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REVIEW PAPER

A state-of-the-art review on geotechnical reinforcement with end-life tires

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ABSTRACT

This study provides a comprehensive exploration of the utilization of scrap tires in geotechnical engineering, focusing on their applications, mechanical behavior, environmental impact, and potential challenges. The utilization of waste tires in engineering applications is of paramount importance, offering a sustainable solution to the escalating challenge of waste tire management. The accumulation of discarded tires poses significant environmental and economic concerns globally, with traditional disposal methods often leading to environmental degradation, fire hazards, and increased land use. By harnessing the inherent properties of scrap tires, such as their durability and energy-absorbing characteristics, geotechnical engineering presents a promising path for repurposing these materials. This review examines how integrating scrap tires into geotechnical projects, such as retaining walls, slopes, and drainage systems, can offer sustainable alternatives while addressing environmental concerns. The paper extensively analyzes the mechanical behavior of sand-rubber mixtures through laboratory investigations. Factors including rubber proportions, aspect ratios, and interaction mechanisms are dissected to understand their influence on shear strength, deformation behavior, and modulus properties. These insights pave the way for optimizing the performance of sand-rubber mixtures in engineering applications. Additionally, the article delves into modeling approaches that simulate the intricate behavior of these mixtures, facilitating better design and analysis. The economic feasibility of incorporating scrap tires is investigated, emphasizing the cost-effectiveness achieved through reduced material costs and enhanced infrastructure durability. The environmental benefits of diverting rubber waste from landfills are discussed, highlighting the alignment with sustainability goals and regulations. Despite the advantages, engineering challenges associated with rubber particles' behavior are acknowledged, and potential solutions are explored. Through a comprehensive synthesis of research findings and practical implications, this review aims to provide a deep understanding of the potential of scrap tires in geotechnical engineering. It concludes by advocating for further research and innovation to harness the full potential of scrap tires, ultimately contributing to a more sustainable and resilient built environment.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
129	10	1

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INTRODUCTION

The accumulation of discarded tires is an escalating concern, due to the environmental hazards like long-term degradation, observed in both developing and developed nations because of the widespread use of vehicles (Daghistani *et al.,* 2023; Ru *et al.,* 2023; Wu *et al.,* 2023a). The conventional methods of disposing of these waste products, such as landfilling or stockpiling, have been proved to be environmentally harmful and economically burdensome (Ahmed, 1993; Safa *et al.,* 2020; Zehtab Yazdi *et al.,* 2022). Tire waste poses a significant challenge as they are non-biodegradable and can take centuries to decompose naturally. The utilization of scrap tires can substantially decrease landfill waste volume and prevent these tires from contaminating ecosystems (Mansouri *et al.,* 2016). To provide a sense of the scale of this issue, statistics from the RMA (2013) indicate that an estimated 3.8 million metric tons of discarded tires have been accumulated in the United States alone. The continuous growth of the stockpile of scrap tires is primarily attributed to the usage of tires in automobiles and trucks (Fareghian *et al.,* 2023; Zeybek; Eyin, 2023). Typically, the composition of these discarded tires includes elements such as carbon black, synthetic rubber, fillers, natural rubber, steel, fabric, and accelerators (Fareghian *et al.,* 2023) (Fig. 1). However, a discernible global trend in the field of civil engineering has emerged, wherein scrap tires are being increasingly utilized, either in their entirety or after undergoing processing, across various applications (Cui *et al.,* 2022; Nikitas and Bhattacharya, 2023; Arefnia *et al.,* 2013; Veena and James, 2023; Trung *et al.,* 2019). This paradigm shift towards the incorporation of discarded tires in civil engineering practices not only provides a viable solution for their sustainable management but also presents an opportunity to address environmental and economic concerns (Abbas-Abadi *et al.,* 2022; Tian and Senetakis, 2022; Valente *et al.,* 2023; Armaghani *et al.,* 2020). The objective of this review paper is to comprehensively examine the integration of scrap tires in geotechnical engineering. By conducting a thorough analysis of existing research studies and industry practices, the study aims to explore the wide range of applications where scrap tires have been used, identify the associated benefits, and address the challenges that may arise. Furthermore, this study will assess the environmental implications of implementing scrap tire applications in geotechnical projects. This study has been conducted in Iran in 2023.

Applications and practical implementations

The utilization of scrap tires, both in their intact form and subsequent processing, has found extensive applications in the realms of civil engineering (Fakhimi and Afrazi, 2023; Gabry, 2023; Zrar and Younis, 2022). In the industrial sector, scrap tires undergo pyrolysis, a thermal treatment process, to extract valuable resources such as carbon black, oil, and scrap steel from the organic constituents of tires (Roy *et al.,* 1990; Shariati *et al.,* 2019; Hosseini and Toghroli, 2021). Within civil engineering, a multitude of applications have emerged (Vratsikidis and Pitilakis, 2023; Wu *et al.,* 2023b; Khari *et al.,* 2019). Scrap tires have been employed as additives to enhance asphalt in road construction, act as effective sound barriers, serve as insulating layers beneath gravel-surfaced roads, function as lightweight aggregates in concrete, and exhibit exceptional performance in the creation of low-noise pavements (Edil and Bosscher, 1992; Eldin and Senouci, 1993; Meiarashi, 2004). In the scope of geotechnical engineering, both intact scrap tires and processed forms have garnered significant attention due to their practical implementation (Erfanianpour *et al.,* 2022; Tasalloti *et al.,* 2021; Zrar and Younis, 2022). These applications encompass a wide range of uses, including the reinforcement of retaining walls and slopes, stabilization of slopes with economic and technical benefits, rehabilitation of tropical soil slopes, improved drainage performance, and the mitigation of settlement and backfill pressure on retaining structures (Ahmed, 1993; Garga and O'Shaughnessy, 2000; Hazarika *et al.,* 2010; Huat *et al.,* 2008; Majedi *et al.,* 2020; Ghanizadeh *et al*., 2022; O'Shaughnessy and Garga, 2000; Poh and Broms, 1995; Tweedie *et al.,* 1998) . Processed scrap tires have exhibited effectiveness in various geotechnical applications. They have been successfully incorporated as subgrade materials to impede water capillary rise and enhance drainage systems. Furthermore, their utilization as lightweight backfills has proven advantageous in terms of settlement reduction, stability improvement, and enhanced drainage characteristics for retaining structures (Bernal *et al.,* 1996; Hazarika *et al.,* 2010; Zornberg *et al.,* 2004a; Riazi *et al.,* 2023). Additionally, the utilization of rubber particles derived from scrap

