 Atterberg Limit

In Table 5, The plasticity index (PI) of soil measures the range of water content at which the soil displays plastic behavior, making it a critical property in geotechnical engineering. This value is determined by the difference between the soil's liquid limit (LL) and plastic limit (PL)[31]. Table 5 presents the results of physical property tests, specifically the Atterberg limits, for the original soil after stabilization with RHA and RCC 15.

Table 4 Average Optimum Moisture Content and Maximum Dry Density of Mixture Variation

Variation	OMC (%)	MDD (kN/m^3)
Soft Clay	20.51	12.93
6 % RHA + 5% RCC	26.45	13.02
6 % RHA + 7% RCC	26.06	13.12
6 % RHA + 9% RCC	26.00	13.17
6 % RHA + 11% RCC	25.67	13.29

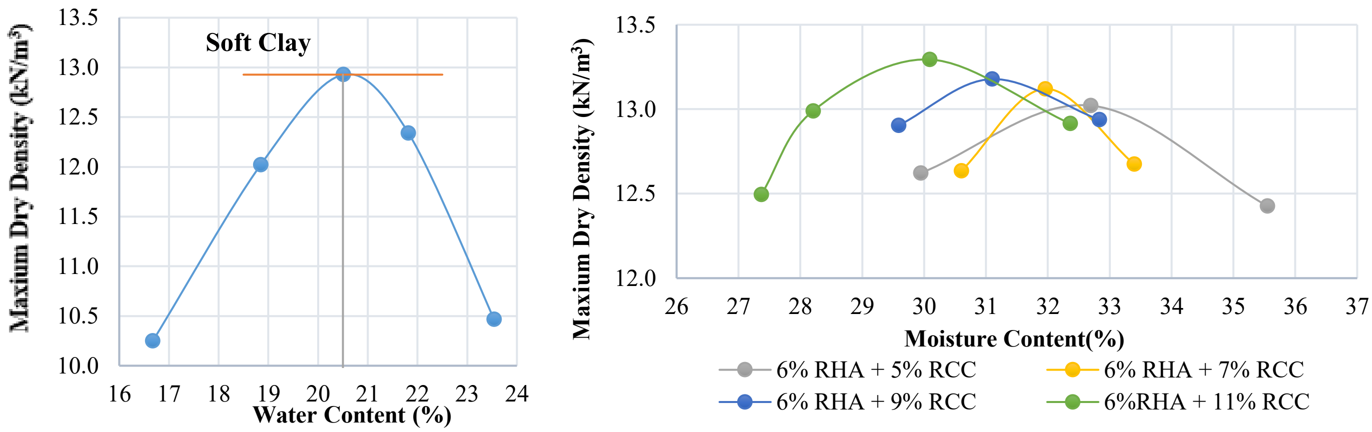

Figure 4 Comparison of moisture-density curves of stabilization soil

Table 5 Atterberg Limit Test Result

Variation	LL	PL	PI
Soft Soil	59.38	29.93	29.45
6 % RHA + 5% RCC	54.67	26.45	28.22
6 % RHA + 7% RCC	52.50	26.06	26.44
6 % RHA + 9% RCC	51.68	26.00	25.68
6 % RHA + 11% RCC	51.23	25.67	25.55

Figure 5 illustrates that adding rice husk ash and Spent Catalyst RCC 15 as stabilizing agents reduces the soil's plastic limit. This reduction occurs because the soil interacts with silica-rich pozzolanic compounds, which encourage cementation and particle bonding. As a result, the soil particles become more aggregated and rigid, reducing their ability to deform plastically over a wider moisture range. Furthermore, Figure 6 illustrates that adding rice husk ash and Spent Catalyst RCC 15 as stabilizing agents reduces the soil's liquid limit. This reduction occurs because the soil is mixed with silica compounds that exhibit pozzolanic properties. These properties promote cementation, increasing the size of soil particles and thereby decreasing the attractive forces between them.

Figure 7 demonstrates that incorporating rice husk ash and spent catalyst RCC 15 as stabilizing materials lowers the plasticity index of the soil. A reduced plasticity index diminishes the soil's potential for swelling and shrinkage[32]. This effect is due to the hydration process of rice husk ash and spent catalyst RCC 15, which exhibit pozzolanic properties that strengthen the bonds between soil particles, creating more stable and rigid aggregates. When mixed with water, rice husk ash and RCC 15 form a paste that binds clay particles and fills the soil's pores. These filled pores become less permeable, enhancing the mixture's resistance to water absorption and thereby decreasing its plasticity

