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SHEAR MODULUS AND DAMPING RATIO OF RECYCLED CONCRETE AGGREGATE FROM CYCLIC TORSIONAL SHEAR TEST

MODUŁ ŚCINANIA I WSPÓŁCZYNNIK TŁUMIENIA KRUSZYWA BETONOWEGO POCHODZĄCEGO Z RECYKLINGU Z CYKLICZNEGO TESTU ŚCINANIA SKRĘTNEGO

STRESZCZENIE. W niniejszym badaniu zbadano właściwości dynamiczne przy małych odkształceniach trzech mieszanek kruszywa betonowego z recyklingu (RCA) przy użyciu badań laboratoryjnych typowych dla gruntów naturalnych, a mianowicie badania cyklicznego ścinania skrętnego (CTS). Do wykonania dwóch próbek wykorzystano pokruszone krawężniki betonowe pochodzące z rozbiórki w Warszawie. Do stworzenia trzeciej próbki wykorzystano pokruszony beton z rozebranych budynków, także z Warszawy, głównie z betonowych elementów ścian i podłóg. Przeprowadzono serię testów CTS w celu zbadania wpływu różnych parametrów, w tym ciśnienia ograniczającego, częstotliwości wzbudzenia i liczby cykli wibracji na moduł G, moduł G_{max}, krzywą degradacji modułu ścinania $G(\gamma)/G_{max}$, współczynnik D, współczynnik D_{min}, zmianę krzywej tłumienia $D(\gamma)/D_{min}$. Uzyskane charakterystyki sztywności i tłumienia analizowanego kruszywa betonowego porównano z charakterystykami naturalnego kruszywa żwirowo-piaskowego – kruszywa naturalnego (NA). Wyniki zebrane z badań CTS wskazują, że wydajność większości destruktu betonowego jest porównywalna z kruszywem naturalnym i może być stosowana jako niezwiązany materiał ziarnisty (UGM).

SŁOWA KLUCZOWE: grunt antropogeniczny, obciążenie cykliczne, tłumienie, sztywność, materiał odpadowy.

ABSTRACT. This study examines the small-strain dynamic properties of three mixtures of recycled concrete aggregate (RCA) using laboratory investigations typical of natural soils, namely cyclic torsional shear (CTS) tests. In order to construct two samples, crushed concrete curbs originating from a demolition site in Warsaw was employed. To create the third sample, crushed concrete from demolished buildings also Warsaw was used, mainly from concrete wall and floor elements. A series of CTS tests were performed to investigate the impact of various parameters, including confining pressure, excitation frequency, and number of vibration cycles on the G−modulus, G_{max}−modulus, shear modulus degradation curve $G(\gamma)/G_{max}$, D−ratio, D_{min}−ratio, variation in damping curve $D(\gamma)/D_{min}$. The resulting stiffness and damping characteristics of the analysed concrete aggregate were compared with those of natural gravel and sand aggregate – natural aggregate (NA). The results collected from the CTS tests indicate that the performance of most RCA is comparable to that of NA and can be used as an unbound granular material (UGM).

KEYWORDS: anthropogenic soil, cyclic loading, damping, stiffness, waste material.

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1. INTRODUCTION

Aggregates are materials that are commonly used in the construction industry. Natural aggregates (NA) are primarily used as materials in earth structures such as dams, slopes, or other earth structures, e.g. road bases. The demand for this material is, therefore, very high [1]. Natural aggregates account for around 88% of the market demand [1]. Problems related to the sustainable development of the natural aggregate market and also with waste management are forcing engineers to incorporate man-made (MM) aggregates in earth structures. Using non-renewable resources such as NA is undesirable, and substitutes are highly recommended, especially in such structures as roads.

The MM materials are mainly disposed of in landfills. They are significant contributors to gross waste products worldwide. One way of dealing with MM materials is to recycle them into aggregates for use in concrete [2, 3]. The second objective of MM-waste recycling is the use as a base and sub-base in road construction layers. These types of soils can also be applied as a fill for embankments or to supplement stabilized soils [4, 5]. Hence, the reuse of reclaimed building materials is essential from a sustainability point of view.

The mechanical and physical characteristics of recycled aggregates differ from those of natural aggregates and require further investigation. A better knowledge of their response to different types of loading or permeability characteristics will result in greater use of this type of material by designers and engineers [6].

In this study, recycled concrete aggregate (shortly RCA) was of particular interest and was approached as an anthropogenic soil. It is a material with less recognized and at the same time more specific physical and mechanical characteristics than e.g. sand. It is very often classified as a weak aggregate, i.e. changing its initial grain size under mechanical loading. RCA is a result of the crushing process, excluding bricks and soft materials. They are then used to produce residual concrete with grain size of 0−63 mm [7]. They are mainly employed in road construction, where their geotechnical parameters (strength and deformation susceptibility) have already been recognized [8].

Tam and Tam [9] examined in detail the physical properties of RCA. They found that i/ the particle density of RCA is between 2.0 and 2.65 Mg/m^3, ii/ the cement paste adhering to the surface of the aggregate is mainly responsible for this variation in particle density, iii/ RCA with high porosity can potentially undergo a high degree of deformation, iv/ an upper limit for the flakiness index of RCA is 40% by mass, and additionally the use of flaky materials is not suitable for the majority of applications. Poon and Chan [10] reported that the water absorption values of the RCA range from 3% to 10%, compared to the values of less than 3% for NA. RCA has also been shown to have higher voids, porosity, and hydraulic conductivity than NA. The high porosity value was due to the presence of cement mortar in the RCA [11]. A hydraulic conductivity of fine RCA was examined on the level of 3.83×10^{-6} m/s which is approximately two orders of magnitude higher than for NA [10]. Los Angeles abrasion loss test at the RCA gave a result of 25% [12]. Typical road laboratory tests, including CBR, compaction, crushing susceptibility, freeze-thaw, and triaxle tests were conducted by, e.g., Aurstad et al. [13]. The test results showed that RCA has a lower CBR as unbound granular material (UGM) and higher optimum moisture content in relation to lower dry density compared to NA. Poon and Chan [14] reported that a soaking period of 4 days had a negligible effect on the CBR value and also presented that the swelling of an RCA sub-base after 4 days of soaking is negligible. The repeated load triaxial test results made by Papp et al. [15] and Bennert et al. [16] demonstrated that RCA accumulated the least amount of permanent strain of all the materials tested, i.e. RCA, reclaimed asphalt, and a dense-graded base course aggregate.

