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# Valorization of Peapod Waste as a Pulverized Organic Additive for Sustainable Soil Stabilization

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**Abstract:** This study investigates the potential valorization of peapod waste—an agricultural by-product commonly discarded during food processing—as a pulverized organic additive for sustainable soil stabilization. Approximately 50% of pea mass is typically lost as pod waste, posing environmental and economic disposal challenges. In this research, peapods were first air-dried, then oven-dried at low temperature to prevent changes in their organic structure. The dried pods were pulverized and incorporated into clayey sand (SC) and low-plasticity clay (CL) soils at 5%, 10%, and 15% proportions under standard Proctor compaction. Unconfined compressive strength (UCS) tests were conducted to assess mechanical improvements. The SC soil exhibited UCS increases of approximately 50%, 75%, and 100% for the respective additive ratios. For the CL soil, 5% addition increased UCS by 20%, while 10% addition led to a slight decrease, though still outperforming the natural soil. All treated samples showed increased axial strain, indicating improved deformability. The results highlight the feasibility of using pulverized peapod waste to enhance the strength characteristics of soils, particularly sandy-clayey types, offering an eco-friendly alternative to conventional stabilizers. This approach supports circular economy principles by repurposing organic waste in geotechnical applications.

**Keywords:** Peapod waste, soil stabilization, organic additive, unconfined compressive strength, sustainable engineering.

## Bezelye Kabuğu Atığının Toz Organik Katkı Maddesi Olarak Sürdürülebilir Zemin İyileştirmede Değerlendirilmesi

**Öz:** Bu çalışma, gıda işleme sırasında sıklıkla atık olarak değerlendirilen bir tarımsal yan ürün olan bezelye kabuğu atıklarının, sürdürülebilir zemin iyileştirme uygulamalarında toz halde organik katkı malzemesi olarak kullanılabilirliğini araştırmaktadır. Bezelyelerin yaklaşık %50'si işleme sırasında kabuk olarak ayrılarak çevresel ve ekonomik açıdan bertaraf sorunu oluşturmaktadır. Bu kapsamda bezelye kabukları önce açık havada, ardından düşük sıcaklıklı etüvde kurutulmuş; daha sonra öğütülerek toz haline getirilmiştir. Elde edilen toz, killi kum (SC) ve düşük plastisiteli kil (CL) zeminlere %5, %10 ve %15 oranlarında eklenerek standart Proctor enerjisinde sıkıştırılmıştır. Karışımlar üzerinde serbest basınç dayanımı (UCS) deneyleri gerçekleştirilmiştir. SC zeminlerde sırasıyla %50, %75 ve %100 oranında dayanım artışı elde edilmiştir. CL zeminlerde ise %5 katkı ile %20 dayanım artışı sağlanmış, %10 katkı ile dayanım az da olsa katkısız zeminden yüksek kalmıştır. Tüm katkılı numunelerde eksenel birim şekil değiştirme artmıştır. Elde edilen bulgular, bezelye kabuğu atığının özellikle killi kum zeminlerin dayanım özelliklerini iyileştirmede çevre dostu ve ekonomik bir katkı malzemesi olarak değerlendirilebileceğini göstermektedir.

**Anahtar kelimeler:** Bezelye kabuğu atığı, zemin iyileştirme, organik katkı, serbest basınç dayanımı, sürdürülebilir mühendislik.

## 1. Introduction

With rapid urbanization and industrialization, construction activities on problematic soils have become inevitable. In the past, foundation engineers had limited options when dealing with such soils, which were generally restricted to abandoning the site, excavating and replacing the weak soil with high-quality material, or designing a foundation system that adapted to the existing soil conditions. However, over time, soil improvement techniques have emerged as a more effective solution for strengthening problematic soils and, consequently, the structures built upon them. Soil stabilization, which involves modifying the in-situ behavior of the soil, has gained increasing popularity due to its ease of application and technical advantages across various soil conditions and construction projects [1].

Various soil improvement techniques have been developed to address different soil conditions and engineering objectives. Among these, fiber-reinforced soil stabilization has become a widely adopted and effective alternative solution. Fiber-reinforced soil improvement methods can be categorized into four main groups [2,3]:

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1. Natural Fibers: Materials derived from natural sources, such as coconut, jute, bamboo, areca, flax, sisal, rice husk, bagasse, and banana peel.
2. Synthetic Fibers: Man-made materials, including polypropylene (PP), polyvinyl alcohol (PVA), polyvinyl chloride (PVC), basalt, steel, and glass fibers.
3. Recycled Fibers: Materials obtained from industrial waste, such as carpet fibers, plastic bottles, and rubber from discarded tires.
4. Composite Fibers: Materials produced by combining multiple fiber types, either of the same or different origins.

