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Effect of Tire-Rubber Inclusion on The Physical and Mechanical Behavior of Granular Soils

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Abstract

The escalating global problem of waste tires, compounded by their non-biodegradable nature and expensive disposal methods, necessitates innovative solutions. This research explores the potential of incorporating tire shreds into fine granular soils by examining their impact on physical and mechanical properties. Key areas of investigation include Compaction Method Efficiency: Evaluating the effectiveness of wet and dry compaction techniques across varying rubber-to-sand ratios. Geometric Influence: Examining how tire shreds geometry affects optimal void ratio and shear strength parameters. Anisotropy & Orientation: Assessing the impact of average rubber chip orientation on the mechanical anisotropy of the resulting binary mixture. By addressing these aspects, this study aims to bridge the gap between environmental concerns and geotechnical applications, potentially offering a sustainable solution for waste tire management while enhancing soil properties.

Keywords: Waste Tires, Geometric Influence, Binary Mixture, Anisotropy.

1 Introduction

The burgeoning global population and industrial boom have dramatically increased end–of–life tire volumes, posing a significant waste management challenge. These non-biodegradable materials require expensive and often environmentally detrimental disposal methods, such as uncontrolled burning in developing nations as mentioned by Imelda et al. (2018) [1]. International efforts have fostered innovative reuse strategies for end-of-life tires in geotechnical and construction applications. For example, incorporating tire scraps into non-cohesive soils demonstrably improves their physical and me-

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chanical characteristics based on the geometric configuration of the tire scrapes. This approach offers a sustainable and potentially cost-effective solution for managing this growing waste stream.
A substantial body of research has investigated the potential benefits of incorporating tire scraps into various applications. However, despite these efforts, significant knowledge gaps remain. This study aims to address some of these gaps.

2 Application of Tire Rubber Scrapes in Geotechnical Engineering

Previous studies have explored the potential benefits of incorporating shredded tires into various geotechnical applications, with promising results. Bernal et al. (1996) [2], documented observations of improved drainage and reduced capillary rise in Georgia in 1990 when shredded tires were used as subgrade material.
Subsequent research by Ahmed. (1993) [3] and Hazarika et al. (2010) [4] highlighted the advantages of using shredded tires in lightweight backfills. These studies reported reduced settlements, improved stability, enhanced drainage, and reduced backfill pressure on retaining structures. Notably, the high permeability and non-clogging properties of rubber particles compared to sand make them particularly attractive for use as drainage layers in embankment structures, as illustrated in Figure 1.

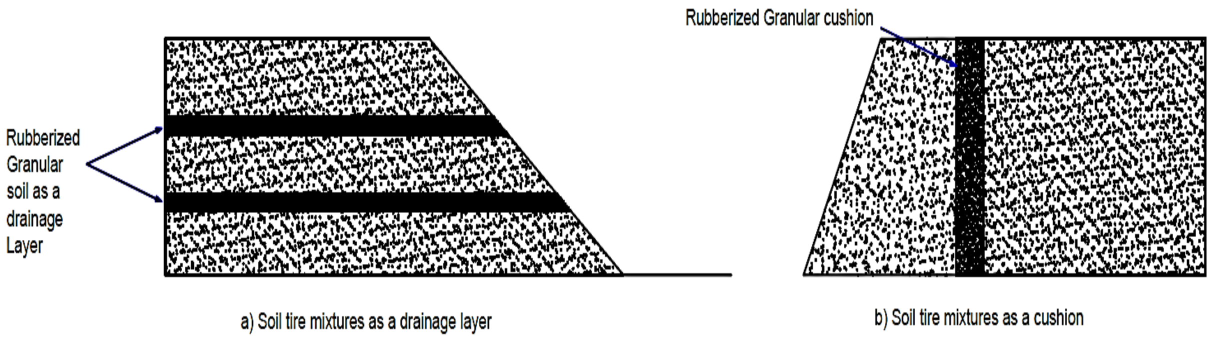


Fig. 1. Schematic view of different sand-rubber mixture applications.