The purpose of this paper is to evaluate the dynamic properties of RCA. How a structure responds to dynamic loading is directly related to how the surrounding soil responds. Therefore, the focus of many researchers over the last few decades has been on studying the behavior of soils under dynamic loading. A dynamic load is one that changes in direction, position, and magnitude, exerting varied forces on a structure. Types of dynamic load include people, traffic, earthquakes, wind, waves, and blasts. The most critical parameters characterizing this soil behavior are the dynamic shear modulus (G) and the damping ratio (D). These two parameters are of concern in many dynamic geotechnical problems in the areas of earthquakes and machine foundations. The shear modulus (G) represents the shear stiffness of the soil, whereas the damping ratio (D) signifies the energy dissipation when waves propagate through the soil layers. At very low strain levels ($\gamma < 10^{-4}$ %) G possesses its maximum value (G_{max}) and D – its minimum value (D_{min}) [17].

The literature available on the investigation of the dynamic properties of RCA is relatively limited. The majority of the research papers have pointed out promising applications for RCA, in particular in pavement geotechnics and earth-retaining support structures. He and Senetakis [18] investigated the dynamic properties of two homogeneous fractions of RCA. They found that the strain-dependent modulus and damping were within the upper and lower limits of the nonlinear curves proposed in the literature for sands. The same authors in their other study [19] performed dynamic tests in a resonant column apparatus on 5 single fraction RCA mixtures. They reported that mixtures with larger grains achieved higher G_{max} values. Furthermore, all tested RCA mixtures behave like natural soils, i.e. the G_{max} value increases with increasing effective stress as the effective stress increases.

In the case of this paper, we propose to complete the geotechnical characterization of RCA with cyclic test methods, using cyclic torsional shear (CTS) tests. In addition to the resonant column method, or bender elements tests, this technique allows the elastic and attenuation properties to be captured. The present work focuses on the small-strain dynamic properties of three mixtures of RCA. A series of CTS tests are performed to investigate the impact of various parameters, including confining pressure, excitation frequency, and number of vibration cycles on the G–modulus, G_{max}–modulus, shear modulus degradation curve $G(\gamma)/G_{max}$, D–ratio, D_{min}–ratio, variation in the damping curve $D(\gamma)/D_{min}$. The resulting stiffness and damping characteristics of the analyzed concrete aggregate are compared to natural gravel and sand.

2. MATERIALS AND METODS

2.1. PARENT DEMOLITION MATERIAL

A recycled concrete aggregate composed of demolished-crushed concrete from Warsaw, the capital of Poland, was employed in the study. The first test material consisted of two unbound crushed concrete mixtures obtained by crushing the kerbstone of a city road, denoted as RCA_1 and RCA_2. The second test material (RCA_3) represented demolition material from the construction of concrete facade walls of Warsaw buildings in the 1990s. The fourth mix was a non-cohesive natural soil, marked as NA. This specimen was used as a reference material.

RCA_1 and RCA_2 were provided by a local supplier and delivered already crushed to the WULS's geotechnical laboratory. The strength class of the concrete and its selected physical and chemical properties were assessed prior to geotechnical testing. These tests were subcontracted to an external company. RCA_3 was supplied as damaged concrete cubic samples with dimensions 150×150×150 mm. The strength class of the analysed RCA was determined to be between C16/20 and C30/35 for the first test material, and between C16/20 and C30/37 for the second test material, according to the PN-EN 206-1 standard [20].

The first parent aggregates were prepared through a set of sieves and two fine recycled concrete aggregate (fRCA) mixtures with a grain size of 0–2 mm were separated. RCA_1 consisted of pure fRCA and the calculated amount of fine fraction (FF) for this fRCA, at a level equal to 5%. FF indicates in the study the content of particles smaller than 0.063 mm. The RCA_2 compound was composed of 85% of fRCA and 15% of FF. Two fRCA specimens with different fractions of fines have been included in this study as a part of a larger research program involving experimental tests at Warsaw University of Life Sciences, Water Centre, Poland, and at the Vytautas Magnus University Agriculture Academy, Institute of Hydraulic Engineering,