A study investigating the use of agricultural waste materials, such as cellulose-based with varying fiber content and lengths bamboo fiber, rice husk ash, and wheat straw fiber, in the stabilization of expansive soils reported significant improvements [4]. Bamboo fiber increased the unconfined compressive strength (UCS) by more than 100%, while rice husk ash reduced the plasticity index, thereby enhancing the engineering performance of the soil. Wheat straw fiber decreased the swelling percentage by 45% and reduced linear shrinkage by half. In another study examining the performance of silty clay soil reinforced with sisal fibers in freeze-thaw cycles [5], the highest UCS value was achieved with a 0.9% sisal fiber content. The addition of fibers reduced thermal conductivity, mitigating the effects of temperature variations and significantly limiting deformations caused by freeze-thaw cycles. Two separate studies on cement-stabilized soils explored the incorporation of various fibers to reduce cement consumption [6,7]. In the first study, areca, coconut, and flax fibers were added, whereas in the second study, banana and coconut fibers were included in the mixture. Both studies found that fiber reinforcement enhanced the strength, durability, and ductility of cement-stabilized soils, with coconut fibers exhibiting superior performance. In two studies where lime stabilization was used for expansive soils [8,9], bagasse fiber (a by-product of sugarcane processing) and coconut fiber were added to the soil. The incorporation of fibers (2% bagasse, 1% coconut fiber) allowed for a reduction in the required lime dosage, while also improving soil strength. Additionally, the combinations of coconut fiber–bottom ash, jute fiber–fly ash, and rice fiber–nano clay were investigated for the stabilization of expansive soils [10-12]. These fiber-stabilizer combinations improved the mechanical performance of the soil, making them promising alternatives for subgrade stabilization and other geotechnical applications.

In studies utilizing polypropylene (PP) fibers for soil stabilization [13-16], additional stabilizing agents such as cement, calcium sulfoaluminate cement (a more environmentally friendly alternative to Portland cement), fly ash, and ground granulated blast furnace slag-based geopolymers were incorporated. All studies demonstrated that the inclusion of PP fibers not only enhanced soil strength under extreme conditions such as freeze-thaw and wetting-drying cycles but also improved ductility. The mechanical properties of clayey sand soils stabilized with PP and polyvinyl alcohol (PVA) fibers were investigated at varying temperatures, and the maximum strength and ductility were achieved at -15°C. Additionally, in cold climates, PVA fibers exhibited superior performance compared to PP fibers [17]. To improve the weak engineering properties of black cotton soil and reduce costs, a polyvinyl chloride (PVC) fiber–fly ash combination was studied. The results indicated an increase of approximately 60–70% in both the California Bearing Ratio (CBR) and unconfined compressive strength (UCS) [18]. A study examining the effects of basalt fibers in metakaolin-based geopolymer-stabilized soils as an alternative to Portland cement stabilization found that the fibers formed strong bonds with the soil matrix, leading to significant improvements in compressive, tensile, and shear strength [19]. To mitigate the swelling potential of expansive soils, micro steel fibers were added alongside orthophosphoric acid, a chemical stabilizer. This combination resulted in notable enhancements in the soil's engineering properties [20]. A study investigating the effects of a glass fiber–nano clay combination in lime-stabilized soils revealed that the addition of nano clay initially increased soil brittleness; however, glass fibers contributed to a more ductile behavior by forming bonding regions between soil particles, ultimately enhancing durability [21]. Similarly, to increase soil strength and transition from a brittle to a more ductile behavior, glass fibers were added to alkali-activated palm oil fuel ash, demonstrating improvements in soil performance [22].

The combined use of nano calcium carbonate, which enhances the strength of low-plasticity clay soils, and carpet waste fibers, which improve residual strength under high deformation, was found to increase both unconfined compressive strength (UCS) and ductility of the soil [23]. In silty sand soils, the incorporation of plastic fibers was observed to increase water absorption and retention capacity. However, when a plastic fiber–cement combination was used, both mechanical and chemical stabilization effects were achieved, effectively reducing water absorption and retention [24]. To evaluate the swelling behavior, unconfined compressive strength, and ductility of high-plasticity bentonite clay soils stabilized with cement, different proportions of waste rubber fibers were incorporated. In addition to its environmental sustainability, the engineering performance of the soil was significantly improved. Specifically, a 2% rubber fiber content reduced the swelling potential by 44% and nearly doubled the UCS. Furthermore, the strong bonding between soil particles enhanced ductility and prevented crack propagation [25].

The stabilization of clay soils using kenaf fiber and rice husk ash resulted in an increase in maximum dry density and a decrease in optimum water content, leading to enhanced mechanical strength [26]. In studies evaluating the combined use of rice husk ash and basalt fibers in cement-stabilized expansive soils, improvements in consolidation and strength parameters were observed. These findings suggest that composite fiber reinforcement could be a promising soil stabilization method [27,28].

This manuscript explores the valorization of peapod waste, classified as an agricultural by-product, as a pulverized organic additive for sustainable soil stabilizations. Given its high fiber and protein content, and water retention capacity, pulverized peapod waste has potential uses beyond the food industry, particularly in geotechnical engineering. Previous studies have investigated the use of natural fibers in soil stabilization; however, limited research has explored the potential of pulverized peapod waste in geotechnical applications. Given the increasing demand for sustainable and cost-effective soil stabilization methods, the use of agricultural by-products presents an eco-friendly alternative. In this study, dried gradually and subsequently pulverized peapod waste was added in varying proportions to clayey sand (SC) and low-plasticity clay (CL) soils obtained from two different test pits. The unconfined compressive strength (UCS) of the stabilized soils was then evaluated and compared. This study hypothesizes that incorporating pulverized peapod waste into soil will improve its mechanical properties, particularly unconfined compressive strength (UCS). The objective of this research is to assess the feasibility of using pulverized peapod waste as a natural fiber additive in soil stabilization, examining its effects on SC and CL soil types. This approach not only offers environmental sustainability and economic benefits but also aims to introduce a novel natural fiber additive into the existing range of soil stabilization materials.

## 2. Materials and Methods

### 2.1. Soil samples and classification

In this study, two different soil samples were collected from test pits (TPs) excavated at two separate locations and classified according to the Unified Soil Classification System (USCS) as clayey sand (SC) and low-plasticity clay (CL). The physical properties of these soil samples, along with the relevant test standards, are detailed in Table 1, while visual representations of the samples are presented in Figure 1.

