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A Comparative Study on the Mechanical Performance of Unreinforced and Reinforced Stone Columns Using Geotextile and Recycled Tire Crumbs

Morteza Pordel [a], Saeed Kouzegaran [b*]

[a] *Toos Institute of Higher Education, Mashhad, Iran*

[b] *Department of Civil Engineering, Faculty of Engineering and Technology, University of Mazandaran, Babolsar, Iran*

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A B S T R A C T

Stone columns are among the most widely adopted techniques for improving soft sediments and loose fine-grained soils. They enhance the strength of weak soils and reduce settlement under applied loads. However, their performance in very soft soils is often limited due to the lateral displacement of column materials into the surrounding soil during loading. This lateral spread and settlement of stone materials reduce the effectiveness of the stone column system. To overcome these challenges, strategies such as increasing confining pressure or reinforcing the stone columns with geosynthetic materials have been explored. In this study, the mechanical performance of stone columns reinforced with geotextile encasement and tire crumbs was compared to that of unreinforced stone columns. Tire crumbs, typically sourced from recycled tires, present an environmentally sustainable alternative by reducing tire waste accumulation in landfills and minimizing the associated environmental risks. Their application in ground improvement contributes to greener geotechnical engineering practices. To evaluate the effectiveness of the proposed reinforcements, consolidated undrained triaxial tests were conducted on various specimens. The results revealed that tire crumbs significantly enhanced the elastic modulus, with an increase of approximately 60% observed in specimens containing 20% tire crumbs. This enhancement is likely due to reduced interlocking and weaker grain-to-grain bonding within the modified column material.

1. Introduction

Loose sands and soft cohesive soils such as clays and silts often exhibit poor engineering properties, including low shear strength, high compressibility, and excessive settlement under loading. To address these limitations, various effective ground improvement techniques, including a variety of geosynthetic reinforcements [1-6] and stabilization methods [7-11] have been used. With growing global efforts toward achieving carbon neutrality, the use of stone columns as a component of composite ground improvement systems has gained widespread popularity in the 21st century, particularly for infrastructure projects involving embankments, foundations, and road subgrades. This trend reflects the increasing emphasis on incorporating environmentally friendly materials and technologies in the construction sector. The earliest documented use of stone columns dates back to 1830 in France, and since the mid-19th century, their application has expanded across Europe and globally due to their simplicity, cost-effectiveness, and environmental compatibility [4, 12-17]. Stone columns are constructed by replacing vertical zones of weak soil with compacted coarse aggregates, forming a composite ground system. This configuration reduces the compressibility and increases the load-bearing capacity of soft ground by redistributing stresses from the surrounding soil to the stiffer stone inclusions.

However, in very soft soils with insufficient lateral confinement, the effectiveness of stone columns can be compromised due to excessive bulging, lateral spreading, and intrusion of the stone into adjacent weak soil, which reduces the efficiency of the

* Corresponding author.
E-mail addresses: skouzagaran@umz.ac.ir (S. Kouzegaran).

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improvement. To mitigate these issues, various methods have been used to improve stone column performance by increasing density and strength, such as horizontal reinforcement layers, grouting, or wrapping stone columns with geosynthetics. The geosynthetic-encased stone column (GEC) system is a relatively new method for improving very soft soils. In this method, stone columns are wrapped with geosynthetics, which, unlike unwrapped columns relying solely on soil confinement, provide increased radial confinement from the geosynthetic wrap, resulting in stronger and stiffer columns, higher bearing capacity, and reduced settlement [18].

Numerous experimental and numerical studies have validated the effectiveness of these reinforcing methods for stone columns. For instance, Malarvizhi and Ilamparuthi [19] conducted a series of laboratory and numerical tests using geogrid-encased columns and reported an increase in bearing capacity by up to 2.2 times for columns with a length-to-diameter (*L/D*) ratio of 10. Their study also demonstrated a notable reduction in settlement ratio from 0.42 in unreinforced columns to 0.22 in reinforced ones. Furthermore, maximum horizontal deformation was reduced from 6.7 mm to 0.17 mm due to geosynthetic encasement. Similarly, Murugesan and Rajagopal [20], Murugesan and Rajagopal [21] performed large-scale model tests on geosynthetic-encased stone columns and found that stiffer encasement materials led to improved load-bearing performance. Their research emphasized the importance of full-length vertical encasement in enhancing column stiffness and controlling bulging.