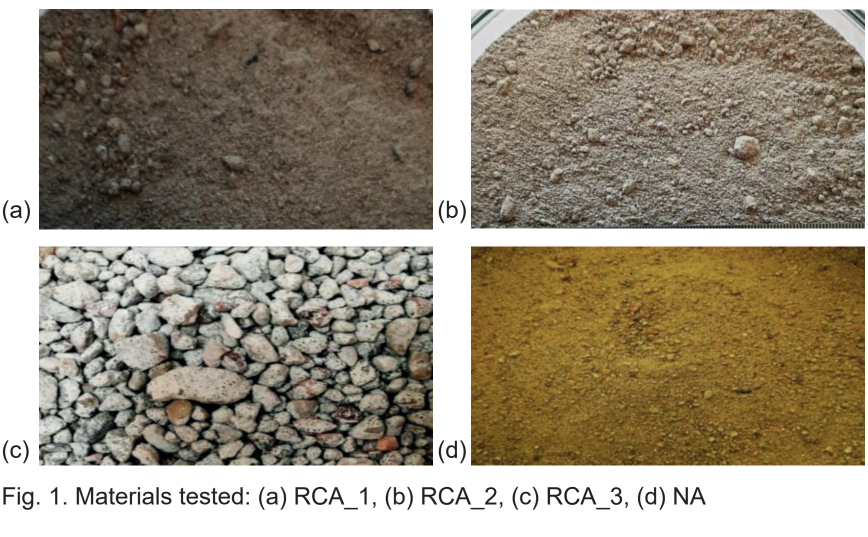


Fig. 1. Materials tested: (a) RCA_1, (b) RCA_2, (c) RCA_3, (d) NA

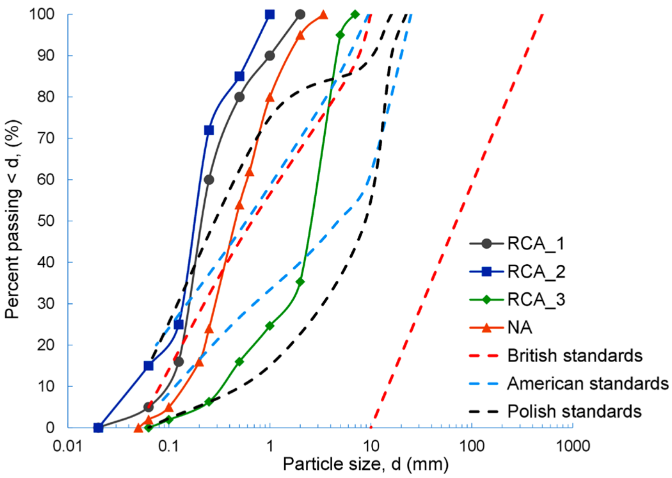


Fig. 2. Soil gradation curve for recycled aggregate (RCA) and natural aggregate (NA) tested in this study (the red dashed line – British standards requirement, light blue dashed line – American standards requirement, black dashed line – Polish standards requirement)

Lithuania. Details of this program can be found in the author's latest publication [21]. The interest in this material is also related to the limited research and practical experience on the proper management and use of fRCA, even though fRCA represents about half of the total Construction and Demolition Waste weight [22]. From the third material delivered, various mixtures were obtained by crushing and subsequent fractionation for further laboratory testing. In the current research, the results only of one selected blend, i.e. RCA_3 fraction 0−7mm, are presented. An image of all test materials is provided in Fig. 1.

For all the RCAs delivered, the dominant component was broken cement concrete (around 99%), and less than 1% were glass and brick. During the preparation of the target mixes, the glass and rock elements were removed.

Conventional laboratory tests and procedures typical of natural soils were used in the geotechnical characterization of all prepared concrete aggregate specimens. The grading curves of four specimens are illustrated in Fig. 2. The grain size characteristics, together with the specific gravity of solids, as well as the compaction parameters, are summarized in Table 1. A detailed description of each concrete aggregate likewise a summary of selected physical and geometric properties can be found in the other author's work [21, 23].

The grain size curves of the RCA and NA mixtures were placed between the limiting curves following the requirements of Polish [24], English [25], and American [26] codes for soil gradation curves used as a road sub-base material (Fig. 2). The mixture that best complies with the aforementioned requirements is the RCA_3 blend, which fits almost 80% of the limit curves. The natural material fits approx. 70% into the Polish requirements for an unbound mix for natural roads [24], whereas the other two mixtures only approx. 40%. The obtained coefficient values (Table 1) allow the classification of the tested parent demolition material as poorly graded fine SAND (RCA_1), SAND with silt (RCA_2), and well-graded GRAVEL with sand (RCA_3). RCA_3 is the material susceptible to the compaction process, and suitable for earth constructions. NA was identified as even-grained, homogeneous SAND. Identification was made according to the Polish Committee for Standardization [27].

The compaction tests carried out, by means of the Proctor method, according to the American Society for Testing and Materials (ASTM) standard [28], indicate the highest dry densities obtained for NA. Quite large ρ_d values were also found for the RCA_3 mixture, except that OMC was the lowest. This is confirmed by the fact that the gravelly

Table 1. Selected physical properties for recycled aggregate (RCA) and natural aggregate (NA) tested in this study

No	Specimen	G_S [a]	d_{50} [b] (mm)	C_u [c] (-)	C_c [d] (-)	ρ [e] (g/cm³)	$\rho_{d,max}$ [f] (g/cm³)	$\rho_{d,min}$ [g] (g/cm³)	e [h] (-)	OMC [i] (%)
1	RCA_1	2.61	0.21	2.36	1.01	1.70	1.556	1.338	0.744	13.5
2	RCA_2	2.61	0.18	4.88	2.49	1.75	1.515	1.285	0.723	16.0
3	RCA_3	2.60	2.50	9.09	2.59	1.80	1.710	1.390	0.600	9.5
4	NA	2.65	0.46	3.93	0.86	1.86	2.014	1.677	0.424	12.0

[a] Specific gravity
[b] Average particle size
[c] Uniformity coefficient $C_u=d_{60}/d_{10}$
[d] Curvature coefficient $C_c=d_{30}^2/(d_{60} \times d_{10})$
[e] Bulk density
[f] Minimum bulk density of soil skeleton
[g] Maximum bulk density of soil skeleton
[h] Void ratio
[i] Optimum moisture content

sands or sandy gravels usually have higher dry density in low moisture content and the density drops with increased water content. The influence of the fine fraction (FF) content on OMC can be seen as well. For a sample with a higher proportion of fines (for RCA_2 FF=15%), OMC is higher and dry densities are smaller.

