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Dynamic shear modulus and damping ratio of recycled concrete aggregate–recycled tire waste mixture using resonant column apparatus

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ABSTRACT

The accumulation of waste tires is a global problem related to natural resources and the environment. The storage or burning of tires causes toxic chemicals to seep into the surrounding environment, which poses a serious ecological threat. Many previous studies have shown that waste tires can be used in geotechnical engineering. It was found that rubber reinforcement can increase the plasticity of sandy soil and improve its shear strength. It can control pore water pressure accumulation and improve dynamic properties. For cohesive soils, rubber additives can reduce dry density and improve compressive strength and soil stability. When mixed with soil with optimum content, waste tires can reduce various adverse effects of waste tire accumulation on the environment. The application of rubber has also a good impact on environmental protection and the promotion of "green design". This paper presents the dynamic properties (shear modulus and damping ratio) of the RCA–RTW mixture for small, medium, and large ranges of shear strain levels (from about $1.5 \cdot 10^{-4}$% to $1.3 \cdot 10^{-2}$%). All specimens are constructed using different percentages of granulated tire rubber and concrete aggregate from curb crushing. A series of laboratory tests, resonant, and damping, are performed in the resonant column apparatus. The maximum shear modulus and minimum damping ratio are presented with the percentage of granulated rubber. The normalization is also applied to the G–modulus and D–ratio data set. Furthermore, a comparison is made between the results obtained for the tested geocomposites and a mixture of pure RCA.

Keywords: dynamic loading; small strains; non-destructive laboratory testing; recycled materials.

1. Introduction

In today's society, reliance on the use of motor vehicles is growing rapidly in various sectors of the economy. Therefore, the continuous increase in the production of motor vehicles not only causes more noise and air pollution but also creates problems in the disposal of waste materials such as tires. Since rubber does not decompose quickly, a suitable disposal method must be found so that it is economical and environmentally friendly (Das and Bhowmik 2020). Some of the standard and effective methods of using waste tires for engineering purposes can be found in geotechnical engineering projects.

From the materials point of view, the tire is a mixture of synthetic and natural rubber, which are added a range of specific substances to ensure performance, durability, and safety. There are different ways of using waste tires (Takano et al. 2015). In general, the use of shredded rubber waste depends on the degree of shredding.

Tire waste, after shredding processes, can be used alone, incorporated into the ground, or mixed with soil. The geotechnical applications of soil-waste tire compositions are favored mainly in transportation infrastructure or in damping systems to reduce vibrations, such as railroad bedding or machine foundations (Edil et al. 2004). Other geotechnical uses of rubber include embankment fill, retaining walls and bridge abutment backfill, insulation layers to limit frost penetration, and drainage layers. Sometimes whole tires are used as retaining walls or reinforcing layers in earth fill or floating breakwater (Aydilek et al. 2006).

Over the past few decades, extensive research has been conducted on the behavior of natural soil-recycled tire waste (NS–RTW) mixtures. These studies are usually based on the evaluation of conventional engineering properties, for example, permeability, compaction characteristics, and/or shear strength parameters, where the mixtures studied are mostly considered under static loading conditions. Regardless of the extensive studies on the physical, chemical, and mechanical properties of NS–RTW mixtures, experimental data on their dynamic properties is rather limited (Okur and Umu 2018). In particular, no reports on the dynamic properties of geocomposites based on anthropogenic soil (e.g. recycled concrete aggregate, RCA) and recycled tire waste (RTW) are readily available in the literature. Most studies to date refer to the mixtures of natural, non-cohesive soils - generally sandy soils. Therefore, this paper focuses on the study of new mixtures derived exclusively from recycled waste materials (from construction, demolition, incineration, or rubber).

The authors previously investigated the compaction properties of RCA–RTW mixtures, their compressibility characteristics, and shear strength characteristics (Gabryś et al. 2021). This made it possible to determine the static properties of such composites. The design of many geotechnical structures like retaining walls, foundations, and slopes subjected to cyclic shear loading conditions (e.g. earthquake or traffic loads) requires the evaluation of the dynamic and cyclic response of RCA–RTW mixtures. Thus, the purpose of this paper is to investigate the small-strain shear stiffness (G_{max}) and shear modulus (G) degradation with increasing shear strain, and damping ratio (D). The quantification of stiffness and damping parameters as a function of the RCA–RTW mixture was performed here. Furthermore, a comparison was made between the results gained for the tested geocomposites and specimens of pure RCA. The results help shed light on the dynamic properties of anthropogenic soil-rubber mixture over a wide range of deformations, which in turn can expand the horizons of the application of recycled materials in construction.

