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Mechanical parameters of soil-rubber mixtures for sustainable geotechnical projects

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Article

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Abstract

The inadequate disposal of rubber waste from scrap tires is a globally recognized problem. In Brazil alone, 12.23 million tires were manufactured in the first quarter of 2024. The incorporation of this solid waste into geotechnical projects can serve to mitigate the environmental impact of its disposal. The results of the characterization, static, and dynamic tests performed on a Brazilian lateritic clayey soil and soil-rubber mixtures are presented in this study. The tests were conducted with pure soil and with soil-rubber mixtures in proportions of 2.5%, 5.0%, 7.5%, 10.0%, 12.5%, and 15.0% of rubber weight in relation to the weight of the pure soil. A novel methodology for determining the damping ratio (D) parameter directly from the top of the compacted pure soil and soil-rubber mixtures is presented. Based on this study, the rubber from shredded scrap tires can be used in applications such as compacted embankments, soil walls reinforced with geosynthetics, and seismic barriers. However, it is not recommended for use in pavement layers. The results indicated that the increase in the percentage of rubber leads to the decrease in the following parameters of the mixture: resilient modulus, shear modulus, elastic modulus and damping ratio. The cohesion of the mixture increase slightly, as the percentage of rubber increase.

1. Introduction

In Brazil alone, 12.23 million tires were produced in the first quarter of 2024, according to the ANIP (2024). Over the decades, several authors around the world have reported results from the use of different types of fibers in soil mixtures, with the objective of improving their mechanical properties. One alternative to achieve this type of improvement is the incorporation of rubber into the soil matrix. Recent examples from literature have demonstrated that the variation in mechanical properties is dependent on both the type of soil and the rubber used (with particular emphasis on its shape and size). The majority of these studies have focused on predominantly sandy soil mixtures and the static behavior characteristics of these composite materials. Unlike other studies the present study used fine-grained soil with lateritic behavior. Rubber from shredded scrap tires was used in the present study.

Cetin et al. (2006) investigated the influence of rubber content on the Atterberg limits on cohesive soil with low plasticity mixed with rubber chippings from recycled tires. This trend was also observed in the present study. They found that w_L decreased when more than 30.0% rubber was incorporated into the soil, while w_p decreased when 10.0% to 20.0% rubber was added.

The reduction in unit weight of composite materials (soil-rubber) was observed by Edil & Bosscher (1994) and Cetin et al. (2006). This is of interest in geotechnical applications where weight reduction of the soil mass is relevant, such as geosynthetic reinforced soil walls and embankments over soft soils (the lower the weight, the smaller the settlement).

The more pronounced increase in strength parameters observed by Cetin et al. (2006) can be attributed to the type of rubber that was used. In the present study, fiber-shaped shredded tire rubber with an average diameter of 5.0 mm was used. In contrast, Cetin et al. (2006) used two distinct types of rubber chippings with equidimensional shapes resembling small cubes. The particle-size distribution indicated that the rubber chippings were not larger than 5.0 mm in equivalent diameter.

Nakhaei et al. (2012) worked with rubber-granular soil mixtures and observed a reduction in the damping ratio (D) with increasing rubber content in the soil. Senetakis et al. (2012) analyzed the dynamic properties of rubber-granular soil mixtures and observed a reduction in the damping ratio with the addition of rubber to the soil. Improvements in the

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damping ratio were observed in soil-rubber mixtures by Okur & Umu (2018).

The existing literature shows that the decrease in the shear modulus (*G*) with increasing shear strain (γ) also occurs in mixtures of sand and rubber, as found by Mashiri et al. (2015), Pistolas et al. (2018) and Okur & Umu (2018) who reported a decrease in *G* due to an increase in the percentage of rubber.

The primary objective of this research was to determine whether there was an improvement or degradation in the mechanical behavior of a Brazilian clayey residual and lateritic soil mixed with rubber in terms of its mechanical properties. The rubber was obtained from shredded scrap tires. Another objective of this study is to present an innovative procedure for measuring the damping ratio (D) of the compacted soil or soil-rubber mixtures.

The rubber content used in the studies was 2.5%, 5.0%, 7.5%, 10.0%, 12.5%, and 15.0% of the rubber weight in relation to the weight of pure soil. The soil was sampled at the Federal University of Juiz de Fora (UFJF), located in the city of Juiz de Fora, Brazil. The objective of the study was to investigate the mechanical behavior of a soil-rubber mixture. To this end, laboratory tests were conducted on pure soil and soil-rubber mixtures. The soil in question is a Brazilian residual soil with a high percentage of fines (54.0%) and lateritic behavior.

A novel methodology for determining the damping ratio (*D*) parameter directly from the compaction tests is presented. The methodology uses an accelerometer attached to the top of compaction socket.

2. Materials and methods

This section outlines the general methodology and standards employed in the tests performed on pure soil and soil-rubber mixtures presented in this section.

2.1 Specimen preparation

Seven materials were used: pure soil and six soil-rubber mixtures. The composite materials were prepared by mixing dry rubber and then dry soil in proportions of 2.5%, 5.0%, 7.5%, 10.0%, 12.5%, and 15.0% of the rubber weight relative to the weight of the pure soil (W_R/W_S), before adding water. The addition of water was gradual, with each addition interspersed with soil homogenization. The mixture was then allowed to rest for 24 hours (inside a sealed plastic bag) in order to achieve a uniform consistency.

The specimens for the mechanical tests (monotonic triaxial tests and damping ratio tests) were prepared by carving the test specimens to standardized dimensions in accordance with the respective normative requirements of each test. Prior to molding, the soil and soil-rubber mixtures were compacted in the Normal Proctor cylinder NBR 7182 (ABNT, 2016c) at their respective optimum compaction moisture contents. The specimens for the dynamic triaxial tests were compacted in the equipment mold ($\emptyset_m$ = 10.0 cm and H_m = 20.0 cm).

2.2 Soil and rubber characterization

The Atterberg limits were determined for the pure soil and soil-rubber mixtures. The liquid limit was determined in accordance with the Brazilian standard NBR 6459 (ABNT, 2016e) using the Casagrande apparatus. Additionally, the liquid limit was determined using the FCT (Fall Cone Test) equipment in accordance with the British Standard BS 1377 (BS, 2022). The plasticity limit was determined exclusively via the glass plate method, employing the Brazilian standard NBR 7180 (ABNT, 2016d). The shrinkage limit test was conducted in accordance with the recommendations set forth in the Brazilian standard NBR 7183 (ABNT, 2014a). A total of 35 tests were conducted to determine the Atterberg limits.

The determination of the grain-size distribution was obtained according to the procedure recommended by the Brazilian standard NBR 7181 (ABNT, 2016b). For the pure soil, the test was performed using sieving and sedimentation. For the pure rubber, the test was done by sieving only. The determination of the unit weight of solids for the pure soil and pure rubber was done using the pycnometer test according to the Brazilian standard NBR 6508 (ABNT, 2014b) and the determination of the natural water content was done using the test recommended by NBR 6457 (ABNT, 2016a). Physicochemical tests were also conducted following the recommendations of Teixeira et al. (2017).