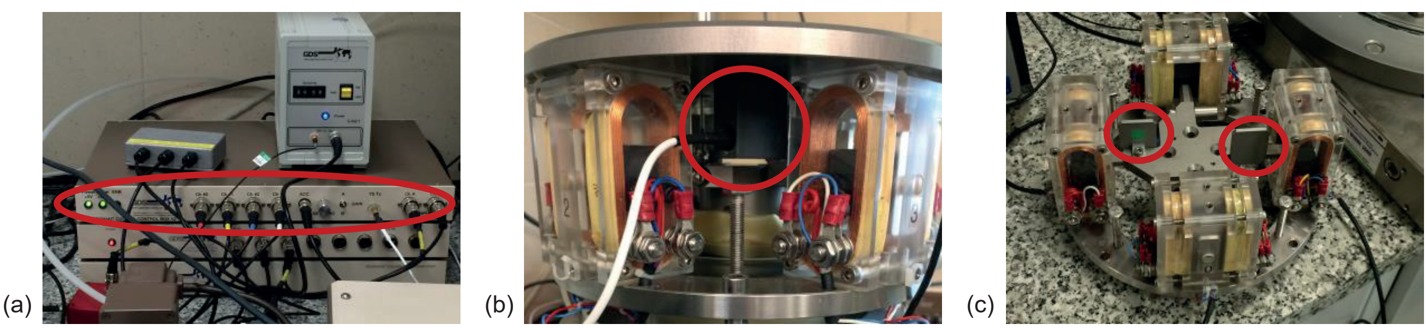
2.2. TESTING METHOD

In this study, all the specimens were prepared directly in an integrated resonant column / cyclic torsional shear device of fixed-free ends and tested in a moist state with optimum moisture content under isotropic pressures in a range of 90 kPa to 270 kPa. The resonant column employed in this research is a computer-controlled apparatus supplied by GDS Instruments, UK. The instrumentation used here differed from that applied in the other author's research [29] by the addition of a new GDSRCA Control Box Module (Fig. 3a). This new model provides more reliable measurements of peak shear strain in torsion shear tests with an accuracy of 1×10^{-6} compared to the shear strain range of 1×10^{-5} − 1×10^{-2} obtained with the standard GDSRCA box [29]. Apart from the new box, the increased experimental accuracy is due to the inclusion of a more accurate proximity sensor with a hardware offset potentiometer, two selectable proximity gain channels, and two input channels for recording axial displacement and porewater pressure. The new high-precision proximity sensor (Fig. 3b) consists of two parts: a sensor and target discs. The target plates are mounted on the rotor arm of the RCA as illustrated in Fig. 3c. They are moving in response to the excitation of the sample. The sensor is mounted on the (stationary) plate of the RCA drive system, monitoring the lateral displacement of the target. As well as the hardware upgrades, a new version of the GDSRCA software was adopted. This modified version included updated calibration settings for the proximitor and transducer input channels. It also enabled digital noise reduction from the torsional shear data, further facilitating data processing [30].

In the cyclic torsional shear (CTS) test, the soil specimen is deformed cyclically at a low frequency (a maximum of 10 Hz), whilst continuously monitoring torque and deformation. From the torque-deformation curves, a relationship between average shear stress and average shear strain is obtained. The shear stress−strain path forms a hysteresis loop which in turn provides the shear modulus and the damping ratio [31].

The wet tamping method was adopted for the specimen preparation in an aluminium split mold with an internal diameter of about 70 mm and a height of about 140 mm. All specimens were compacted in four layers and each layer was densified by manually applying tamping by a wooden hammer. The authors decided to test dense and very dense mixtures at an initial relative density (D_r)=76% for RCA_1 and D_r>85% for RCA_2, RCA_3, and NA. For getting a uniform density, the under-compaction effect is induced by the energy from tamping the next layers during specimen preparation. The under-compaction of each layer was calculated following the equations given by Bai (2011) [32]. Using this method, the average density of 1.78 g/cm^3 and the average initial void ratio of 0.62 were obtained (the detailed values are summarized in Table 1). Each mixture of RCA was saturated under a back pressure equal to 440 kPa to reach a Skempton's B value in the range of B = 0.8−0.9, and then isotopically consolidated at predefined mean effective stresses (p' = 90, 180, and 270 kPa).

Following preparation within the resonant column, CTS tests were performed at three different frequencies,



(a) (b) (c)

Fig. 3. Torsional shear upgrade (elements highlighted in red): (a) GDSRCA Control Box v2, (b) proximitor sensor, (c) proximitor targets

namely 0.1 Hz for 10 cycles, 1.0 Hz for 10 cycles, and 10 Hz for 100 cycles. The following output amplitude voltages were applied to drive the torsional system: A = 0.01 V, 0.02 V, 0.03 V, 0.04 V, 0.05 V, 0.06 V, 0.07 V, 0.08 V, 0.09 V, 0.1 V, 0.2 V, 0.3 V, 0.4 V, 0.5 V, 0.6 V, 0.7 V, 0.8 V, 0.9 V, and 1.0 V.

In Fig. 4 the examples of the stress−strain responses obtained for the RCA_1 mixture at different loading conditions (different amplitude voltage and loading frequency) at p' = 90 kPa are displayed. The presented hysteresis loops were gained for the 3rd cycle of loading [33, 34] and they show peak shear strain values equal to approx. +/- 9.02×10^{-5} % for A = 0.01 V, +/- 1.02×10^{-3} % for A = 0.1 V, +/- 1.17×10^{-2} % for A = 1.0 V, peak shear stress values corresponding to +/- 6.82×10^{-2} % for A = 0.01 V, +/- 6.67×10^{-1} % for A = 0.1 V, +/- 5.81% for A = 1.0 V. As can be observed, the greater the output amplitude voltage and the higher the loading frequency, the larger shear strains and stresses are reached (minimum by 1 order of magnitude). Note that both the G − modulus and D − ratio of each composition could be clearly obtained from each of the loadings. The gradient of the straight line that joins the endpoints of the hysteresis loop indicated the typical level of shear stiffness exhibited by the soil, which is also referred to as the secant shear modulus (G_{sec}). The damping ratio was calculated from Eq. 1, which describes the ratio of energy dissipated to the elastic energy stored in the system [35]:

$$D = \frac{\text{Area of the hysteresis loop}}{2\pi G_{sec}\gamma_{max}^{2}} , \qquad (1)$$

where:
G_{sec} is the secant shear modulus,
γ_{max} is the shear strain at the load reversal point.