Fig. 1: Stockpiling scrap tires in the environment

tires as a drainage layer in embankment structures has demonstrated high permeability and non-clogging attributes (Hazarika *et al.,* 2010; Mohajerani *et al.,* 2020; Momeni *et al.,* 2023; Rezamand *et al.,* 2021). The reinforcement of embankments with processed scrap tires has been extensively investigated, revealing enhanced strength and reduced settlement compared to non-reinforced structures (Li *et al.,* 2016; Shah *et al.,* 2016b). Noteworthy studies have examined real-scale highway embankments utilizing sand-rubber mixtures, assessing settlement behavior, environmental impacts, and temperature variations (Abdolrahim, 2012). These investigations have showed the advantages of sand-rubber mixtures, including their lightweight nature, cost-effectiveness, ease of compaction, and efficient drainage (Majedi *et al.,* 2021; Yadav and Tiwari, 2019; Faizi *et al.,* 2017). Nevertheless, challenges arise when employing rubber particles alone in geotechnical structures, encompassing issues related to high deformation, compaction, and self-heating mechanisms. Addressing these concerns necessitates the removal of exposed steel components from intact scrap tires and the incorporation of soil particles to mitigate self-heating and reduce the deformation response (Youwai and Bergado, 2003). Importantly, extensive studies have indicated that rubber particles have negligible effects on groundwater quality within the specified ranges of civil engineering applications.

Size classification of processed scrap tires

The size classification of processed scrap tires holds significant importance within the realm of geotechnical engineering, particularly concerning its applications in construction projects (Shah *et al.,* 2016a). Geotechnical engineers frequently employ processed scrap tires as a sustainable and economically viable substitute for traditional materials. Accurate size classification of these tires is essential to ascertain their suitability for specific applications (Akbarimehr *et al.,* 2020; Tiwari *et al.,* 2012; Yang *et al.,* 2020; Shariat *et al.,* 2018). By systematically categorizing processed scrap tires into distinct size groups, engineers can effectively evaluate their physical characteristics, including particle size distribution, void ratio, and compaction behavior (Dabic-Miletic *et al.,* 2021; Li *et al.,* 2010; Tran *et al.,* 2022). This knowledge proves to be helpful in the design and optimization of geotechnical constructions, for instance embankments, retaining walls, and road pavements. Moreover, the size classification of processed scrap tires enables the appropriate selection of engineering techniques and the formulation of efficient waste management strategies, thereby advancing environmentally conscious practices within the field of geotechnical engineering. Well-established standards, such as ASTM D6270–08 (2012) and the ETRA (2013), provide guidelines for effectively classifying these rubber particles. These standards outline specific size ranges for the resulting rubber particles obtained through cutting methods, with magnetic separation being employed to remove any metallic strips or

Table 1: Size classification of processed scrap tires

ASTM D6270–08 (2012)		ETRA (2013)	
Name	Size	Name	Size
Powdered Rubber	< 425µm	Fine Powders	< 500µm
Ground Rubber	425µm-2mm	Powders	< 1 mm
Granulated Rubber	425µm-12mm	Granulate Rubber	1mm-10mm
Rough Shred	50˟50˟50-762˟50˟50	Rubber Chips	10mm-50mm
Tyre Chips	12mm-50mm	Rubber Shreds	50mm-300mm
Tyre Shreds	50mm-305mm	-	-

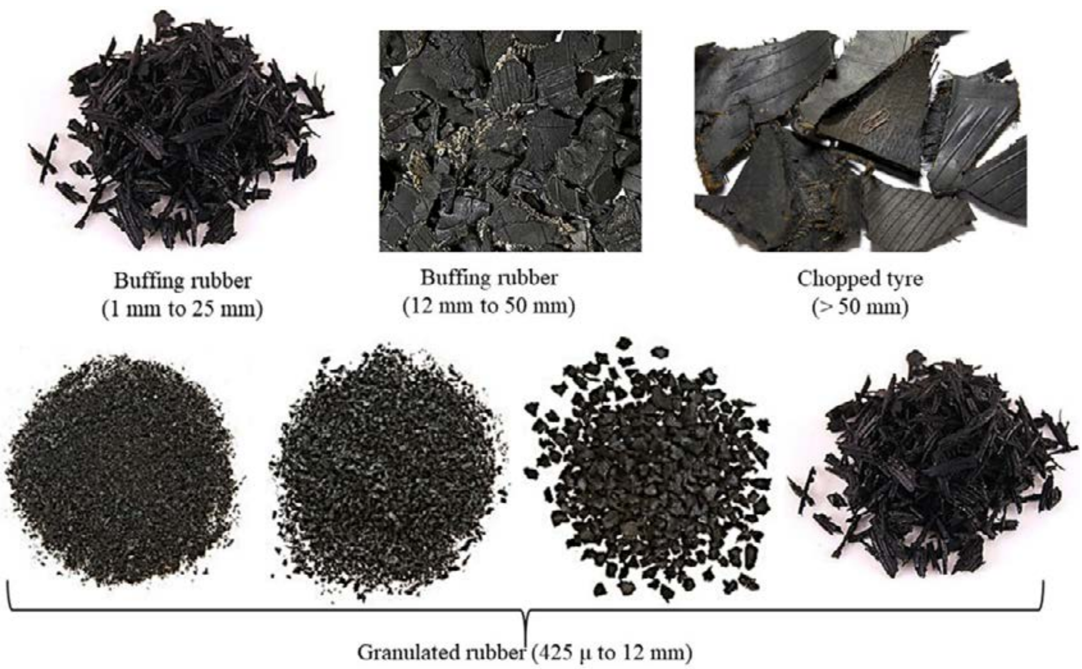

Fig. 2: Visual representation of types of rubber particles (Mistry *et al.,* 2021)

components. Table 1 presents the size classifications of processed tires as defined by the ETRA (2013) and ASTM D6270–08 (2012). Moreover, Fig. 2 visually depicts four distinct types of rubber particles, observed in prior studies (Edincliler *et al.,* 2013; Foose *et al.,* 1996).