Mahmoud et al. (2023) [5] proposed a novel method for improving the bearing performance of loose granular soils while addressing environmental concerns. This technique termed sand-rubber compacted piles (SRCP), incorporates shredded end-life tires into sandy soil, creating composite inclusions that enhance both bearing capacity and energy absorption capabilities. The authors conducted an experimental investigation to evaluate the performance of SRCPs, focusing on the influence of initial soil density, the rubber-soil ratio (R/S) by weight, and pile distribution. Field plate load tests (FPLTs) revealed a significant increase in the ultimate bearing capacity compared to traditional Sand Compacted Piles (SCPs). Notably, SRCPs offer a potentially cost-effective alternative to conventional sand compacted piles, promoting both geotechnical and environmental sustainability.

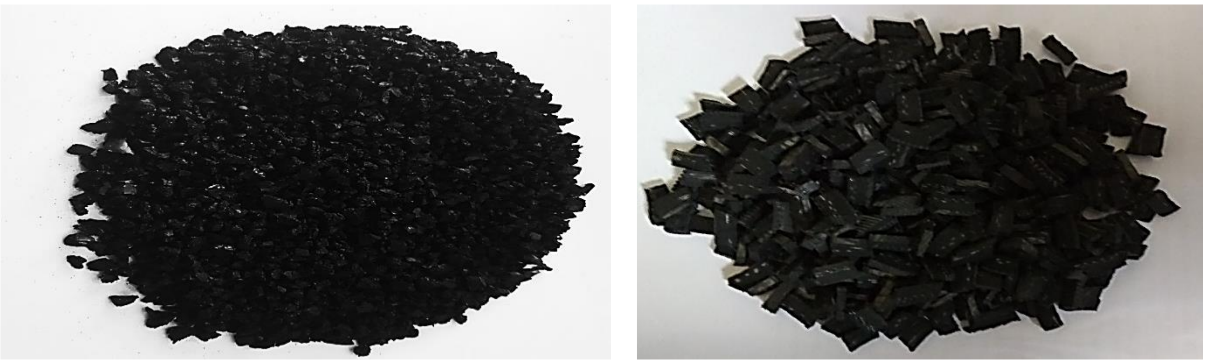
3 Research Significance:

Several critical issues arise when working with rubber-soil mixtures, particularly with increasing rubber content. Achieving optimal compaction becomes increasingly challenging due to factors like the inherent elasticity of rubber particles and the potential for segregation due to differing densities between components. This reduced homogeneity further complicates the characterization of the mixture's mechanical behavior, specifically its anisotropic shearing response. Understanding the influence of various factors, such as tire shreds' geometric characteristics, and their concentration in the mixture, on both compaction efficiency and anisotropic behavior is crucial for the effective utilization of these materials.

4 Methodology

A comprehensive experimental investigation was undertaken to elucidate the influence of incorporating tire shreds on the geotechnical properties of the granular soil according to ASTM standards. The study focused on quantifying the interaction between three key physical parameters: tire shred geometry, specific gravity, and compaction characteristics (maximum and minimum dry densities). This systematic approach aimed to unveil the complex interplay between these factors and their combined impact on the overall physical and mechanical attributes of the resulting composite material.

Tire shred geometry, two types of tire shreds were employed in this study: rubber chips with dimensions (3mm X 5mm X 10 mm), and granular rubber grains of average size 5 mm to investigate the impact of the tire shred geometric characteristics on both the dry unit weight and the shearing behavior of the mixture.



a) Granular Rubber b) Rubber Chips

Fig. 2. Different types of tire shreds used in the study

Soil particle size, a grain size analysis was conducted on the soil and tire shred samples following ASTM D422 [6] standards to determine the distribution of the particle's sizes. This information was then employed to classify both the soil and the tire shreds.