**Table 1.** Index properties of the soils used in this study.

| Properties | TP-1 | TP-2 | Test Standard |
|---|---|---|---|
| Specific Gravity | 2.61 | 2.63 | ASTM D854 [29] |
| Gravel Content (%) | 0.0 | 1.0 | ASTM C117 [30]<br>ASTM D7928 [31] |
| Sand Content (%) | 50.1 | 14.1 | |
| Silt Content (%) | 46.3 | 77.9 | |
| Clay Content (%) | 3.6 | 7.0 | |
| Liquid Limit (%) | 54.1 | 48.7 | ASTM D4318 [32] |
| Plastic Limit (%) | 28.7 | 26.3 | |
| Plasticity Index (%) | 25.4 | 22.4 | |
| USCS | SC | CL | ASTM D2487 [33] |

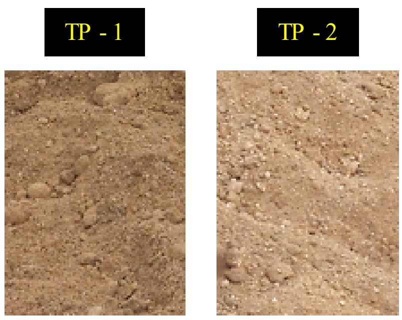



**Figure 1.** Visual representation of the soils used in this study.

### 2.2. Pulverized peapod preparation and characterization

After the peas were processed for consumption, the resulting peapod waste was first air-dried under ambient conditions, followed by low-temperature oven drying (below 60˚C) to maintain its internal structure. The dried peapods were then ground into a fine powder using a kitchen processor. The stepwise process of drying and pulverizing the peapod waste is illustrated in Figure 2. The particle size distribution of the pulverized peapod was determined, and the granulometric curves of both the pulverized peapod and soil samples are presented in Figure 3.

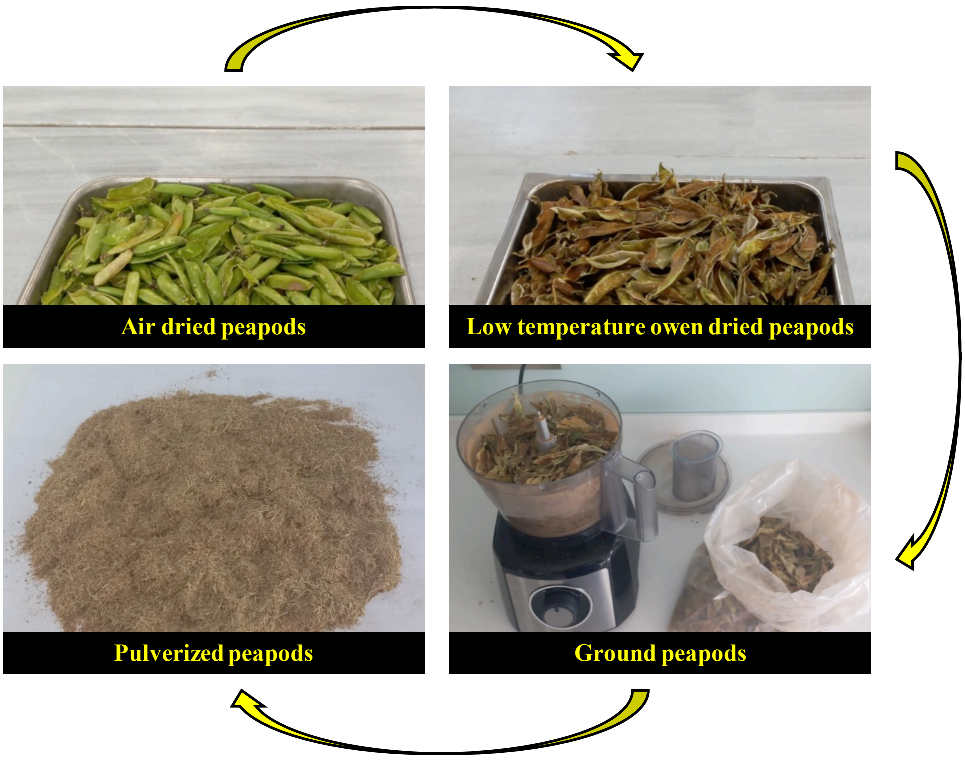



**Figure 2.** The stepwise process of drying and pulverizing peapods.

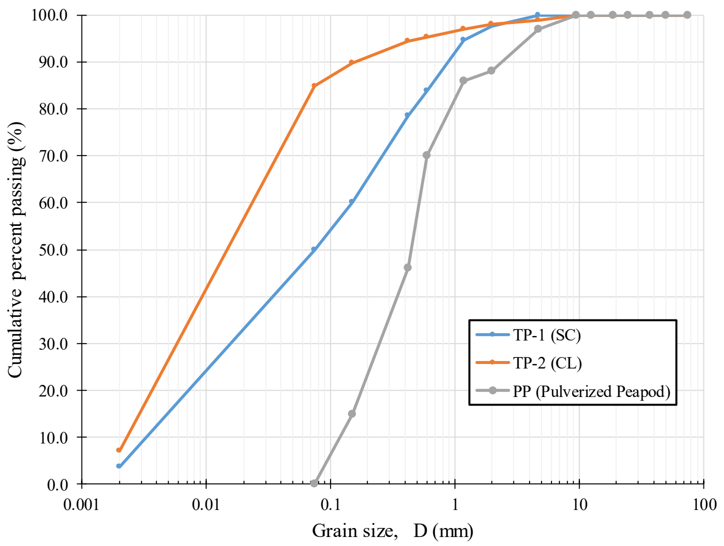



**Figure 3.** Granulometric curves of soil samples and pulverized peapod.

### 2.3. Compaction and sample preparation

Before proceeding with the sample preparation stage, the Standard Proctor test was conducted in accordance with the ASTM D698 standard [34] on the sand and clay soils collected from the test pits. As a result of these tests, the maximum dry densities and optimum moisture contents of the soils were determined. The Proctor curves for the two different soil types are presented in Figure 4.