2.3 Standard compaction tests and compaction tests with damping ratio measurement

Compaction tests were performed on pure soil and soil-rubber mixtures to determine the optimum moisture content and the maximum dry weight of the samples, following the recommendations of the Brazilian standard NBR 7182 (ABNT, 2016c). All tests were carried out using the standard Proctor compaction energy.

The specimens (with and without rubber) used in the monotonic triaxial tests, dynamic triaxial tests, and damping ratio tests were molded from compacted samples under the previously determined optimum moisture content and maximum dry unit weight. This methodology ensured that all results from the aforementioned tests reflected a condition in which the soil was compacted for a specific study.

In addition to the standard compaction tests, a series of compaction tests with an accelerometer attached (Figure 1a) to the socket were conducted on the pure soil and the mixtures. In these tests, only values corresponding to the optimum moisture content obtained in the compaction curves were used, resulting in unit weight values equal to $\gamma_{d,max}$. As with the standard compaction tests, the energy applied in these tests was standard Proctor. An accelerometer was affixed to the top of the socket in order to measure acceleration during the fall and peal (Figure 1b). By interpreting the acceleration values, the damping ratio (*D*) parameter was determined for the pure soil, pure rubber and soil-rubber mixtures.

After the compaction of the pure soil and the mixtures under optimum moisture conditions, five determinations were made per specimen to determine the damping ratio of the pure soil, the mixtures, and the pure rubber. The determinations were made in the center of the compacted specimen inside the compaction cylinder, which is the same one used for the compaction tests according to the Brazilian standard NBR 7182 (ABNT, 2016c).

The determination of damping ratios was conducted using a Bruel & Kjäer 4507-B-005 piezoelectric IEPE accelerometer (100 mV/g sensitivity, frequency range between 0.4 and 6000 Hz, maximum operating level ± 5 g, and temperature operating range between – 54 and 100 °C). For each test, the socket was released from a height of 10.0 cm to standardize the measurements. A total of five measurements were taken for each specimen. The average of the five measurements represents the *D* value for the soil-rubber mixtures, pure soil, and pure rubber. Vibration data was recorded using a Lynx ADS1800 acquisition system with eight analog inputs at an acquisition rate of 12.000 Hz.

Damping ratio is a dimensionless measure that describes the behavior of oscillations in a system following a disturbance. Many systems exhibit oscillatory behavior when disturbed from their static equilibrium position. Damping ratio is therefore a measure that describes the rate at which oscillations decrease with time.

An automatic modal identification procedure, based on the Stochastic Subspace Identification (SSI) data technique, was used to calculate damping ratios from the acceleration responses. This procedure was described in detail by Cardoso et al. (2017). The objective of these tests is to evaluate the change in the damping ratio (*D*) value as a function of the increase in rubber content in the soil.

2.4 CIU triaxial tests

Triaxial tests at constant confining stress were carried out to evaluate the deformation modulus (*E*) and the effective (c' and ϕ') and total (c and ϕ) strength parameters of the pure soil and soil-rubber mixtures. The hyperbolic parameters *n* and *K* were also evaluated using the methodology presented by Duncan et al. (1980). Such parameters are part of the empirical equation of Janbu (1963), which relates the variation of the elastic modulus as a function of the confining stress (σ_3). The soil-rubber mixtures for these tests contained 10.0% and 15.0% rubber.

The specimens were subjected to CIU-type tests, which were saturated and then hydrostatically consolidated. After hydrostatic consolidation, the specimens were subjected to shear under undrained conditions. Pore pressures were measured during the tests and the confining stresses applied were equal to 50, 75, 150, and 225 kPa. The tests were performed in accordance with the recommendations of ASTM D4767-11 (ASTM, 2020), at a strain rate of 0.02 mm/min. In this case, a PVC pipe with an inner diameter of 38 mm and a height of 76 mm was used. A total of 12 triaxial tests were performed.

(a) (b)

Figure 1. Damping Ratio (D) Measurement Equipment: (a) Bruel & Kjäer 4507-B-005 Piezoelectric IEPE accelerometer; (b) Schematic figure of the apparatus for damping ratio measurements.

2.5 Dynamic triaxial tests

Dynamic triaxial tests were performed to determine the shear modulus (*G*) and the resilient modulus (M_r). The soil-rubber mixtures for these tests contained 5.0%, 10.0%, and 15.0% rubber. The tests were performed with confining stresses (σ_3) of 20, 35, 50, 70, 105, and 140 kPa, according to the test method established by the Brazilian Standard DNIT 134 (DNIT, 2018).

The tests were performed with 10 loading/unloading cycles. The parameters *G* (shear modulus), γ (shear strain), and M_r (resilient modulus) were calculated based on the average results of the last 5 cycles out of 10 cycles of loading and unloading applied to the specimen. At total of 18 stress pairs (σ_1/σ_3) were applied in a set of 10 loading/unloading cycles. The loading and unloading cycles were applied at a frequency of 1 Hz, in accordance with the aforementioned standard.

From these tests, it was possible to determine the shear modulus (*G*) versus shear strain (γ) curves and also the resilient modulus (M_r) versus deviator stress (σ_d) curves. The values of G_o, the maximum shear modulus, were also determined. A total of 18 dynamic triaxial tests were performed.

3. Results and discussion

This section presents the results of the tests described in Section 2 along with a discussion of the findings.

3.1 Characterization of the soil and rubber

The soil was classified as residual lateritic by partial chemical analysis as a function of the values of the weathering indices, k_i (1.56) and k_R (1.13), according to Teixeira et al. (2017). The cation exchange is low (2.9) and kaolinite is the predominant clay mineral.

The residual lateritic soil used in the present research is classified as ML type, according to the USCS classification. In its pure state, the soil has the Atterberg limits: liquid limit 44% FCT (Fall Cone Test), liquid limit 37% (Casagrande equipment), plasticity limit 31% and shrinkage limit 25%.

The results of the Atterberg limits for pure soil and the soil-rubber mixtures are presented in Figure 2. It was observed that as the rubber content increases, the liquid limit decreases slightly, but the value of w_L corresponding to 15.0% rubber content remains almost the same as the value of w_L for pure soil. Therefore, the addition of rubber up to 15.0% does not affect this characteristic of the soil when evaluated using both the FCT and Casagrande methods.

A slight difference (up to 8.52%) was observed between the w_L values determined by the Casagrande and the FCT methods. The shrinkage limit (w_S) and the plastic limit (w_p) determined by the FCT method exhibited a similar tendency of slight decrease with increasing rubber content. The plastic limit (w_p) determined by the glass plate method NBR7180 (ABNT, 2016d) showed a slight increase as the rubber content increased to 7.5%. A significant difference (up to 16.10%) was observed in the w_p values obtained by the Casagrande and FCT methods. The plasticity index (*PI*) ranged from 5.65% in pure soil to 9.80% in the mixture with 15.0% rubber.