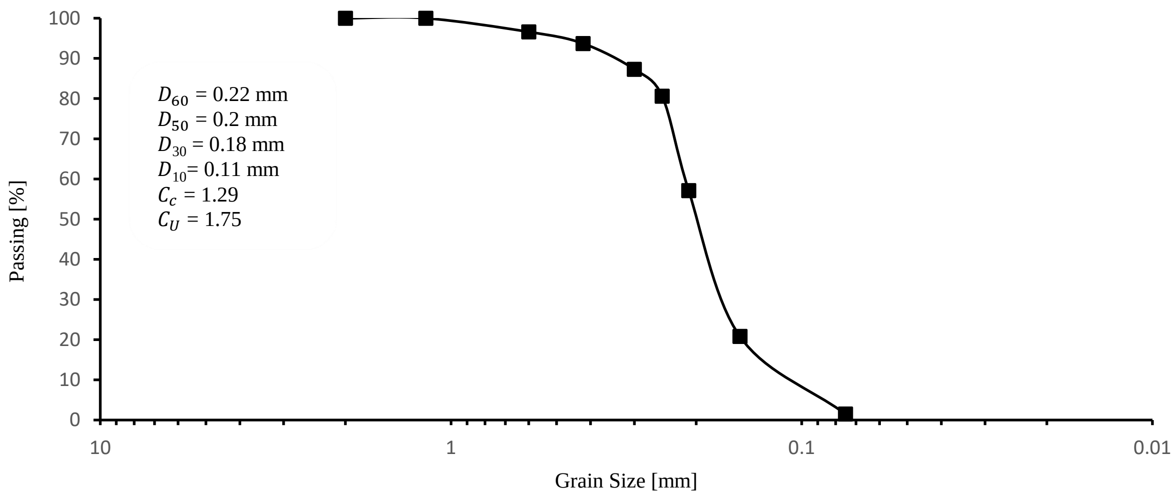


Fig. 3. Grain Size Distribution of the sandy soil

The maximum dry density of binary soil mixtures was determined employing various techniques outlined by ASTM guidelines. This study employed two compaction methodologies: dry placement using a vibration table as outlined in ASTM D4253 [7] and wet placement methods including the standard Proctor test (ASTM D698) [8] and the modified Proctor test (ASTM D1557) [8]. This investigation aimed to assess the efficiency of these techniques for different binary mixtures.

The minimum dry density of the binary soil mixture was determined by adhering to the dry placement method outlined in ASTM D4254-00 [10]. A funnel was utilized to carefully pour the soil into a designated mold, creating uniform layers without particle segregation. Each layer was meticulously leveled using a straight edge, ensuring no free fall exceeded 20 mm.

Direct shear tests [11] were conducted on sand-rubber mixtures with varying rubber-to-sand (R/S) ratios based on gravimetric proportions ranging from 0% to 100%. The study aimed to investigate the shear strength parameters and the influence of average rubber chip orientation on their shearing behavior. To achieve this, a dedicated 100 mm x 100 mm shear box was chosen, deemed particularly suitable for testing sand mixed with tire shreds. Specimen preparation involved calculating the required weight of the R/S mixture based on the maximum dry density values obtained from the preceding compaction tests for each mixture and the shear box volume. Meticulous care was taken during preparation to ensure consistent uniformity across all specimens. Figure 4 presents the experimental program for the direct shear box tests, designed to investigate the shearing behavior of rubber-sand mixtures. The program systematically evaluates the influence of the rubber-to-sand (R/S) ratio on the mixtures' shear strength, as well as the anisotropic shearing response arising from the average orientation of the rubber chips. To minimize result variability, each test is prudently repeated three times, and the mean value is calculated for robust data analysis.

