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THE IMPACT OF ADDITION OF DIFFERENT SHAPES OF TIRE WASTE ON SOIL PROPERTIES

Purpose. To support and contribute to ecological and sustainable solutions, this paper aims to experimentally validate previous studies that proposed alternatives for improving soil characteristics using harmful waste.

Methodology. This study investigates the incorporation of different percentages (2 %, 4 %, 6 %, and 8 %) of ground tire waste (GTW), powdered tire waste (PTW), and fibrous tire waste (FTW) into sandy soils (SS) to evaluate their effects on mechanical properties and particle density.

Findings. The results indicate that the addition of tire waste consistently reduces both the density of soil solids and the maximum dry density due to the lower density of the tire materials compared to sand. The most pronounced reduction is observed with fibrous tire waste (FTW), resulting in a particle density of 2.19 t/m^3 for the soil and a maximum dry density of 1.57 t/m^3 at an 8 % incorporation rate, making these mixtures suitable for lightweight embankments. In terms of mechanical performance, GTW maintains high California Bearing Ratio (CBR) values, while PTW leads to a significant decline. Conversely, FTW enhances unconfined compressive strength (UCS) to 82 kPa, compared to 68.5 kPa for pure sand.

Originality. The results of this study show the potential of tire waste in improving the mechanical properties and density of sandy soils, highlighting the importance of using waste in the field of geotechnics.

Practical value. The findings reveal the potential of applying tire waste as an eco-friendly, sustainable, and cost-effective solution for infrastructure development.

Keywords: *soil, waste tire, powdered tire, ground tire, fibrous tire, geotechnical tests*

Introduction. Researchers have consistently worked on addressing challenging soil conditions, demonstrating a keen interest in enhancing soil properties. Their focus is on the effective utilization of existing waste materials by incorporating them into problematic soils to create improved and sustainable soil mixtures. Innovative methods of the use of waste materials such as fly ash, construction waste, and used tires help address geotechnical, environmental, and economic challenges. This not only optimizes soil performance but also promotes sustainable and environmentally beneficial solutions.

According to the 2019 data from the ETRMA, more than 4 million tons of used tires were produced in the EU28+4, and approximately 3.5 million tons of this total were considered End-of-Life Tires (ELT) which were collected and treated for material recycling and energy recovery. Approximately 3 % were used in civil engineering applications, 52 % were recycled, and 40 % were used for co-incineration. The remaining 5 % either went to stock or had unknown uses [1]. Used pneumatic tires typically contain synthetic and natural rubber, carbon black, elastomer compounds, steel cords, and textile fibers by weight, along with several other inorganic and organic compounds [2, 3].

The usual ways to manage or get rid of this dangerous waste, like putting it in a landfill, piling it up, or burning it, are known to greatly harm the environment, ecosystems, and people's health. The case of the fire erupted in one of Kuwait's largest tire landfills in the Salmi region, which currently holds over 40 million tires. In conformity with the analysis by Pure Energy Circle in 2021 [4], it is reported that annually, one billion waste tires are discarded, and this number is anticipated to rise to 1.2 billion by 2030. In January 2024, the summary report from CalRecycle [5] on the used tire market in California estimated a total increase in the quantity of managed tires in 2022 compared to 2021, rising from 0.55 million tons to 0.6 million. As stated by Yadav and Tiwari, the United States, the European Union, Japan, and India contribute to almost 88 % of the world's ELT production [6].