2. Materials and Methods

In this research, a synthetic material recycled tire waste offered by the local shredding company was used. Ground rubber without any textile or steel cord in the size of 0.5–2.0 mm was taken. This material was sieved and separated into two different uniform sizes: powder (P) with a diameter size respectively 0.5–1.0 mm and granulate (G) with dimensions 1.0–2.0 mm (Fig. 1a and 1b). Both rubber additives did not contain any amounts of the textile parts or steel belts. Both applied recycled rubber wastes are not harmful to health. They have been positively assessed in terms of health by the national institute of hygiene.

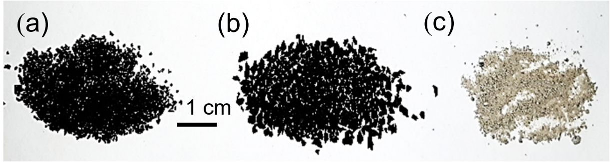

Figure 1. Testing materials: (**a**) RTWP – recycled tire waste powder 0.5–1.0 mm; (**b**) RTWG – recycled tire waste granulate 1.0–2.0 mm; (**c**) RCA – recycled concrete aggregate

For the soil material, the recycled concrete aggregate was used. RCA is an example of anthropogenic material that is a product of construction demolition (Duda et al. 2016). As an artificial aggregate, RCA has a different structural composition compared to natural aggregates. RCA contains fragments of the cement matrix, which consists of anhydrous cement and hydration products that form a porous microstructure. The high water absorption of RCA, especially the outer layers called "attached mortar," may be responsible for the lower mechanical properties compared to natural aggregates (Pepe et al. 2014).

RCA in this research was taken from a building demolition site in Warsaw, by the skid-mounted impact crusher. The strength class properties of the construction concrete, made from Portland cement, were estimated at the level from C16/20 to C30/35, based on the data obtained from building plans. Then, the material was fractionated using a mechanical shaker and divided into several types, each one composed of sieved fractions. In this study, only one type with grain diameter dimensions 0–2.0 mm was investigated in the laboratory (Fig. 1c). The aggregates were 99% composed from broken cement concrete, the rest being glass and brick ($\Sigma(Rb, Rg, X) \leq 1\%$ m/m), under standard ISO 17892–4:2016, and contained no asphalt or tar elements. Rubber and soil properties are summarized in Table 1.

Table 1. Properties of recycled rubber waste and recycled concrete aggregate

Used material properties	RTW	RCA
Specific gravity[a] G_s	1.15-1.19	2.61-2.62
D_{50}[b] (mm)	0.65-2.5	0.092-0.2
C_u[c]	1.97-2.46	2.86-5.60
C_c[d]	0.79-1.14	0.91-1.29
e_{max}[e]	0.88-1.09	1.04-1.23
e_{min}[f]	0.70-0.86	0.71-0.91

[a] according to ASTM D854
[b] median diameter
[c] uniformity coefficient
[d] curvature coefficient
[e] maximum void ratio
[f] minimum void ratio

In order to investigate small, medium and large–strain responses of RCA–RTW mixtures, four different compositions were prepared with varying percentages of recycled rubber content. The samples were coded as follows:

- M1_R – composition of RCA, 10% of RTWP, 10% of RTWG and 0% of fine fraction (FF) of RCA,
- M2_R – composition of RCA, 15% of RTWP and 10% of FF of RCA,
- M3_R – composition of RCA, 10% of RTWP and 20% of FF of RCA,
- M4_R – composition of RCA, 5% of RTWP and 30% of FF of RCA.

The proportion of rubber waste by mass (χ%) in RCA–RTW mixtures considered in this study is maximum equal to 20%, corresponding to a proportion of rubber waste by volume of 35–40%. RCA–RTW (20%) was identified as the optimum mixture, avoiding rubberlike behavior of the composition (Kim and Santamarina 2008). Particle size distribution curves of tested mixtures together with their photos are shown in Fig. 2.