laboratory analysis of discarded tires in geotechnical engineering

Thorough laboratory investigations are imperative for obtaining comprehensive insights into the behavior of soil-rubber mixtures to ensure the optimal utilization of scrap tires in geotechnical applications. Considerable investigations have been undertaken to examine the behavior of soils when mixed with rubber fragments. Most of the research conducted has concentrated on granular materials that have been strengthened using rubber particles, also significant investigations have been carried out regarding the behavior of rubber-reinforced clay soils (Al-Tabbaa and Aravinthan, 1997; Cabalar, 2011; Özkul and Baykal, 2007). Achieving homogeneity and preventing segregation between constituents are critical aspects for successful laboratory and field applications of soil-rubber mixtures (Jahandari *et al.,* 2021). Segregation may arise due to disparities in size, density, stiffness, and shape between rubber and soil particles, particularly when mixtures contain higher rubber proportions (Fareghian *et al.,* 2023; Pincus *et al.,* 1994). Visual inspections have traditionally been employed to assess segregation, although quantitative evaluation of segregation has been proposed using sieve analysis on samples obtained from various locations within an embankment (Badarayani *et al.,* 2021; Toghroli *et al.,* 2020). However, a systematic approach to evaluating the uniformity of laboratory experiments involving sand-rubber mixtures and field applications is currently lacking. Various fabrication techniques have been implemented to mix sand and rubber materials and investigate segregation phenomena. Several variables, including rubber type, size, rubber content, and the ratio of rubber particle size to sand particle size ($^{D_{Rubber}}/_{D_{Sand}}$), impact the mechanical characteristics of sand-rubber mixtures. Previous studies have predominantly focused on the strength and compression characteristics of sand-rubber mixtures. Traditional triaxial tests have been extensively employed to analyze the behavior of these mixtures (Ahmed, 1993; Akbarimehr and Hosseini, 2022; Bergado *et al.,* 2005; Chaney *et al.,* 1996; Hazarika *et al.,* 2012; Jastrzębska, 2019; Kawata *et al.,* 2007; Mashiri *et al.,* 2015; Noorzad and Raveshi, 2017; Promputthangkoon, 2009; Takano *et al.,* 2014; Youwai and Bergado, 2003; Zornberg *et al.,* 2004a). Additionally, direct shear tests (Edil and Bosscher, 1992; Foose *et al.,* 1996; Ghazavi, 2004; Ghazavi and Sakhi, 2005) have been employed to investigate the strength behavior of sand-rubber mixtures. Furthermore, the influence of rubber content on the compressive response of sand-rubber mixtures has been extensively explored through oedometer apparatus (Jamshidi Chenari *et al.,* 2019; Kim and Santamarina, 2008; Neaz Sheikh *et al.,* 2012; Zhou *et al.*, 2022; Fakharian *et al.,* 2023; Ngo and Valdes 2007; Valdes and Evans, 2008).

Influence of rubber proportion

The mechanical performance of sand-rubber mixtures is notably affected by the proportion of rubber integrated into the mixtures (Fu *et al.,* 2023). Accurate evaluation and selection of the rubber proportion are essential for achieving the desired performance and functional properties of these mixtures. Several methodologies have been proposed to quantitatively assess the rubber proportion, including the sand fraction (Sf), rubber fraction (FR), and gravimetric or rubber content (χ). The sand and rubber fractions represent volume-based proportions, while the gravimetric or rubber content is expressed in terms of mass-based proportions. To calculate the volume of rubber in the content, these measures are defined using Eqs. 1 to 6 (Terzaghi and Peck, 1948). Equations 1 and 2 define the sand and rubber fractions and equation 3 shows how to calculate rubber content.

$$\boldsymbol{S_f} = \frac{\boldsymbol{V_S}}{\boldsymbol{V_S} + \boldsymbol{V_R}} \quad (1)$$

$$F_R = \frac{V_R}{V_S + V_R} \quad (2)$$

$$\chi = \frac{M_R}{M_S + M_R} \quad (3)$$

Where, V_S and V_R correspond to the volumes of sand and rubber particles, respectively, and M_S and M_R represent the masses of sand and rubber particles, respectively. These parameters can be interrelated using Eqs. 4 to 6 (Terzaghi and Peck, 1948).

$$\boldsymbol{S_f} = 1 - \boldsymbol{F_R} \quad (4)$$

$$\chi = \frac{G_R}{G_R + G_S\left(\frac{1}{F_R} - 1\right)} \quad (5)$$

$$\chi = \frac{S_f}{G_R + G_S\left(\frac{S_f}{1 - S_f}\right)} \quad (6)$$

Where, G_S and G_R signify the specific gravities of soil and rubber particles, respectively.

Several researches have been conducted to analyze how varying the rubber content affects the mechanical properties, including strength and deformation behavior of mixtures, consisting of sand and rubber (Bandyopadhyay *et al.,* 2023; Dai *et al.,* 2023; Farooq and Nimbalkar, 2023; Afrazi *et al.,* 2022). These studies aim to identify the optimal rubber content that enhances the mechanical properties while ensuring stability and performance. The findings from these investigations contribute to an improved understanding and design of sand-rubber mixtures for geotechnical applications.

Strength response of sand-rubber mixtures

A substantial volume of research has been conducted to explore the strength characteristics exhibited by sand-rubber mixtures at different rubber content levels (Zhang *et al.,* 2023). Lee *et al.* (2007) performed drained conventional Triaxial tests on sand-rubber mixtures with a rubber-to-sand diameter ratio (D_{Rubber}/D_{Sand}) of approximately 0.25 and different sand fractions (S_f). The results revealed a decrease in peak strength and an increase in axial strain at peak strength for mixtures with lower sand fractions. To study the strength and deformation behavior of sand-rubber mixtures, Youwai and Bergado (2003) conducted Triaxial drained compression tests under different confining pressures. The mixtures consisted of various rubber fractions (FR) ranging from 0 Percent (%) to 100%, using cubical rubber particles. The findings indicated a reduction in maximum strength with increasing rubber volume fraction, accompanied by an increase in shear strain at peak strength. Notably, mixtures with higher rubber fractions exhibited no apparent peak strength. Bergado *et al.* (2005) investigated the behavior of sand-rubber mixtures under various confining pressures, with a rubber-to-sand diameter ratio (D_{Rubber}/D_{Sand}) of approximately 20 and different rubber fractions (FR) ranging from 0% to 100%. The experimental results showed a decrease in peak strength and an increase in distortional strain as the rubber fraction increased. Additionally, the stiffness of the mixtures decreased with the incorporation of rubber particles, while the volumetric behavior demonstrated an increased tendency to compress with higher rubber fractions. Noorzad and Raveshi (2017) conducted Triaxial testing on sand-rubber mixtures under different confining pressures, varying the rubber fractions (FR) from 0% to 50% and maintaining a rubber-to-sand diameter ratio (D_{Rubber}/D_{Sand}) of approximately 25. The results indicated a reduction in peak strength and an increase in residual strength with increasing rubber content, corroborating the findings reported by Bergado *et al.* (2005). Several investigations have examined the shear strength behavior of sand-rubber mixtures under varying conditions. Chaney *et al.* (1996) performed Triaxial compression tests on sand-rubber mixtures with a rubber-to-sand diameter ratio (D_{Rubber}/D_{Sand}) of approximately 20, subjecting the mixtures to different confining pressures. The addition of rubber particles resulted in reduced shear strength and an increase in axial strain at peak shear strength. Hazarika *et al.* (2012) conducted drained Triaxial compression tests on sand-rubber mixtures with a rubber-to-sand diameter ratio (D_{Rubber}/D_{Sand}) of approximately 2, revealing a decrease in peak shear strength, accompanied by increased axial strain for mixtures with higher rubber fractions. Additionally, researchers have investigated the impact of different rubber fractions on the decrease in shear strength observed in sand-rubber mixtures when exposed to varying levels of confining pressures. Kawata *et al.* (2007) performed Triaxial drained compression tests on sand-rubber mixtures with a rubber-to-sand diameter ratio (D_{Rubber}/D_{Sand}) of approximately 0.4, demonstrating a decrease in shear strength with increasing rubber fractions in both loose and dense mixtures. Fu *et al.* (2014), Lee *et al.* (2014) and Takano *et al.* (2014) conducted shear tests on sand-rubber mixtures, observing reductions in shear strength as the rubber fraction increased. Moreover, researchers have examined the effect of rubber particle size, shape, and aspect ratio on the strength response of sand-rubber mixtures. Mashiri *et al.* (2015) investigated the behavior of sand-rubber mixtures containing tire chips with a specific aspect ratio. The experimental results indicated a dependence of the optimum rubber percentage on the aspect ratio, shape, and rubber particles' size. Zornberg *et al.* (2004a) conducted Triaxial compression tests on sand-rubber mixtures containing tire shreds with a specific aspect ratio, revealing an initial increase followed by a decrease in shear strength as the rubber fraction increased.