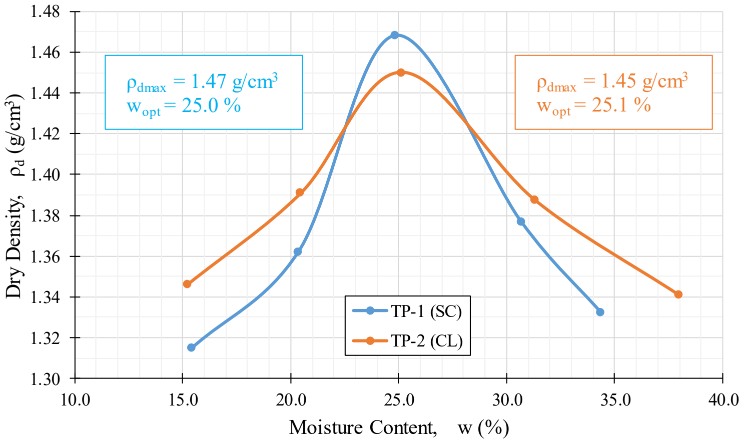



**Figure 4.** Standard Proctor test results of soil samples.

Based on the compaction characteristics obtained, the predetermined amounts of dry soil samples and water were thoroughly mixed in a small container until a homogeneous mixture was achieved. The prepared mixture was then left in a humid environment for 24 hours before sample preparation to allow the water to fully penetrate the soil particles. After the curing period, the mixture was remixed, and the required amount of material for each layer was weighed and divided into containers. In this way, natural soil samples were prepared at maximum dry density and optimum moisture content, corresponding to Standard Proctor density. In addition to the natural soil samples, stabilized soil specimens were prepared by adding pulverized peapod waste at varying proportions (5%, 10%, 15%) relative to the target dry weight of the soil. The visual representations of these specimens are presented in Figure 5.

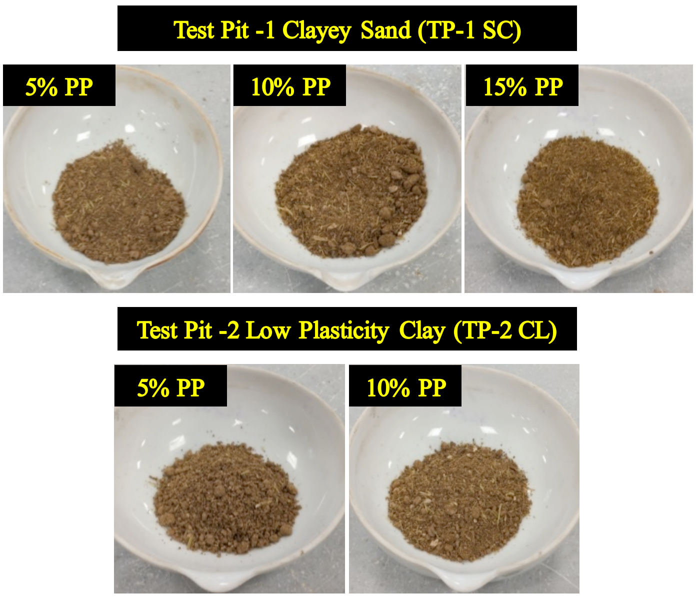



**Figure 5.** Mixtures with varying proportions of pulverized peapod waste.

During the preparation of the test specimens, a special compaction mold, shown in Figure 6, was used. This equipment consists of the compaction mold main body, sample ring, compaction mold top cap, and layer rammers. To minimize voids and ensure a homogeneous structure, the test specimens were compacted in layers. The top surface of each compacted layer was roughened using an appropriate tool to promote bonding between layers. Using the compaction mold, specimens with a diameter of 38 mm and a height of 78 mm were prepared. The layer volumes were controlled during compaction, as the difference in rammer lengths ensured uniform compaction for each layer. Finally, the three-layered specimens within the sample ring were extracted using a hydraulic sample extruder to be prepared for testing.


**Figure 6.** Compaction mold and components.

### 2.4. Experimental setup and testing procedures

The unconfined compressive strength (UCS) tests on the compacted specimens were conducted in accordance with the ASTM D2166 standard [35] using a computer-controlled testing machine, as detailed in Figure 7. The testing machine consists of:

- A loading chamber that allows easy placement of the specimen and enables the application of axial load via a piston,
- A load cell that measures the axial load applied to the specimen,
- A displacement gauge that records deformations occurring in the specimen,
- A main control panel that allows vertical movement of the lower platen on which the loading chamber is mounted.