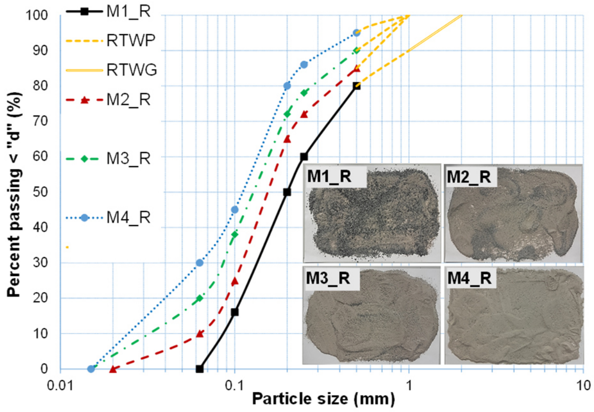

Figure 2. Particle size distributions and photos of tested materials

Tested blends were prepared by careful hand mixing of rubber with recycled concrete aggregates at different weight ratios. Since field applications of rubber-soil mixtures are usually made above the groundwater level, it seems that the dry deposition method is more appropriate to replicate field conditions. Therefore, the dry deposition technique was chosen for sample preparation. RCA was dried out in an oven for 24 hours at 105ºC, and the tire waste was left at room temperature for 36 hours. Compaction was attained by tamping, using a wooden hammer. The authors decided to test very dense mixtures at an initial relative density (D_r) > 85%. For getting a uniform density, the under-compaction effect induced by the energy from tamping next layers during specimen preparation. The under-compaction of each layer was calculated following the equations given by Bai (2011). All the mixtures were tamped in four layers, in an aluminium mould of 70 mm diameter and 140 mm height. As different composition proportions were investigated, each mixture presented slightly different dry density, which was $\rho_d = 1.30$ g/cm^3, 1.38 g/cm^3, 1.46 g/cm^3, and 1.50 g/cm^3, for mixtures M1_R, M2_R, M3_R, and M4_R, respectively. For all tested blends, the ρ_d values were approaching the maximum dry densities. The values of the maximum and minimum void ratio, as well as the maximum and minimum dry density for analysed compounds are included in Gabryś (2023). The soil grains in the prepared mixtures are the same size as rubber particles or slightly smaller than rubber particles. Since the rubber content is smaller than 30% and $D_{RTW} \geq D_{RCA}$, the RCA skeleton controls the behaviour of the mixtures.

The initial stages of the measurements included: flushing of the equipment (especially saturation of the pore pressure system), specimen's saturation (by the back pressure method), control of Skempton's parameter B (the value higher than 0.95 meant reaching full saturation) and consolidation. These procedures are identical to that used in conventional triaxial testing.

All the mixtures were tested at three different effective stresses, i.e., 90, 180, and 270 kPa (covering a range of pressures expected in many geotechnical applications) (Tasalloti et al. 2020).

The dynamic tests were performed in an integrated resonant column / cyclic torsional shear device. The experimental results of the standard resonant column (RC) test are presented in this paper. RC test is based on the theory of wave propagation in prismatic rods. The analysis of the test data was described in detail by Drnevich (1985) using ASTM D4015.

The GDS Resonant Column Apparatus was used in this study (Fig. 3) to excite one end of an isotopically confined solid cylindrical soil specimen. This apparatus is an example of fixed–free resonant column, where the soil specimen fixed at the bottom (the passive end) and free at the top (the active end) was oscillating only in a torsional mode. The instrumentation, placed on the top of the sample, included a loading cap, an electromagnetic drive system incorporating precision wound coils and a permanent magnet, a counter-balance, and an accelerometer. The energisation mode of coils was switchable by software in order to provide the torsional tests (Sas et al. 2017).

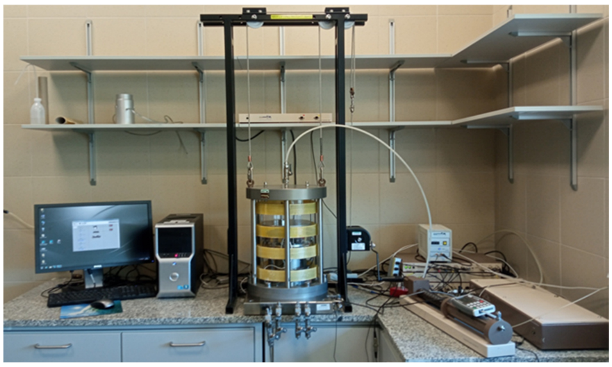

Figure 3. Resonant column / torsional shear apparatus – view of the laboratory stand

