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Influence of Waste Rubber Powder on the Physical and Mechanical Behavior of Clay Soils

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Abstract

transportation networks. One major challenge is the presence of weak soils. Clayey soils, due to their high plasticity and deformability, are considered problematic, and improving their geotechnical properties remains a key issue in civil engineering. Recently, the use of waste materials, especially waste rubber powder, as sustainable soil stabilizers has gained attention.This study examines the influence of different contents (5%, 10%, and 15%) and particle sizes (0.5, 1.3, and 3.5 mm) of waste rubber powder on the strength and mechanical behavior of clayey soils. Untreated clay was used as a control, and standard laboratory tests—including Atterberg limits, compaction, consolidated drained direct shear, and unconfined compressive strength—were conducted according to ASTM standards.The results show that adding rubber powder lowers the liquid limit, plastic limit, optimum moisture content, and maximum dry density. Higher rubber content reduced unconfined compressive strength, while the internal friction angle increased and cohesion decreased.Overall, incorporating waste rubber powder offers a sustainable approach to improving the engineering performance of clayey soils while reducing the environmental burden of rubber waste.

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INTRODUCTION

The role and significance of transportation in the social, economic, and political dimensions of modern societies are undeniable. Transportation networks are closely intertwined with key components, such as economic growth, national security, and social equity. With the increasing global population, the demand for suitable soils in infrastructure and road construction has become more pressing. Enhancing the geotechnical properties of soils has therefore emerged as a critical issue in civil engineering.

Clayey soils, from a geotechnical perspective, are considered problematic due to their high plasticity and substantial deformation potential. The strength and stability of such soils are often insufficient for structural applications, making soil stabilization or modification essential. Soil improvement through stabilization is a widely adopted method in design practice, and the addition of specific materials has proven effective in enhancing behavioral parameters such as strength, stress–strain response, and permeability. Traditionally, stabilizers such as lime, cement, and bitumen have been employed for this purpose.

One of the key requirements in large-scale geotechnical projects, especially in infrastructures like highways, dams, and airports, is cost reduction. To address this, the reuse of waste tire products, in shredded or powdered form, has been proposed as a low-cost soil additive. While traditional stabilizers like cement, lime, and bitumen are effective, their relatively high cost has encouraged the search for more economical alternatives. Consequently, the use of industrial waste materials as alternative stabilizers has gained attention in recent years. Recycling rubber waste not only helps mitigate environmental pollution but also offers economic and technical benefits in geotechnical and pavement engineering applications.

For decades, engineers around the world have conducted numerous studies to evaluate the effects of various materials on soil stabilization, aiming to identify viable solutions for improving soil performance. One such material is waste rubber, particularly in the form of shredded or powdered rubber, which has received considerable attention. With the growing population and decreasing availability of suitable construction land, the competition among different ground improvement techniques has intensified. Additionally, the increase in solid waste generation has prompted researchers to explore new approaches for reusing these materials in construction.

The transportation and road construction sectors, which constitute a significant portion of national infrastructure development, are directly linked to the tire industry. In light of increasing environmental concerns and the growing number of waste tires in countries like Iran, addressing this issue has become particularly important. Waste tires decompose very slowly in natural environments. Therefore, in recent years, various methods have been proposed for recycling and reusing waste tires. One promising solution involves incorporating rubber waste into construction materials. Due to the favorable geotechnical properties of waste rubber, its use as a soil additive has the potential to significantly improve the mechanical behavior of clayey soils.

The application of rubber waste in geotechnical engineering, particularly in combination with soil, has gained significant attention in recent decades as a method for mitigating environmental impacts and enhancing certain mechanical properties of soils. One of the main drivers of this approach is the massive volume of scrap tires, which are non-biodegradable and pose major challenges for waste disposal. For instance, approximately 279 million used tires are generated annually in the United States (Massey, 2020), and the numbers in the United Kingdom are estimated at around 25 million passenger car tires and 3 million truck tires per year (Bridgwater & Mumford, 1979). The accumulation of such waste presents serious public health concerns (Jastrzębska, 2019).

