Analysis of the behavior of expansive soil modified with recycled tire rubber

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Abstract: Expansive soils undergo large volumetric strains due to their mineralogical composition, which causes them to expand when their water content increases. Hence, these soils are considered difficult to use in geotechnical engineering applications. Usually, expansive soils are chemically stabilized; however, recent studies have shown that incorporating tire-waste rubber into soil samples decreases the expansion. The basis of the present research is the modification of soil using tire-waste rubber as a stabilizing agent. The soil was sampled in Tarímbaro Michoacán, Mexico, and an index laboratory characterization of the soil was performed, classifying it as high-plasticity silt (MH) with a high expansion index. To analyze the variation of the volumetric behavior, swelling tests were performed on different soil-rubber mixtures using an instrumented oedometer to measure the expansive pressure. These mixtures covered a range of rubber incorporations at 5%, 10%, and 20% of the dry soil mass. Additionally, a scanning electron microscopy (SEM) was conducted to examine the microstructural interactions between the soil matrix and rubber particles. SEM images revealed morphological changes in each of the mixtures. The results indicate a significant decrease in swelling pressure, resulting in soil stabilization and reduced volumetric strains.

Introduction

The rapid growth of cities and industries has generated significant waste materials, including waste tires. Effectively handling and disposing of these materials is crucial for society due to their economic and environmental impact. Many practices and techniques have recently been developed to recycle and reuse waste tires. Their physical properties, such as high durability, low density, hydrophobicity, and high energy dissipation, make them suitable for geotechnical applications [1]. In civil engineering, recycled rubber has been used widely for several purposes, such as lightweight embankments, drainage systems, asphalt mixes, and railways [2] [3]. Previous studies have confirmed that clayey soils mixed with recycled rubber exhibit a decrease in volumetric swelling and contraction, as well as an increase in shear strength [4]. According to the standard ASTM D6270 [5], by-products of tire waste rubber are categorized by their shape and size as follows: (1) Tire-derived aggregate (TDA), which consists of pieces ranging from 50 to 300 mm in size. (2) Tire chips, which are rectangular or triangular in shape and range in size from 12 to 50 mm. (3) Fiber-shaped tire chips, pieces 1 to 2 mm in size. (4) Granulated rubber, particles ranging from 0.425 to 12 mm, and (5) Ground rubber, pieces smaller than 0.425 mm (Fig 1). The most common approach to obtaining recycled rubber is through a mechanical process, which involves several shredding and grinding steps. In this process, waste tires are passed through grinders and sieves until the desired particle size and separation of the rubber, steel wires, and textile fibers are achieved [6]. There is an additional process called cryogenic grinding, where the grinding is performed after the rubber is cooled using liquid nitrogen, allowing it to be easily crushed [7].

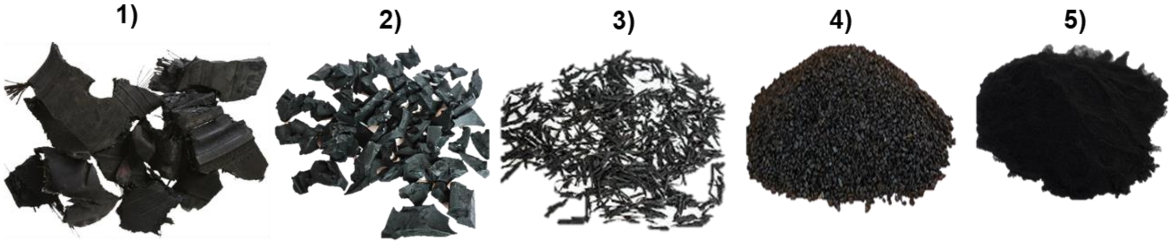

Figure 1: Size and shape classification of recycled tire rubber, 1) TDA, 2) chips, 3) fibers, 4) granulated rubber, and 5) grounded rubber.

According to the standard ASTM D6270 [5], the unit weight of rubber is approximately 30% to 50% lower than that of most common soils, making rubber an adequate alternative for use in lightweight embankments. Recycled tire rubber has similar strength properties to conventional soils; however, due to its low elasticity modulus, this material features a high level of compressibility [8]. Shear strength has been the subject of extensive research; nevertheless, strain is regarded as the main parameter that determines the applicability of recycled tire rubber in most cases [9].