Literature review. Tire waste has become widely used in various geotechnical applications in many forms, including whole tires, shredded tires, tire chips, granulated tires, and tire powder. The use of tire waste to treat sandy soils can improve certain properties while mitigating others. An empirical investigation by Amin et al. (2023) suggests substituting traditional fill with a mixture of sand and 10 to 40 % by weight of tire waste, obtained from ground rubber with dimensions not exceeding 5 mm. The best performance in terms of shear strength was achieved with 30 % tire chips. However, direct shear tests show lower values of cohesion and friction compared to triaxial tests, which provide more reliable results by incorporating additional parameters such as saturation, pore water pressure, deformation, and volumetric change [7]. This trend aligns with the findings of Tiwari, et al. (2017), who found that adding 25 % crumb rubber to dune sand increases the friction angle, making it suitable as a lightweight backfill for retaining walls [8]. Similarly, Al-Rkaby (2019) observed that adding 10 and 20 % granulated tire rubber to sand increases shear strength but reduces the stress ratio. While the major principal strain rises with rubber content, lateral strains decrease significantly [9]. In contrast, the findings of researchers Madhusudhan, et al. (2019) and Cabalar (2011) indicate that adding sand and rubber particles slightly reduces both the internal friction angle and shear strength [10, 11].

To examine the behavior of sand–tire chip (STCh) mixtures through triaxial testing, the study by Mashiri, et al. (2015) reveals that the percentage of tire chips (TCh) significantly influences their behavior. The optimal mixture, comprising 65 % sand and 35 % tire chips, is identified. Additionally, the study investigates the effects of confining pressure and relative density on STCh, concluding that shear strength increases with higher confining pressure and relative density [12]. The experimental studies by Rao and Dutta (2006), as well as Marto, et al. (2013) and Bali Reddy, et al. (2016), based on triaxial and direct shear tests, indicate that adding tire chips up to a certain proportion significantly reduces the void ratio and enhances the soil's shear characteristics. They suggest that this improvement shows potential for highway and embankment construction [13–15]. Additionally, Bali Reddy, et al. (2016) confirm the effectiveness of tire chips in decreasing specific gravity, dry density values, and moisture content [15]. Furthermore, the addition of 8 % tire chips increases the soaking CBR value up to 1.6 times that of sand alone [16]. Balunaini, et al. (2014) confirmed previous research and added that shred-sand mixtures have superior shear strength compared to chip-sand mixtures, using large-scale direct shear testing [17]. Increased rubber content reduced density and CBR [18, 19], thereby increasing permeability and compressibility, and did not change the angle of friction [19]. The study by Tiwari, et al. (2012) in California reveals that adding shredded rubber tires to different types of sand, following the modified Proctor procedure reduces the water content required for compaction while maintaining a satisfactory maximum dry density [20].

Purpose and tasks. The results of a variety of experimental tests enrich the database of such research and strengthen existing recognition by validating or refuting previous conclusions. Studies on the integration of tire waste into soils have highlighted various advantages and challenges. These investigations have shown that the behavior of soil-waste mixtures is influenced by soil types, the forms of waste used, and the experimental parameters employed. The strategy of incorporating recycled tires in geotechnical applications adds economic and environmental value, as it reduces material costs while preserving resources. The insights gained from these studies provide useful recommendations on potential applications and suggest optimal usage rates.

In this context, the current study aims to enhance and deepen this knowledge by focusing specifically on sandy soil. It will analyze the soil's properties when mixed with various forms of tire rubber waste, incorporating 2, 4, 6, and 8 % by weight of rubber. The experimental program will include measurements of specific gravity (G_s), Proctor compaction, California Bearing Ratio (CBR), unconfined compressive strength (UCS), and direct shear tests. This comprehensive approach will help validate, unify, and enrich the findings of previous research while offering practical insights into the behavior of soil-waste mixtures.

Materials. ***Materials Properties.*** The research aims to determine the impact of used tire waste (powdered, ground, and fibrous) on the geotechnical properties of sandy soil. Natural Algerian soil and tire waste from the Algerian market were used to validate the findings for real projects. Based on the technical specifications, the tire waste and soil used in the study have the following characteristics:

1. Sand: The sandy soil used for this study is collected from the Filfila mountains located in the Skikda region in Algeria. It underwent several laboratory identification tests following standard procedures. Table 1 illustrates the results of these tests according to the Unified Soil Classification System (USCS), It is classified as Poorly graded sand (SP). The particle size distribution for the soil is given in Fig. 1.