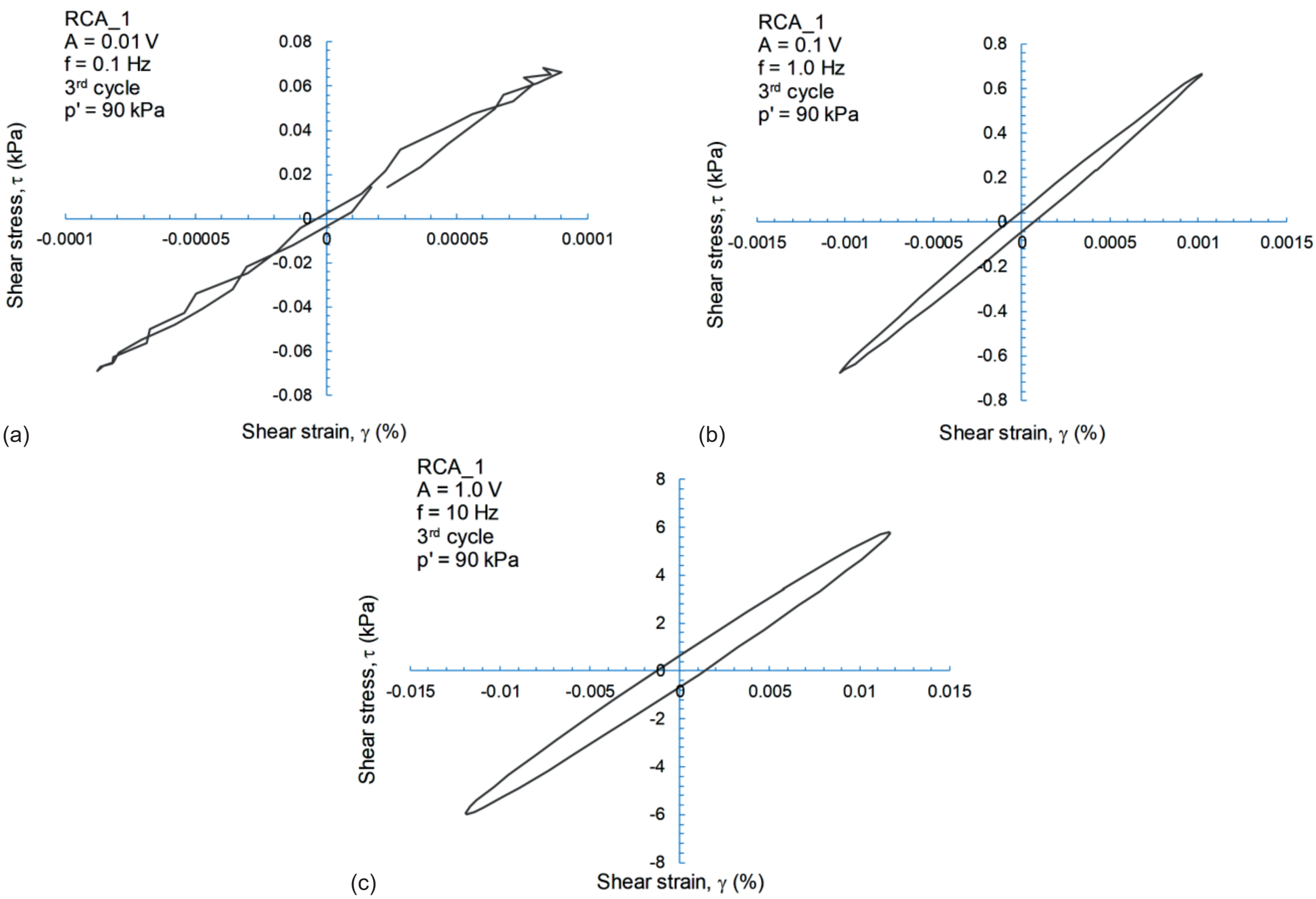


Fig. 4. Typical cyclic hysteresis loops for the RCA_1 mixture: (a) A = 0.01 V, f = 0.1 Hz, (b) A = 0.1 V, f = 1.0 Hz, (c) A = 1.0 V, f = 10 Hz

3. TEST RESULTS AND DISCUSSION

The laboratory stiffness and damping results from the cyclic torsional shear tests are investigated and presented herein. The test results are displayed as various plots revealing the impact of, inter alia, confining pressure, excitation frequency, and number of vibration cycles on the dynamic parameters of RCA.

In Fig. 5 some selected dynamic diaphysis curves for the NA blend (Fig. 5a) and the RCA_1 mix (Fig. 5b) are shown. These are formed by combining the peak values of the shear stress−strain hysteresis loops for different load steps. For all specimens of RCA tested as well as for the natural aggregate increasing stress−strain curves have been obtained. The maximum dynamic shear stress has not yet been identified and it can be assumed that it will occur at higher strain values. In general, the CTS test provides dynamic properties in the low strain range. In the case of NA, the amplitude of the shear strain does not exceed 0.01%, while it is less than 0.015% for the RCA_1 mixture, for example. At this stage, it is rather difficult to predict the direction of change τ_d vs. γ_d. For soil mixtures, albeit natural soils, the literature reports a hyperbolic relationship [36].

As illustrated in Fig. 5, regardless of the type of material tested, the loading has no effect on the results produced. In contrast, the effect of the average effective stress can be noticed. Higher p' pressure shifts the curves to the left and upwards.