Moreover, experiments conducted by Gniel and Bouazza [22] and Nishant and Kumar [23] on sand columns with geosynthetic reinforcement inside unit cells showed significant reductions in axial strain and increased bearing capacity compared to unreinforced columns. Zheng et al. [17] studied geosynthetic-encased sand columns in soft clay beds, finding up to 3.5 times increase in bearing capacity. Srijan and Gupta [24, 25] extended these findings by combining vertical encasement with horizontal reinforcement layers, demonstrating further improvement in lateral confinement and load distribution. Their experimental and numerical simulations using Plaxis3D confirmed the benefits of combined reinforcement strategies in reducing lateral deformations and enhancing overall performance. Rathod et al. [26] explored the use of woven polypropylene textiles as an alternative to traditional geotextiles. They observed that a double-layer configuration halved the lateral displacement compared to single-layer encasement, and polypropylene offered a cost-effective solution while maintaining significant performance gains.

Nonetheless, geosynthetic materials such as geotextiles and geogrids are often expensive, which can be a limiting factor for large-scale applications. To address this issue, alternative reinforcing agents have been considered to compensate for the tensile weakness of stone column aggregates. Among these, shredded rubber, an elastic, low-cost material derived from recycled waste tires, has shown promise as a partial or full substitute for synthetic reinforcements. Its tensile properties contribute to improved load distribution and deformation control within the column. In addition to mechanical benefits, the use of tire crumbs presents significant environmental advantages. Millions of tires are discarded globally each year, posing major challenges for waste management. By incorporating rubber waste into ground improvement systems, not only is landfill usage reduced, but the long-term environmental hazards associated with tire stockpiles, such as fire risks and leaching of contaminants, are also mitigated. This approach supports the development of more sustainable and eco-friendly geotechnical solutions. Meanwhile, while in the majority of recent studies various geosynthetic materials have been studied, there remains a gap in research regarding alternative reinforcement materials such as tire crumbs.

Therefore, this study seeks to evaluate the mechanical performance of stone columns reinforced with geotextile encasement, tire crumbs, and their combination, in comparison to unreinforced stone columns. Using a series of consolidated undrained triaxial (CU) tests under controlled laboratory conditions, key strength parameters, including internal friction angle, cohesion, and stiffness modulus, are measured and analyzed. By addressing the current gap in research on rubber-based reinforcement, this investigation aims to offer new insights into the viability of incorporating recycled rubber as a sustainable, cost-effective alternative for enhancing the load-bearing behavior and overall efficiency of stone columns in soft ground improvement projects.

2. Test procedure

2.1. Specification of materials used

In this section, the physical properties of the used materials are presented.

- **Stone column materials**

The stone column materials used in this study consist of angular (sharp-edged) aggregates. The materials used for the stone columns fall under the GP category (well-graded gravel) of the Unified Soil Classification System. The grain size distribution curve of the stone column materials is presented in Fig. 1, and other specifications of the stone column materials are provided in Table 1.

- **Properties of the enclosing geotextile**

In this study, an enclosing geotextile was used to improve the bearing capacity and performance of the stone column soil. The geotextile used is a non-woven type made of polypropylene. The specifications of the geotextile are presented in Table 2. Additionally, Fig. 2 shows the enclosing geotextile used in the stone columns studied.

- **Properties of crumb rubber**

Waste tires are processed into various particle sizes, typically categorized into three types: tire shreds (D_{50} > 50 mm), tire chips (12 mm < D_{50} < 50 mm), and tire crumbs (D_{50} < 12 mm). The rubber particles used in this study fall into the tire crumbs category, with particle sizes ranging from 1 to 4 mm. According to international standards, the size of any individual particle should not exceed one-third of the smallest dimension of the larger testing apparatus. Fig. 3 shows the crumb rubber material used in the tested samples.