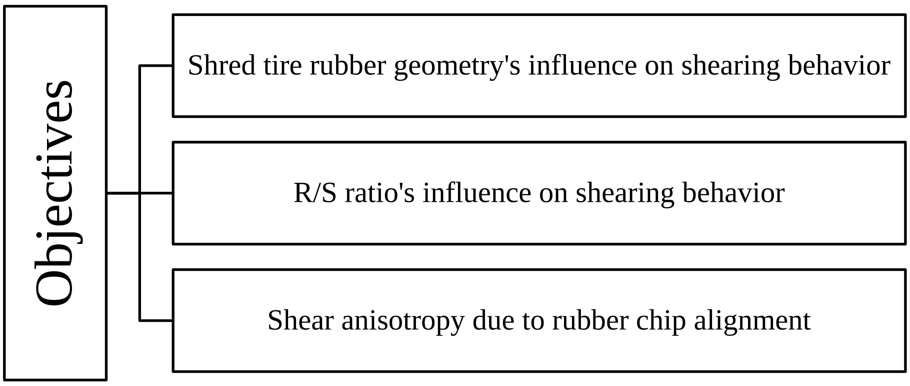


Fig. 4. Main objectives from shearing investigation

This study's initial objective explores the geometrical influence on the shearing behavior of rubber-sand mixtures. Shear box tests with varying R/S ratios up to 100% investigated the mixtures' shear strength under three distinct normal stresses (49.81, 196.1, and 294.2 KPa). All tests employed randomly oriented rubber chips and maximum dry density for the mixtures. Unveiling the role of rubber chip alignment in anisotropic mechanics forms the concluding objective. By conducting shear box tests on mixtures with vertically, randomly, and horizontally oriented chips (see Fig. 5.), this study delves into the anisotropic response of rubber-sand mixtures.

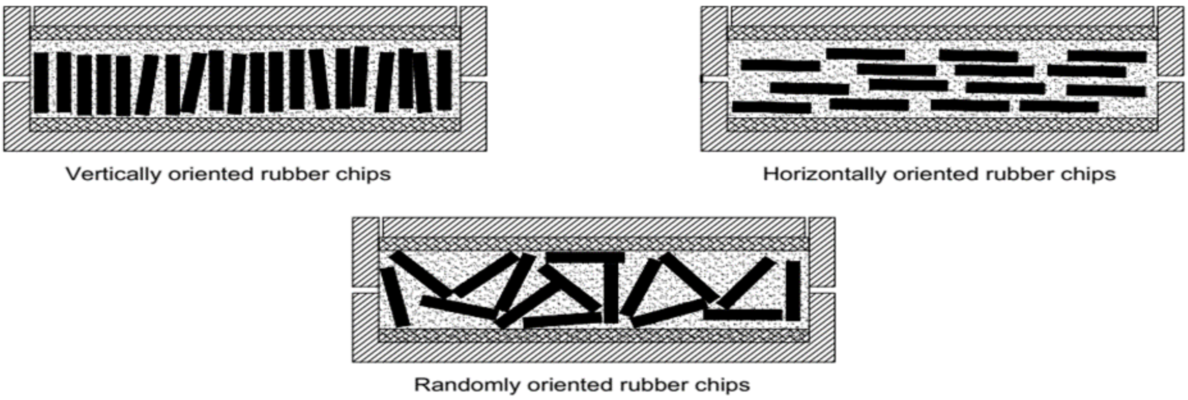


Fig. 5. Average orientation of rubber chips in binary mixtures

5 Results and Discussion:

As for the compaction efficiency, figure 6 shows the compaction effectiveness of wet and dry placement compaction methods based on three common compaction methods: vibration table method (dry placement compaction), modified and standard proctor test (wet placement compaction) for binary mixtures of sand and rubber chips. The analysis reveals a distinct correlation between maximum dry density (MDD) achieved through different compaction methods and the R/S ratio.