Figure 3 shows the particle size distributions for the pure soil and the pure rubber. Note that the pure soil contains 54% clay content. The pure soil has an activity index (*A*) of 0.12, indicating that it is non-active clay. The specific weight of soil solids (γ_s) was determined to be 28 KN/m^3 using a pycnometer test in accordance with Brazilian Standard NBR 6508 (ABNT, 2014b). Figure 3 depicts the particle size distribution of pure soil and rubber particles. Figure 4 shows the rubber used in this study, where filaments with an average length of 5.0 mm can be observed.

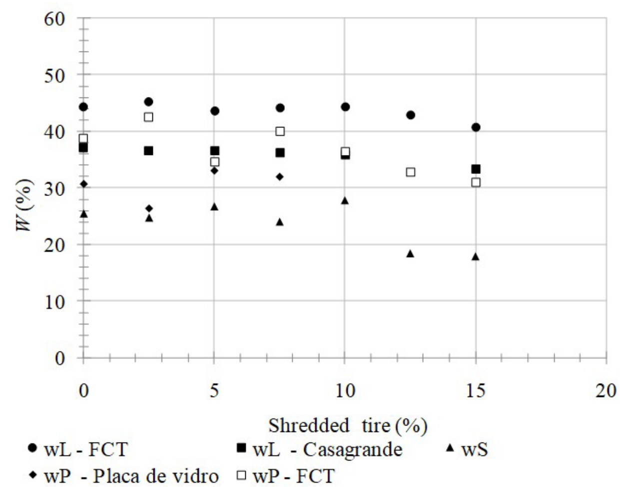

Figure 2. The variation in the Liquid, Plastic, and Shrinkage Limits with an increase in rubber content (weight).

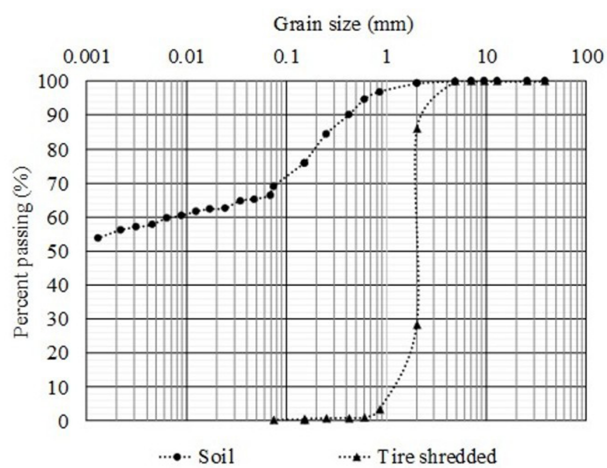

Figure 3. Grain-size distribution - pure soil and rubber from shredded tires.

All mixtures used were also classified as ML type (high plasticity silt); i.e., rubber contents up to 15.0% did not change the soil classification in the case of unified classification. This was due to the small variation of the liquid and plastic limits with respect to the rubber content as shown in Figure 3.

The rubber used in this study is classified as SP (SUCS Classification) according to its particle-size distribution and the value of the coefficient of uniformity, Cu = D_{60}/D_{10} = 2 / 1.2 = 1.7 (see Figure 3). The unit weight of rubber solids is 12.8 KN/m^3, based on the pycnometer test performed according to the Brazilian Standard NBR 6508 (ABNT, 2014b). The natural moisture content (W) was 0.8%, determined by drying the rubber in an oven according to the Teixeira et al. (2017) manual. It should be noted that as the rubber content increases, the specific weight of the mixture's solids gradually decreases, since the unit weight of the rubber solids is lower than that of the pure soil solids.

Figure 4. Rubber chippings employed in this research were obtained from shredded scrap tires (scale in centimeters).

3.2 Standard compaction tests and tests with damping ratio measurement

Figures 5a through 5g show the compaction curves obtained for the pure soil and the mixtures. The results show that the compacted pure soil has a maximum apparent specific weight of 16.1 KN/m^3 and an optimum moisture content of 26%. The dry unit weight and optimum moisture content were determined for the pure soil and the mixtures containing 2.5%, 5.0%, 7.5%, 10.0%, 12.5% and 15.0% rubber.

Table 1 presents the results in terms of dry unit weight and optimum moisture content. As expected, the maximum dry unit weight values decreased with increasing rubber content, while the optimum moisture content values did not show a well-defined variation trend.

It is noteworthy that for the pure soil the unit weight (γ) is equal to 20.1 kN/m^3, whereas for the mixture with 15.0% rubber the value of γ = 16.4 kN/m^3, which represents a reduction in the unit weight of the compacted soil of 18.4%. Therefore, as previously stated, this is an advantage for projects such as reinforced soil walls and embankments compared to soft soils.

The optimum moisture content values of the soil-rubber mixtures remained relatively consistent, ranging between 25.5% and 28.5%. Therefore, the rubber content (up to 15.0%) did not significantly impact the optimum moisture content.

Cetin et al. (2006) reported that the optimum moisture content was 19.0% for pure soil and 24% for the soil-rubber mixture with 50.0% rubber. Thus, there is a slight variation in the optimum moisture content with the addition of rubber. Kalkan (2013), while studying mixtures of predominantly clayey soil and rubber, also observed a slight variation in optimum moisture content with the incorporation of rubber into the soil. Edil & Bosscher (1994) worked with rubber-sand and rubber-soil mixtures. These authors also found that the addition of rubber did not significantly change the optimum moisture content.

Table 1. Dry unit weight and optimum moisture content from standard compaction tests.

Material	$\gamma_{d,max}$ (kN/m^3)	W_o (%)	γ (kN/m^3)
Pure soil	16.0	25.5	20.1
Mixture 2.5%	14.7	27.5	18.7
Mixture 5.0%	14.2	26.2	17.9
Mixture 7.5%	13.6	25.8	17.1
Mixture 10.0%	13.4	25.5	16.8
Mixture 12.5%	13.2	26.3	16.7
Mixture 15.0%	12.8	28.5	16.4

Note: $\gamma_{d,max}$ = maximum dry unit weight; W_o = optimum moisture content; γ = unit weight; $\gamma = \gamma_d \cdot (1 + W)$.