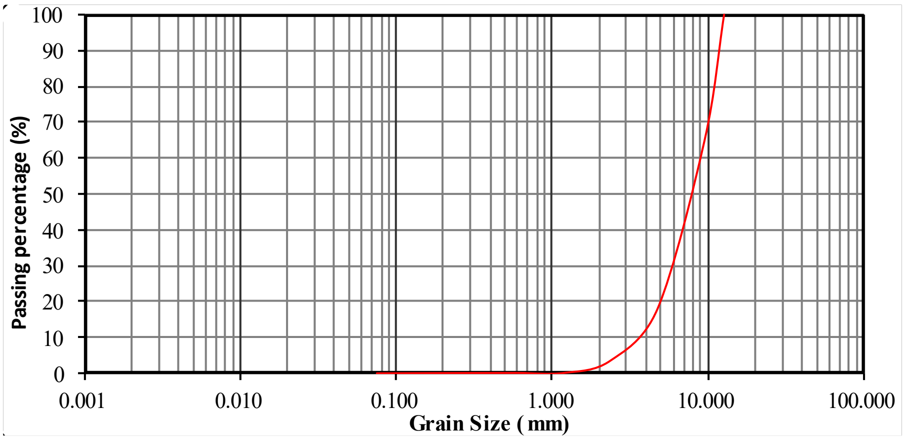

Fig. 1. Grain size distribution of ston column soil.

Table 1. Properties of stone column materials.

No.	Parameter	Value
1	Soil classification (USCS)	GP
2	Coefficient of uniformity (Cu)	4.7
3	Coefficient of curvature (Cc)	0.9
4	Specific gravity of soil particles (Gs)	2.66
5	Maximum dry unit weight (g/cm³)	1.77
6	Minimum dry unit weight (g/cm³)	1.54

Table 2. Specifications of the geotextile used in the tests.

Parameter	Value
Fiber material	Polypropylene
Ultimate tensile strength (kN/m)	5.1
Strain at ultimate strength (%)	54
Thickness (mm)	2.3
Mass per unit area (g/m²)	250

Fig. 2. Enclosing geotextile used in the stone columns.

Fig. 3. Crumb rubber used in the samples.

2.2. Test setup

Consolidated undrained (CU) triaxial tests were selected for this study as they closely simulate in-situ stress paths in saturated cohesive soils where drainage is limited during loading. CU tests also provide both total and effective stress parameters, making them particularly suitable for evaluating the short- and intermediate-term behavior of reinforced columns in soft soil applications. In this test, after the sample is consolidated under a confining pressure (σ_3), axial loading is applied under undrained conditions. The test procedure, properties of the tested materials, and sample dimensions are presented in Table 3. The selected confining pressures of 0.5, 1.0, and 1.5 kg/cm² were chosen to simulate typical stress ranges encountered in shallow to moderately deep ground improvement applications under embankments and foundations. These values are representative of effective overburden pressures at depths between 2 m to 6 m, which are commonly addressed using stone columns in field practice.

Table 3. Description of the tested samples.

No.	Material	Test Type	Confining Pressure (kg/cm²)
1	Stone Column	Triaxial	0.5 – 1.0 – 1.5
2	Stone Column + 10% Crumb Rubber	Triaxial	1.0
3	Stone Column + 20% Crumb Rubber	Triaxial	-
4	Stone Column + 30% Crumb Rubber	Triaxial	-
5	Stone Column + Enclosing Geotextile + 20% Crumb Rubber	Triaxial	0.5 – 1.0 – 1.5
6	Stone Column + Enclosing Geotextile	Triaxial	0.5 – 1.0 – 1.5

Each specimen was prepared by compacting the material in three layers inside a cylindrical mold. A wet tamping compaction method was used, where each layer was compacted manually with a steel rod using consistent energy to achieve the desired dry density. The surface of each compacted layer was roughened with a sharp object before placing the next layer to promote interlayer bonding. Fig. 4 illustrates the different stages of the test execution.