2. Tire Waste: To assess the impact of the size of the incorporated rubber on the geotechnical properties of sandy soils, three distinct sizes of tire waste were obtained from the market for this study. The tire waste used, produced by shredding and then grinding scrap tires until obtaining small granulated and powdered sizes, had most of the steel extracted using magnetic separation. According to ASTM D6270-20 and as specified by Tasalloti, et al. (2021) [21] and Gill, et al. (2020) [22], the granulated tire sizes employed in this study are ground GTW and powdered PTW. Tire waste in the form of fibers FTW ranging from 1 mm to around 15 mm in length is obtained through a process called "rasping" or "buffing" using a machine that removes the old tread layer from worn tires in preparation for retreading. Refer to Figs. 1 and 2 to gain further clarity on the differences. A chemical and mechanical analysis was performed on the tire waste, with the results presented in Table 2.

Table 1

Properties of the used soil

Properties	Values	Standards
Sand Equivalent SE, %	80	ASTM D2419-22
Coefficient of Curvature C_c	0.90	ASTM D 2487-17e1
Coefficient of Uniformity C_u	1.63	
Methylene Blue Value MBV	0.33	ASTM C1777-20
SO_4^{2-}	1.22	
Gypse $CaCO_3$	2.17	

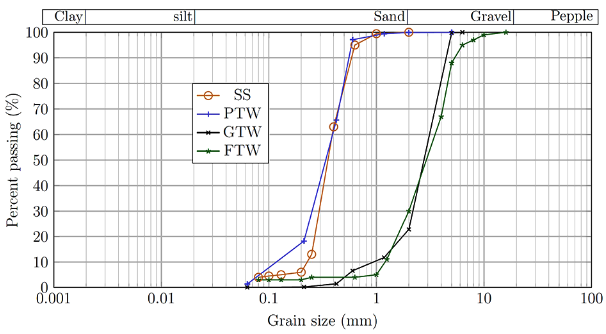

Fig. 1. Grain – size distributions of the investigated materials

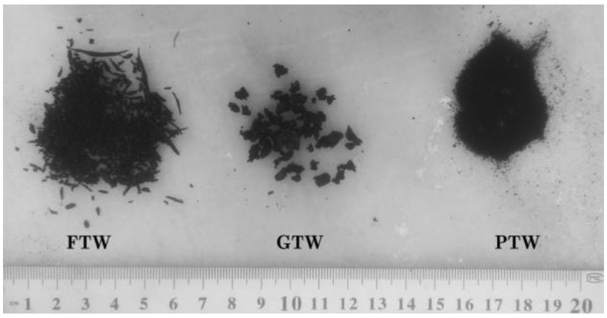

Fig. 2. The three shapes of employed tire waste

Table 2

Chemical and mechanical analysis of a sample of tire waste

Chemical Composition	Values
Polymerized Hydrocarbons, %	49.2
Synthetic Rubber, %	28.3
Carbon Black, %	19.6
Steel, %	0.06
Abric, %	1.4
Zinc Oxide, %	1.8
Sulfur, mg/kg	47
Cadmium, mg/kg	11
Chromium, mg/kg	92
Nickel, mg/kg	82
Lead, mg/kg	48
Mechanical Composition	Values
Tensile Strength, Mpa	11.8
Breaking strength, Kg/mm^2	3.1
Elasticity, %	42
Density, kg/m^3	3.43
Radiation Resistance	Excellent
Water Permeability	0
Methane Permeability	0.00251
Internal friction angle (ϕ)	26.3

Methods. Specimens of sandy soil mixed with waste tires were subjected to several tests. The process began with characterizing the specific gravity (G_s) of the mixtures, followed by Proctor compaction tests and mechanical tests, including the CBR test, direct shear test, and triaxial (UU) test with σ_3 equal to zero, which is equivalent to the UCS test. These tests were conducted by incorporating the different shapes of waste tire into sandy soil at specific weight proportions, which were 2, 4, 6 and 8 %, to evaluate their effect on soil properties. The protocol used in all tests followed the specific American standards (ASTM: American Society for Testing and Materials) applicable to each test.