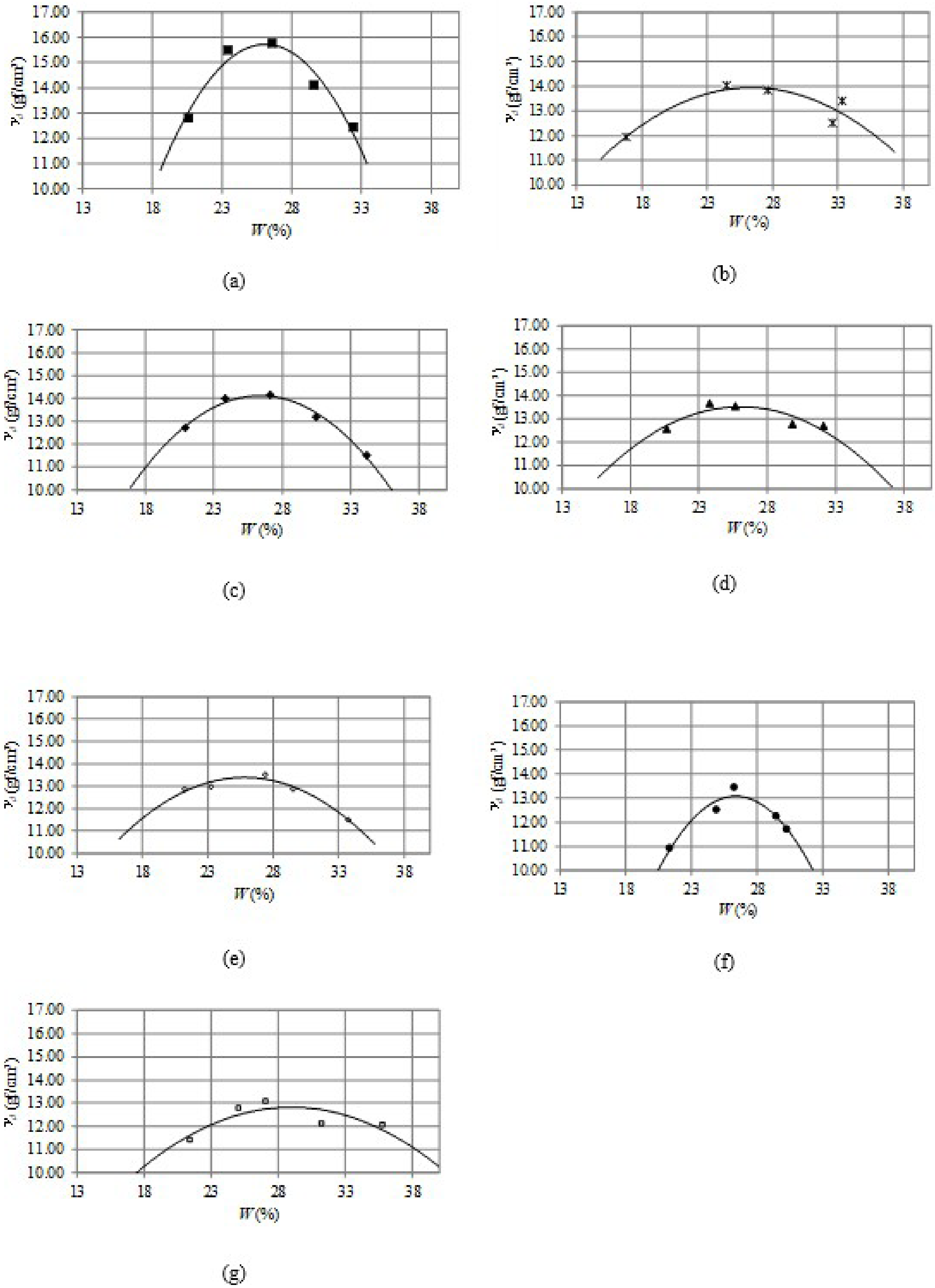

Figure 5. Compaction curves: (a) pure soil; (b) Mixture 2.5%; (c) Mixture 5.0%; (d) Mixture 7.5%; (e) Mixture 10.0%; (f) Mixture 12.5%; and (g) Mixture 15.0%.

Figure 6 shows the relationship between percent of rubber content and average damping ratios (five determinations were made for each soil-rubber mixture). Each point on the graph is the result of five tests, each characterized by the fall of a single socket (instrumented with an accelerometer). Figure 6 shows that as the rubber content increases, the damping ratio (D) decreases. This behavior is more evident when comparing the pure soil condition with the condition in which the rubber content varies from 2.5% to 15.0% and when comparing the corresponding D values with the D value for pure rubber. Therefore, the addition of rubber to the soil results in higher energy absorption. The damping ratio values D = 3.5 and D = 0.6 were obtained for pure soil and pure rubber, respectively. Note that the average value obtained for the soil-rubber mixtures was D = 1.2.

The introduction of rubber into the soil matrix can be important for projects located in areas subject to seismic loads. For example, the higher the amount of rubber in the mixture, the higher the vibration absorption of the composite structure in the event of an earthquake. The procedure for determining the damping ratio (D) presented in this study can be used directly in the field to evaluate this parameter.

3.3 CIU triaxial tests

This section presents the results of the CIU triaxial tests with pore pressure measurement. Figures 7, 8 and 9 show the results of deviator stress (σ_d) versus specific axial strain (ε_a) curves for the confining stresses used, which were 50, 75, 150, and 225 kPa.

As shown in Figures 7, 8 and 9, an increase in axial strain (ε_a) was observed in the composite material (10.0% and 15.0% mixtures) up to the maximum shear strength ($\sigma_{d,max}$) compared to the behavior of the pure soil.

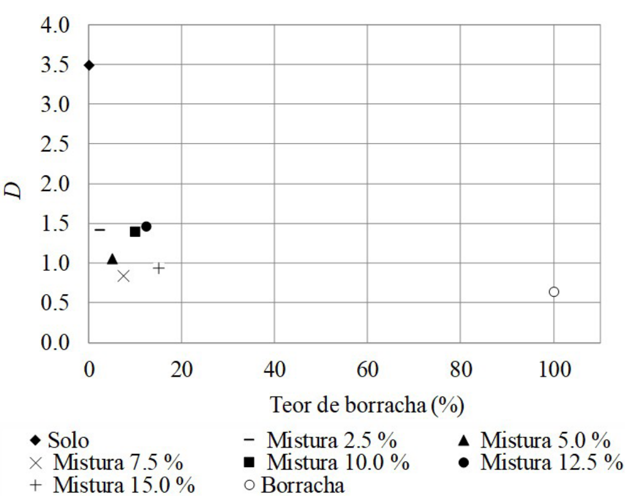

Figure 6. Rubber content versus damping ratio (D) plot.

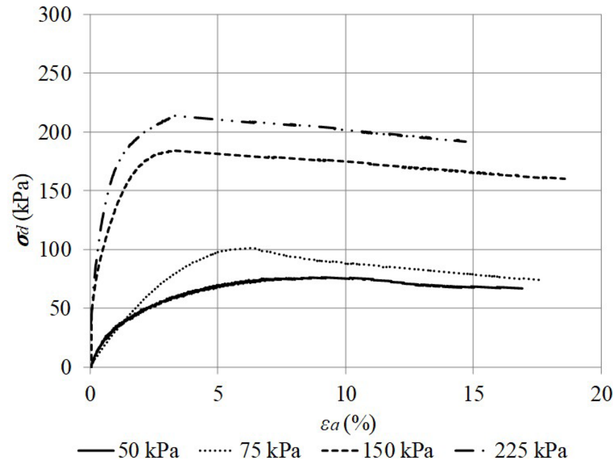

Figure 7. Deviator stress (σ_d) x specific axial strain (ε_a) curves - pure soil.