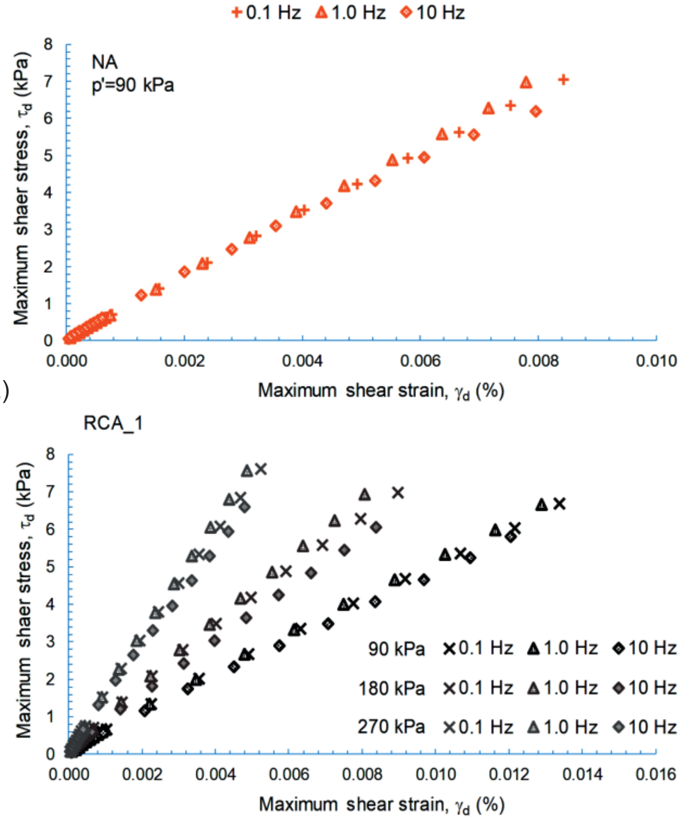


Fig. 5. Dynamic diaphysis curves – examples for: (a) NA, (b) RCA_1

Figs. 6−8 are examples of the experimental data obtained for the dynamic properties of all soil specimens tested under the different evaluated conditions. The variation in the G−modulus versus shear strain amplitudes revealed a mean effective stress dependency on the mixture stiffness. From Fig. 6, it can be observed that as the p' pressure increases, the dynamic shear modulus of the specimens increases as well. The coarsest mixture (the RCA_3 sample) is characterized by the highest stiffness values, obtained as around 120, 180, and 250 MPa for p' of 90, 180, and 270 kPa, respectively, for strain levels below 1×10^{-4} %. In contrast, the finer, poorly−graded materials, with 5 and 15% of fines (RCA_1 and RCA_2), have stiffness up to 100 MPa lower. The natural aggregate tested (at 90 kPa only) ranks between the RCA_1, RCA_2, and RCA_3 compounds. Additionally, note that similar to natural materials [36] the G−modulus of RCA decreases with the increase in shear strain. This

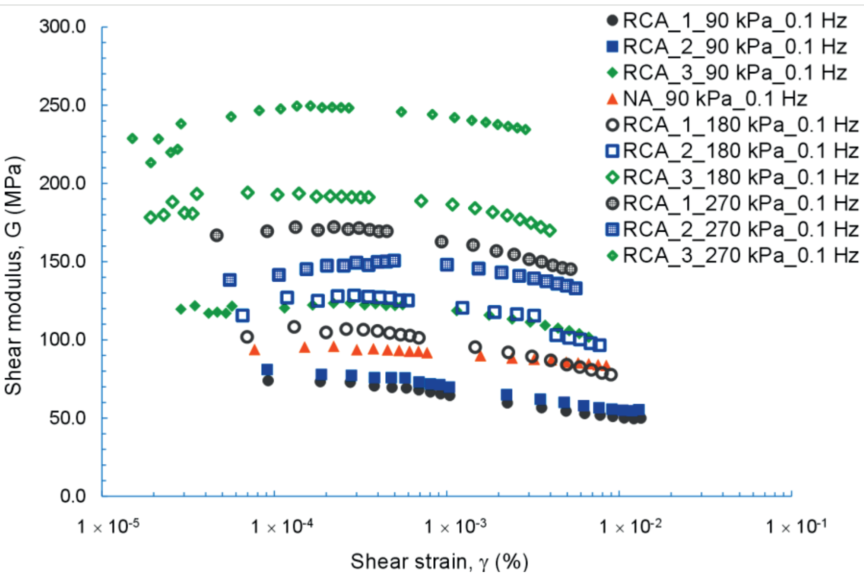


Fig. 6. Comparison of secant shear modulus measured from CTS tests for f = 0.1 Hz