Identification of the specific gravity (G_s) of the sandy soil-waste tire mixtures. Following the procedure described by ASTM D854-23, the specific gravity of the sandy soil and the mixtures with added tire wastes was determined.

Proctor testing of sandy soil-tire waste mixtures. The compaction tests, conducted according to ASTM D698-12 standards, aimed to establish the dry density moisture content (DD-MC) relationships of SS-TW mixtures. To ensure uniform distribution, reconstituted mixture samples were prepared by hand-mixing dry sand with three different shapes of tire waste, each with varying water content. The samples were then compacted into three equal layers in the Proctor mold, following Method A of the same standard.

California bearing ratio (CBR) test on compacted soil samples. The samples were prepared as stipulated by Method C of ASTM D698-12, with the optimum water content predefined previously, and then subjected to the CBR test as specified in ASTM D1883.

Testing of soil samples for UCS tests. In this study, the unconfined compressive strength (UCS) was determined by conducting an unconsolidated undrained triaxial test under confining stress of $\sigma_3 = 0$ and a strain rate of 0.36 %/min, which is equivalent to the dimension of our specimen at 0.5 mm/min, following ASTM D2850-15. The samples were created by combining various percentages of tire waste with sandy soil and water, which were then tamped to fill molds measuring 70 mm in diameter and 140 mm in height to achieve maximum density for each SS-TW mixture, as established by the Proctor test. The UCS value refers to the peak stress difference (deviator stress) on the σ-ε curve, with the axial strain at which this maximum stress is reached referred to as the strain at failure (ε_f, %).

Testing of Soil Samples for Direct Shear Tests. The reconstituted sandy soil samples were prepared using the same mold and method as in the Proctor test, with the optimal water content precalculated to achieve the maximum dry density for each mixture. Using a specific tool, the specimens were accurately cut to fit the Casagrande apparatus for direct shear testing, conducted according to ASTM D3080 standards under Consolidated Drained (CD) conditions at stresses of 0.5, 1, and 1.5 bars.

Results and discussion.

1. Effect of adding tire waste on the specific gravity of solids G_s in the mixture. As illustrated in Fig. 3, the specific gravity of pure sand (G_s) is 2.57. The incorporation of tire waste (all types combined) leads to a progressive decrease in the solid particle density, and this decrease is proportional to the increase in the percentage of waste added (2, 4, 6, 8 %). GTW decreases the particle density slowly but remains relatively higher than the other types. FTW shows a more pronounced decrease in particle density, while PTW causes the greatest reduction in density, reaching 2.19 (t/m^3) at 8 % content. Tire waste is generally less dense than the mineral particles of sand, so its incorporation lowers the overall density of the solid particles.

The powdered form (PTW) occupies more volume for a given weight, which explains the greater decrease in density compared to GTW and FTW. Their addition also lightens the soil-tire mixture, which can be advantageous for applications requiring lightweight materials (e.g., lightweight embankments). However, this reduction in density may affect the compactness and mechan-

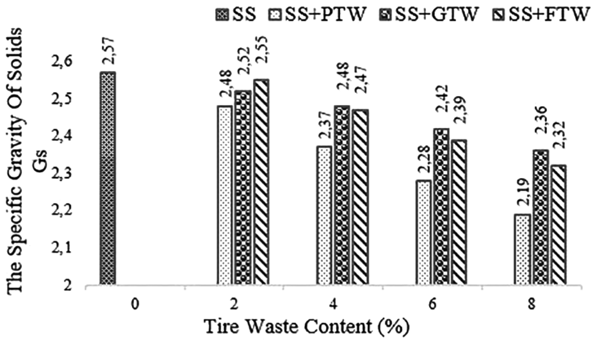

Fig. 3. Effect of adding tire waste on G_s in the mixture

ical stability, necessitating an optimization of the proportions based on geotechnical requirements.