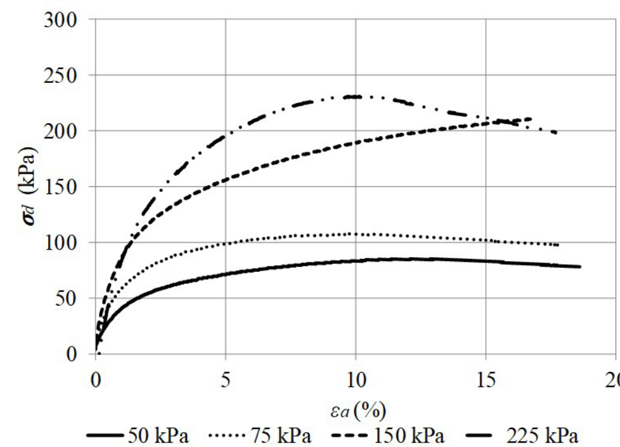

Figure 8. Deviator stress (σ_d) x specific axial strain (ε_a) curves - mixture with 10.0% rubber.

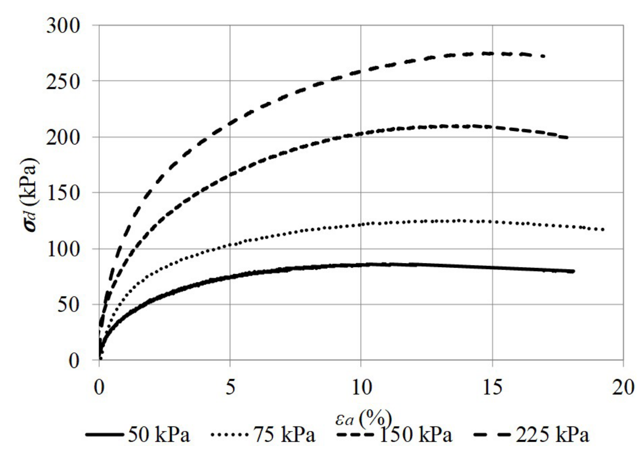

Figure 9. Deviator stress (σ_d) x specific axial strain (ε_a) curves - mixture with 15.0% rubber.

The incorporation of rubber allows the composite to tolerate higher deformations, making it more ductile than the pure soil. The pure soil exhibited low peak strength (for σ_3 = 75, 150, and 225 kPa), whereas the mixtures demonstrated maximum deviator stress only in the case of a 10% rubber content mixture and σ_3 = 225 kPa.

Thus, the addition of rubber helps prevent the loss of shear strength in conditions where the soil-rubber mixtures are subjected to deformations of considerable magnitude, such as those exceeding 10.0%. This condition can occur in geotechnical structures subjected to very high static loads or even in structures subjected to earthquake-induced loading or even moderate seismic events.

Figure 10 presents the shear strength envelope in terms of effective and total stresses for pure soil. Figures 11 and 12 show the same types of envelopes for mixtures containing 10.0% and 15.0% rubber, respectively.

The shear strength parameters, cohesion and friction angle, were determined for the pure soil and the soil-rubber mixtures. The parameters were determined from the total and effective shear strength envelopes. Table 2 shows the shear strength parameters of the pure soil and the mixtures in terms of total (c and ϕ) and effective (c' and ϕ') parameters.

As for the total strength parameters (c and ϕ), Table 2 shows that there was no discernible trend in the increase or decrease of these parameters in relation to the addition of rubber. In general, the total shear strength parameters increase with the addition of rubber compared to the pure soil. This is not occurs except in the case of total cohesion (31 kPa) for the mixture with 10% rubber content. The decrease in the cohesion of the 10% mixture appears to be compensated by an increase in the friction angle.

The effective strength parameters (c' and ϕ') showed a slight upward trend as more rubber was added. The effective cohesion increased from 20 kPa to 26 kPa as the rubber content increased to 15.0%. The effective friction angle increased slightly from 44.0° to 45.0°.

In general, the addition of rubber contributed to an increase in the shear strength of the soil in terms of effective parameters. The mechanical behavior of the composite material improved somewhat, but not significantly. It is important to emphasize that the incorporation of rubber into the soil matrix does not cause a deterioration of the original shear strength, i.e. the parameters of the pure soil. The total cohesion of 31 kPa in the mixture 10% rubber is not the general rule. This behavior (decrease in cohesion with addition of rubber) may be related to some heterogeneity in the specimens in terms of distribution of rubber particles. In this case, there may be some overconcentration or under concentration of rubber. The problem of the spatial distribution of the rubber particles has a greater impact when the dimensions of the specimens are small, as was the case with the specimens used in the tests (diameter = 38.0 mm and height = 76.0 mm).

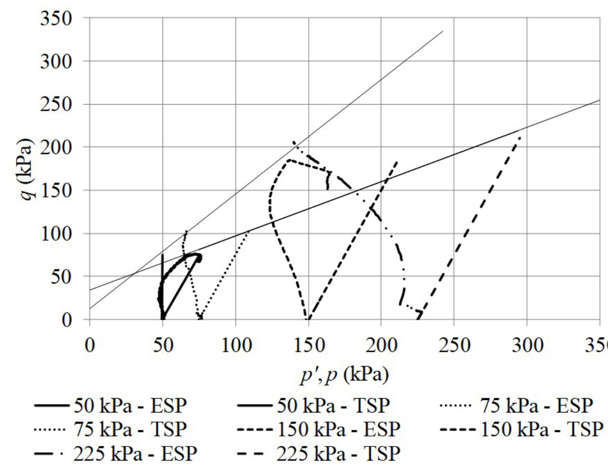

Figure 10. Shear strength envelope (q x p', p) for pure soil. TSP = total stress path; ESP = effective stress path.

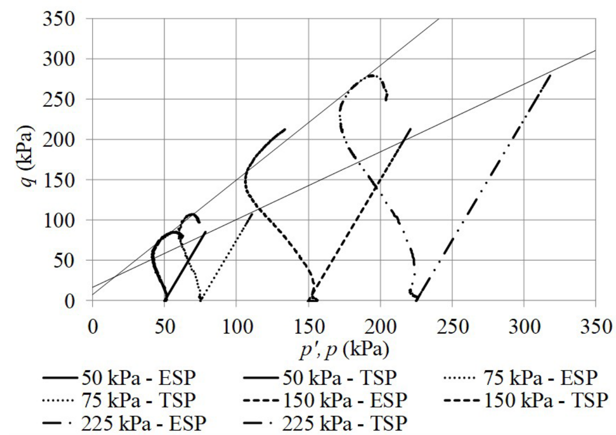

Figure 11. Shear strength envelope (q x p', p) for a mixture with 10.0% rubber. TSP = total stress path; ESP = effective stress path.