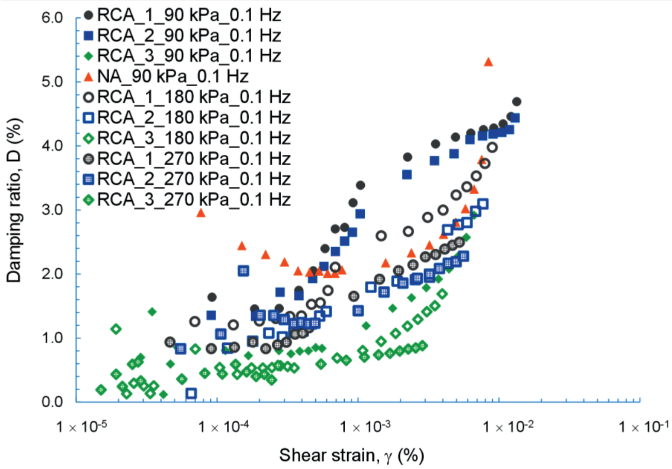


Fig. 7. Comparison of damping ratio measured from CTS tests for f = 0.1 Hz

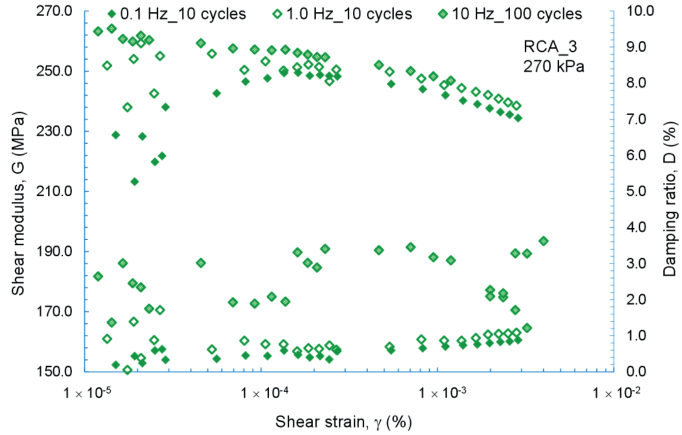


Fig. 8. Effect of excitation frequency and number of vibration cycles on dynamic shear modulus and damping ratio of the RCA_3 mixture under p' = 270 kPa

phenomenon is called stiffness degradation and it is more pronounced for the finer mixtures, up to 30% (at p' = 90 and 180 kPa) or 14% (at p' = 270 kPa) of the maximum G value, once 1×10^{-3} % shear strain is exceeded.

The variation in the D−ratio with shear strain is presented in Fig. 7. Generally speaking, at shear strain amplitudes less than about 1×10^{-2} %, the damping ratios of all the mixtures increase as the shear strain develops. However, the trend shows a small increase or even no change in damping ratio values (e.g. 1.0%−1.5% for RCA_2, 0.3%−0.7% for RCA_3) for shear strains below 1×10^{-3} %, and a large increase (up to 4% for RCA_2, 3% for RCA_3) once this strain threshold is exceeded. The highest damping was achieved for the RCA compounds with fine particles; D was recorded at almost 5% for the smallest mean effective stress. Fig. 7 indicates that the coarser the test material, the smaller the damping capacity compared to the fRCA material. The tests carried out on recycled concrete aggregate at different p' revealed that the D−ratio slightly decreases with the increasing p' pressure.

As is visible in Fig. 8 the dynamic properties of the RCA mixtures depend on the loading conditions. The shear modulus reduction curve trend is slightly located higher as the number of cycles increases. However, increasing the strain level above 1×10^{-3} % causes this tendency to disappear and the impact of vibration cycles becomes negligible. The number of cycles translates into the loading frequency. At the frequencies of 0.1 Hz and 1.0 Hz, the test results showed no appreciable difference between the G−modulus values. The current research consists of the results of natural sands by Bolton and Wilson [38] and Lo Presti et al. [39].

As for the G values, similar conclusions can be drawn for the D−ratio dependency on f and No of cycles. Higher frequency and higher number of cycles give higher damping, which, however, remains constant for shear strains below 1×10^{-3} %. The results for the RCA mixtures do not correspond to the damping characteristics of sands [40]. In general, the damping ratio for e.g. dry sands significantly decreases with an increasing number of vibration cycles. This decrease in the D parameter for sands occurs mostly within the first 10 cycles.

The values of the initial (maximum) dynamic shear modulus, determined by means of CTS tests, are presented in Fig. 9 as a function of the mean effective stress. As for natural non-cohesive materials [41], they increase non-linearly with the p' pressure. The dependence can be expressed with the power function:

$$G_{max} = a\cdot(p')^{b} \quad , \tag{2}$$

where:

a – corresponds to the G_{max} value at 1 MPa,

b – is the exponent of the stress−state dependency law that describes the evolution of G_{max}.

All stress−state dependency laws reported in Fig. 9 were derived under a coefficient of determination $R^2 \geq 0.96$. In the table included in Fig. 9 the parameters that describe the function used are summarised. However, no function could be found using the data collected in this study for natural aggregate, due to insufficient data.

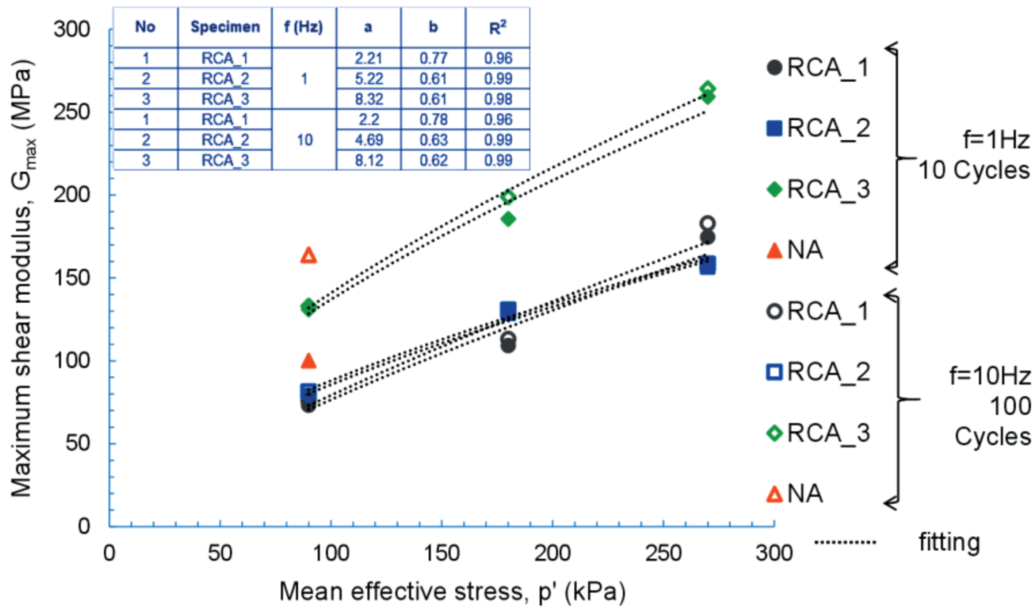


Fig. 9. Dependence of the maximum shear modulus on the mean effective stress

As shown in Fig. 9, the maximum dynamic shear modulus characterizes the RCA_3 mixture, which may be explained by the higher content of coarse grains and greater density. Depending on the p' pressure and frequency, the difference between G_{max} of the RCA_3 mix and the other fine RCA compounds is on average 42%–49%, in favour of the RCA_3 mix.