Deformation behavior of sand-rubber mixtures

The deformation behavior of sand-rubber mixtures is greatly affected by the rubber content present in the mixtures. To investigate this behavior, Neaz Sheikh *et al.* (2012) conducted one-dimensional compression tests on sand-rubber mixtures with varying rubber fractions (FR) of 0%, 10%, 20%, 30%, and 40%. The mixtures were subjected to incremental pressures up to 745 Kilopascal (kPa), followed by unloading to 38 kPa. The results revealed that higher rubber fractions contributed to increased compressibility and swelling responses, indicating the significant role of rubber content in controlling the compressible and swelling behaviors. The swelling and compression indexes exhibited a consistent increase corresponding to the rubber fractions (Fig. 3).

To further comprehend the deformation behavior of sand-rubber mixtures, Lee *et al.* (2007) performed oedometer tests on mixtures with a rubber-to-sand diameter ratio ($^{D_{Rubber}}/_{D_{Sand}}$) of approximately 0.25. The sand fraction (Sf) varied from 0 to 1, and the mixtures were subjected to various effective stresses up to 556 kPa. The findings indicated that the vertical strain decreased with increasing Sf. Additionally, the investigation of constrained modulus ($M = \frac{\Delta\sigma_V}{\Delta\epsilon_V}$) and maximum shear modulus demonstrated that both modulus values increased with higher sand fractions (or reduced rubber fractions) under all confinement conditions. Notably, mixtures with a sand fraction of 0.6 exhibited an intermediate behavior, transitioning from sand-like behavior at higher confinement to rubber-like behavior at lower confinement (Figs. 4 and 5).

Similarly, Kim and Santamarina (2008) conducted oedometer tests on sand-rubber mixtures with

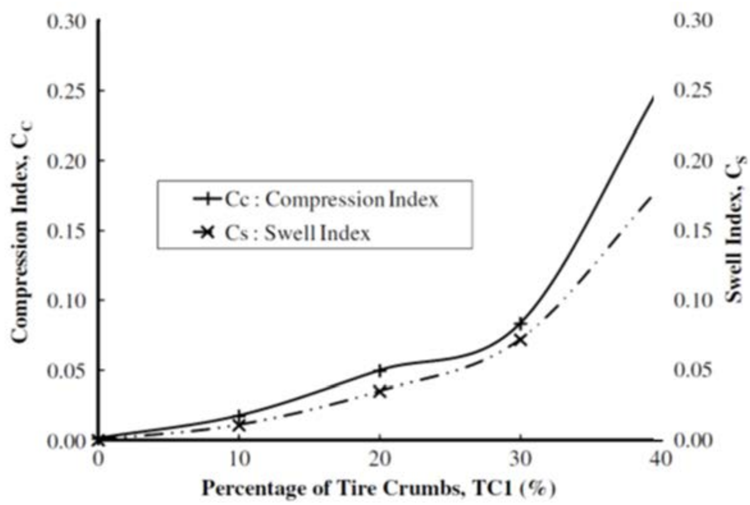

Fig. 3: Compression and swelling indexes of sand-rubber mixtures (Neaz Sheikh *et al.*, 2012)

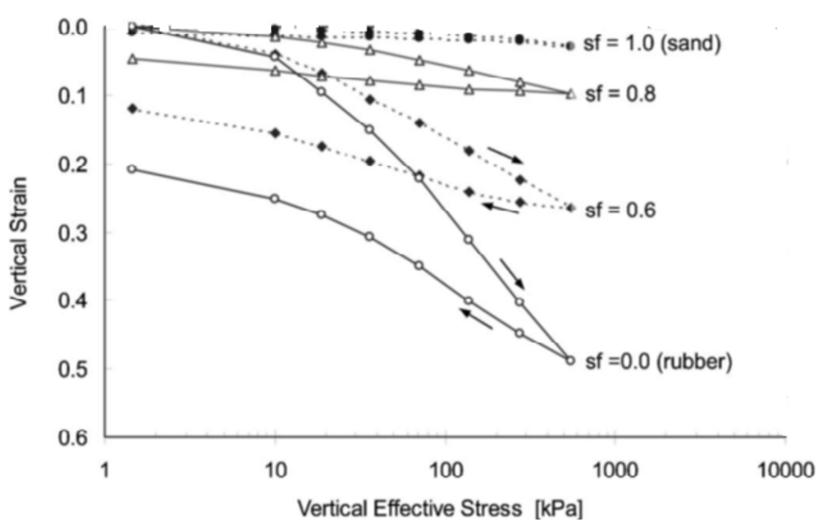

Fig. 4: Vertical strain vs. vertical stress in oedometer tests (Lee *et al.*, 2007)