Expansive soils

Soils that experience significant volume changes due to fluctuations in water content are referred to as expansive soils. [10]. From the perspective of geotechnical engineering, expansive soils are the least desirable for any civil or construction project, as they are prone to causing severe damage to infrastructure [11]. Various techniques and materials have been proposed for stabilizing soils, with chemical stabilization producing the best results [12]. Expansive soils are characterized by the presence of symmetrical-shaped clayey minerals belonging to the smectite group, where montmorillonite is a key component [13]. The main criteria for identifying expansive clayey minerals in soils are based on mineral identification and inferential tests. Direct tests are part of inferential tests, which physically determine the soil expansion using one-dimensional consolidation tests to measure the soil swelling using an oedometer [14].

While recent studies have explored the behavior of soil-rubber mixtures with favorable results, the available data are limited, and several questions remain about their performance, particularly regarding the optimal incorporation percentage. Following this principle, the present research involves an experimental study of the behavior of soil mixtures containing granulated rubber. To do so, laboratory tests were conducted to determine the free swell and swell pressure of the soil-rubber mixtures, using rubber contents of 0%, 5%, 10%, and 20% of the soil's dry weight.

Material properties and experimental program

Materials

According to the Unified Soil Classification System (USCS), the soil analyzed in this research corresponds to a high plasticity silt (MH). This soil was sampled in the municipality of Tarímbaro in the Mexican state of Michoacan. In the area where the soil was obtained, significant features of expansive soils were observed, including damage to nearby buildings and constructions due to fluctuations in the water content of the foundation soil. The physical and index properties measured through laboratory tests, as well as the standard procedure followed, are presented in Table 1.

Table 1: Physical and index properties of the soil tested.

Property	Value	Standard Designation
Specific gravity, Gs	2.69	ASTM D854 [15]
Clay content (<2 μm) (%)	18.72	ASTM E2651 [16]
Silt content (2-75 μm) (%)	53.49	
Sand content (0.075–4.75 mm) (%)	16.23	ASTM D6913 [17]
Liquid limit, w_L (%)	82.77	ASTM D4318 [18]
Plasticity index, IP (%)	41.07	
USCS classification	MH	ASTM D2487 [19]
Optimum water content, w_{opt} (%) (*)	33.2	ASTM D698 [20]
Maximum dry unit weight, γ_{dmax} (kN/m^3) (*)	12.3	

(*) Standard Proctor Test

The recycled tire rubber was obtained through the recycling center “Grupo ECORMX” in the same municipality where the soil was sampled. The company's activities include waste tire collection, storage, and mechanical processing. In this final step, the waste tire is processed into shreds and ground to various particle sizes. The recycled rubber obtained from this company is classified as granular particles, with pieces of a maximum size of 2 mm. The specific gravity of this material is 1.11, as determined by the procedure outlined in ASTM UOP766 [21]. It is worth mentioning that the rubber obtained is free of wires and any steel or textile residue. The particle size distribution of the soil and the granulated rubber are shown in Fig 2.

Preparation of mixtures

For this research, three different soil-rubber mixtures were considered, consisting of rubber contents of 5%, 10%, and 20% of the dry weight of the soil. The specific gravity of the mixtures was theoretically calculated using equation 1. The authors proposed this equation based on weight-volume relationships for soils.

$$S_{SC} = \frac{w_s + w_c}{V_{sc}(\gamma_w)} \tag{1}$$

Where S_{SC} is the specific gravity of the mixture, w_s is the weight of the soil, w_c is the weight of the rubber, V_{sc} is the volume of mixture solids, γ_w is the unit weight of water. The standard Proctor compaction method was used to determine the water content and maximum dry densities tests. Swelling tests were performed using an oedometer to assess the influence of rubber inclusion on the geotechnical behavior of the soil. These tests evaluated the free swell and swell pressure for each soil-rubber mixture and the natural soil without recycled rubber.