(a) (b) (c) (d)

Fig. 4. Stages of the test execution: (a) Sample preparation, (b) and (c) Loading to failure, and (d) Geotextile-encased samples after failure.

Based on the information presented, in this study, the values of shear strength parameters were obtained through Consolidated Undrained Triaxial Tests (CU) for the following cases for comparison purposes:

- Stone column,
- Stone column with 10% crumb rubber,
- Stone column with 20% crumb rubber,
- Stone column with 30% crumb rubber,
- Stone column with enclosing geotextile,
- Stone column with enclosing geotextile and 20% crumb rubber,

The obtained results were compared accordingly. It is worth mentioning that the crumb rubber was added to the samples by weight percentage, and after complete mixing with the stone column material, the mixture was used to prepare the samples. Additionally, stress-strain curves from the tests were also plotted and analyzed. The confining pressure applied in each test is shown in the deviatoric stress–axial strain diagrams.

3. Research findings

Table 4 presents the findings related to moisture content, dry density, angle of internal friction (φ), cohesion (C), effective angle of internal friction (φ'), and effective cohesion (C'), obtained from the Consolidated Undrained Triaxial Tests (CU).

Table 4. Shear strength parameters from consolidated undrained triaxial tests.

Material Description	Shear Strength Parameters				Moisture Content (%)	Dry Density (g/cm³)
	φ (°)	C (kg/cm²)	φ' (°)	C' (kg/cm²)		
Stone Column	30.10	0.04	31.3	0.04	10.0	1.70
Stone Column + Geotextile Encasement	35.60	0.08	36.9	0.07	–	–
Stone Column + Geotextile Encasement + 20% Tire crumbs	34.50	0.13	35.6	0.12	8.8	1.68
Stone Column + 20% Tire crumbs	23.20	0.37	24.8	0.39	–	–

It should be noted that Mohr–Coulomb failure envelopes from the CU triaxial tests and deviatoric stress–strain results (effective and total stress) for the samples are shown in Figs. 5 to 8. Based on these results, increasing the confining pressure leads to higher deviatoric stress and strain.

Fig. 9 presents a comparison of the internal friction angles obtained from the triaxial tests. The results show that the highest values of internal friction angle (φ) and effective internal friction angle (φ') were achieved in stone column samples reinforced with enclosing geotextile, as well as those reinforced with a combination of geotextile and crumb rubber.

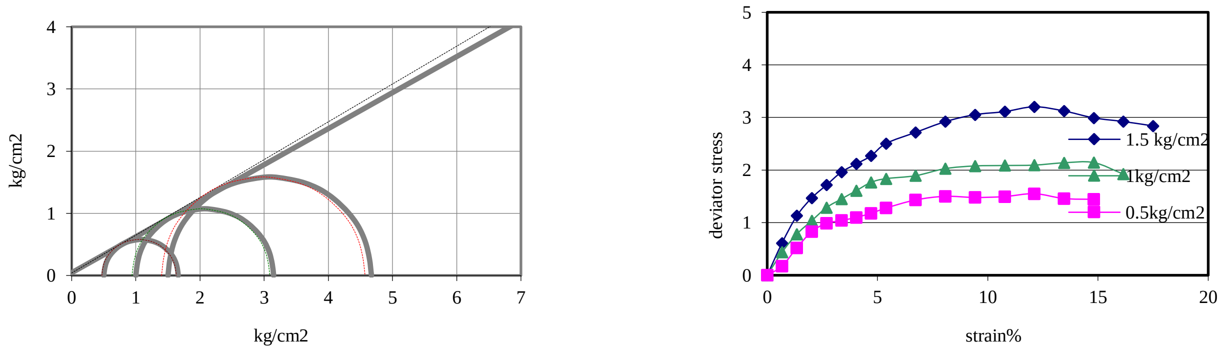

Fig. 5. CU triaxial test results for stone column materials.