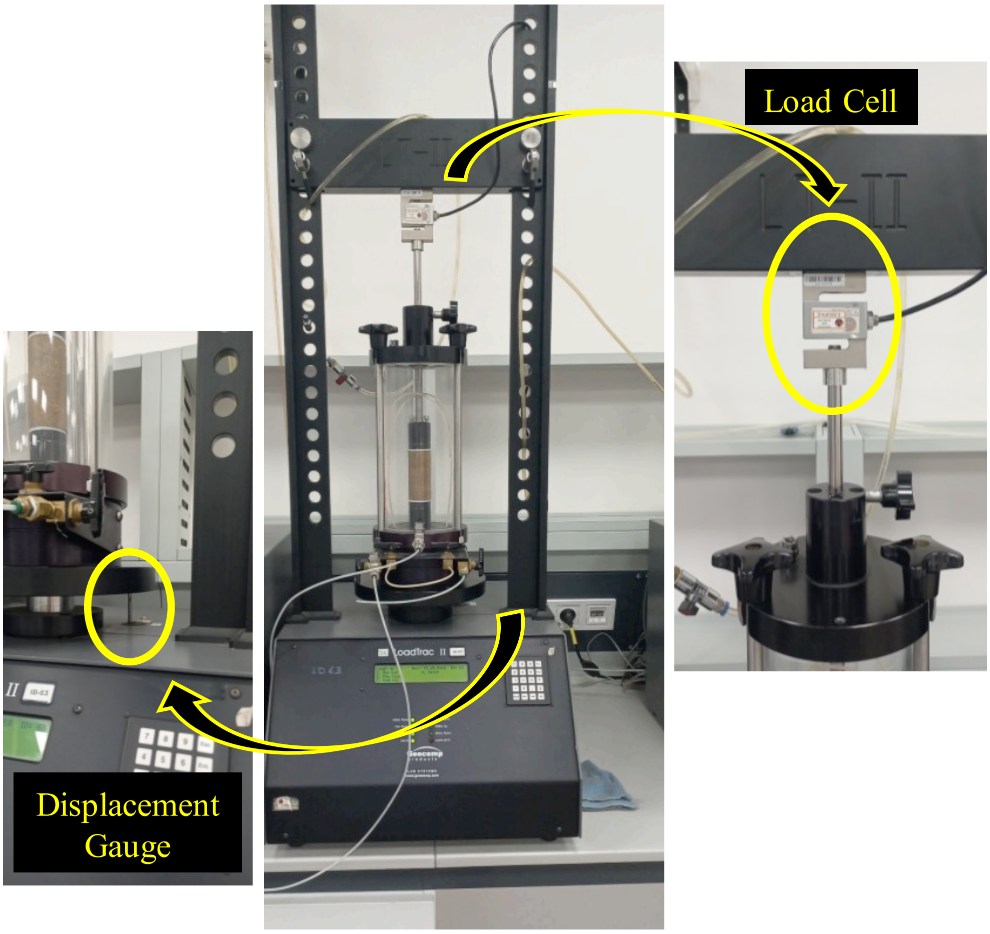



**Figure 7.** Computer-controlled unconfined compressive strength test machine and equipment.

For both unstabilized and stabilized mixtures, each test was conducted on three identical specimens, and the unconfined compressive strength (UCS) of the sample was determined as the average value of these three tests. The primary reason for using three identical specimens was to ensure the repeatability and reliability of the test results. If any outlier values were observed—either significantly higher or lower than the others—they were excluded from the average calculation. The prepared test specimens used in these experiments are presented in Figure 8.

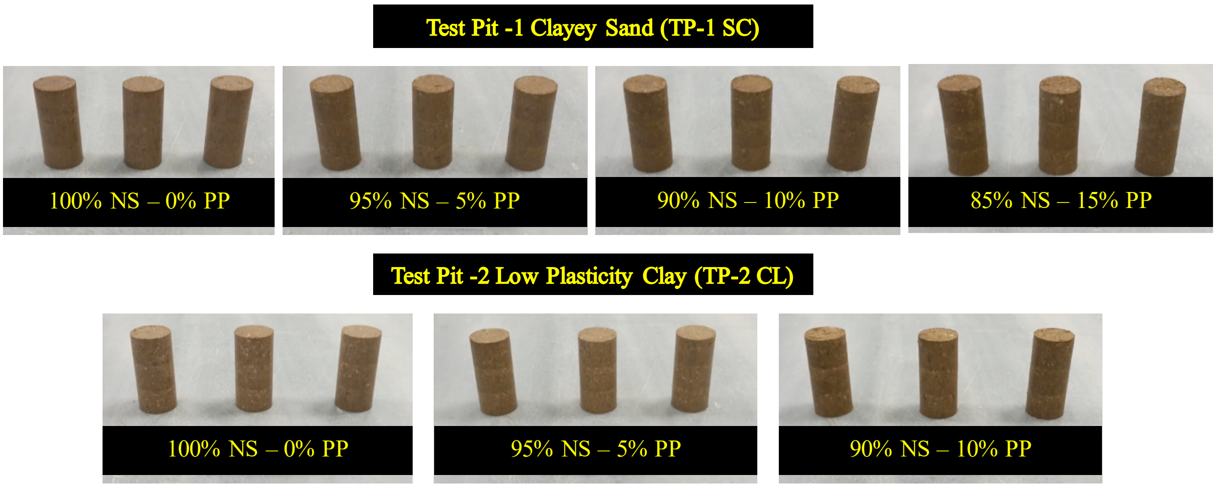



**Figure 8.** Specimens prepared using unstabilized and various proportions of stabilized mixtures.

## 3. Results and Discussion

Unconfined compressive strength (UCS) tests were conducted on unstabilized and pulverized peapod waste-stabilized specimens compacted at Standard Proctor Energy (SPE) level for two different soil types. The axial stress–axial strain curves and post-test specimen photographs for these samples are presented in Figure 9 through 15.