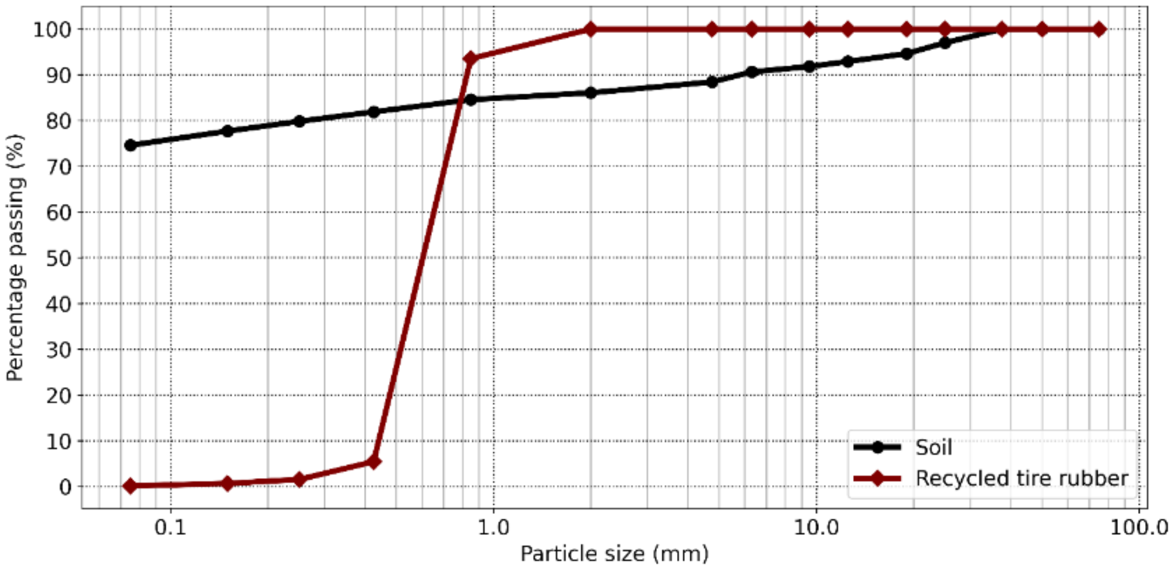

Figure 2: Grain size distribution curve.

Swelling pressure tests

The testing procedure adopted in this research to determine free swelling and swell pressure of soils is based on the ASTM D4546 standard [22]. The test specimens were compacted to the maximum dry density and water contents corresponding to a degree of saturation of 50±2%, following the recommendation of the ASTM D4829 standard [23]. Equation 2 was used to determine the degree of saturation.

$$S = \frac{wG_c\gamma_d}{G_s\gamma_w - \gamma_d} \tag{2}$$

Where S is the grade of saturation, G_c is the specific gravity of the soil, γ_d is the maximum dry density, γ_w is the density of water, and w is the water content. Adopting a degree of saturation of 50%, the water content was solved from equation 2. The results are shown in Table 2. The specimen preparation and the equipment used are shown in Fig. 3.

Table 2: Water content used for sample preparation.

Soil mixtures	Degree of saturation (%)	Maximum dry density (kN/m³)	Specific gravity	Water content (%)
Soil	50	12.3	2.69	21.3
5% recycled tire rubber	50	12.1	2.57	21.1
10% recycled tire rubber	50	11.6	2.34	20.9
20% recycled tire rubber	50	11.2	2.16	20.6

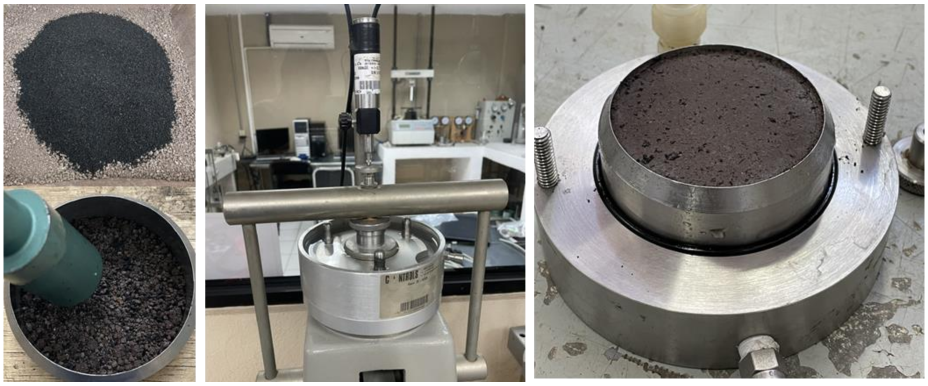

Figure 3: Soil mixture, specimen compaction, and oedometer equipment.