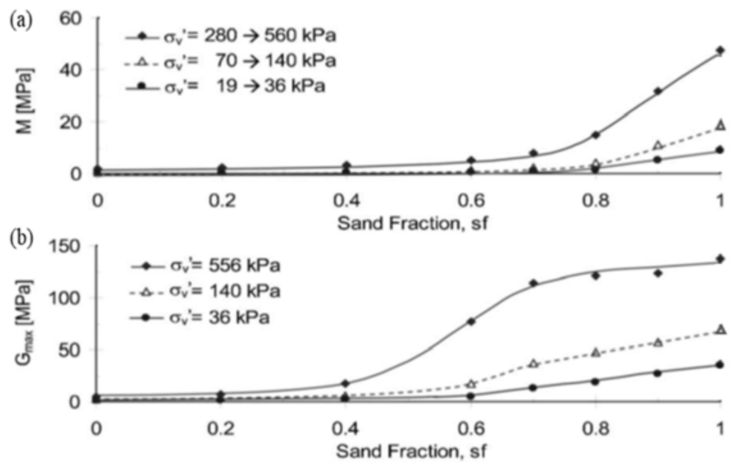

Fig. 5: (a) Constrained modulus at middle strain; (b) Small strain shear modulus (Lee *et al.,* 2007)

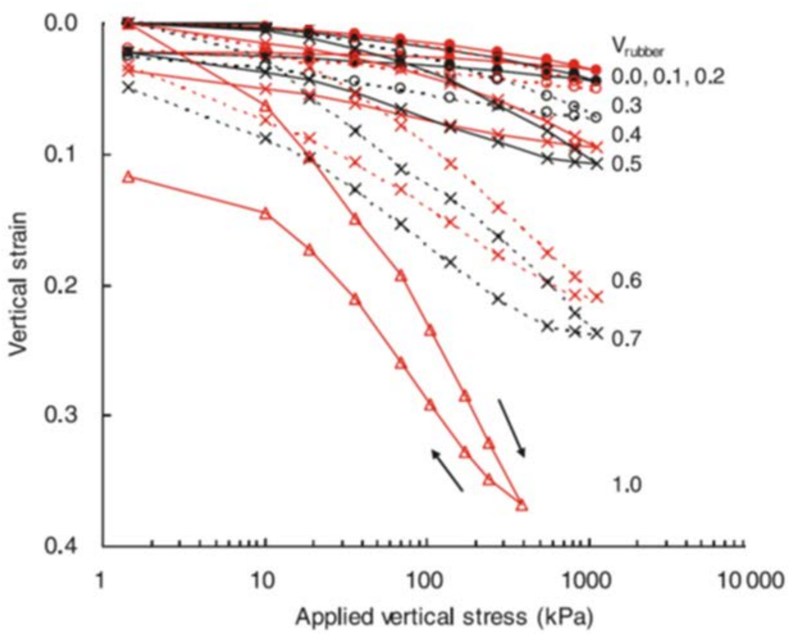

Fig. 6: Vertical strain vs. vertical stress in oedometer tests (Kim and Santamarina, 2008)

a rubber-to-sand diameter ratio ($^{D_{Rubber}}/_{D_{Sand}}$) of approximately 10, encompassing varied rubber fractions (FR) from 0 to 1. The investigation revealed that increased rubber fractions led to higher compression and swelling behavior. Mixtures with sand fractions of 0.4-0.5 exhibited an intermediate behavior, transitioning from sand-like to rubber-like behavior. Additionally, the constrained modulus decreased with increasing rubber fractions, aligned with the findings of Lee *et al.* (2007) (Figs. 6 and 7) and Kim and Santamarina (2008).

Influence of rubber particle aspect ratio

The aspect ratio (η) of the rubber particles, indicating the relationship between their length and width, play a substantial role in affecting the

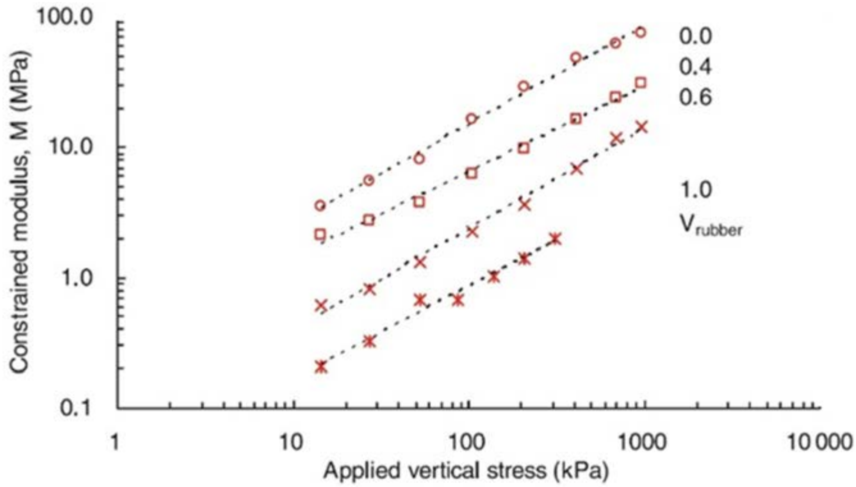

Fig. 7: Constrained modulus of sand-rubber mixtures (Kim and Santamarina, 2008)

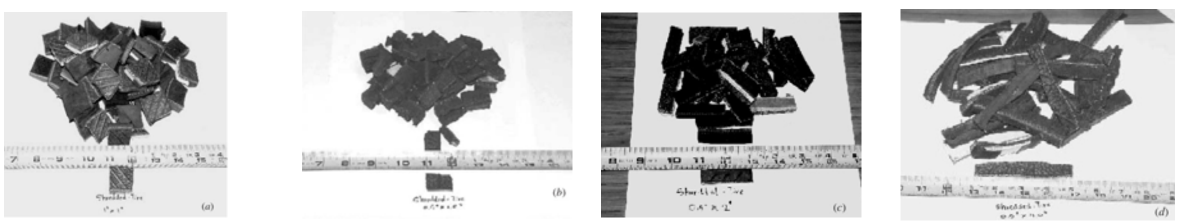

Fig. 8: The visual depiction of tire shreds exhibiting various aspect ratios: (a) η = 1 (25.4 mm * 25.4 mm); (b) η = 2 (12.7 mm * 25.4 mm); (c) η = 4 (12.7 mm * 50.8 mm); (d) η = 8 (12.7 mm * 101.6 mm) (Zornberg *et al.,* 2004a)

mechanical characteristics of sand-rubber blends. Visual examination reveals four distinct types of tire shreds having aspect ratios of 1, 2, 4, and 8 (Zornberg *et al.,* 2004a). The incorporation of tire shreds into sand mixtures introduces characteristics reminiscent of fiber-reinforced sand, resulting in improved peak shear strength (Foose *et al.,* 1996; Zornberg *et al.,* 2004a).