Similarly, Salaheldin, et al. [23], Al-Neami [16], Anvari, et al. [24], Bali Reddy, et al. [15]. reported similar findings regarding the reduction in the specific gravity of solids, regardless the dimensions or shape of the waste tire particles, these findings align with the results of this research.

2. Effect of adding tire waste on proctor parameters OMC and MDD of the mixture. *Optimum Moisture Content*. The graph in Fig. 4 demonstrates the effect of adding tire waste on the optimal moisture content (W_{opt}) for a sandy soil mixture with different types of tire waste (GTW, PTW, FTW). The optimal moisture content for pure sand is 11.29 %, representing the amount of water required to achieve maximum density during compaction. The incorporation of tire waste results in a gradual decrease in W_{opt} as the percentage of waste increases (2, 4, 6, 8 %). For FTW, the decrease in W_{opt} is moderate, reaching 10.16 % at 8 % content. For GTW, the optimal moisture content follows a similar trend but is slightly lower than FTW, reaching 10.08 % at 8 %. PTW shows a slower decrease in W_{opt}, stabilizing at 10.42 % for 8 % content.

Powders retain more water, explaining this difference. Tire waste has a different water absorption capacity compared to the mineral particles of sand. Their low density and porous or fibrous structure reduce the overall water demand for optimal compaction. Coarser particles, like GTW, create larger voids and thus require less water than PTW or FTW.

Compared to the findings of Al-Neami (2018) [16] and Abdullah, et al. (2023) [18], this study confirms the impact of waste tire incorporation on reducing optimal moisture content.

In geotechnical projects, the baseline value of the maximum water content required for compaction minimizes the risks of shrinkage, swelling, and freeze-thaw of soils, thereby ensuring the stability and durability of infrastructures. This advantage is provided by the addition of tire waste, which is beneficial technically, economically, and environmentally.

Maximum Dry Density. The incorporation of tire waste leads to a gradual decrease in the maximum dry density (γ_d) as the percentage of waste increases (from 2 to 8 %). This is explained by the lower density of tire waste compared to sand particles. With GTW, the density decreases slightly, reaching 1.58 t/m^3 at 8 %. With PTW and FTW, the density follows a similar trend but remains generally lower than that observed with GTW, achieving 1.57 t/m^3 at an 8 % content, as fibers and powders create more voids in the mixture. These results are depicted in Fig. 5.

The reduction in density is due to the lower density of tire materials compared to sand. The fibers and finer particles from the tires increase the overall porosity of the mixture, which reduces the maximum achievable compaction achievable. These results are in line with those of Salaheldin, et al. [23], Aksoy, et al. [25], Al-Neami [16], Abdullah, et al. [18], Bali Reddy, et al. [15], who observed similar trends in their research on the effects of incorporating various shapes of tire waste on the maximum dry density (MDD) of sand.

The incorporation of tire waste is ideal for applications requiring lighter materials, such as embankments or areas where low density is beneficial. However, excessive reduction in dry density could affect the stability and mechanical strength of the compacted soil.

3. Effect of adding tire waste on California Bearing Ratio (CBR) of the mixture. This graph in Fig. 6 depicts the effect of adding tire waste on the California Bearing Ratio (CBR) of sand mixtures with different types of tire waste. Without any tire waste, the CBR index is 16.6.