The ASTM procedure suggests testing four identical specimens subjected to increasing vertical stress levels. The first specimen is used to achieve the maximum expansion of the soil without restrictions; therefore, a relatively low load should be applied to this specimen, allowing for the measurement of the free swell of the soil. The applied load to the first specimen was 1 kPa. After 10 minutes of the load application, each specimen is inundated with distilled water while maintaining the stress level. Then, the strain data was recorded for at least 48 hours, ensuring that the strain rate was kept under 0.005 mm/h. Finally, the soil expansion strain is determined using equation 3.

$$\varepsilon_s = \frac{100\,\Delta h_2}{h_1} \tag{3}$$

Where ε_S is the soil expansion strain, Δh_2 is the vertical strain of the specimen after wetting, and $h_1 = h - \Delta h_1$, h is the initial height of the specimen, and Δh_1 is the specimen strain after stress application and immediately before wetting. To determine the degree of saturation, the wet mass of each sample was obtained at the end of each test. These samples were then dried in a convection oven for 24 hours, after which their dry mass was recorded. The swell pressure is the minimum stress required to prevent soil swelling. To determine this pressure, strain data are recorded for each stress level, which may result in swelling or collapse after wetting. The swell/collapse strains are plotted versus each vertical stress. This graph determines the swell pressure as the stress corresponding to zero strain.

Results and discussion

Free swelling

Free swell curves for each soil-rubber mixture are shown in Fig. 4, where the test time (in seconds) is plotted versus vertical strain (mm). This data shows a free expansion of 29.42% was obtained for the natural soil without rubber. This value decreased as rubber content increased, resulting in free swell values of 21.96%, 15.61%, and 9.80% for rubber contents of 5%, 10%, and 20%, respectively. These values result in significant reductions in the free swelling of the original soil, achieving a 25.36% decrease in expansion with 5% rubber, a 46.94% decrease with 10% rubber, and the highest reduction of free swell is obtained with a mixture containing 20% rubber, resulting in a 66.69% reduction in swelling.

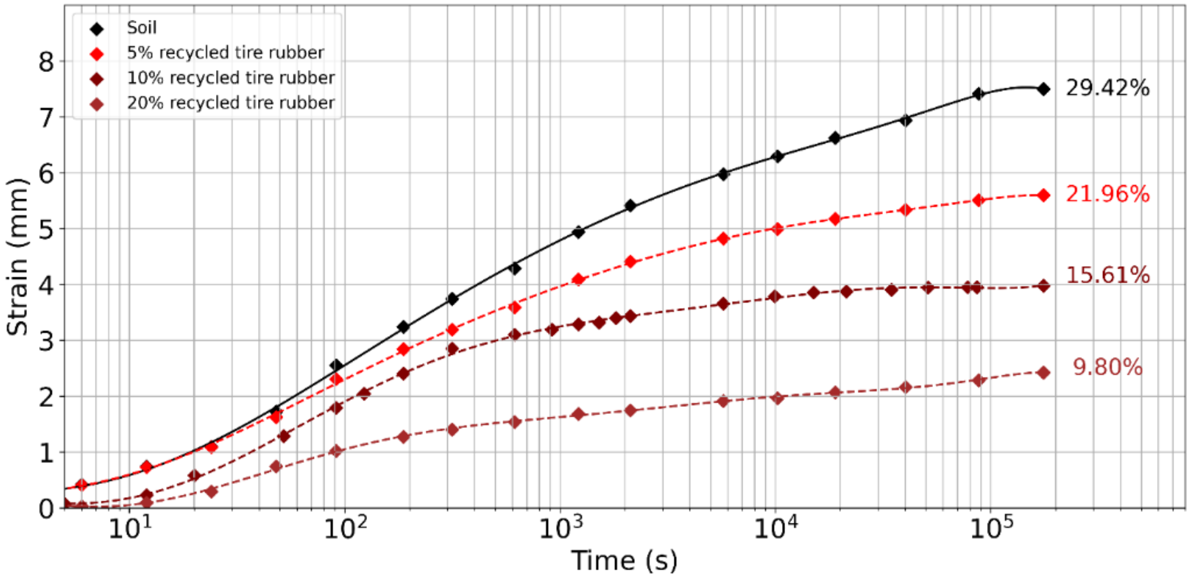

Figure 4: Time-swell curves for free swell analysis.