Various geotechnical applications have been proposed for shredded rubber, including the reinforcement of soft subgrades in road construction, erosion control, slope stabilization, backfill for retaining structures, embankment materials, asphalt additives, and frost depth mitigation (Nightingale & Green, 1997; Poh & Broms, 1995; O'Shaughnessy & Garga, 2000; Lee et al., 1999; Foose et al., 1996; Tuncan et al., 1998).

Numerous laboratory investigations have indicated that rubber inclusions can improve the mechanical behavior of soils, although the degree of improvement depends on soil type and the amount of rubber added. Yoon et al. (2004) in South Korea showed that using rubber mats in layered systems increased bearing capacity and reduced settlement, with the first layer having the most significant effect. However, the influence decreased as the soil density increased.

In contrast, other studies have reported limited benefits of rubber inclusion. Ghazavi (2004), through consolidated direct shear tests on sand–rubber mixtures, found no significant effect on internal friction angle and emphasized the environmental benefits over mechanical performance. Ayothiraman & Meena (2011) highlighted the advantages of shredded rubber in generating low horizontal stress and high compressibility, which help reduce lateral pressure on retaining walls. However, their results also showed that increasing the rubber content led to a decrease in internal friction angle.

Regarding cohesive soils, the findings have been more inconsistent. Carraro et al. (2013), in a series of triaxial tests on expansive soils, reported a reduction in stiffness modulus and a slight increase in Poisson's ratio. Similarly, Ramirez et al. (2015), in consolidated drained (CD) triaxial tests on clay, observed an increase in shear strength up to a certain level of confining pressure, followed by a decrease at higher pressures.

Cetin et al. (2006) observed that adding up to 40% shredded rubber increased cohesion, but beyond that threshold, cohesion began to decline. Balasooriya et al. (2012) also reported a nonlinear trend in internal friction angle, where cohesion initially decreased and then increased with higher rubber content.

In another laboratory investigation, Hataf & Rahimi (2006) studied the effect of randomly distributed rubber particles in sandy soils. They found that the bearing capacity ratio (BCR) increased up to 3.9 when rubber content reached 40% and the aspect ratio of 4:1 was used. However, exceeding this threshold led to a decrease in BCR.

In a separate study, Moghaddas Tafreshi et al. (2019) examined the behavior of foundations over layered rubber–soil mixtures (RSM) using plate load tests. Results showed that incorporating RSM layers enhanced the bearing capacity and reduced settlement. Numerical analyses further demonstrated that rubber layers improved subgrade resistance by distributing the stress more effectively.

Boushehrian & Hataf (2008) investigated the enhancement of clayey soil bearing capacity using reinforcing materials such as geosynthetics. Their research analyzed the effects of parameters like depth, number, and stiffness of geogrid layers on the bearing capacity of ring footings, which provides a basis for comparing this performance with rubber-reinforced clays. In another study focused on reducing long-term settlements in cyclically loaded footings, Boushehrian et al. (2011) used geosynthetics and grid anchors. Experimental and numerical results on square footings over reinforced sand showed significant reductions in settlement, offering a benchmark for evaluating rubber waste as an alternative reinforcement strategy.

A review of existing literature reveals that most research has focused on non-cohesive soils and primarily used strip-type rubber particles. The majority of studies have targeted strength parameters such as internal friction angle, cohesion, and stiffness modulus. However, the present study specifically investigates the effects of adding waste rubber powder to clayey soils, a combination that has received less attention in past research. This approach not only aims to enhance geotechnical behavior but also offers a sustainable solution for reducing tire waste.

In this study, the effects of various percentages of rubber powder on Atterberg limits, maximum dry unit weight, elastic modulus, internal friction angle, cohesion, and unconfined compressive strength of clayey soils will be evaluated. It is hypothesized that the addition of rubber powder can enhance the unconfined compressive strength of clay and improve its shear strength parameters, including cohesion and internal friction angle.

Research Methodology

Materials and Methods

The objective of this study is to evaluate the effects of incorporating recycled rubber powder into clayey soil on its strength-related properties, including shear strength and unconfined compressive strength. To achieve this goal, a series of standard geotechnical laboratory tests were conducted, including direct shear, unconfined compressive strength (UCS), Atterberg limits, and compaction tests.