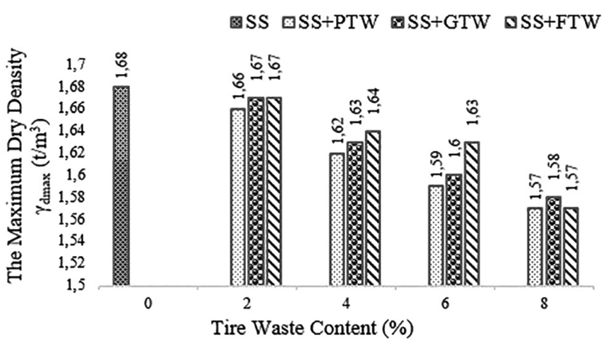

Fig. 5. Effect of adding tire waste on MDD in the mixture

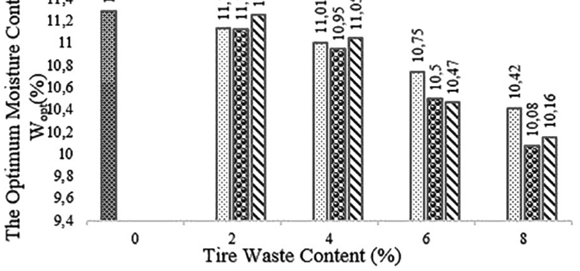

Fig. 4. Effect of adding tire waste on OMC in the mixture

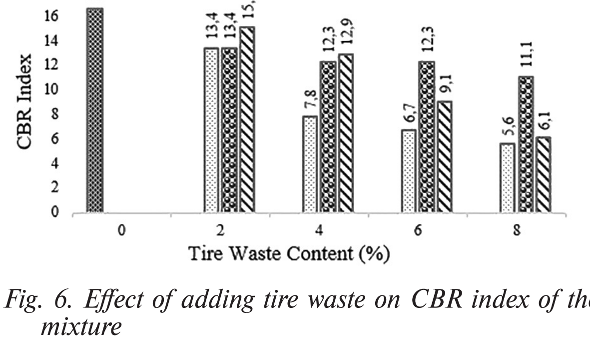

Fig. 6. Effect of adding tire waste on CBR index of the mixture

GTW maintains higher CBR values compared to other types of tire waste. PTW causes a significant drop in the CBR index as the percentage increases. FTW yields intermediate results but tends to decrease the CBR index beyond 2 % of the added tire waste.

The addition of tire waste generally reduces the CBR index compared to pure sand (without tire waste), as highlighted in the conclusions of Abdullah, et al. (2023) [18], who recorded a similar reduction when incorporating rubber crumbs into sandy soils.

4. Effect of adding tire waste on the unconfined compressive strength (UCS) of the mixture. This graph in Fig. 7 describes the effect of adding tire waste on the Unconfined Compressive Strength (UCS) of sand mixtures with different types of tire waste. Without the addition, the UCS value of pure sand is 68.5 kPa. The addition of 8 % PTW significantly reduces the UCS value to 54.1 kPa, well below that of pure sand. In contrast, the addition of 8 % GTW increases the UCS value to 78.6 kPa, higher than that of pure sand. Similarly, the addition of 8 % FTW results in a notable improvement in UCS, reaching 82 kPa.

In summary, the addition of FTW and GTW enhances the strength of sand, while PTW decreases this strength compared to pure sand. It is interesting to note that the results found by Saberian, et al. (2018) [26]; Soltani, et al. (2022) [27] are consistent with those observed in this study, particularly with regard to the improvement in the UCS value (q_u).

5. Effect of adding tire waste on the unconfined compressive strength (UCS) of the mixture. *The cohesion.* Fig. 8 illustrates the effect of adding tire waste to sand mixtures and its impact on cohesion. Pure sand exhibits the highest cohesion at 36 kPa (with no tire waste added). The cohesion decreases steadily as the tire waste content increases (from 2 to 8 %). All mixtures demonstrate a reduction in cohesion compared to pure sand, with only slight variations among the three types of tire waste. The addition of tire waste significantly reduces cohesion, indicating that the mechanical strength of the mixture declines as the tire waste content increases.

The internal friction. This graph in Fig. 9 shows the impact of incorporating tire waste on the internal friction angle of mixtures containing sand and tire waste. Pure sand achieves an internal friction angle of 14°. With increasing tire waste content, the internal friction angle exhibits slight variations but tends to decrease overall. The most significant reduction occurs with FTW at higher percentages (6 and 8 %), where the internal friction angle drops to 12°. Conversely, mixtures containing sand and GTW or PTW demonstrate greater consistency, maintaining an internal friction angle close to 14° even at higher tire waste contents.