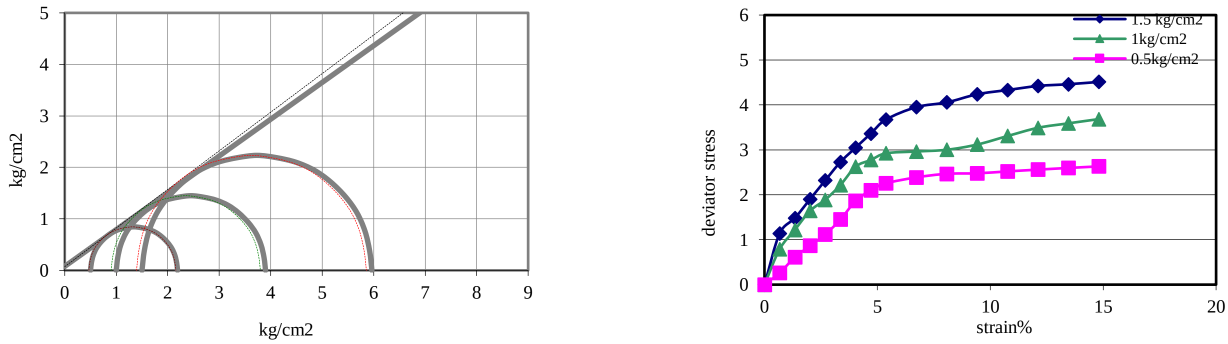

Fig. 6. CU triaxial test results for stone column + geotextile encasement.

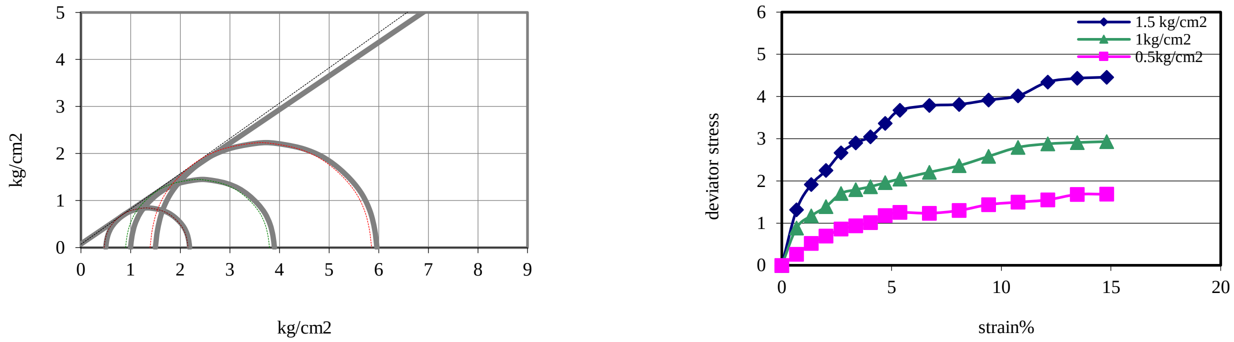

Fig. 7. CU triaxial test results for stone column + 20% tire crumbs.

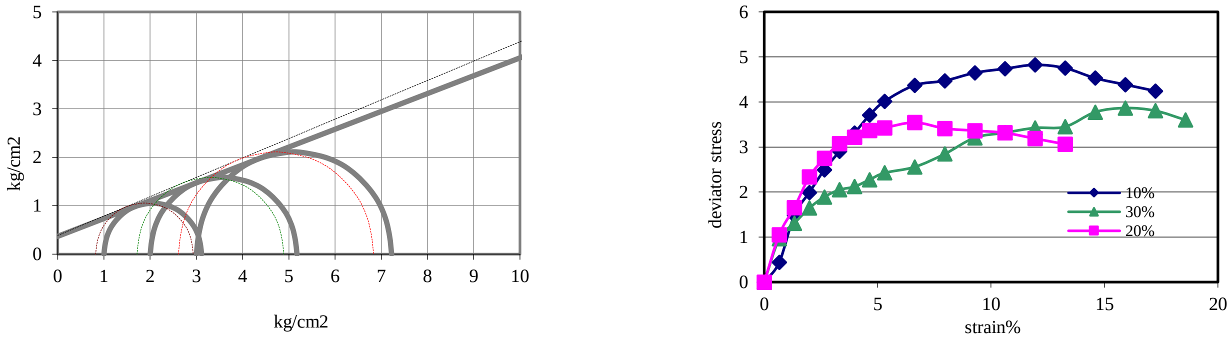

Fig. 8. CU triaxial test results for stone column + geotextile encasement + 20% tire crumbs.