To investigate the impact of rubber particle aspect ratio on the behavior of sand-rubber mixtures, a study conducted by Zornberg *et al.* (2004a) utilized Triaxial compression tests. The tests involved samples that included tire shreds with the aspect ratios mentioned earlier (Fig. 8). These tests were conducted under three different confining pressures: 48.3 kPa, 103.5 kPa, and 207 kPa. The experimental results, as illustrated in Fig. 9, indicated that increasing the aspect ratio of the rubber particles leads to higher deviatoric stresses regardless of the applied confining pressures. This observation can be attributed to the enhanced pull-out resistance experienced by the tire shreds, thereby promoting increased tensile forces within the rubber particles.

Influence of rubber-sand size ratio

The size ratio between rubber and sand in soil mechanics holds considerable importance as it directly impacts diverse engineering properties and soil behaviors. The adding of rubber particles to sand can modify the mechanical characteristics of the soil mixture (Hsiao and Lin, 2023; Mei *et al.,* 2023; Wu *et al.,* 2023a).

Strength response of sand-rubber mixtures

The mechanical characteristics of sand-rubber mixtures are notably impacted by the size ratio (Sr) between rubber and sand, which describes the relationship between the average grain sizes

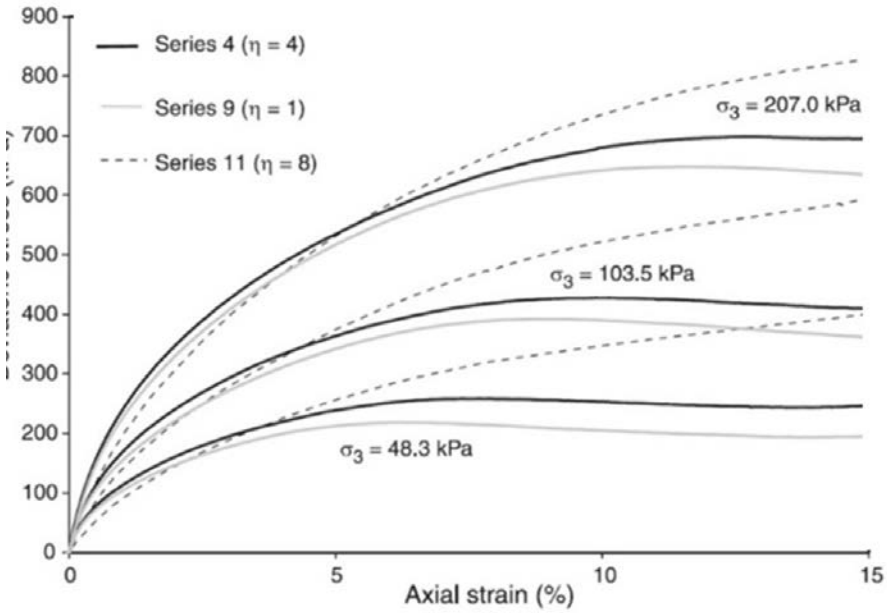

Fig. 9: The deviatoric stress-axial strain response for sand-rubber mixtures with various aspect ratios (Zornberg *et al.*, 2004a)

of rubber and sand particles (Cheng *et al.*, 2023; Yimsiri and Soga, 2010; Zornberg *et al.*, 2004b; Wu *et al.*, 2023b). Triaxial compression tests were carried out on sand-rubber mixtures by Neaz Sheikh *et al.* (2012), employing size ratios of 4 and 7, while subjecting the samples to a confining pressure of 207 kPa. The findings indicated that mixtures characterized by a higher size ratio demonstrated increased shear strength in comparison to mixtures with a lower size ratio (Neaz Sheikh *et al.*, 2012). Similarly, Noorzad and Raveshi (2017) investigated the impact of size ratio on sand-rubber mixtures under various confining pressures and observed that mixtures with higher size ratios displayed higher deviatoric stresses compared to mixtures with lower size ratios. The reason behind this phenomenon lies in the greater interfacial area between smaller rubber particles and sand particles found in mixtures characterized by lower size ratios. As a result, the interactions between sand particles are diminished, thus causing a reduction in sand-sand interactions. In another study by Promputthangkoon (2009), undrained Triaxial monotonic tests were conducted on sand-rubber mixtures with different rubber-sand size ratios of approximately 1.7, 3.3, 5.7, and 11.4. The results clearly showed that the shear strength of the mixtures was significantly influenced by the size of the rubber particles. Specifically, an increase in rubber particle size resulted in higher shear strength. Moreover, the utilization of larger rubber particles led to the development of more pronounced negative pore pressure within the sand-rubber mixtures. In their research, the authors examined loose sand-rubber mixtures with a void ratio of 0.86. Three rubber particle types with D-rubber/D-sand ratios of 0.25, 1, and 4 were used, along with varying rubber-sand ratios (5%-50%) in over 300 shear tests. Shear strength and deformation responses depended on rubber proportions and size ratios. Initially, friction angle increased and cohesion intercept reduced up to 20% rubber, then reversed. Shear strength's sensitivity to rubber fraction was limited, as indicated by dimensional analysis.

Deformation behavior of sand-rubber mixtures

The size ratio (Sr) and rubber proportions have an impact on the deformation response and interaction mechanisms of sand-rubber mixtures

(Akbarimehr *et al.,* 2023; Al-Fatlawi *et al.,* 2023; Dehghanbanadaki *et al.,* 2021; Badarayani *et al.,* 2023). Kim and Santamarina (2008) conducted studies that highlighted the impact of these factors. Mixtures with a lower ratio of rubber particle diameter to sand particle diameter ($^{D_{Rubber}}/_{D_{Sand}}$) exhibit pore filling at the particle level and distortion of rubber chains. On the other hand, mixtures with a higher $^{D_{Rubber}}/_{D_{Sand}}$ ratio display stiffness and arching effects. The behavior of these mixtures is governed by fabric, particle-level mechanisms, and macroscale characteristics. Particle segregation and spatial percolation phenomena are observed in samples with varying size ratios (Lee *et al.,* 2014). Further investigations by Lee *et al.* (2009) explored the effect of $^{D_{Rubber}}/_{D_{Sand}}$ using different size ratios (Sr) ranging from 4.7 to 0.35. The constrained modulus of the mixtures was analyzed. It was found that for mixtures with Sr < 1, the constrained modulus remained relatively constant, while for mixtures with Sr > 1, the constrained modulus increased. The behavior was attributed to the formation of load carrying chains before rubber particle deformation in mixtures with smaller sand and larger rubber particles. Conversely, in mixtures with smaller rubber particles and larger sand particles, rubber particle deformation occurred before the establishment of load carrying chains between sand particles. The small strain shear modulus was also examined to assess the influence of size ratio. Lee *et al.* (2009) found that the contact area between particles played a crucial role in determining the small shear modulus. Mixtures with Sr < 1 and Sr > 1 exhibited increased shear modulus due to the contact area effect. The lowest small strain shear modulus was observed in mixtures with Sr ~ 1, indicating a lower stiffness at the particle contacts. Interparticle contacts were identified as significant contributors to the shear strength stiffness.