Properties of the Materials Used

The soil used in this study is a clayey soil, the particle size distribution of which is presented in Table 1. According to the Unified Soil Classification System (USCS), the soil is classified as CL (inorganic clay of low to medium plasticity).

Table 1: Composition of the soil used in the study

Component	Percentage (%)
Sand	1.20
Gravel	18.10
Fine Courses	80.70

To evaluate the plasticity characteristics of the soil, Atterberg limits tests were conducted. The results showed a liquid limit (LL) of approximately 36.86% (based on 25 blows) and a plastic limit (PL) of approximately 31.22%, indicating moderate plasticity behavior.

The maximum wet unit weight of the untreated soil was approximately 20.3 g/cm³, which decreased to around 18.3 g/cm³ upon the addition of rubber powder. In all specimens, the matrix unit weight (i.e., the unit weight of the soil excluding the rubber volume) was kept constant to ensure both accurate control of rubber content and consistency in total sample unit weight.

The optimum moisture content of the natural soil was determined to be 19.5%.

Recycled Rubber Powder

The recycled rubber powder used in this study was obtained from waste passenger vehicle tires. The powder was classified into three particle size ranges:

1. 0 to 0.5 mm
2. 1 to 3 mm
3. 3 to 5 mm

Figures 1 and 2 illustrate the produced rubber powder derived from the waste tires.

Fig 1. Image of the produced rubber powder.

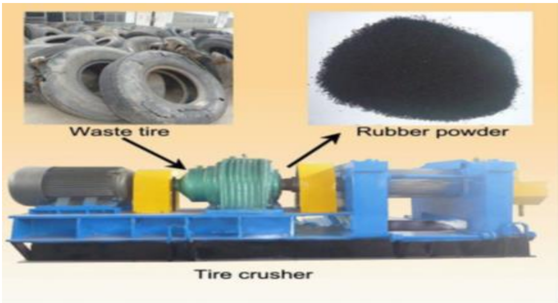

Fig 2. Image of the rubber powder production process.

Sample Preparation

Soil specimens were prepared by mixing the clayey soil with varying weight percentages of rubber powder: 0%, 5%, 10%, and 15%. These percentages were selected based on prior studies and preliminary laboratory test results. Previous research has reported the use of rubber content up to 25% in similar applications.

Table 2 summarizes the specifications of the tested soil–rubber mixtures.

Table 2: Specifications of the Tested Samples

Sample No.	Rubber Particle Size (mm)	Rubber Content (%)	Initial Moisture Content (%)
1	0 (Control)	0	3 – 5
2	0 – 0.5	5	3 – 5
3	1 – 3	5	3 – 5
4	3 – 5	5	3 – 5
5	0 – 0.5	10	3 – 5
6	1 – 3	10	3 – 5
7	3 – 5	10	3 – 5
8	0 – 0.5	15	3 – 5
9	1 – 3	15	3 – 5
10	3 – 5	15	3 – 5

Research findings

Effect of Rubber Powder Content on Atterberg Limits

Liquid Limit (LL)

To perform the liquid limit test, the selected clayey soil was first passed through a No. 40 sieve and washed with water to remove impurities. The oven-dried soil samples were then mixed with different percentages of water and tested using the Casagrande apparatus under standard impact procedures. After recording the number of blows, the corresponding moisture content was calculated for each specimen. This procedure was repeated for both untreated soil and mixtures containing 5%, 10%, and 15% rubber powder, with three different particle sizes.

The test results indicate that the addition of rubber powder generally reduces the liquid limit of clay soil. The most significant reduction was observed in mixtures containing 10% rubber content.

For 0.5 mm particles, the LL decreased by 2% at 10% rubber content, but then increased by 1.1% at 15% rubber. For 1–3 mm particles, a 0.25% decrease was observed at 10% content, followed by an increase of 1.4% at 15%. For 3–5 mm particles, the LL decreased up to 4.5% at 5% rubber and decreased by 1% at 15%.

In general, adding up to 10% rubber powder improves (reduces) the liquid limit. Additionally, increasing particle size tends to increase the final LL values. This may be attributed to a higher void ratio and reduced cohesion between soil particles as rubber size and content increase.