A harmonic torsional excitation was applied to the top of each mixture by the use of an electric motor. In a certain frequency range (from 10 to 200 Hz), a harmonic torsional load of constant amplitude was applied and the response curve (strain amplitude) was measured. The shear wave velocity (V_S) was obtained by recording the resonant frequency of the first mode. The G_{max} parameter was calculated from the shear wave velocity and soil density. The D parameter of the material was obtained from the distribution of free vibrations after the imposed vibrations ceased. After the determination of G_{max} and D_{min}, the cyclic torsional harmonic load amplitude was increased to obtain the strain-dependent shear modulus and damping values for a wide strain range (from about $1.5 \cdot 10^{-4}$% to $1.3 \cdot 10^{-2}$%. Each specimen was tested under between 10 and 20 output amplitude values to change strain levels.

3. Results

The test results obtained from the resonant column apparatus are presented and discussed in this section. The dynamic properties of RCA–RTW blends, the influence of rubber waste, and finally the comparison with the specimen of pure RCA are discussed subsequently.

In Fig. 4, typical frequency variation curves as a function of strain are shown. It can be seen that the value of the strain increases with increasing frequency up to the resonant frequency (f_r), after which the level of strain begins to decrease. The lowest frequency, which shows the maximum value of shear strain, gives the resonant frequency of the sample under different confining pressures. The symmetry of the curves concerning the resonant frequency indicates the linear-elastic behavior of the tested mixtures in the low strain range. As deformation increases, the frequency response curve becomes increasingly asymmetric and shifted to the left. This corresponds to the behavior of natural soil (Gabryś 2014).

The effect of RTW on the curves of strain versus frequency is also noticeable here, for the mean effective stress p'=90 kPa and input amplitude A=0.08 V. As the rubber content increases, the values of both resonant frequency and shear strain decrease. This trend is generally observed at all confining pressures and input amplitudes. The maximum f_r is found for the pure recycled concrete aggregate sample, whereas the minimum, approximately twice as low, for the M1_R mixture, with a 20% of rubber insert. The M1_R mixture is the most outlier of the others. The next three compositions, M2_R, M3_R, and M4_R, are characterized by similar values of both f_r and γ.

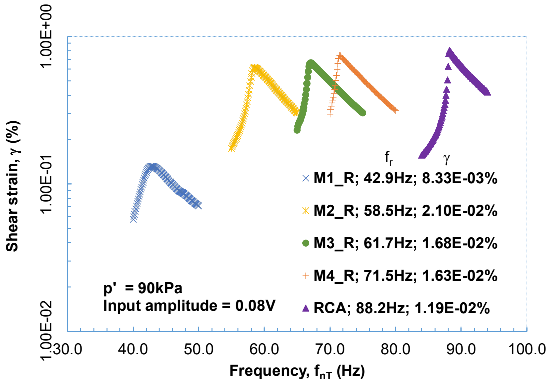

Figure 4. Typical amplitude vs. frequency curves from RC test results

In Fig. 5, exemplary free vibration decay curves, along with calculated results of logarithmic decrement (δ) and viscous damping ratio (D), are displayed. In this figure, the total recorded data for Peak Amplitude against the Number of Cycles is shown. The highest values of the damping parameters are characterized by the mixture M1_R, with 20% rubber waste content. The damping parameters decrease with a decrease in χ. Analyzing the data presented in Fig. 5, it can be observed that the more rubber-modified the mixture, the faster the decay takes (the decay is represented only by the straight section of the graph). In the case of M1_R, the decay takes less than 10 cycles, while for the mix M4_R (χ=5%) it takes 30 cycles.