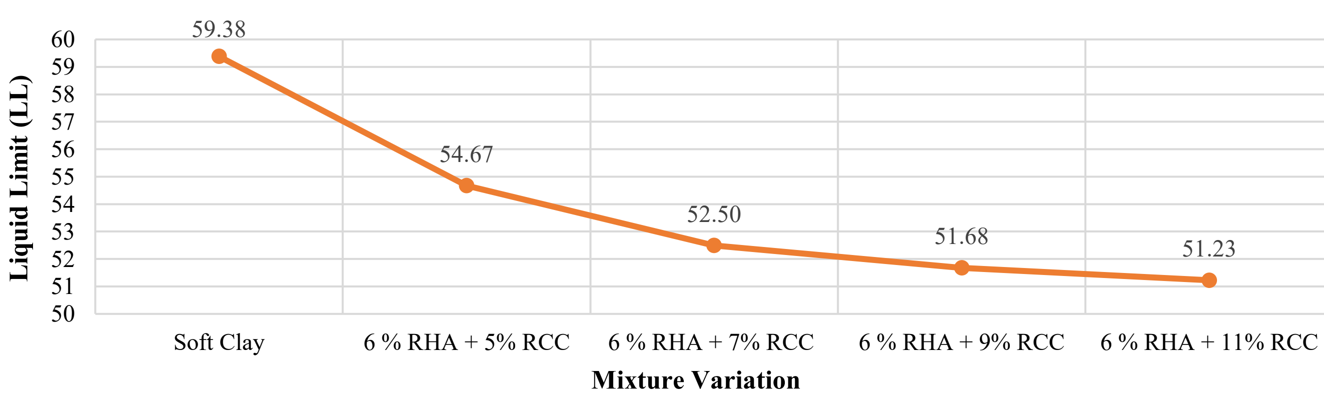

Figure 5 Liquid Limit Graph

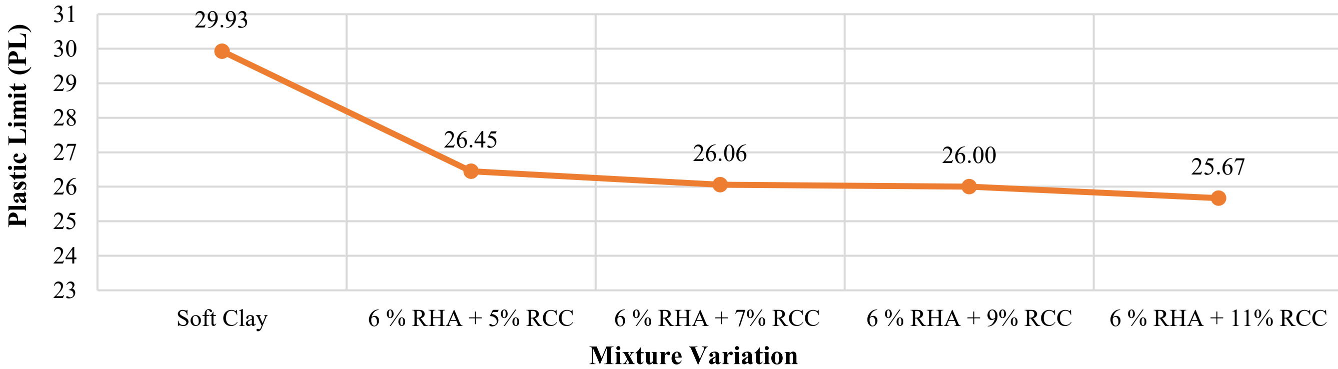

Figure 6 Plastic Limit Graph

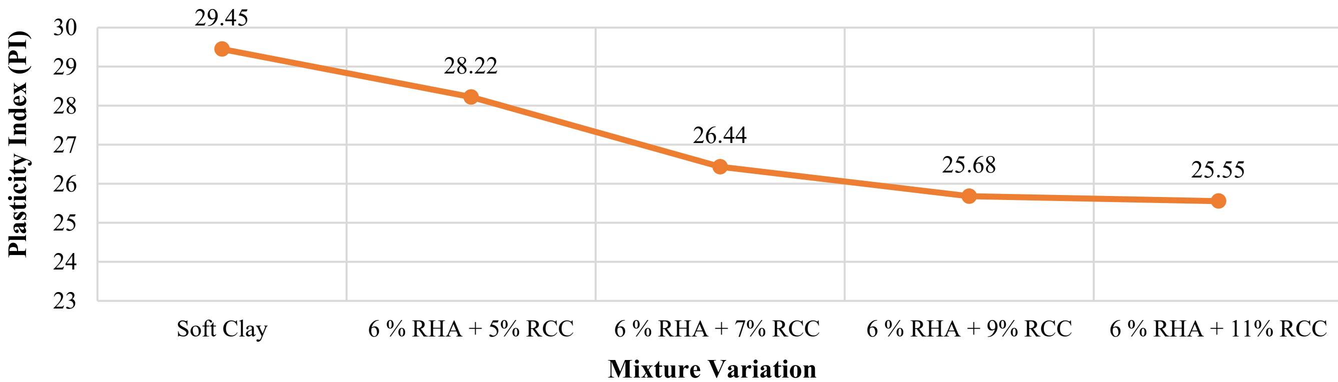

Figure 7 Plasticity Index (PI) Graph

4.3 Unconfined Compression Test (UCS)

The results of the unconfined compression test provide the values of unconfined compressive strengths (q_u) for the original soil and the variations of soil stabilized with rice husk ash (RHA) and spent catalyst RCC 15 with 3 days of curing time. These results include the values of compressive strength (q_u) and c_u (shear strength values) for each mix variation, which can be found in Table 6.

Furthermore, from Figure 8, unconfined compressive strength of the original soil is measured at 0.412 kg/cm². As the percentage of spent catalyst RCC 15 in the mixture increases, the compressive strength of the soil correspondingly rises. This increase in the q_u value can be attributed to the chemical compounds present in both rice husk ash and spent catalyst RCC 15, which effectively bond with the soil particles. The cementation process facilitated by the pozzolanic characteristics of these additives reduces the plasticity of the stabilized soil, thereby enhancing its compressive strength[33]. In the mixture containing 6% rice husk ash and 11% spent catalyst RCC, the q_u value reaches 1.822 kg/cm², marking the highest strength