Effect of confining pressure

The behavior of sand-rubber mixtures under confining pressure follows a similar pattern to that observed in traditional sand specimens. The shear strength characteristics of the mixtures are notably influenced by the applied confining pressures, regardless of the rubber proportions. Noteworthy investigations by Ahmed (1993), Bergado *et al.* (2005), Chaney *et al.* (1996), Neaz Sheikh *et al.* (2012), and Zornberg *et al.* (2004a) have highlighted the pronounced effect of confining pressure on the shear strength behavior of sand-rubber mixtures. Specifically, Zornberg *et al.* (2004a) underscored the intensified reinforcement mechanism of rubber particles at lower confining pressures. Experimental results, exemplified by the deviatoric stress response of sand-rubber mixtures illustrated in Fig. 10 provide compelling evidence of the confinement-induced influence on the behavior of these mixtures.

Modeling of soil-rubber mixtures

The modeling of soil-rubber mixtures is a complex and multidisciplinary task in the field of geotechnical engineering. It involves the development of mathematical models and computational techniques to simulate the behavior of soil mixed with rubber particles (Fu *et al.,* 2023; Zhang *et al.,* 2023). Various aspects need to be considered in the modeling process, including the mechanical properties of both the soil and rubber, the distribution and arrangement of rubber particles within the soil matrix, and the interaction between the two materials. The modeling approaches can range from simplified analytical models to more sophisticated numerical simulations, such as finite element or discrete element methods. These models aim to capture the unique behavior exhibited by soil-rubber mixtures, including their enhanced energy dissipation, improved damping characteristics, and altered mechanical response under different loading conditions. Accurate and reliable modeling of soil-rubber mixtures is crucial for understanding their performance in geotechnical applications and facilitating the design and optimization of structures built on or with these materials (Lv *et al.,* 2023; Wang *et al.,* 2023; Zhang *et al.,* 2023). In the study conducted by Lee *et al.* (1999), a constitutive model was proposed to simulate the behavior of sand-rubber mixtures with a rubber fraction of 40% by weight. However, the model had limitations in accurately representing post-peak strength, plastic strain, and dilative response, which were identified as significant drawbacks. Although the model provided accurate predictions under at-rest conditions, it tended to overestimate the behavior under active conditions. Youwai and Bergado (2003) proposed another constitutive model to simulate the stress and deformation behavior of sand-rubber mixtures. While the model showed

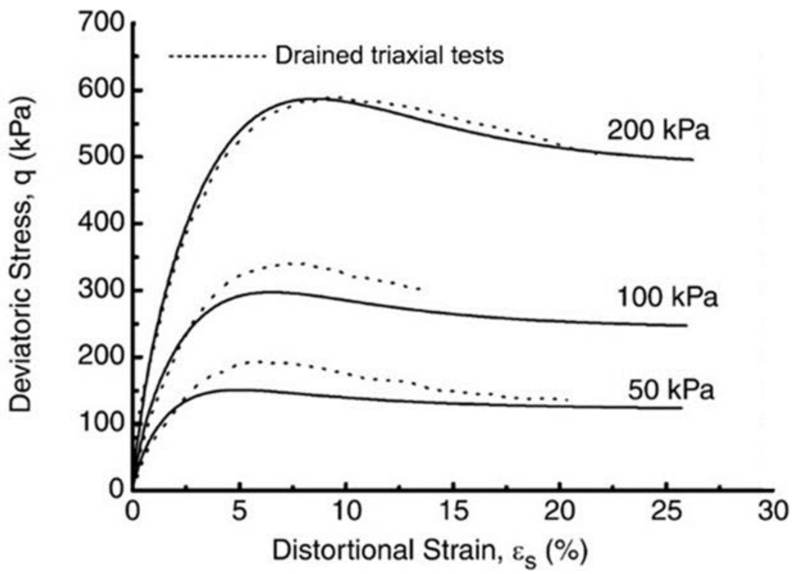

Fig. 10: Deviatoric stress-distortional strain under three different confining pressures

promise in capturing the overall behavior, challenges were encountered in accurately predicting the critical state at large strains due to the observed dilation of the mixtures. To address these limitations, Mashiri *et al.* (2015) developed a semi-empirical constitutive model based on the critical state framework. This model successfully predicted the stress-strain and volumetric behaviors observed in monotonic Triaxial drained tests conducted by Zornberg *et al.* (2004a) and Mashiri *et al.* (2015). In a different approach, Takano *et al.* (2014) employed a 3D discrete element method based on molecular dynamics to simulate sand-rubber mixtures. Unlike conventional models using spherical particles, this approach utilized non-spherical particles (clumps) to represent the mixtures. To account for computational limitations, the width of the simulated shear box was reduced to 20 mm. While the model effectively predicted the shear strength behavior of the mixtures under a confining pressure of 100 kPa, limitations were observed in accurately predicting the vertical displacement of mixtures with rubber fractions of 0% and 20%.

Cost effectiveness of using sand-rubber mixtures

The utilization of alternative materials in civil engineering applications has gained considerable attention in recent years due to the need for sustainable and cost-effective construction practices. One such innovative approach is the incorporation of rubber particles into traditional construction materials like sand, leading to the formation of sand-rubber mixtures. These mixtures not only offer potential engineering benefits but also present an avenue for cost savings in various construction projects (Tsiavos *et al.,* 2019).

Material cost

The cost effectiveness of using sand-rubber mixtures primarily stems from the utilization of waste rubber, which can be sourced from discarded tires, conveyor belts, and other rubber products (Lopera Perez *et al.,* 2017). Compared to the traditional production of construction materials, such as concrete or asphalt, which often require costly extraction and processing of raw materials, incorporating waste rubber particles can significantly reduce the material cost component of construction projects (Assaggaf *et al.,* 2022). The availability of waste rubber at lower or even zero cost, along with potential savings in transportation and disposal fees for rubber waste, contributes to the economic viability of sand-rubber mixtures.

Reduced maintenance and longevity

While initial construction costs are a significant consideration, the long-term cost effectiveness of construction materials cannot be overlooked (Alwi

Assaggaf *et al.,* 2022; Bisht and Ramana, 2017). Sand-rubber mixtures have demonstrated improved resilience and durability due to the unique properties of rubber particles, such as their ability to absorb impact and distribute loads (Al-Tayeb *et al.,* 2013; Al-Tayeb *et al.,* 2013; Ngo *et al.,* 2019). This enhanced durability can translate to reduced maintenance and repair needs over the lifespan of the constructed infrastructure, leading to potential long-term cost savings. The decreased frequency of repairs and replacements, particularly in high-traffic areas like roads and pavements, adds to the overall cost effectiveness of employing sand-rubber mixtures.