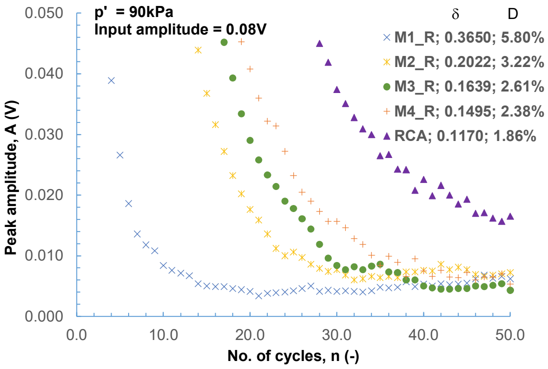

Figure 5. Typical free vibration decay curves from damping test

In Fig. 6, the degradation of the mixture stiffness is shown in the modulus reduction curves with the progression of shear strain. In Fig. 7, the change in damping ratio versus shear strain is presented. In both of the above figures, the effect of mean effective stress on the dynamic behaviour of the tested soil–rubber compositions is exposed. When the p' increases then the G–modulus increases and the D–ratio decreases. The contact pressure between artificial soil particles, as in the natural aggregates, increases with the increase in the p', therefore all the specimens exhibit higher G and lower D (Das and Bhowmik 2020).

The curves of the mixtures presented in Fig. 6 (a-d) and Fig. 7 (a-d) are showing a good agreement with the curves of the pure RCA specimen. Over the whole strain range, their course is similar to that of clean RCA, especially in the case of rubber content less than 15% (M3_R and M4_R). The exception is the blend M2_R, with exactly 15% of rubber additive, which results deviate from the other mixtures, and does not cover the trend in the dynamic behavior of soil–rubber compositions.

The degradation in stiffness is more significant with an increasing amount of rubber. The largest reduction in G–modulus values occurs for the M1_R mix, the smallest one – for the RCA specimen. In the M1_R mix (Fig. 6a), RCA is modified with two sizes of RTW, powder and granulate. The rubber sizes are relatively bigger, up to 2.0 mm; therefore, they have a larger void ratio in comparison to the other three mixtures (Fig. 8). As the void ratio (e) of the mixture increases, at a given cell pressure, the shear modulus values decrease.

The degradation in G values is also influenced by the p' stress. For the mean effective stress higher than 90 kPa, for RTW equal to 20%, this reduction is of an order of about 27%. When modifying RCA with less than 20% of rubber waste, the stiffness degradation is more significant for lower pressure values. This fact can be attributed to the small number of rubber particles and their small size, up to 1.0 mm, filling the gaps between the recycled concrete particles, making the mixture denser and thus stiffer.

For the specimen of pure anthropogenic aggregate, the reduction in the G–modulus is of the order of about 13%, regardless of the mean effective stress.

The strain range in which the decrease of stiffness occurs is about the same for all the mixes tested, ranging from 10^{-3}% to 10^{-2}%.

The damping characteristics of the tested RCA–RTW mixtures (Fig. 7) enable us to notice the relationship between the damping ratio and RTW content, as well as the p' stress. The increasing trend of the D–parameter with increasing rubber content is visible here. A significant increase in the damping ratio is obtained for the M1_R and M2-R mixtures, with at least 15% of RTW. The inclusions of 20% of rubber particles result in damping of about 3 to around 6.5%. The damping ratio of pure RCA is 3 times lower, reaching maximum value of 2%.

The variation of damping concerning the mean effective stress is more correlated with the M1–R mix and the pure recycled concrete specimen. As the p' stress increases, the D-parameter decreases, which is more pronounced at higher strains, $\gamma > 10^{-3}$%. This is due to the increasing stiffness of the material.

In the case of the mixtures tested, the addition of even 5% of RTW significantly affects the small-strain shear modulus (Fig. 9). The 5% of rubber inclusion results in a reduction in G_{max} of pure RCA of about 26%. The increase in the RTW content by another 5% in subsequent mixtures, leads to a decrease in G_{max} of about 20-30% on each composition. The greatest difference in G_{max} values is between χ=20% and χ=15%, at least for the two first pressures applied in the present investigation (90 and 180kPa).