As shown in Fig. 4, the expansion process consists of 3 common swell stages: initial, primary, and secondary [24]. The initial swell is related to the soil microstructure, where the active clayey minerals (e.g., montmorillonite) expand within the soil voids. This expansion continues until all the interconnected voids are filled with water. The primary expansion also begins at the microstructure level. In time-swell curves, this expansion is described graphically by a linear segment with a steep slope. The primary expansion stage typically accounts for up to 80% of the total strain. Finally, the secondary stage also intervenes in the soil microstructure, with low increments that depend on time and soil micropores.

Swelling pressure

Seven identical specimens were tested for each soil-rubber mixture by applying different vertical stresses: 1, 20, 50, 100, 200, 400, 600, and 800 kPa. Strain data was recorded for 72 hours for each specimen tested. The obtained swell/collapse curves are presented in Fig. 5, where the vertical stress (kPa) is plotted versus strain (%). The swell pressure corresponds to the vertical stress that produces no strain (i.e., zero strain). As shown in such figure, the swell pressure measured for the natural soil equals 655.1 kPa. However, for the soil-rubber mixture with 5% rubber, this pressure decreases to 302.7 kPa, representing a 54% reduction in the natural soil expansion. For the mixtures with rubber contents of 10% and 20%, the swell pressures obtained were 98.0 kPa and 48.0 kPa, respectively, indicating a decrease of 85% and 93% in the original natural soil expansion.

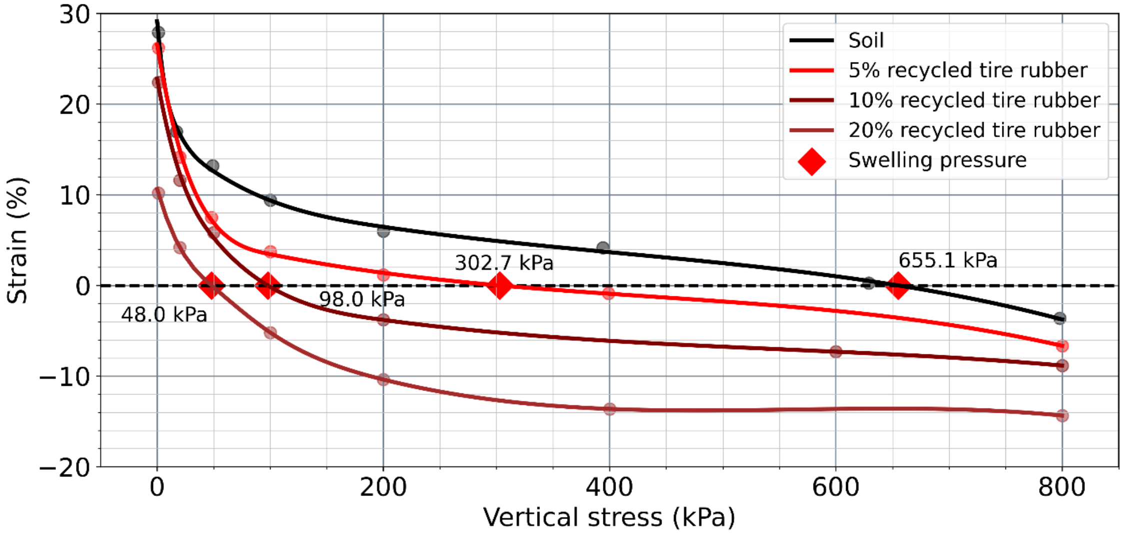

Figure 5: Vertical stress-strain curves for evaluating swelling pressure.