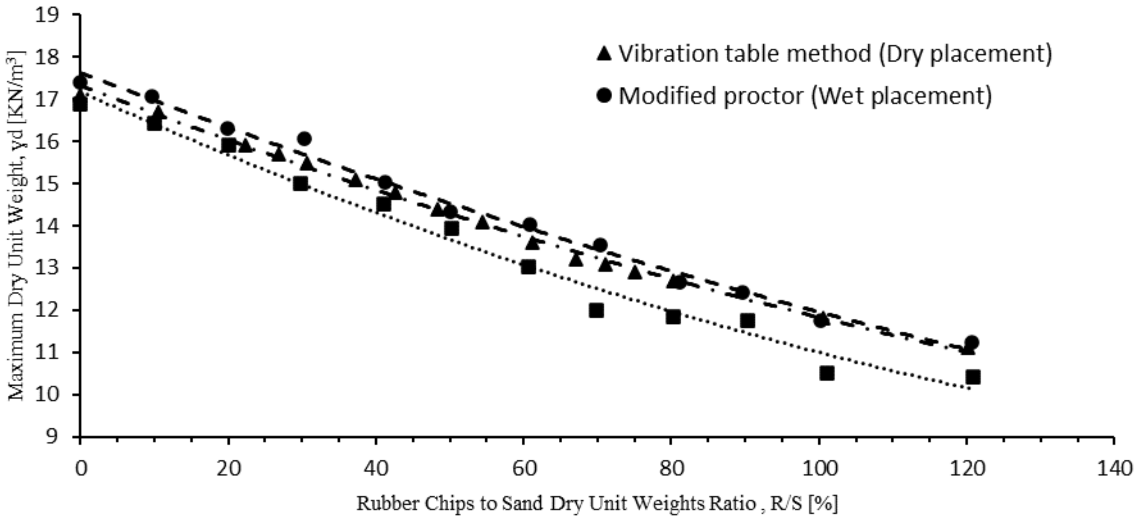


Fig. 6. Compaction effectiveness of wet and dry placement techniques based on R/S ratios

Initially, for ratios ranging from 0% to 40%, where the rubber chip volume is similar to the sand volume, observed deviations in MDD values between compaction methods are minimal and consistent with previously established findings by Waldemar & Paulina, 2016 [12]. However, beyond this threshold, as the R/S ratio increases and rubber chips constitute over 50% of the mixture volume (see Fig. 7.), achieving homogeneity and uniformity becomes increasingly challenging. This translates to a gradual decline in the effectiveness of both standard and modified Proctor tests in accurately capturing the MDD, with deviations from the vibration table method diminishing compared to lower R/S ratios. The results from Fig. 6. highlight the limitations of these standardized compaction methods when applied to highly heterogeneous mixtures with significant rubber chip content, emphasizing the need for alternative evaluation techniques for such materials.

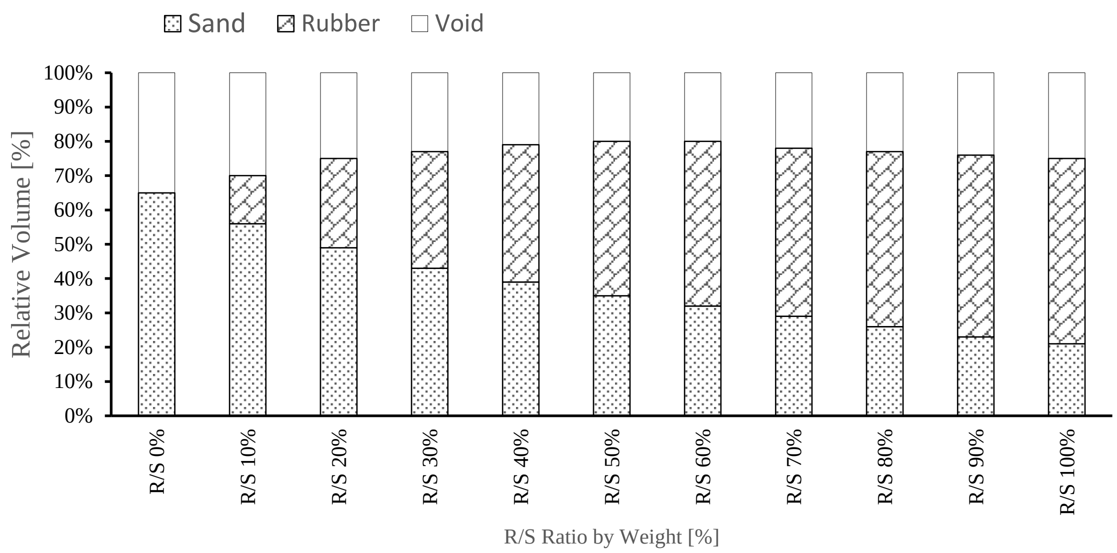


Fig. 7. The volumetric relationship between the components of the binary mixture at different R/S ratio

Influence of Rubber Chips on Void Ratio: As evident in Fig. 8., the presence of rubber chips significantly impacted the void ratio of the mixtures for both dense and loose mixtures. The graph depicts the relationship between the void ratio and R/S ratio, determined using the vibration table compaction method.