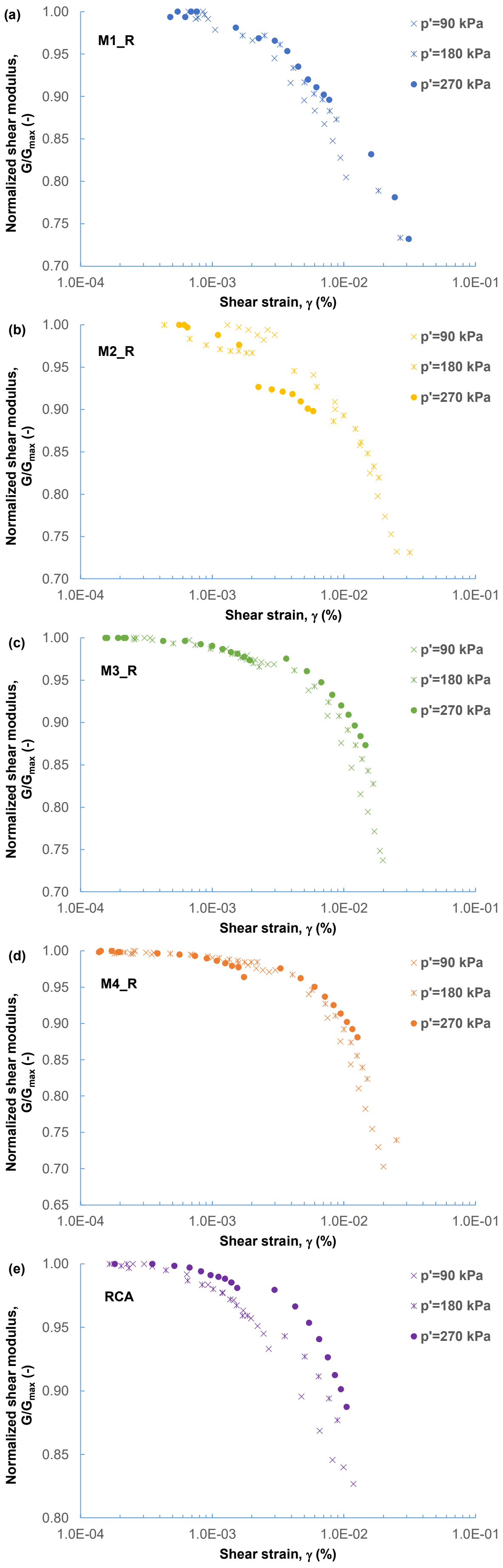

Figure 6. Normalized shear modulus versus shear strain: (**a**) M1_R; (**b**) M2_R; (**c**) M3_R; (**d**) M4_R; (**e**) RCA

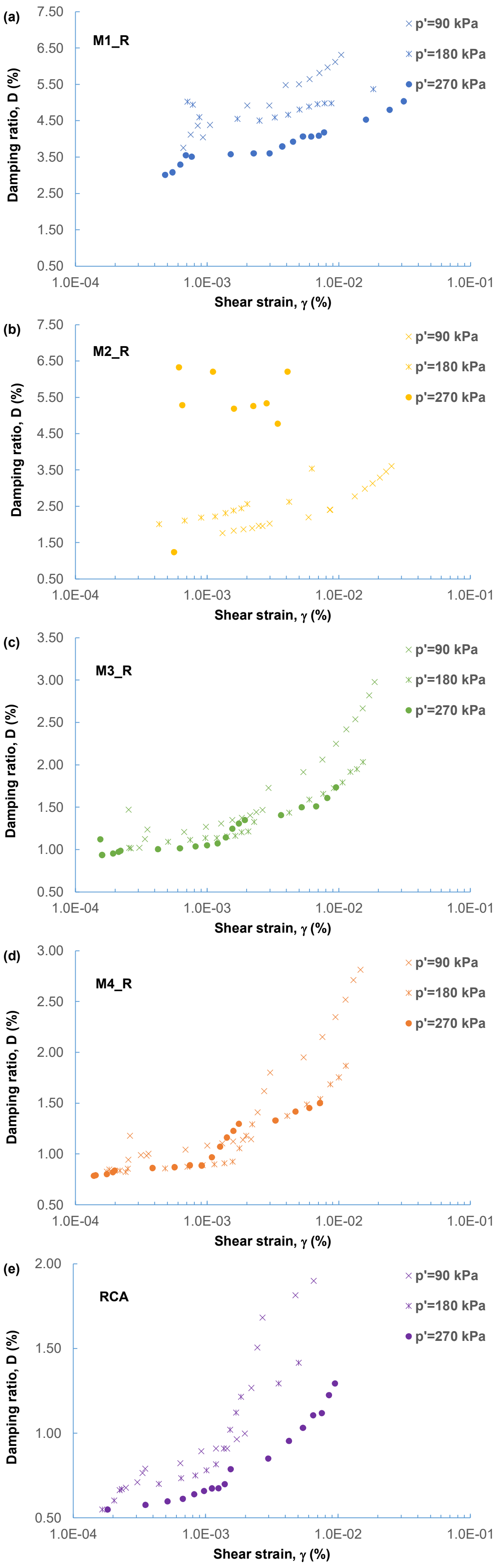

Figure 7. Damping ratio modulus versus shear strain: (**a**) M1_R; (**b**) M2_R; (**c**) M3_R; (**d**) M4_R; (**e**) RCA