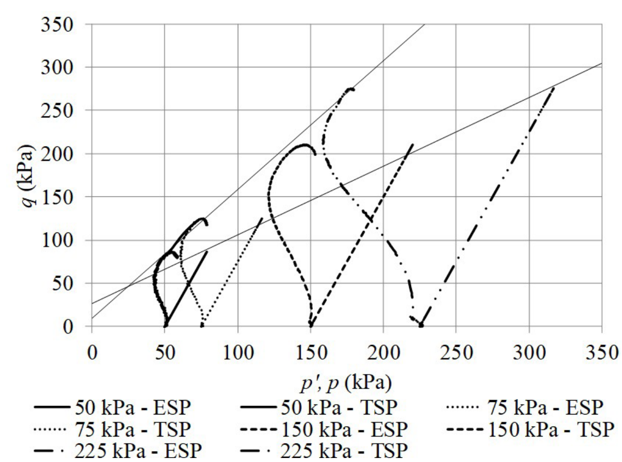

Figure 12. Shear strength envelope (q x p', p) for a mixture with 15.0% rubber. TSP = total stress path; ESP = effective stress path.

Table 2. Effective and total strength parameters - pure soil and soil-rubber mixtures.

Materials / Parameters	c (kPa)	ϕ (°)	c' (kPa)	ϕ' (°)
Pure soil	44	39	20	44
Mixture (10.0%)	31	57	23	45
Mixture (15.0%)	44	52	26	45

Table 3. $E_{50\%}$ values obtained from the σd x εa curves as a function of confining stress and rubber content.

Materials	$E_{50\%}$ (MPa)			
	σ_3 = 50 MPa	σ_3 = 75 MPa	σ_3 = 150 MPa	σ_3 = 225 MPa
Pure Soil	4.5	8.0	24.0	27.8
Mixture (10.0%)	2.8	7.9	17.5	18.3
Mixture (15.0%)	2.1	6.0	10.5	13.8

In this sense, the observed increase in strength, although small, can be attributed to the rubber particles acting as reinforcing fibers within the soil matrix. For practical applications, the use of effective parameters is more consistent with the condition of the soil-rubber mixture compacted under optimum moisture content conditions and without generating excess pore pressure. It is noteworthy that the strength gain occurs even with a reduction in the apparent specific weight of the composite materials, which is advantageous for several types of geotechnical projects, i.e. less weight and more strength.

Table 3 presents the values of the secant modulus of elasticity ($E_{50\%}$) related to the 50.0% $\sigma_{d,max}$ (maximum deviator stress) for all confining stresses used in the triaxial tests (σ_3 = 50, 75, 150, and 225 kPa).

Table 3 shows a tendency for $E_{50\%}$ to increase with increasing confining stress, as expected and reported in the literature (Rao & Dutta, 2006), while $E_{50\%}$ decreases with increasing rubber content. This behavior was observed regardless of the confining stress (σ_3) applied to the specimen. Mashiri et al. (2015) also observed this $E_{50\%}$ reduction behavior as increasing amounts of rubber were added to the soil.

Therefore, the addition of rubber to the soil matrix makes the composite more deformable than pure soil. Typically, the $E_{50\%}$ is reduced by a factor of two when comparing pure soil to a mixture containing 15% rubber. From a practical engineering standpoint, it is not recommended for rigid foundations such as footings and raft foundations.

To provide parameters for modeling geotechnical structures using the Hardening Soil Model, hyperbolic parameters of pure soil and soil-rubber mixtures at 10% and 15% were obtained. Janbu's (1963) equation translates the dependence of the initial elastic modulus (E_i) on the confining stress (σ_3), as shown below by Equation 1:

$$E_i = K \cdot P_a \cdot \left(\frac{\sigma_3}{P_a} \right)^n \tag{1}$$

where K = hyperbolic model parameter; n = modulus exponent (hyperbolic model parameter); σ_3 = confining pressure and P_a is the atmospheric pressure (= 101.53 kPa).

The values obtained for K and n are presented in Table 4, considering the pure soil and the mixtures containing 10% and 15% rubber. These parameters were determined by means of the Duncan et al. (1980) methodology.

The values of n show that the higher the percentage of rubber, the higher the rate of increase in the elastic modulus. The values of K show that the higher the percentage of rubber, the lower the initial elastic modulus.

3.4 Dynamic triaxial tests

The results of dynamic triaxial tests on the pure soil and soil-rubber mixtures are presented in this section. Figure 13 illustrates the results obtained for the G (shear modulus) versus γ (shear strain) curves and Figure 14 shows the results obtained for the M_r (resilient modulus) versus σ_d (deviator stress) curves.

The effects of shear strains (γ) produced by load/unload cycles in the pure soil and soil-rubber mixtures are shown in Figure 13 in terms of variation in shear modulus (G). The results generally show a decrease in the initial shear modulus (G_0) as the shear strains increase, as expected. This