among all variations tested and exceeding that of the original soil. The results indicate a positive correlation between increased RCC content and the unconfined compressive strength (qu) up to 11%. The highest qu value (1.822 kg/cm²) was observed at 11% RCC, suggesting that further increase may yield additional gains. However, practical field applications and previous literature suggest diminishing returns or potential workability issues beyond this percentage. Therefore, 10–11% RCC can be considered an optimal range, balancing performance improvement and economic viability.

Table 6 Unconfined Compression Test Result

Variation	q_u (kg/cm²)	c_u (kg/cm²)
Soft Clay	0.412	0.206
6 % RHA + 5% RCC	0.799	0.399
6 % RHA + 7% RCC	1.354	0.677
6 % RHA + 9% RCC	1.759	0.879
6 % RHA + 11% RCC	1.822	0.911

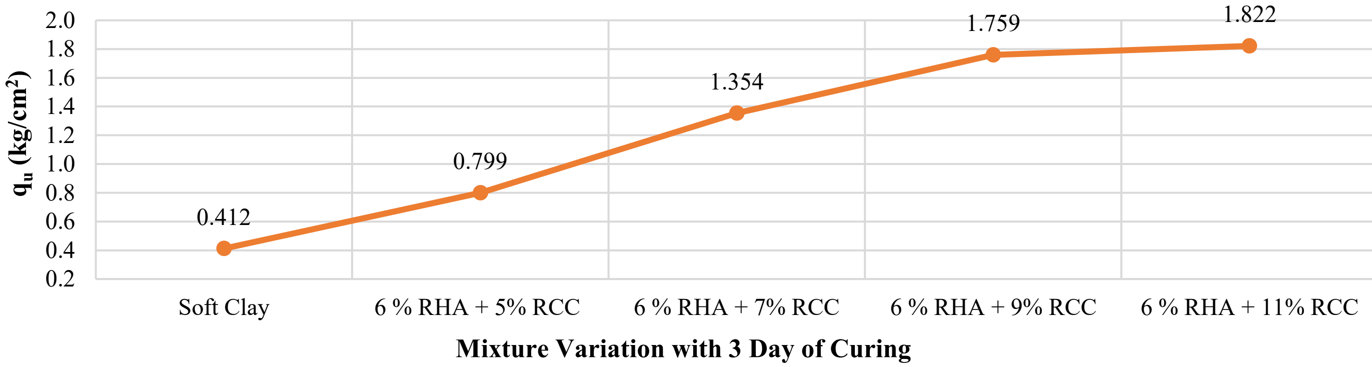

Figure 8 Unconfined Compression Test Result Graph

4.4 California Bearing Ratio (CBR) Test

The California Bearing Ratio (CBR) test conducted on soil stabilized with rice husk ash and spent RCC 15 catalyst demonstrated an improvement in the soil's bearing capacity under both unsoaked and soaked conditions. As illustrated in Figure 9, under unsoaked conditions, the CBR value of the original soil increased from 4.75% to 6.60% at the fourth variation. Meanwhile, in soaked conditions, the CBR value rose from 3.30% to 6.20% during the same period.