Scanning electron microscopy tests (SEM)

The morphology of the mixtures was analyzed using a scanning electron microscope (SEM) to examine their microstructural characteristics. Samples of approximately 1 cm^3 were utilized, ensuring that the observed surfaces accurately represented the overall material. SEM imaging provided high-resolution visuals of the internal structure, enabling the identification of key morphological aspects such as particle distribution, interfacial interactions, and void formation. Figure 6 displays the SEM images obtained for each mixture, revealing a clear trend: significant morphological changes occur as the rubber content increases. Larger voids become more apparent, likely because of the lower density and irregular shape of the rubber particles. These voids reduce direct contact among soil particles, altering the original matrix responsible for the soil's expansiveness.

The higher porosity found in soil-rubber mixtures is due to the flexible properties and uneven rubber shape, which allows it to avoid compacting like soil, leading to larger spaces between particles. The increased porosity enables the soil's expansion within the voids, alleviating stresses caused by expansion pressures. SEM observations also indicate that rubber creates voids and acts as a mechanical shock absorber, dispersing internal stresses and reducing pressure buildup at points of contact with the soil. This redistribution of stresses contributes to the lower expansion pressures observed in oedometer tests. Further studies, such as energy-dispersive X-ray spectroscopy (EDS), could provide deeper insights into the composition and bonding mechanisms at the interface.

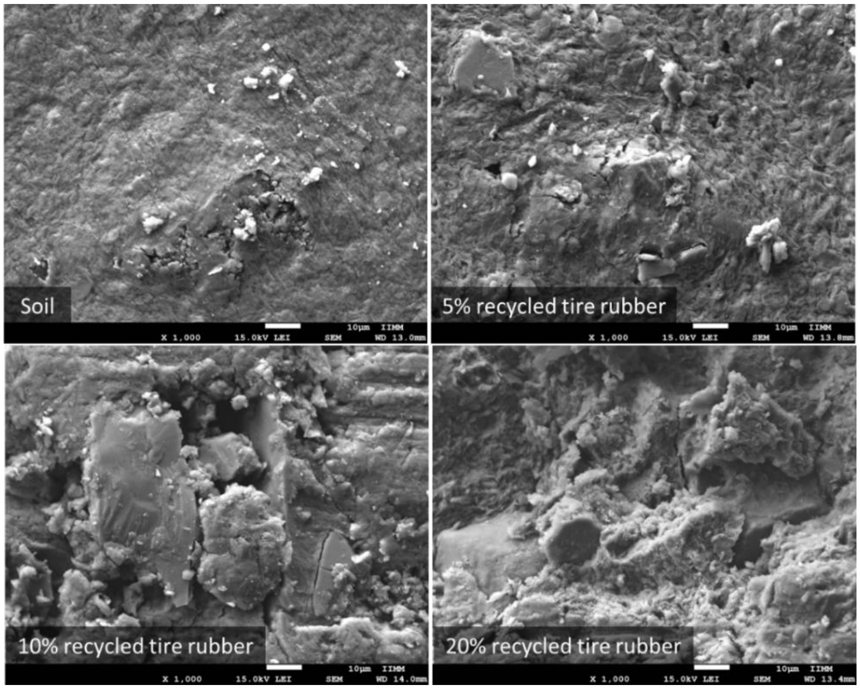

Figure 6: Microstructure of soil mixtures at 1000X.

Conclusions

This experimental research focused on the applicability of granulated recycled tire rubber (<2 mm) as a potential material for stabilizing expansive soil, using rubber contents ranging from 5% to 20% of dry soil weight. The main finding of this study is that recycled rubber effectively decreases soil expansion. Utilizing rubber contents of 5%, 10%, and 20%, the subsequent reductions were recorded:

- For free swell: 25%, 47%, and 67%, respectively.
- For swell pressure: 54%, 85%, and 93% respectively.

While the best results were obtained with the 20% rubber mixture, some warnings should be acknowledged. These mixtures were difficult to process and required higher compact energies to achieve the desired densities. The results indicate that recycled rubber can be a sustainable alternative for mitigating the volumetric changes of expansive soils resulting from moisture variations. However, a comprehensive geotechnical characterization of soil-rubber mixtures requires additional mechanical strength testing, such as triaxial or compression tests, to reduce uncertainty regarding their applicability. Furthermore, SEM analysis revealed that increasing the rubber content leads to larger voids and decreased soil-rubber contact, which may compromise mechanical properties performance. Although swelling is reduced, additional studies, such as EDS analysis, are needed to optimize the reliability of these mixtures for geotechnical applications.

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