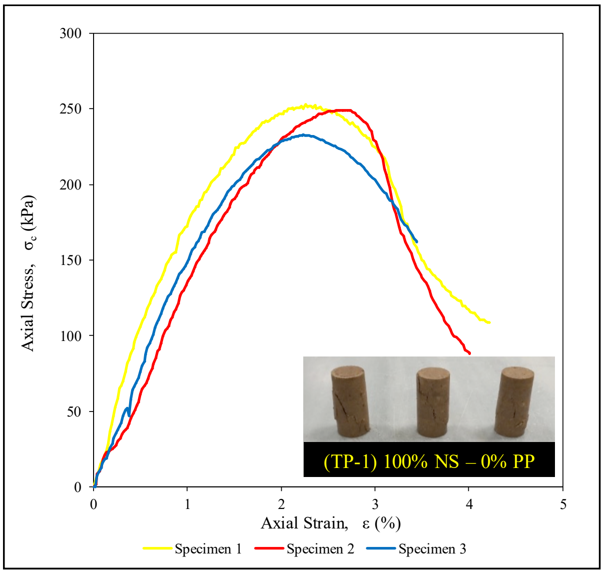



**Figure 9.** Test results and photos of unstabilized SC specimens compacted at SPE level.

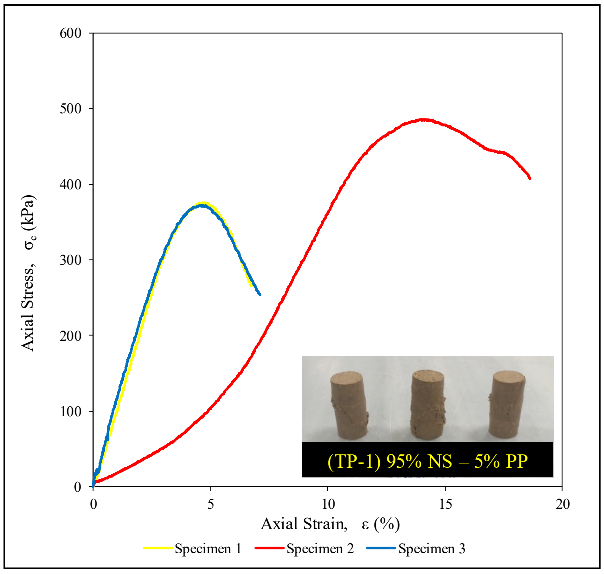



**Figure 10.** Test results and photos of SC specimens with 5% pulverized peapod waste compacted at SPE level.

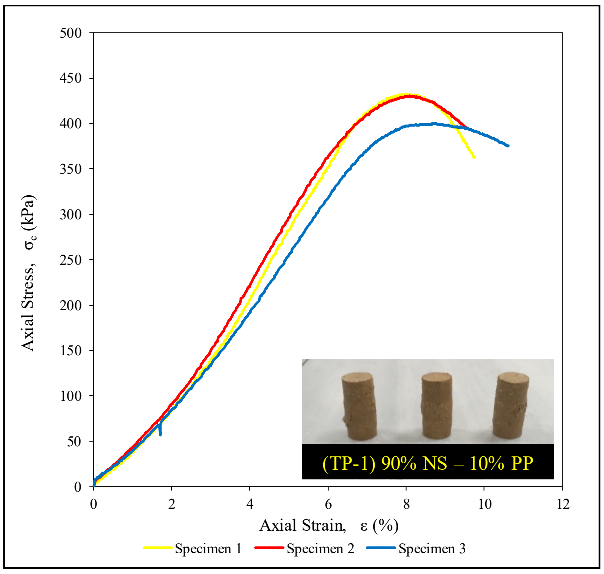



**Figure 11.** Test results and photos of SC specimens with 10% pulverized peapod waste compacted at SPE level.

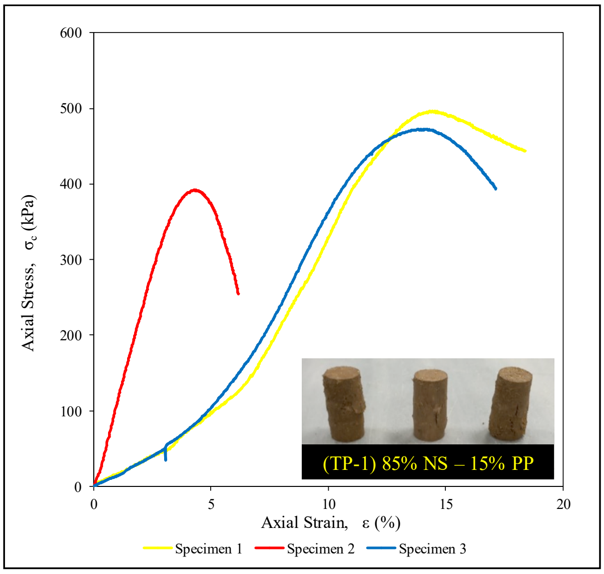



**Figure 12.** Test results and photos of SC specimens with 15% pulverized peapod waste compacted at SPE level.

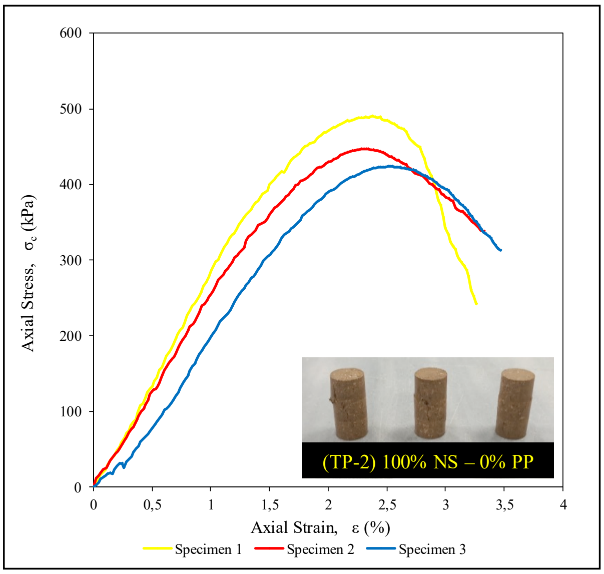



**Figure 13.** Test results and photos of unstabilized CL specimens compacted at SPE level.

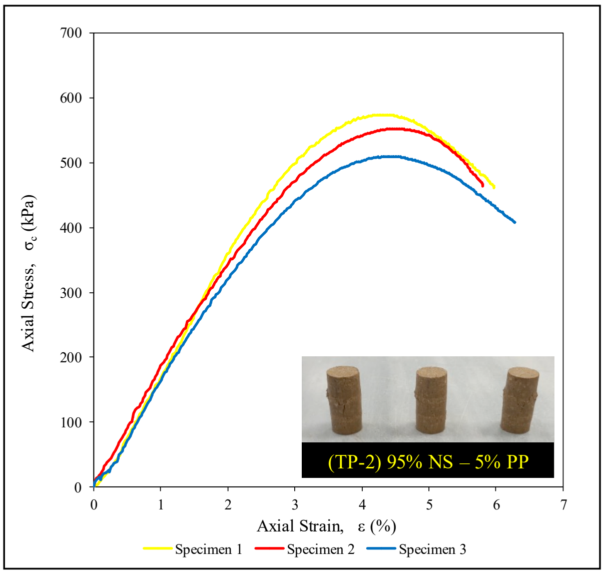



**Figure 14.** Test results and photos of CL specimens with 5% pulverized peapod waste compacted at SPE level.

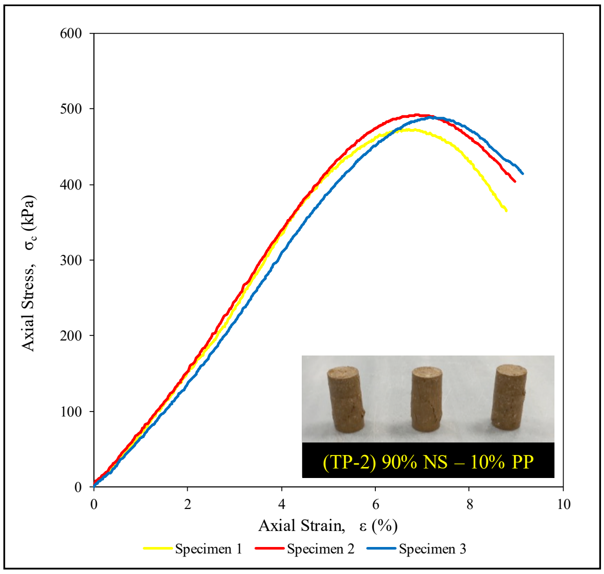



**Figure 15.** Test results and photos of CL specimens with 10% pulverized peapod waste compacted at SPE level.