Rubber powder contains non-polar and hydrophobic particles and does not tend to absorb water like clay. By replacing part of the clay particles (which are hydrophilic), the amount of water required to reach a fluid state is reduced.

Plastic Limit (PL)

To determine the plastic limit, approximately 20 grams of soil were taken from previously prepared samples and manually rolled into a thread until it reached a diameter of 3 mm, at which point cracking was observed. The corresponding moisture content was then measured. The results of these measurements are summarized in Table 3.

Table 3 presents the plastic limit (PL) values for untreated clay and mixtures containing varying percentages and sizes of rubber powder.

Table 3. Plastic Limit Values for Pure Clay and Rubber-Soil Mixtures with Different Rubber Sizes and Contents

Rubber Particle Size (mm)	Rubber Content (%)	Plastic Limit (PL %)
(Pure clay)	0	31.22
0 – 0.5	5	29.88
0 – 0.5	10	29.10
0 – 0.5	15	29.10
1 – 3	5	28.89
1 – 3	10	28.14
1 – 3	15	28.00
3 – 5	5	28.01
3 – 5	10	26.94
3 – 5	15	25.05

The results indicate that the addition of rubber powder in various sizes generally leads to a reduction in the plastic limit (PL) of clay soil, although the degree of reduction depends on both the rubber content and particle size.

Rubber powder reduces the cohesion between clay particles, causing the soil to crack at lower moisture levels and reduces its plastic Limit.

Effect of Rubber Powder Content on Compaction Parameters

As expected the optimum moisture content of clay (OMC) decreased with the addition of rubber powder. The maximum reduction was approximately 2.5%. Both the wet unit weight and dry unit weight of the clayey soil consistently decreased with increasing rubber content. Specifically, the wet unit weight dropped from 20.3 g/cm³ to 18.3 g/cm³ as the rubber content increased. These results are summarized in Table 4.

Table 4. Effect of Rubber Content onOptimum Moisture Content and Soil Unit Weight

Rubber Content (%)	Optimum Moisture Content (%)	Wet Unit Weight (g/cm³)	Dry Unit Weight (g/cm³)
0	19.5	20.3	17.0
5	18.5	19.5	16.5
10	18.0	18.8	15.9
15	17.0	18.3	15.64

The compaction test results revealed that increasing the percentage of rubber powder led to a reduction in both the optimum moisture content (OMC) and the maximum dry unit weight. This reduction can be attributed to the lower specific gravity of rubber particles and the increase in soil porosity caused by the presence of these lightweight additives. They also have elastic properties and, under pressure, limits the compaction of the soil. In the other hand, since rubber powder is waterproof, achieving proper compaction requires less water to reach the maxim dry density.

Specifically, the optimum moisture content decreased from 19.5% (for pure clay) to approximately 17%, while the wet unit weight dropped from 20.3 g/cm³ to 18.3 g/cm³ with increasing rubber content. At higher percentages of rubber powder (usually more than 10-15%), the reduction in density becomes more noticeable.

Effect of Rubber Powder on Shear Strength Parameters

Clay samples containing 0%, 5%, 10% and 15% of rubber powder and granules were prepared at their optimum moisture content and compacted in three layers, with 25 blows per layer using a standard Proctor hammer. The target dry unit weight of all specimens was maintained at 1.8 g/cm³.

Following 18 hours of saturation under vertical stress, the direct shear tests were performed at a displacement rate of 0.048 mm/min, and under vertical (normal) stresses of 0.5, 1.0 and 1.5 kg/cm². These stress levels were used to calculate the internal friction angle (ϕ) and cohesion (C) of each mix.

Table 5 summarizes the shear stress values obtained from direct shear tests for both the untreated clay and rubber-treated samples with various rubber sizes and contents.

Table 5. Shear Stress (τ) Results Under Three Normal Stresses for Rubber-Clay Mixtures

Rubber Content (%)	Rubber Size (mm)	=0.5 kg/cm²σ	=1.0 kg/cm²σ	=1.5 kg/cm²σ
0	—	0.58	0.73	0.95
5	0–0.5	0.53	0.74	0.91
5	1–3	0.54	0.81	1.02
5	3–5	0.56	0.92	1.09
10	0–0.5	0.59	0.85	1.03
10	1–3	0.53	0.84	1.07
10	3–5	0.57	0.93	1.21
15	0–0.5	0.53	0.72	0.97
15	1–3	0.58	0.84	1.15
15	3–5	0.54	0.81	1.14

The direct shear test results indicate that adding rubber powder influences shear strength behavior in a nonlinear manner, depending on both particle size and rubber content.