Among the tested configurations, the use of geotextile encasement demonstrated the most significant improvement in friction angle, indicating enhanced lateral confinement. However, it is important to note that rubber shreds alone had a limited effect on the friction angle, with values slightly lower than those of the unreinforced stone columns.

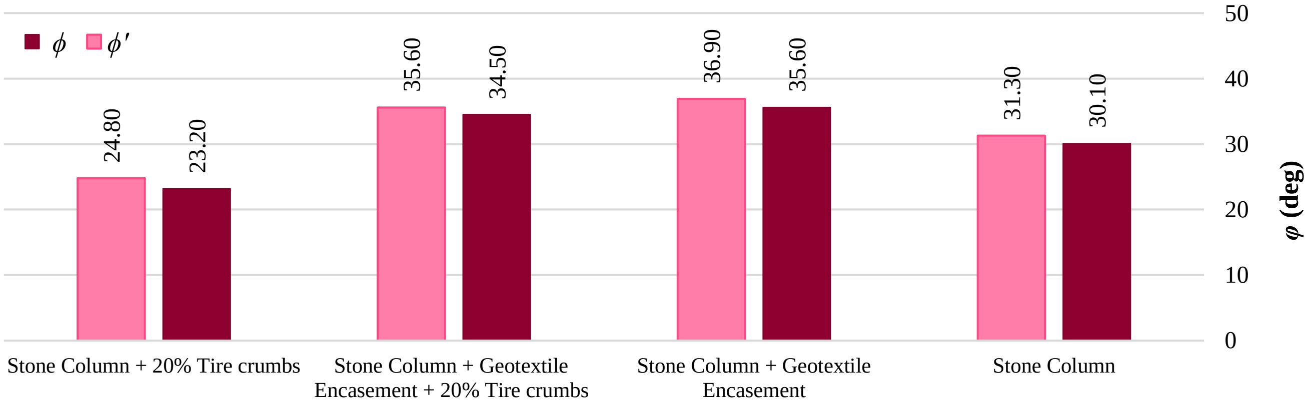

Fig. 9. Comparison of internal friction angle (φ) and effective internal friction angle (φ') in reinforced and unreinforced samples.

The comparison of cohesion values obtained from triaxial tests indicates that the minimum cohesion (C) and effective cohesion (C') values belong to the stone column samples, followed by the stone column samples with geotextile encasement, and then the stone column samples with both geotextile encasement and tire crumbs (Fig. 10). According to this figure, the highest cohesion (C) and effective cohesion (C') values are related to the natural subgrade soil, followed by stone column samples with various percentages of tire crumbs. This finding suggests that geotextile encasement does not significantly increase the cohesion of the samples. Overall, considering these findings, it can be concluded that tire crumbs have no considerable effect on the shear strength parameters of the samples.

Fig. 11 compares the secant and tangent elastic modulus values among the tested samples. Accordingly, the highest elastic modulus is observed in the stone column with 20% tire crumbs, followed by the samples with 10% tire crumbs, geotextile encasement, and 30% tire crumbs, respectively.

Therefore, it can be concluded that tire crumbs have a significant effect on the elastic modulus values, with the most pronounced improvement observed in the sample containing 20% tire crumbs. However, as the results also show, the elastic modulus in samples containing 30% tire crumbs decreased. This reduction may be attributed to a lack of grain interlock and bonding within the sample.