Neaz Sheikh, et al. (2013) [28] reported similar findings in their study of two types of tire waste (ground and granulated rubber) mixed with sand. Anvari, et al. (2017) [24] demonstrated that the internal friction angle of sand decreases as the content of granulated rubber increases, particularly at high relative densities of the mixture. Additionally, Abdullah, et al. (2023) [18]; Madhusudhan, et al. (2019) [10] noted a slight decrease in the internal friction angle when adding rubber crumbs to sand. Similarly, Salaheldin, et al. (2024) [23]; Cabalar (2011) [11] and Asadi, et al. (2018) [29] observed this behavior in their studies on granular rubber, while Aksoy, et al. (2021) [25] indicated a comparable decrease in strength in the case of rubber chips, compared to pure sand. These results are also consistent with those obtained from a drained triaxial test on three types of rubber (powder, granular, and ground) added to sand, which showed a decrease at 10 % rubber content, conducted by Li, et al. (2020) [30].

Conclusions. This article's experimental findings demonstrate how adding tire waste (GTW, PTW, and FTW) affects the mechanical and physical characteristics of sand. The following are the primary observations:

1. Pure sand has a Specific Gravity of Solids G_s = 2.57. Depending on the proportion of tire waste added, the addition of tire waste gradually lowers its density, whereas FTW and PTW produce more noticeable declines, GTW produces a gradual one. The maximum dry density (γ_{dmax}) of the sand-tire waste combination will gradually decline as a result of this drop in G_s.

Because of its low density and larger occupied volume, PTW in particular dramatically reduces the specific gravity (G_s) to 2.19 and Maximum Dry Density (γ_{dmax}) to 1.57 t/m^3 at 8 % content. Although it may have an impact on compaction and mechanical stability, this

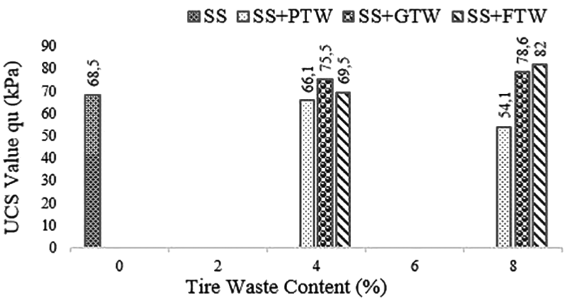

Fig. 7. Effect of adding tire waste on UCS value (q_u)

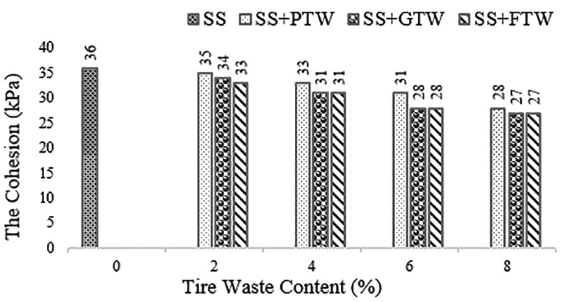

Fig. 8. Effect of adding tire waste on the cohesion (C) of the mixture

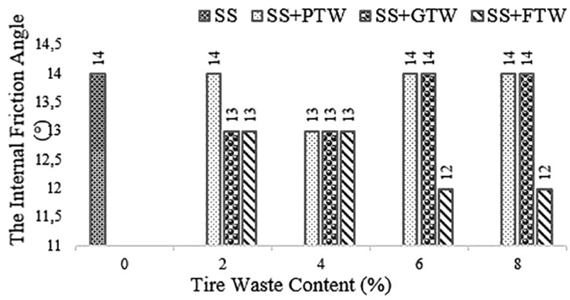

Fig. 9. Effect of adding tire waste on the internal friction of the mixture

decrease makes the mixes lighter, which might be useful for some applications like lightweight embankments.

2. The optimal water content (W_{opt}) also decreases with the addition of tire waste. FTW and GTW show moderate reductions, while PTW exhibits a slower decrease. This reflects a modification in the absorption and compaction behavior of the sand-tire waste mixture.