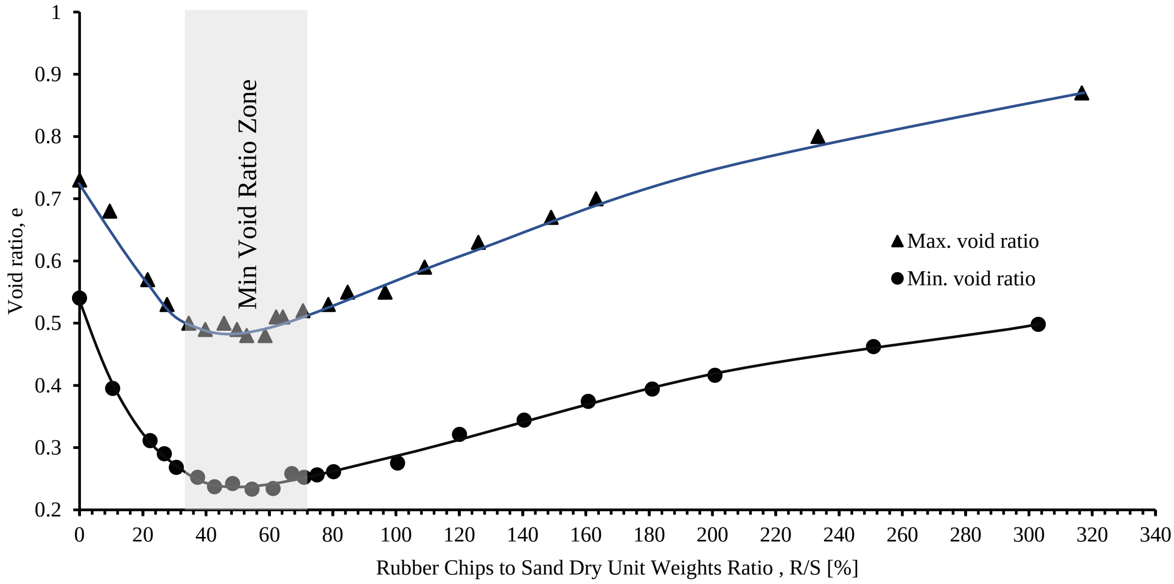


Fig. 8. The correlation between void ratio and R/S ratio for rubber chips

Rubber chip addition significantly affects the void ratio, reflecting its influence on mixture packing. In Region 1 (R/S < 20), sand dominates, leading to a decrease in void ratio as rubber chips replace sand-void combinations as mentioned by Ahmed, 1993 [13]. As R/S increases (20-60), rubber chips (25-48% volume) share structural responsibility with sand. Sand primarily fills voids between chips, minimizing the void ratio. Fig. 9. shows the values of void ratios of different rubber shreds.