The corresponding Mohr–Coulomb parameters (ϕ and C) were calculated using the linear fit of shear stress vs. normal stress data, and are presented and discussed.

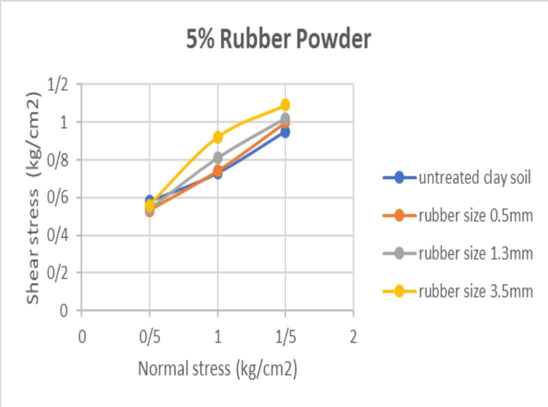

Fig 3. Shear stress–strain curves obtained from direct shear tests on clay samples mixed with 5% rubber powder at different particle sizes

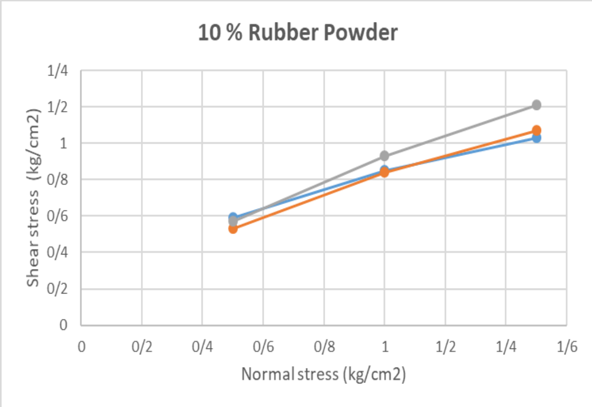

Fig 4. Shear stress–strain curves obtained from direct shear tests on clay samples mixed with 10% rubber powder at different particle sizes

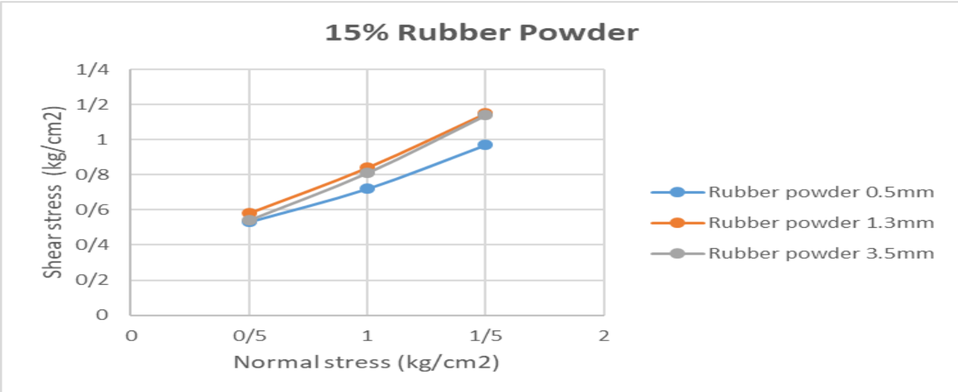

Figure 5. Shear stress–strain curves obtained from direct shear tests on clay samples mixed with 15% rubber powder at different particle sizes

Mohr–Coulomb Parameters (C and ϕ): The cohesion (C) and internal friction angle (ϕ) values derived from the shear strength envelopes are presented in Table 6.