As observed in the graphs, the strength and axial strain values obtained from identical specimens were closely aligned, leading to the use of average values for determining the unconfined compressive strength (UCS) and axial strain of the samples. However, for SC soil specimens containing 5% and 15% pulverized peapod waste, one of the three identical specimens exhibited a significantly different strength and strain value compared to the others; thus, it was excluded from the average calculation.

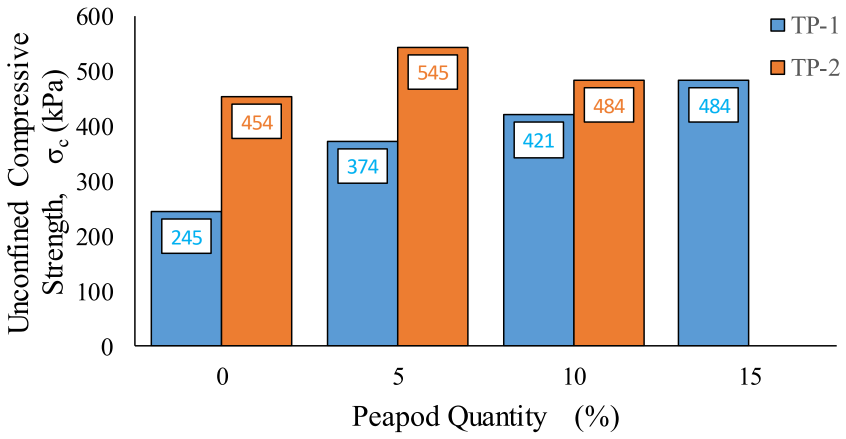
Examining the post-test specimen photographs, it was observed that most of the samples exhibited angular fractures, whereas barrel-shaped failure was rarely observed. This suggests that the specimens generally displayed brittle material behavior, indicating that the fiber stabilization did not lead to a highly ductile response.

During the planning phase of the study, it was initially intended to incorporate pulverized peapod waste at the same proportions (5%, 10%, and 15%) in both soil types. However, based on the UCS test results, SC specimens exhibited a continuous increase in strength with increasing additive content, while CL specimens showed an initial increase followed by a slight decrease at 10% additive content. Due to this decline, it was not deemed necessary to prepare CL specimens with 15% pulverized peapod waste.