Environmental and regulatory benefits

In addition to economic advantages, the use of sand-rubber mixtures aligns with sustainability goals and environmental regulations (Gigli *et al.,* 2019). Incorporating waste rubber into construction materials diverts rubber waste from landfills, contributing to waste reduction and a more circular economy. This alignment with environmental objectives might lead to potential incentives or support from regulatory bodies, further enhancing the cost effectiveness of this innovative approach.

Engineering considerations

While the economic benefits are promising, it is essential to acknowledge the potential engineering considerations associated with sand-rubber mixtures. These mixtures might require modifications in construction techniques, equipment, and quality control procedures. Therefore, a thorough assessment of the construction process, including any additional labor or equipment requirements, must be conducted to accurately evaluate the overall cost effectiveness of using sand-rubber mixtures.

Application of scrap tires in geotechnical engineering

Retaining walls and embankments

Scrap tires can be used as lightweight fill materials in the construction and building of retaining walls and embankments. Their low density and their essential characteristics reduce the lateral earth pressure exerted on retaining walls, reducing the requirements for additional structural reinforcements. Many researchers around the world studied this application of waste tires (Ma *et al.,* 2023; Hazarika *et al.,* 2023; Garga *et al.,* 2000; Li *et al.,* 2020). For instance, Li *et al.* (2020) studied the dynamic behavior of using waste tires in retaining walls and showed that using waste tires enhance the dynamic performance of retaining walls. However, it should be mentioned that adding and mixing rubber particles is not an easy task and it's one of the obstacles which need attention and some real project studies.

Drainage properties

The void spaces within the scrap tires particles provide effective drainage pathways, allowing for the efficient removal of excess pore water. This characteristic makes them suitable for use in drainage systems, such as leachate collection layers in landfills and beneath roadways to combat waterlogging (Edil *et al.,* 2005; Czarna *et al*., 2023). To determine the effects of drainage properties of waste tires in landfills, Edil *et al.* (2005) showed that using waste tires can efficiently increase the quality of the leachate.

Ground improvement

The use of scrap tires as a geotechnical fill material can improve the load-bearing capacity of weak or compressible soils. As mentioned earlier, tire-derived aggregate (TDA) could be used to reinforce soils and increase their shear strength, making them suitable for supporting heavy structures like buildings and bridges. Various studies have assessed the efficacy of scrap tires in ground improvement and showed that using scrap tire can significantly increase the shear behavior of soils (Wang *et al.,* 2023*;* Nikitas and Bhattacharya*,* 2023).

CONCLUSION

This review study has provided a comprehensive examination of the application of scrap tires in geotechnical engineering, aiming to explore diverse applications, identify associated benefits, and address challenges. By analyzing existing research studies and industry practices, this paper has shed light on the integration of scrap tires in geotechnical engineering projects such as retaining wall reinforcement, slope stabilization, and improved drainage systems. The evaluation of environmental implications and economic feasibility has underscored the importance of sustainable practices in geotechnical engineering. Through literature investigations, the behavior of sand-rubber mixtures has been thoroughly analyzed, considering various factors such as rubber proportions, aspect ratios, and interaction mechanisms. The findings have revealed the effects of rubber content on the shear strength, strain behavior, compressibility, and constrained modulus of the mixtures. These insights contribute to the advancement and understanding of sustainable geotechnical engineering practices, facilitating the effective utilization of scrap tires while minimizing plagiarism concerns. The accumulation of scrap tires poses significant environmental and economic challenges worldwide. Conventional methods of disposal have proven to be environmentally harmful and economically burdensome. By integrating scrap tires into geotechnical engineering methods, the aim is to tackle these issues and concurrently advance sustainability goals. The utilization of scrap tires in various applications, such as retaining wall reinforcement, slope stabilization, and improved drainage systems, has shown promising results. Extensive research has been conducted on the mechanical behavior of sand-rubber mixtures, yielding valuable insights into their strength and deformation characteristics. It is important to note that challenges exist when employing rubber particles alone in geotechnical structures, including issues related to high deformation, compaction, and self-heating mechanisms. However, through proper removal of exposed steel components from scrap tires and the incorporation of soil particles, these challenges can be mitigated. Furthermore, extensive studies have indicated that rubber particles have negligible effects on groundwater quality within specified ranges of civil engineering applications. To maximize the benefits of scrap tire integration, the size classification of processed tires is crucial. Established standards provide guidelines for effectively categorizing rubber particles based on size, allowing for their optimal utilization in various applications. Additionally, modeling approaches have been developed to simulate the behavior of sand-rubber mixtures, although further research is needed to accurately capture the post-peak strength, plastic strain, and dilative response of these mixtures. In conclusion, the utilization of scrap tires in geotechnical engineering presents an opportunity to address the environmental and economic challenges associated with their accumulation. By exploring the diverse range of applications, evaluating environmental implications, and understanding the behavior of sand-rubber mixtures, this review paper contributes to the advancement and understanding of sustainable geotechnical engineering practices.

AUTHOR CONTRIBUTIONS

M. Shariati performed the literature review, analyzed and interpreted the data, prepared the manuscript text, and manuscript edition. M. Afrazi performed the literature review, analyzed and interpreted the data, prepared the manuscript text, and manuscript edition. H. Kamyab performed the literature review, analyzed and interpreted the data, prepared the manuscript text, and manuscript edition. S. Rouhanifar performed the literature review, analyzed and interpreted the data, prepared the manuscript text, and manuscript edition. E. Toghroli helped in the literature review and manuscript preparation. M. Safa helped in the literature review and manuscript preparation. C. Shreeshivadasan helped in the literature review and manuscript preparation. H. Afrazi helped in the literature review and manuscript preparation.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS	DEFINITION
%	Percent
D_{Rubber}/D_{Sand}	Rubber-to-sand diameter ratio
$\Delta\sigma_V$	Volumetric stress change
$\Delta\epsilon_V$	Volumetric strain change
G_R	Specific gravities of rubber particles
G_S	Specific gravities of soil particles
M_R	Masses of rubber particles
M_S	Masses of sand particles
V_R	Volumes of rubber particles
V_S	Volumes of sand particles
ASTM	American Society for Testing and Materials
FR	Rubber fraction
kPa	Kilopascal
mm	Millimeter
Sf	Sand fraction
Sr	Size ratio
η	Aspect ratio
µm	Micrometer
χ	Gravimetric or rubber content
$M = \dfrac{\Delta\sigma_V}{\Delta\epsilon_V}$	Constrained modulus

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