3. The CBR is affected differently by the addition of tire waste. While PTW causes a notable decline in CBR values, GTW maintains higher levels. FTW are in the middle, but they are less effective than 2 % more content.

4. When GTW and FTW are added, the UCS increases in comparison to pure sand, reaching its highest values at 8 % content. On the other hand, PTW dramatically lowers this resistance, indicating a less desirable performance.

5. The addition of tire waste gradually reduces the cohesion of the mixture. Pure sand is the most cohesive, regardless of size or shape, and its value decreases as waste levels increase.

6. Even at high concentrations, mixtures including GTW and PTW retain an internal friction angle that is comparable to that of pure sand. At high percentages, on the other hand, FTW significantly reduces this angle, suggesting that the interactions between the particles are becoming weaker.

These findings present a novel and sustainable approach to tire waste utilization in the geotechnical construction industry. They enable the valorization of these materials, providing solutions that cater to the requirements of infrastructure projects. Achieving the ideal balance between weight reduction, mechanical strength, and environmental durability may be accomplished by choosing the right shape of tire waste and optimizing proportions.

To better understand the unique impacts of each form of waste (GTW, PTW, and FTW) on the mixture's characteristics, we decided to carry out more testing and optimize the current proportions before thinking about adding other materials. The findings demonstrate that by reusing current waste and without needlessly expanding the range of material types evaluated, dose modifications alone can occasionally enhance performance and advance a sustainable strategy.

The present work provides a strong baseline for future investigations towards hybrid mixtures, as well as employing binders, which could lead to improved mechanical behavior of sand-tire waste mixtures. This strict scientific approach allows us to reach practical conclusions and develop new geotechnical solutions that are ecological, sustainable, and economically attractive. Thus, even if some technical problems are still open, the application of used tires as a soil stabilization material has bright opportunities for the civil engineering field. This study provides the foundation for future research that will actively support responsible waste management while addressing contemporary geotechnical challenges. These methods, which turn trash into a resource, present a chance to create infrastructure that is more economical, sustainable, and ecologically friendly. They are also crucial in the shift to more ecologically conscious and conscientious building practices.

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Вплив додавання різних форм відходів шин на властивості ґрунту

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Мета. Щоб підтримати й зробити внесок у екологічні та стійкі рішення, ця робота має на меті експериментально перевірити попередні дослідження, що пропонували альтернативи покращення характеристик ґрунту з використанням шкідливих відходів.

Методика. У цьому дослідженні вивчається включення різних відсотків (2, 4, 6 та 8 %) подрібнених відходів із перероблених шин (GTW), порошкоподібних відходів шин (PTW) і волокнистих відходів шин (FTW) у піщані ґрунти (SS) для оцінки їхнього впливу на механічні властивості та щільність частинок.

Результати. Результати показують, що додавання відходів із перероблених шин послідовно знижує як щільність твердих частинок ґрунту, так і максимальну суху щільність через нижчу щільність матеріалів шин у порівнянні з піском. Найбільш виражене зниження спостерігається при додаванні волокнистих відходів шин (FTW), у результаті чого щільність частинок для ґрунту становить 2,19 т/м^3, а максимальна суха щільність – 1,57 т/м^3 при нормі закладення 8 %, що робить ці суміші придатними для легких насипів. Із точки зору механічних характеристик, GTW підтримує високі значення California Bearing Ratio (CBR), у той час як PTW призводить до значного зниження. І навпаки, FTW підвищує міцність на стиск без обмежень (UCS) до 82 кПа у порівнянні із 68,5 кПа чистого піску.

Наукова новизна. Результати цього дослідження показують потенціал відходів шин для покращення механічних властивостей і щільності піщаних ґрунтів, підкреслюючи важливість використання відходів у галузі геотехніки.

Практична значимість. Результати дослідження розкривають потенціал використання відходів шин як екологічно чистого, сталого й економічно ефективного рішення для розвитку інфраструктури.

Ключові слова: *ґрунт, перероблені шини, порошкоподібні відходи, подрібнені відходи, волокнисті відходи, геотехнічні випробування*

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