Table 6. Values of Cohesion (C) and Internal Friction Angle (ϕ) for Various Rubber Contents and Particle Sizes

Rubber Content (%)	Rubber Size (mm)	Cohesion, C (kg/cm²)	Friction Angle, ϕ (°)
0	—	0.39	20
5	0–0.5	0.34	21
5	1–3	0.30	26
5	3–5	0.31	29
10	0–0.5	0.38	23
10	1–3	0.28	29
10	3–5	0.25	33
15	0–0.5	0.28	24
15	1–3	0.28	30
15	3–5	0.22	31

The internal friction angle (ϕ) increased with the addition of rubber, particularly at 10% rubber content and with larger particle sizes (3–5 mm). The highest ϕ value of 33° was recorded under these conditions.
This improvement is mainly due to the interlocking effect between coarse rubber particles and the surrounding soil matrix, which enhances resistance to sliding and increases particle-to-particle friction.
In contrast, cohesion (C) values decreased as rubber content increased—especially for larger rubber sizes.This reduction in C can be attributed to the disruption of clay particle bonds caused by the presence of rubber particles, which do not contribute to

electrochemical attraction or capillary forces that normally bind clay particles together.At low contents (5%), the behavior remains balanced, with a modest increase in ϕ and only slight loss in C, suggesting minimal interference in the soil fabric.

At 15% content, although ϕ remained high, the drop in cohesion became more pronounced, likely due to the dilution of the clay matrix and increased presence of voids, which weaken intergranular contact.

10% rubber powder with 3–5 mm particle size yields an optimal improvement in shear strength. It maximizes internal friction without critically compromising cohesion, making it a favorable choice for clay soil stabilization from both mechanical and environmental perspectives.

Rubber powder weakens the bonding between clay particles. It increases internal friction angle of soil due to enhanced internal friction angle.

Effect on Unconfined Compressive Strength (UCS)

To evaluate the mechanical behavior of clay mixed with varying percentages of waste rubber powder, unconfined compressive strength (UCS) and the strain at failure were measured under controlled laboratory conditions. The samples were compacted under standard procedures and subjected to axial loading at a constant strain rate.The main objective of this study is to investigate how the rubber content and particle size influence both the compressive strength and the ductility of the clay. The results provide a clear comparison across the different rubber mixtures and allow interpretation of how rubber addition affects load-displacement behavior of clay.The unconfined compressive strength (qu) and corresponding axial strain at failure (ε) for clay samples mixed with 5% rubber powder of various particle sizes are presented in Table 7. The results are compared with those of pure clay under identical test conditions.

Table 7. UCS and Axial Strain for 5% Rubber-Modified Samples

Rubber Content (%)	Rubber Size (mm)	UCS, qu (kg/cm²)	Axial Strain, ε
0	—	6.90	0.34
5	0–0.5	6.80	0.36
5	1–3	6.80	0.33
5	3–5	6.80	0.297

The results indicate that adding 5% rubber powder—regardless of particle size—did not significantly alter the peak compressive strength compared to pure clay. The UCS remained nearly constant at around 6.8–6.9 kg/cm². However, an important change was observed in the strain behavior:The rubber-modified samples exhibited a more gradual and uniform strain progression, indicating increased ductility and a more stable failure pattern.The stress–strain curves of these samples showed smoother gradients, which reflect a less brittle failure mode than the sharp peak typically observed in pure clay.Small variations in UCS values, as seen in the table, are considered to be within the acceptable range of experimental error, rather than a direct result of material behavior. This is further supported by observed failure surfaces, which showed more even deformation in the rubber-treated samples.While 5% rubber powder did not enhance compressive strength, it modified the deformation behavior toward a more ductile response. This could be beneficial in geotechnical applications where strain accommodation and post-peak load redistribution are important.For clay samples containing 10% rubber powder of various particle sizes are summarized in Table 8.