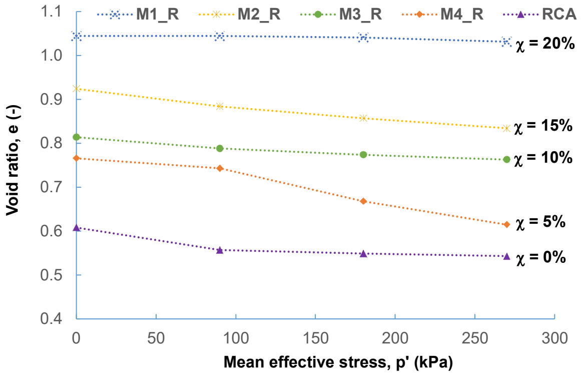

Figure 8. Void ratio versus mean effective stress for a different proportion of RTW

As also discussed for G_{max}, in the case of high rubber content (the M1_R blend, with ≥ 20% per mixture weight), and at all confining pressures, the small–strain damping ratio is the highest (Fig. 10). The increase of about 3% over the M2_R specimen (χ=15 %) occurs. This effect of the rubber inclusion is not as significant for D_{min} when RTW ≤ 15%. Thereafter, the decrease in rubber content of each 5% causes a decrease in D_{min} of another 0.5-0.3%.

The effect of the rubber is because, for small shear deformations, the damping mechanisms are mainly because of friction at the interface of the grains, rather than their dislocation.

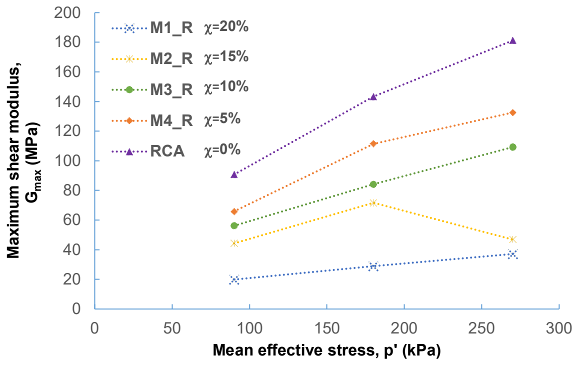

Figure 9. Maximum shear modulus (small-strain shear modulus) versus mean effective stress for a different proportion of RTW

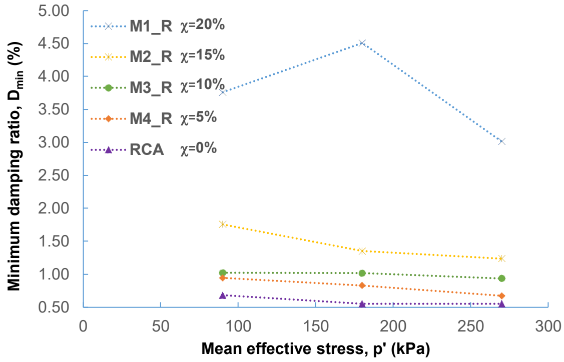

Figure 10. Minimum damping ratio (small-strain damping ratio) versus mean effective stress for a different proportion of RTW

In the case of granular soil mixtures with granular rubber, such as those studied in this research, the increase in D_{min} occurs due to the higher coefficient of friction between the soil and rubber grains, as well as due to the mechanical interlocking of the grains; the latter is more effective due to the local deformation of the rubber grains in their contact with the soil grains of the mixture.