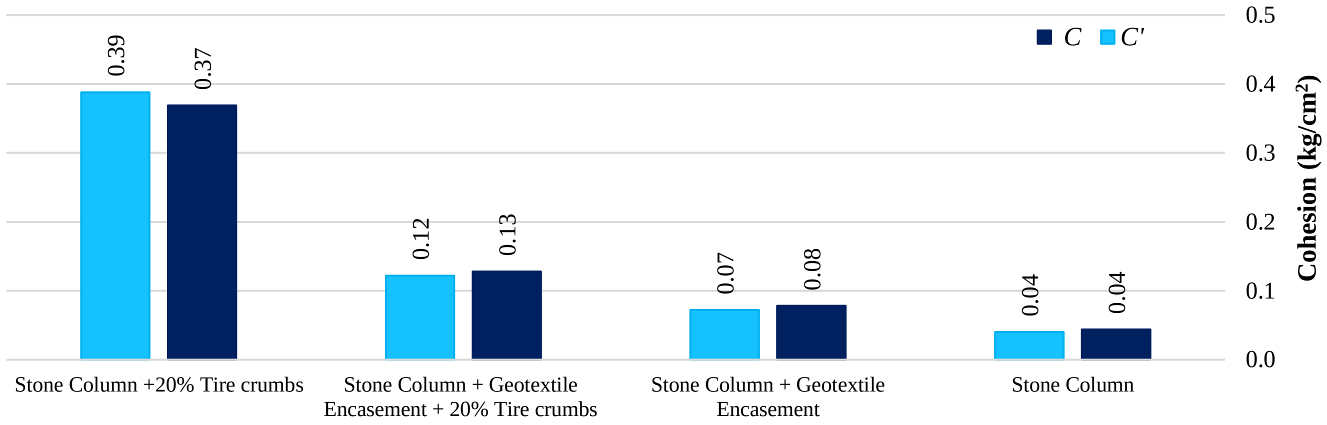

Fig. 10. Comparison of cohesion (*C*) and Effective cohesion (*C′*) in Triaxial test samples.

In contrast, the samples with 20% tire crumbs exhibit proper particle bonding while also providing the necessary elasticity through the tire crumbs. The lower internal friction angle values observed in stone column samples with varying percentages of tire crumbs may also be related to this issue.

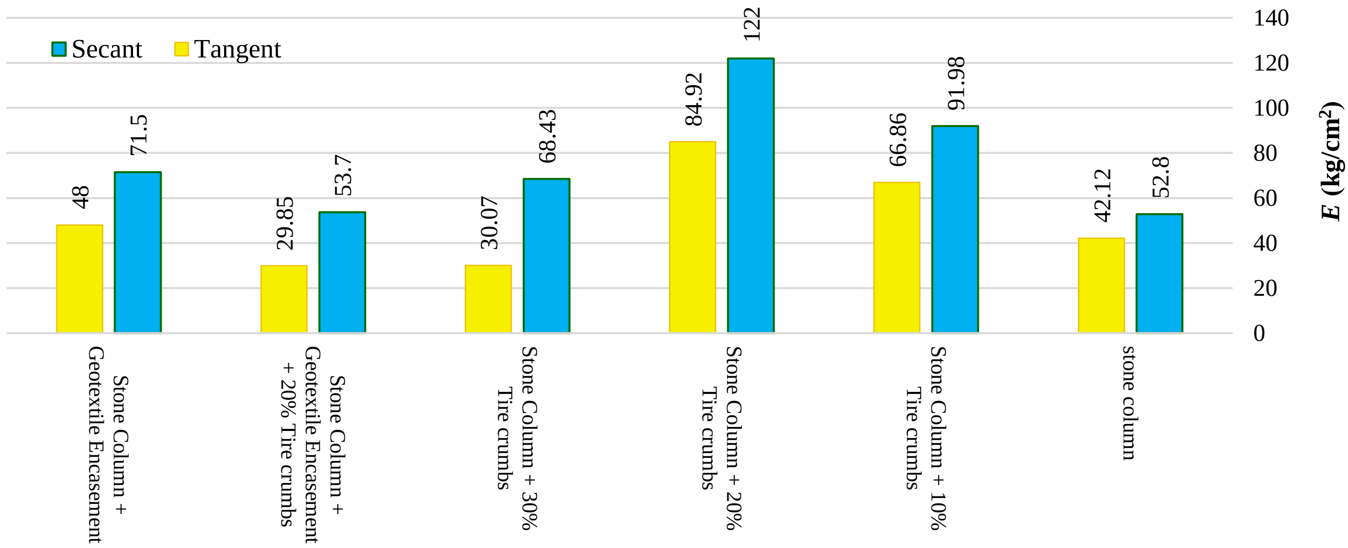

Fig. 11. Comparison of secant and tangent elastic modulus in the tested samples.