The different responses observed in SC and CL soils suggest that soil type plays a crucial role in fiber stabilization efficiency. The incremental strength gain in SC soils indicates enhanced fiber interlocking, whereas the slight decline in CL specimens at 10% pulverized peapod waste content may be linked to excess organic matter affecting the clay structure. In light of the experiences gained from literature studies, it has been observed that while natural fiber additives improved soil strength, excessive organic content may lead to reduced cohesion in fine-grained soils. This aligns with the observed trend in CL soils, where a strength reduction was noted beyond 5% pulverized peapod waste.

The obtained UCS and axial strain values for both soil types, as a function of pulverized peapod waste content, are compared using bar charts in Figure 16.

As seen in Figure 16, the unconfined compressive strength (UCS) of the SC soil, obtained from TP-1, increased with higher additive content. In contrast, for the CL soil collected from TP-2, the UCS initially increased with a 5% additive content but showed a slight decrease at 10% content, although it remained higher than the unstabilized sample. With the increase in additive content, axial strain values also increased for all specimens. The strength of the stabilized specimens was higher than that of the natural (unstabilized) specimens for both soil types. Additionally, when comparing the test results of different soil types for both unstabilized and stabilized specimens with the same additive content, it was observed that the TP-2 soil (CL) exhibited higher strength and lower deformation compared to TP-1 soil (SC). This indicates that CL soil is mechanically more stable than SC soil, likely due to its higher cohesion and lower compressibility.



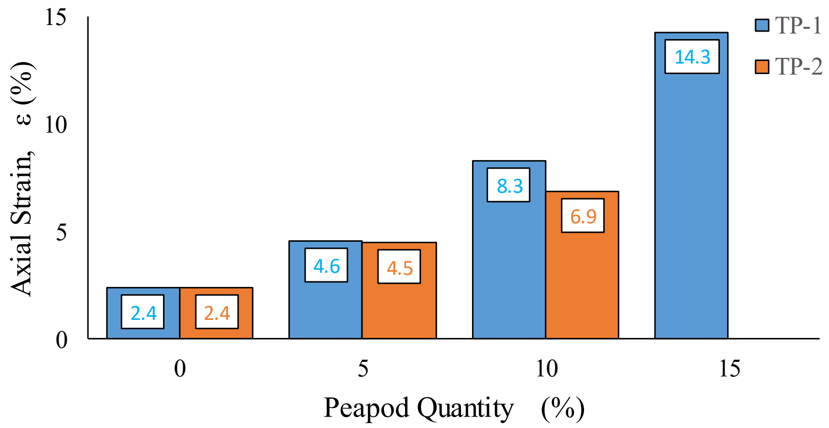




**Figure 16.** Comparison of data obtained from unconfined compressive strength tests for all specimens.

## 4. Summary and Conclusions

This study investigated the potential of utilizing pulverized peapod waste as a natural fiber additive in soil stabilization applications. Peapod waste, which is generated in significant amounts during food processing, was dried and pulverized before being added in varying proportions (5%, 10%, and 15%) to clayey sand (SC) and low-plasticity clay (CL) soils. The prepared specimens were compacted at standard Proctor energy and subjected to unconfined compressive strength (UCS) tests to assess the mechanical performance of the stabilized mixtures. The findings of the study can be summarized as follows:

- The addition of pulverized peapod waste significantly improved the unconfined compressive strength (UCS) of SC specimens. The strength increased by approximately 50%, 75%, and 100% for 5%, 10%, and 15% additive contents, respectively.
- For CL specimens, the UCS increased by 20% with 5% additive content. However, a slight strength reduction was observed at 10% content, likely due to excess organic matter interfering with the soil matrix cohesion. Despite this reduction, the UCS remained higher than that of the natural soil.
- All stabilized specimens exhibited higher axial strain values compared to unstabilized soils, indicating increased deformability.
- The failure mode of the specimens was mostly brittle with angular fractures, suggesting that fiber stabilization did not lead to a highly ductile behavior. This behavior may be attributed to insufficient

fiber-soil interlocking and the relatively low tensile resistance of peapod fibers compared to synthetic counterparts.

- Pulverized peapod waste has been demonstrated as a potential sustainable soil stabilizer, particularly for clayey sand soils, improving their strength characteristics.
- The results confirm that agricultural waste materials can be repurposed to enhance geotechnical properties, contributing to environmental sustainability.
- While strength improvements were observed, the brittle failure mode suggests that additional studies are needed to investigate potential modifications for enhancing ductility.

While the findings demonstrate the potential of pulverized peapod waste in soil stabilization, further research is necessary to optimize its application. Based on these findings and to expand the scope of the study, the following suggestions are proposed:

- The effect of pulverized peapod waste on different soil types should be investigated to determine its suitability for a broader range of geotechnical applications.
- Microstructural and chemical analysis of pulverized peapod waste-stabilized soils should be conducted.
- Future studies could examine the combination of peapod fibers with other natural or synthetic fibers, as well as their interaction with various stabilizing agents (e.g., lime, cement, geopolymers) to enhance soil performance.
- Further investigations could explore optimal fiber processing techniques to enhance bonding between peapod fibers and soil particles.
- Long-term durability studies should be conducted to evaluate the performance of pulverized peapod waste-stabilized soils under environmental variations such as moisture fluctuations and freeze-thaw cycles.

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