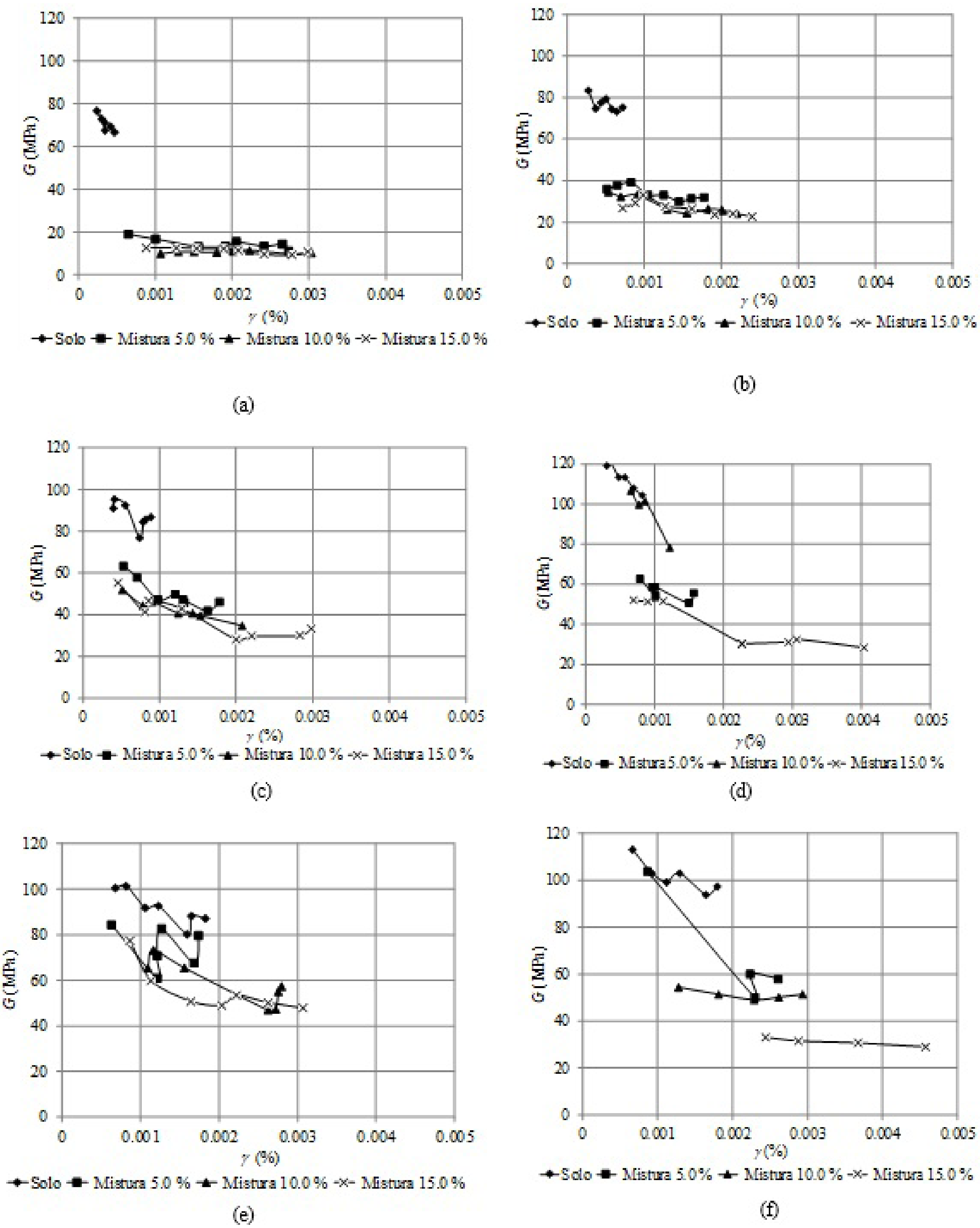

Figure 13. Shear modulus (G) versus shear strain (γ) curves for different confining stresses: (a) σ_3 = 20 kPa; (b) σ_3 = 35 kPa; (c) σ_3 = 50 kPa; (d) σ_3 = 70 kPa; (e) σ_3 = 105 kPa; (f) σ_3 = 140 kPa.

Table 4. Hyperbolic model parameters for pure soil and soil-rubber mixtures (10.0% and 15.0%).

Soil / Mixture	K	n
Pure Soil	120	1.00
Mixture 10.0%	100	4.56
Mixture 15.0%	90	1.51

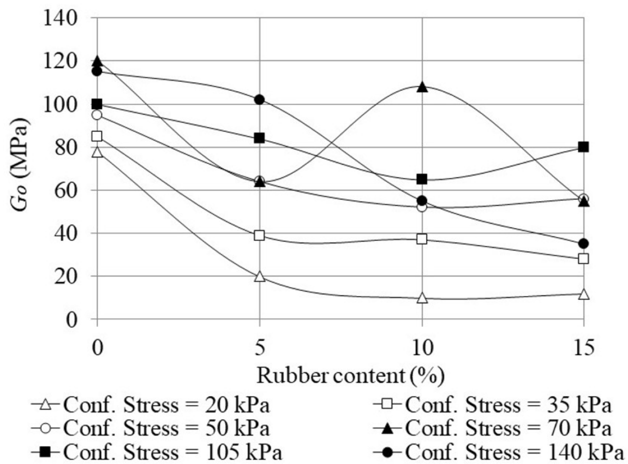

Figure 14. Values of G_0 (in MPa) vs. rubber content and confining stresses (σ_3).

behavior was observed for all conditions tested, i.e., rubber contents of 0.0%, 10.0%, and 15.0%.

The decrease in G value occurs as the rubber content in the soil increases. The G value decreases significantly for rubber contents between 0.0% and 5.0%. Above 5.0% rubber content, the G value decreases at a slower rate. Figure 13 also shows that the G values decrease significantly at higher confining stresses. Therefore, the rate of reduction decreases at low confining stresses of 20 kPa and 35 kPa. Figure 14 shows the initial shear modulus (G_o) for rubber contents ranging from 0.0% to 15.0% and the confining stresses applied in the dynamic triaxial tests (σ_3).

Figure 14 shows a decrease in the initial, or maximum, shear modulus (G_0) as the percentage of rubber added to the soil increases. This behavior was observed for all confining stresses (σ_3) applied to the tests. As the rubber content increases, the highest G_0 decrease rates are observed in tests with lower confining stresses, between 20 and 50 kPa. Figure 14, shows that the shear modulus G_0 tends to increase with the confining stress. This behavior becomes more evident as the confining stresses approach 70 kPa.

The resilient modulus is an essential parameter in the design of paving structures, subjected to loading/unloading cycles. Figure 15 shows the deviator stress (σ_d) versus resilient modulus (M_r) curves for the ten loading cycle stages applied. The curves include pure soil and soil-rubber mixtures with 5.0%, 10.0% and 15.0% rubber content.

Figure 16 presents the resilient modulus (M_r) results obtained from dynamic triaxial tests, varying the confining stress and the rubber content.

The results in Figure 16 show a tendency for the resilient modulus to decrease with a gradual increase in deviator stress (σ_d), with the opposite effect observed in a few cases. Another behavior observed was the gradual decrease of the resilient modulus with increasing rubber content. Because of this observed behavior, the addition of rubber to the soil may not favor the use of rubber in pavement layers. Regarding the maximum deviator stress ($\sigma_{d,max}$), no significant increase or decrease was observed after the addition of rubber.

The results presented in Figure 16 show that, in general, the resilient modulus (M_r) tends to increase with increasing confining stress (σ_3), even when rubber is added to the soil. This behavior was only absent for the 140 kPa confining stress. Figures 14 and 16 show that the inclusion of rubber in the soil tends to reduce the stiffness of the mixture, resulting in lower values of shear modulus (G) and resilient modulus (M_r) compared to pure soil. The main reason for this behavior is the lower modulus of elasticity for the rubber mixtures compared to the pure soil.