The strain-dependent damping ratio as a function of the dynamic shear modulus ratio is presented in Figs. 11 and 12. In Fig. 11, as an example, the results of the tests for the M1_R mix, with 20% of rubber, are shown. While, in Fig. 12, the same results are presented but for the M4_R blend, with 5% of rubber. Despite the RTW amount added to anthropogenic soil, as the dynamic shear modulus increases, the dynamic damping ratio decreases following a decreasing polynomial function, in the general form of:

$$f(D) = C_1\left(\frac{G}{G_{max}}\right)^2 + C_2\left(\frac{G}{G_{max}}\right) + C_3 \qquad (1)$$

The smaller the rubber content, the faster the decrease in the value of $D = f(\frac{G}{G_{max}})$. The curves $D = f(\frac{G}{G_{max}})$ fall sharply down (Fig. 11). More experiments need to be conducted in order to estimate the values of the C_1, C_2, and C_3 constants.

Comparing the linear threshold shear strain (γ_{tl}) with the volumetric cyclic threshold strain (γ_{tv}), regardless of the RTW additive, γ_{tl} is more or less the same, in the order of approx. 0.001% for G/G_{max} = 0.99. γ_{tv}, however, which is equal to approx. 0.01%, relates to a modulus reduction (G/G_{max}) between 0.60 and 0.85.

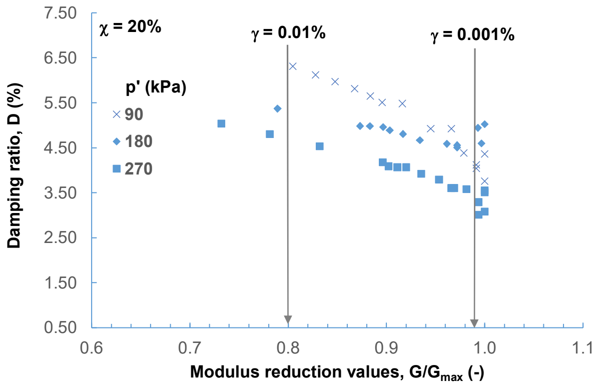

Figure 11. Relationship between shear modulus and damping ratio for χ=20 % of RTW

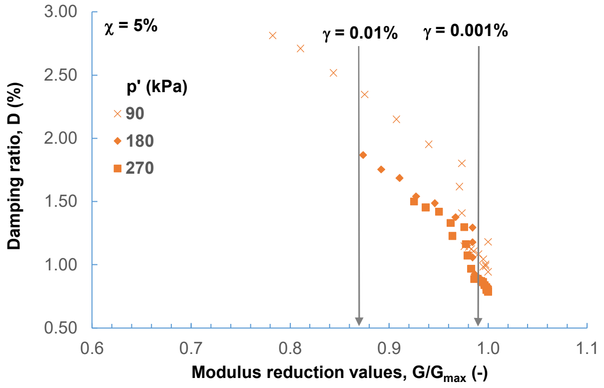

Figure 12. Relationship between shear modulus and damping ratio for χ=5 % of RTW

For the M4_R mixture, no such reduction in G–modulus could be achieved at all, hence γ_{tl} represents the strain level at a value of $G/G_{max} = 0.87$. Based on the experimental studies performed, it can be concluded that the lower the rubber content, the smaller the range of the non-linear stress-strain behavior of the mixture.

4. Conclusions

The dynamic behavior of mixtures made of waste materials, stiff mineral anthropogenic aggregates (RCA) mixed with recycled soft particles (RTW), is studied based on a set of standard resonant column tests. The laboratory tests presented in this article are part of a larger research project that aims to provide useful insights to facilitate the application of RCA–RTW compositions as geotechnical materials. The effects of shear strain, mean effective stress, and most importantly rubber content on the shear modulus (G), and damping ratio (D), are discussed here. Rubber content is considered through the proportion of rubber materials in the weight of the mixture.

The main beneficial aspect of adding rubber particles in granular anthropogenic soil is the improvement of the dynamic properties of the ‘parent’ soil, especially damping characteristics. The experimental results for mixtures made of small RCA grains and of similar size or slightly larger RTW particles show that even a small amount of rubber ($\chi < 10\%$) results in a reduction of the G and G_{max}–modulus by an average of about 20-25% (due to the soft nature of rubber), as well as an increase in the D–ratio by an average of approx. 2-3% (due to the energy absorption nature of rubber). A positive increase in stiffness could most likely be achieved with a slightly different mix design. It would be necessary to select the proportions of the rubber additive to the soil in such a way that the ratio of median particle sizes $\left(\frac{D_{50,RTW}}{D_{50,RCA}}\right) \leq 1$, where soil forms percolating skeleton and rubber-rubber particle interaction takes place (Gabryś 2023).

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