In Fig. 10 the variations in the damping ratio with the mean effective stress for recycled and natural aggregates are presented. Comparable to NA, the damping ratio of three RCA compounds demonstrates a decrease in the value of the D–ratio with the increasing p' pressure. For the RCA_3, a decrease in the D–ratio is the smoothest with the lowest damping ($0.12\% \leq D_{min} \leq 1.78\%$), in contrast to the other studied soils. The largest values of D_{min} were detected for fRCA with 15% of fines, especially for p' = 90 kPa ($1.34\% \leq D_{min} \leq 3.36\%$). For the subsequent pressures applied, the RCA_1 mix with 5% of fines

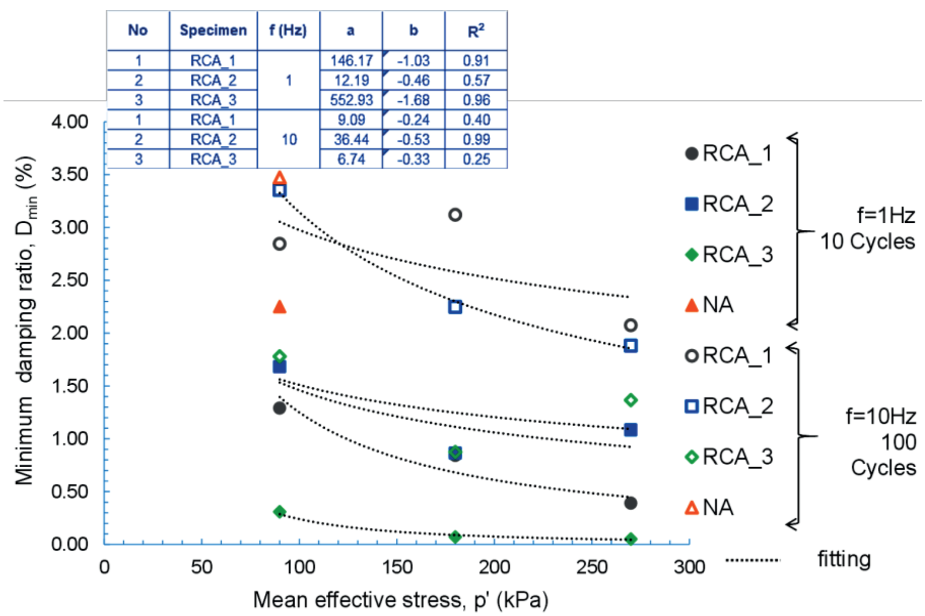


Fig. 10. Dependence of the minimum damping ratio on the mean effective stress

presented the largest D_{min} values ($0.39\% \leq D_{min} \leq 3.12\%$). As in the case of the stiffness of the mixtures tested, due to the non-linear decrease in the D_{min} values with p', an attempt was made to express the dependence of D_{min} on p' by means of a power function, as follows:

$$D_{\min} = a \cdot (p')^{b} , \qquad (3)$$

where:

a – corresponds to the D_{min} value at 1%,

b – is the exponent of the stress–state dependency law that describes the evolution of D_{min}.

The constants in Eq. (3) are summarized in the table included in Fig. 10. Unfortunately, the small R^2 values are indicative of an inadequate fit of the model to the data and necessitate further research.

4. CONCLUSIONS

Recycled Concrete Aggregate (RCA) is a construction and demolition material that in an unbound state can be placed as a subbase in road structures. Over the last decades, there have been many investigations that highlighted the physical and mechanical properties of this material. Nevertheless, the successful application of RCA still needs more tests. For the sustainable development of road engineering, utilization of recycled material is essential. The present study investigates the dynamic behavior of different RCA mixtures, together with one specimen of NA, based on a series of CTS tests conducted in the modified resonant column apparatus.

First of all, the results obtained show similar characteristics of man-made soils and their similar trends of change during cyclic loading as for natural materials. This similarity to natural materials confirms their potential for use as a replacement material for natural sand, for example. It is important to remember the factors supporting the RCA engineering applications, which include CO_2 reduction (contributing to the circular economy), cessation of landfills, a decrease in scarcity of raw materials, and reduced costs [42].

In terms of the utilization of the test material in road construction, considering the grain size distribution, primarily fine recycled concrete aggregates (fRCAs) do not meet the requirements of Polish, English, and American standards regarding the acceptance of this particular material as road substructure. It should be highlighted that the already coarser RCA (fractions finer than 63μm = 0%) fulfills the above-mentioned requirements.

Available experimental data demonstrate that the fRCA mixtures are very effective in damping vibrations from passing vehicles (up to 6% damping ratio for shear strains below 1×10^{-2} %), but do not improve the rigidity of the roadbed (shear modulus varies between 50 and 180 MPa). In contrast, if the subbases or bases are made with coarser anthropogenic material (coarser RCA), they may exhibit increasing dynamic shear modulus with values even more than 250 MPa and wave attenuation of 1%–2%. The tested coarse aggregate is thus characterized by stiffness comparable to that of a natural aggregate.

Summarising, the possible applications of the investigated recycled materials, in addition to road and/or pavement construction, taking into account the increasing diversity and complexity of loads such as traffic, waves, and earthquakes, include their use as a promising backfilling material, especially in seismically active terrains or those exposed to various vibrations. This expansion of the application of RCA to geo-structures seems more appropriate for fRCA. Further studies need to be carried out to confirm this application, which will cover e.g. static properties, their long-term performance in drainage, and environmental sustainability tests.

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