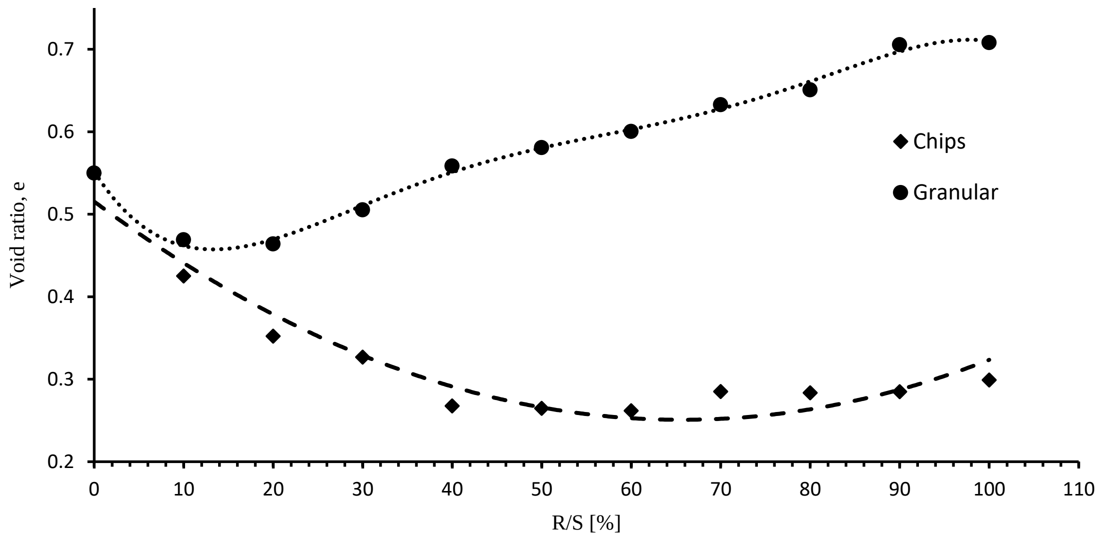


Fig. 9. The correlation between void ratio and R/S ratio for different tire shreds

Conversely, insufficient sand content (R/S > 60) increases the void ratio, characteristic of rubber-dominated regions. Adding rubber influences void ratio and consequently, shearing behavior. Notably, minimum void ratio reduction (14.7%) for granular inclusions occurs at R/S = 10%, indicating dense packing and potentially improved shear strength. However, the maximum reduction (52.3%) for chip reinforcement is observed at a higher R/S (60%), suggesting a distinct packing mechanism and potential shearing behavior compared to granular mixtures. Further research is needed to elucidate the interplay between void ratio, rubber type, and shearing behavior across R/S ratios. As for the specific gravity of the binary mixtures. Fig. 10. shows the influence of the R/S ratios on the specific gravity of the binary mixture.

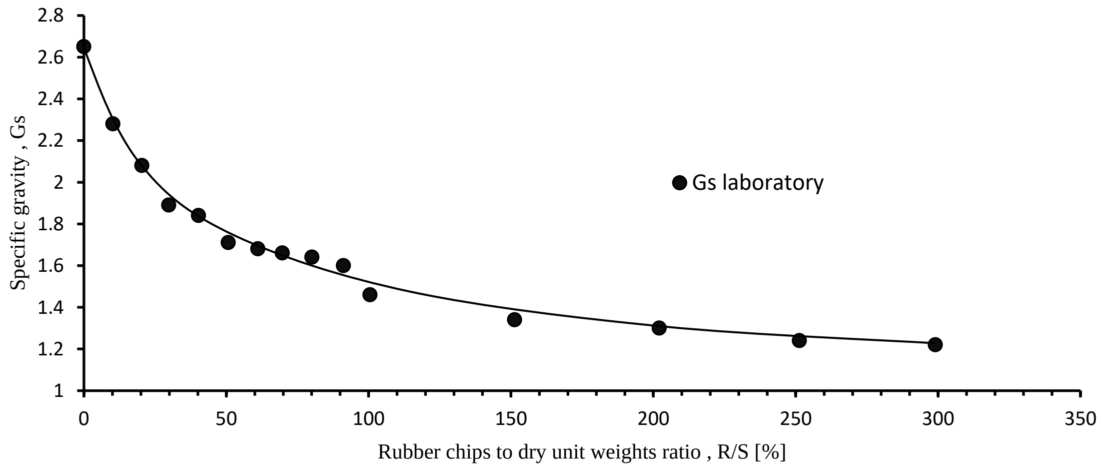


Fig. 10. The values of the specific gravity based on R/S ratios

The Fig. 11. demonstrates the significant influence of rubber chip orientation on shear strength. Vertically oriented chips exhibit a consistently higher frictional angle across all R/S ratios, reaching a maximum of 47° at 60% R/S (6° increase compared to random orientation). Conversely, horizontally oriented chips display a lower frictional angle, with a maximum of 36°. This contrasting behavior aligns with the chip orientation relative to the shearing surface. vertical orientation provides added resistance, while horizontal orientation facilitates sliding, thus reducing shear strength.