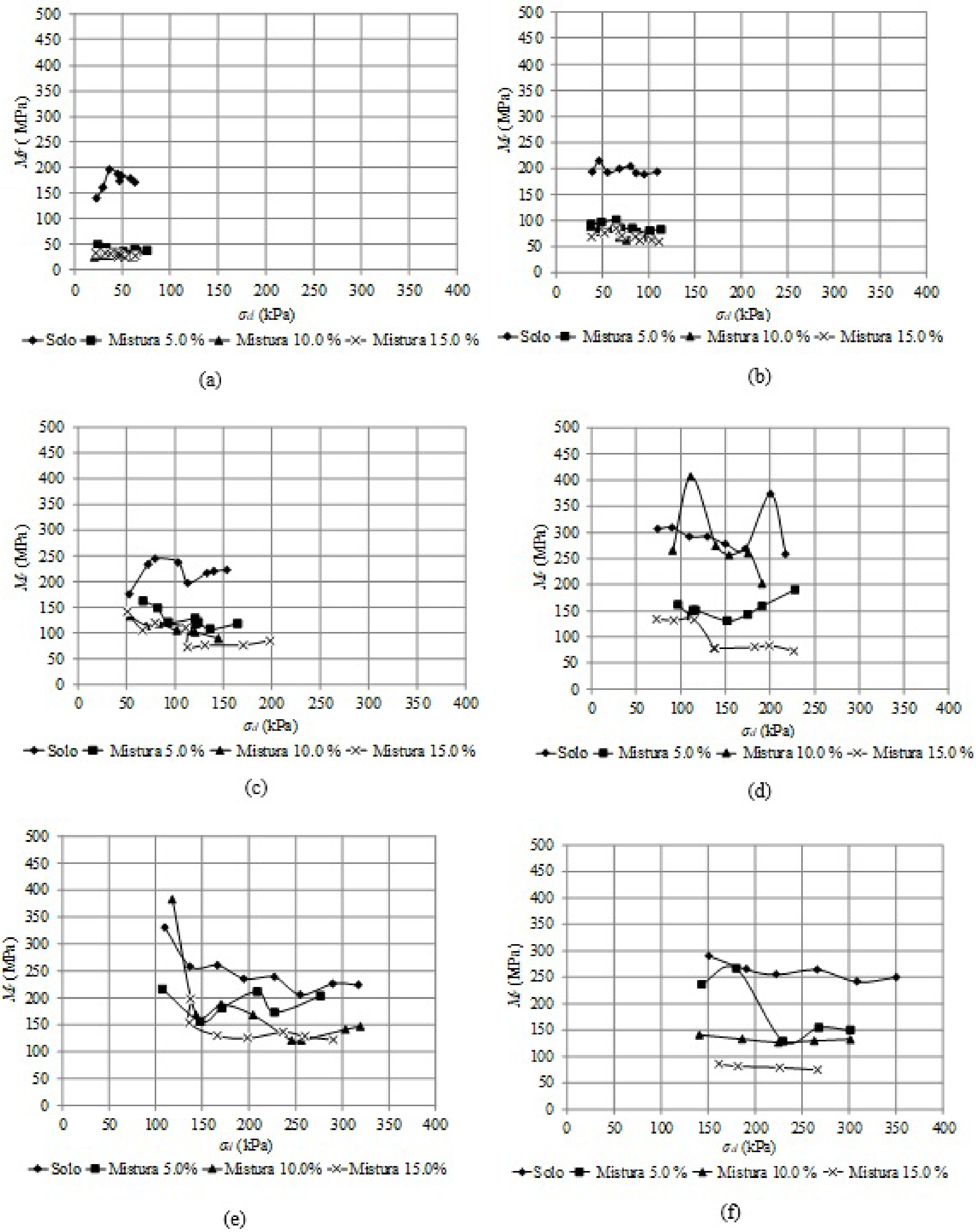

Figure 15. Resilient modulus (M_r) versus deviator stress (σ_d) curves for different confining stresses: (a) σ_3 = 20 kPa; (b) σ_3 = 35 kPa; (c) σ_3 = 50 kPa; (d) σ_3 = 70 kPa; (e) σ_3 = 105 kPa; (f) σ_3 = 140 kPa.

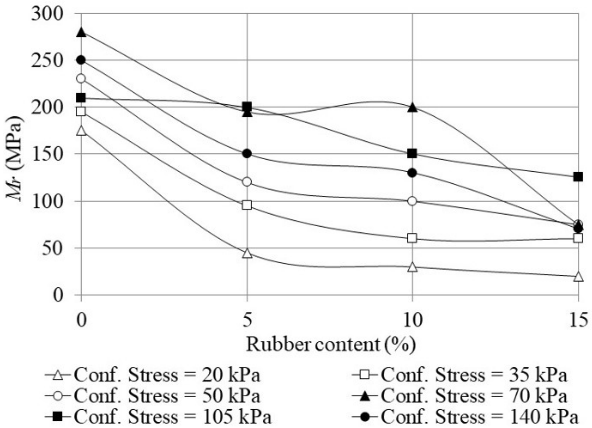

Figure 16. Values of M_r (in MPa) vs. rubber content and confining stress (σ_3).

4. Conclusions

Regarding the geotechnical parameters obtained after testing the pure soil and the soil-rubber mixtures, the following conclusions can be made:

- Liquid and plastic limits change little with addition of up to 15.0% rubber. Therefore, the plasticity index of the clay also changes little with the addition of up to 15.0% rubber. Therefore, the pure soil is still governing the behavior of the mixtures;
- Regarding the standard compaction tests, the results indicated that the optimum moisture remained practically unchanged with the addition of rubber and that the dry unit weight decreased as the percentage of rubber in the mixture increased. Regarding the dynamic compaction tests using accelerometers, the addition of rubber promotes the decrease in the initial damping ratio (D) with respect to the pure compacted soil. This behavior was observed for the lateritic residual soil with a high content of fine particles used in this research;
- The results of triaxial monotonic tests showed that the effective cohesion (c') and the effective friction angle (ϕ') tended to increase slightly with increasing rubber content, representing a gain in shear strength. This trend was not observed for the total parameters (c and ϕ). A decrease in the secant elastic modulus ($E_{50\%}$) was observed with increasing rubber content;
- Regarding dynamic triaxial results, the following observations were made: a) a decrease in the initial shear modulus (G_0) with increasing rubber content and b) a decrease in the shear modulus (G) with increasing shear strain (γ). In general, an increase in the resilient modulus (M_r) was observed with the increase in confining stress, even when higher amounts of rubber were added to the soil. However, the resilient modulus decreased sharply for the same confining stress as the rubber content increased.

Based on this study, the rubber from shredded scrap tires can be used in applications such as: a) compacted embankments; b) soil walls reinforced with geosynthetics; and c) seismic barriers. The first application is more useful regarding sustainability because the volume of compacted composite material involved is very large, depending of the project. The use of the soil-rubber mixture is not recommended in pavement layers.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have reviewed and affirmed the content of the paper and there is no financial interest to report.

Authors' contributions

Lorena Gomes Abrantes: conceptualization, data curation, formal analysis investigation, methodology, software, writing – original draft. Claudio Fernando Mahler: validation, writing – review & editing. Mario Vicente Riccio Filho: supervision, validation, writing – review & editing. Daniel de Almeida Campos Soares: software, validation. Alexandre Abrahão Cury: software, validation.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

Declaration of use of generative artificial intelligence

This work was not prepared with the assistance of generative artificial intelligence (GenAI).

List of symbols and abbreviations

c	Total cohesion
c'	Effective cohesion
n	Modulus exponent (hyperbolic model parameter)
w_L	Liquid limit

w_p	Plastic limit
w_s	Shrinkage limit
A	Activity index
C_u	Coefficient of uniformity
CIU	Consolidated, isotropic, and undrained triaxial test
D	Damping ratio
E	Elastic modulus
$E_{50\%}$	Secant elastic modulus at 50%
E_i	Initial elastic modulus
G	Shear modulus
G_o	Initial shear modulus
K	Hyperbolic model parameter
H_m	Height of the mold
M_r	Resilient modulus
P_a	Atmospheric pressure (= 101.53 kPa)
$USCS$	Unified Soil Classification System
V_t	Total volume
W	Water content
W_o	Optimum moisture content
W_R	Weight of rubber
W_S	Weight of soil
γ	Shear strain
$\gamma_{d,\ max}$	Maximum dry unit weight
γ_n	Unit weight
γ_s	Unit weight of solids
ε_a	Axial strain
σ_1	Major principal stress
σ_3	Minor principal stress
$\sigma_d = \sigma_1 - \sigma_3$	Deviator stress
σ_n	Normal stress
ϕ	Total friction angle
ϕ'	Effective friction angle
$\emptyset_m$	Diameter of the mold

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