Table 8. UCS and Axial Strain for 10% Rubber-Modified Samples

Rubber Content (%)	Rubber Size (mm)	UCS, qu (kg/cm²)	Axial Strain, ε
0	—	6.90	0.34
10	0–0.5	6.90	0.35
10	1–3	6.70	0.264
10	3–5	6.00	0.231

The results indicate that the addition of 10% rubber powder led to slight variations in UCS compared to the pure clay sample:

- Both Small particles (0–0.5 mm) and larger particles (1–3 mm and 3–5 mm) did not improve the strength or even slightly reduced it.
- The axial strain at failure decreased with increasing particle size—dropping from 0.35 to 0.231. This implies a reduction in ductility at higher rubber particle sizes.
- Although the peak compressive strength remained relatively stable, the behavior of the samples under load changed noticeably:
- The observed reduction in strain at failure in samples with coarser rubber particles indicates increased stiffness and a transition to brittle behavior at lower strains.
- Visual examination of the failure mechanisms revealed that specimens incorporating coarser rubber particles demonstrated significantly constrained deformation propagation and more distinctly defined failure planes.

At 10% rubber content, fine rubber particles may slightly enhance compressive strength and maintain deformability, but coarser rubber sizes tend to reduce strain capacity, which could be critical in applications requiring post-yield deformation.

Table 9 presents the unconfined compressive strength (qu) and corresponding axial strain at failure (ε) for clay samples mixed with 15% rubber powder of various particle sizes.

Table 9. UCS and Axial Strain for 15% Rubber-Modified Samples

Rubber Content (%)	Rubber Size (mm)	UCS, qu (kg/cm²)	Axial Strain, ε
0	—	6.90	0.34
15	0–0.5	6.30	0.231
15	1–3	5.00	0.165
15	3–5	4.20	0.132

The data reveal a clear trend in the variation of UCS and axial strain with increasing rubber powder content:

- Increasing the rubber powder content beyond 5% generally does not improve the unconfined compressive strength and in some cases, especially at 15%, causes a reduction in UCS.
- Samples with 5% rubber powder showed UCS values close to that of pure clay, with only slight improvement in strain at failure, although minor fluctuations likely due to experimental error were observed, consistent with the failure patterns.
- At 10% rubber powder content, the UCS remained comparable to pure clay; however, the axial strain at failure decreased, indicating reduced ductility.
- The most pronounced effects were observed at 15% rubber powder, where the UCS was nearly halved compared to pure clay, and the axial strain at failure also dropped by approximately 50%. This indicates a significant reduction in both strength and deformability.
- These results suggest that increasing rubber powder content and particle size beyond optimal limits leads to diminished mechanical performance, likely due to decreased effective cohesion between rubber and soil particles and the high elasticity of rubber particles, which hinders effective stress transfer within the sample.

Rubber powder, due to its elastic and flexible structure, does not tolerate compressive loads effectively. At higher mixing percentages (typically above 10-15%), the reduction in uniaxial strength becomes more noticeable.

While adding rubber powder at higher percentages and larger particle sizes tend to reduce both the strength and ductility of clay soils. This trade-off highlights the importance of optimizing rubber powder content and particle size for geotechnical applications, especially in critical infrastructure projects requiring enhanced soil performance. In this study, the best balance of ultimate strength and corresponding strain was observed for the 10% rubber powder with 0–0.5 mm particle size mixture**.**

Results

After conducting numerous tests on various rubber powder mixtures with different gradations, the following results can be summarized as the general conclusion.Rubber powder contains non-polar and hydrophobic particles and does not tend to absorb water like clay.As a result, the soil mixed with rubber powder, reaches a liquid state from a plastic state faster (i.e., it requires less water to achieve a liquid consistency).Rubber powder reduces the cohesion between clay particles, causing the soil to crack at lower moisture levels and lose its plastic Limit.Rubber particles have lower density than clay particles. They also have elastic properties and, under pressure, limits the compaction of the soil. At higher percentages of rubber powder (usually more than 10-15%), the reduction in density becomes more noticeable. In the other hand, since rubber powder is waterproof, achieving proper compaction requires additional water to help bond the soil and rubber particles.The incorporation of rubber powder adversely affects clay particle cohesion while exhibiting a non-linear relationship with internal friction angle. At low concentrations, the rubber particles may marginally enhance the internal friction angle through particle interlocking. However, beyond a critical threshold, the material's frictional resistance deteriorates due to dominant rubber-to-rubber interactions.Rubber particles, due to its elastic and flexible structure, does not tolerate compressive loads effectively. At higher mixing percentages (typically above 10-15%), the reduction in uniaxial strength becomes more noticeable.

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