4. Conclusion

This study evaluated the mechanical behavior of stone columns reinforced with geotextile encasement, tire crumbs (rubber shreds), and their combination, and their effects on the shear strength parameters and stiffness characteristics under consolidated undrained triaxial loading conditions. The incorporation of tire crumbs in geotechnical systems not only diverts significant volumes of waste from landfills but also mitigates the environmental hazards associated with stockpiling discarded tires, such as fire risks and leachate generation, while promoting circular economy practices." The main findings are summarized as follows:

- Among the tested configurations, the combination of geotextile encasement and tire crumbs yielded the highest values of internal friction angle (φ) and effective internal friction angle (φ'), indicating improved confinement and interlocking behavior under shear loading. However, tire crumbs alone did not significantly enhance frictional resistance, as plain stone columns still showed slightly higher friction angles compared to those reinforced with varying percentages of rubber.
- In contrast, cohesion and effective cohesion values (C and C') were highly positively influenced by the inclusion of tire crumbs. Stone columns incorporating tire crumbs exhibited the highest cohesion values, suggesting improved bonding and energy absorption within the composite material. This highlights the ability of tire crumbs to contribute to resistance against shear failure, particularly through their elastic and deformable nature.
- Notably, the elastic modulus was most significantly enhanced in the sample reinforced with 20% tire crumbs, followed by the sample with 10%. This indicates that rubber inclusion substantially improves the stiffness of the column system, particularly at an optimal content level. The results also suggest that the shear mechanism is influenced by the amount of rubber added; higher rubber content increases horizontal strain at failure, likely due to the flexibility and energy dissipation characteristics of the rubber particles.
- The results suggest that the inclusion of 20% tire crumbs led to the highest improvement in elastic modulus up to 60%

compared to unreinforced stone columns. However, its effect on shear strength parameters, especially the friction angle, is limited. Geotextile encasement is more effective in increasing the friction angle than in improving cohesion or stiffness. Therefore, a combined approach of geotextile encasement with optimal tire crumbs content offers a balanced improvement in both strength and deformability properties, which can be beneficial for soft ground improvement applications.

- A comparative assessment indicates that while geotextile encasement provides the highest improvement in shear strength, it involves significantly higher material and installation costs. In contrast, tire crumbs often freely available as waste, offer a cost-effective alternative. The hybrid system (20% tire crumbs + geotextile) tested in this study achieved a balanced performance, approaching the peak values of each reinforcement type alone. This suggests that combined use can optimize both cost and mechanical performance, making it a practical solution for large-scale applications with budget constraints.
- Overall, tire crumb inclusion in stone columns represents a promising dual-benefit solution—enhancing mechanical properties such as cohesion and stiffness while contributing to waste reduction and resource recycling (simultaneously addressing environmental concerns associated with tire waste). By repurposing waste tires as a geotechnical reinforcement material, this study supports a sustainable and eco-friendly approach to ground improvement. The reuse of tire crumbs not only reduces dependence on synthetic materials but also helps mitigate the environmental footprint of infrastructure projects.

Statements & Declarations

Author contributions

Morteza Pordel: Conceptualization, Investigation, Methodology, Formal analysis, Writing - Original Draft, Writing - Review & Editing.

Saeed Kouzegaran: Conceptualization, Methodology, Formal analysis, Project administration, Supervision, Writing - Review & Editing.

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Data availability

The data presented in this study will be available on interested request from the corresponding author.

Declarations

The authors declare no conflict of interes.

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