Table 7 California Bearing Ratio Test Result

Variation	CBR unsoaked (%)	CBR soaked (%)
Soft Clay	4.75	3.30
6 % ASP + 5% RCC	6.40	5.70
6 % ASP + 7% RCC	6.50	5.80
6 % ASP + 9% RCC	6.55	5.95
6 % ASP + 11% RCC	6.60	6.20

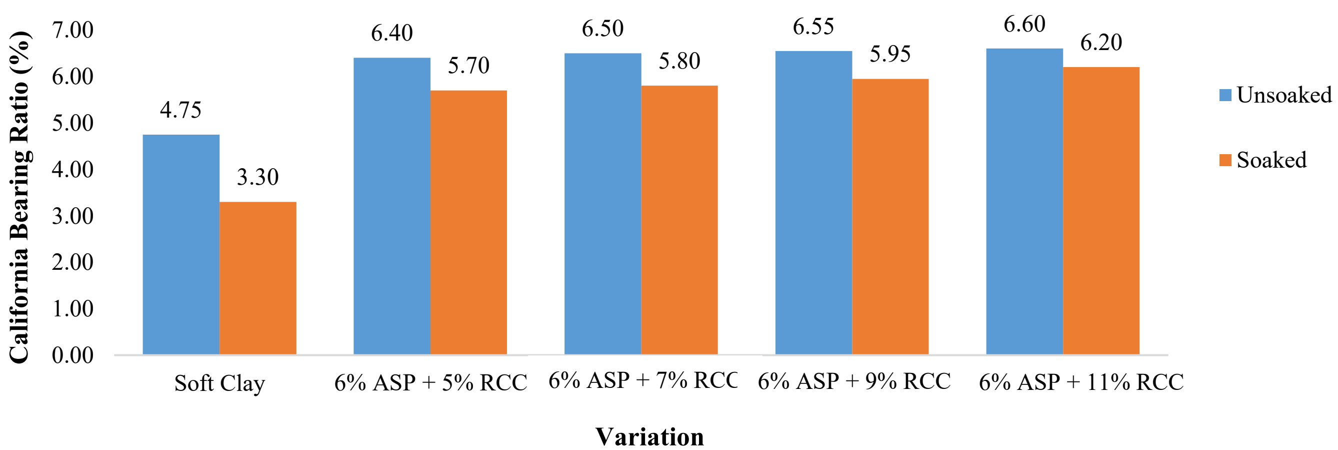

Figure 9 California Bearing Ratio Test Graph

This improvement is attributed to the pozzolanic reaction between the high silica content in rice husk ash, water, and calcium from the soil, resulting in the formation of calcium silicate hydrate (C-S-H) compounds that strengthen the soil structure. On the other hand, the spent RCC catalyst plays a role in reducing soil porosity and reinforcing the stabilization process, thereby enhancing the soil's strength. This makes the soil more stable and suitable for construction applications, even in environments with high moisture levels or standing water. From the test results, the fourth variation demonstrated the best performance, indicating that a more homogeneous and optimized combination of additional materials can significantly enhance the soil's bearing capacity.

5. CONCLUSION

The results of the Atterberg limit tests show that the plasticity index (PI) of the untreated soft clay was 29.45%, which decreased to 25.55% after stabilization with 6% Rice Husk Ash (RHA) and 11% spent RCC 15 catalyst. This reduction confirms the effectiveness of RHA and RCC 15 in enhancing soil stability through pozzolanic reactions that promote cementation and reduce plastic behavior. Compaction test results revealed an improvement in the Maximum Dry Density (MDD) from 12.93 kN/m³ to 13.29 kN/m³ and an increase in Optimum Moisture Content (OMC) from 20.51% to 25.67%, indicating better compaction behavior with increasing RCC 15 content.

Unconfined Compressive Strength (UCS) values also improved significantly, increasing from 0.412 kg/cm² in the soft clay to 1.822 kg/cm² in the stabilized mixture. Similarly, the California Bearing Ratio (CBR) test results demonstrated enhanced bearing capacity, with unsoaked values increasing from 4.75% to 6.60% and soaked values from 3.30% to 6.20%. These findings collectively demonstrate that the combined use of 6% RHA and up to 11% spent RCC 15 catalyst significantly enhances the geotechnical performance of soft clay. This stabilization method not only improves mechanical properties but also offers a sustainable approach by utilizing industrial and agricultural waste materials, making it suitable for broader construction applications.

This study primarily targets applications in embankment and low-load subbase systems, where CBR and density are critical parameters. Nevertheless, the observed increase in undrained cohesion (c_u) and unconfined compressive strength (q_u) also indicates potential for use in structural subgrade applications. Future research is recommended to include consolidation settlement tests and triaxial CU testing to evaluate long-term performance under sustained structural loads.

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