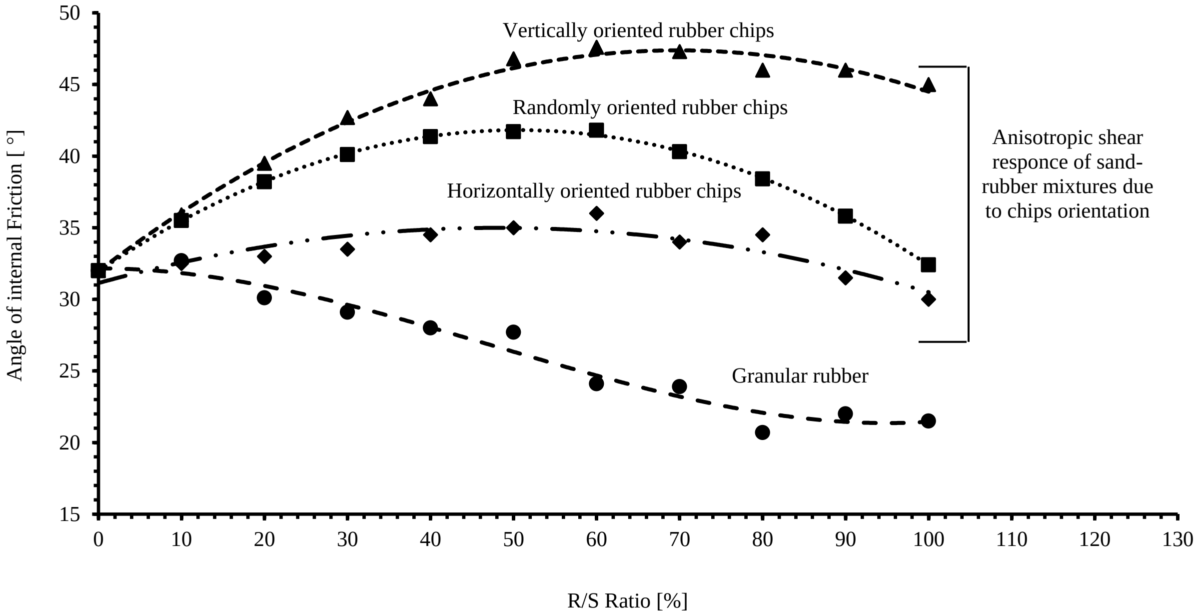


Fig. 11. The correlation between the angle of friction and R/S ratio for different tire shreds

While vertical rubber chip orientation demonstrably enhances shear strength compared to random or horizontal configurations, achieving perfect perpendicular alignment in field applications remains a significant challenge. Careful consideration is crucial when handling such anisotropic characteristics, as existing soil mechanics codes typically neglect the influence of non-uniform mechanical behavior. Further research and innovative techniques are necessary to bridge the gap between laboratory findings and the practical implementation of vertically oriented rubber chips for optimized shear strength benefits.

6 Conclusions:

The main conclusions of the study are presented as follows:

1- Dry compaction methods are more effective than wet compaction methods, especially with a mixture of higher R/S ratios.
2- Including tire shreds in granular soils can significantly impact their geotechnical characteristics. While often observed to decrease dry density due to the inherently lower density of rubber compared to soil, the effect on shear strength is less straightforward and depends on various factors. Understanding the complex interplay between tire shred properties, content, and mixing methods with specific geotechnical properties is crucial for accurate assessment and potential optimization.
3- The average orientation of the rubber chips highly impacts the shearing behavior of the binary mixture. Vertical rubber chip orientation offers demonstrably higher shear strength, but achieving perfect alignment in the field remains elusive. Addressing this anisotropy is crucial as current soil mechanics codes overlook non-uniform mechanical behavior. Bridging the gap

between laboratory findings and practical implementation requires further research and innovative techniques to unlock the full potential of vertically oriented rubber chips for shear strength optimization.

4- This study investigates the influence of tire shred geometry on binary mixtures' physical and mechanical properties. The research demonstrates that the geometric shape of tire shreds significantly impacts the mixture's void ratio and shear strength. Specifically, incorporating fine sand with rubber chips demonstrably modifies the shear behavior and achieves minimum void ratio values compared to a binary mixture of sandy soil and granular rubber.

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