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REVIEW

Experimental research on compressibility characteristics of recycled concrete aggregate: recycled tire waste mixtures

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Abstract

The utilization of processed rubber and construction waste in lieu of soil as a substrate could improve significantly seismic performance, while addressing the pressing environmental issue of how to reutilize and dispose of, i.e., automotive tires and demolition by-products. In this study, a series of laboratory tests explore the influence of recycled tire waste (RTW) and recycled concrete aggregate (RCA) fine particles on the compressibility parameters of RCA–RTW mixtures. The results revealed that the addition of rubber waste to RCA causes an increase in its compressibility and consolidation index (c_v) while prompting a power law decrease in the associated void ratio. It is found that all RCA–RTW mixtures are characterized by higher values of the compression (C_C) and swelling (C_S) indexes when compared to the pure RCA specimens while presenting a primary and secondary constrained modulus of fewer than 42 MPa and 96 MPa, respectively.

Keywords Recycling · Environment · Waste · Anthropogenic soil · Oedometer tests

Introduction

Solid wastes are produced from commercial, industrial, and all forms of anthropogenic activities [1]. Some of these wastes are usually dumped in landfills whereas others are disposed of in water bodies, drainage ditches, and fallows surrounding human homes. Such unhealthy dumping of waste is very dangerous to humans, animals, and plants due to their often high levels of toxicity. Therefore, the social, environmental, and economic costs of solid waste disposal are too high to ignore [2].

Among materials of hard disposal, the rapid growth of industrialization in different societies has dramatically increased waste tire generation. Such a material is classified as non-degradable, the landfill of which produces hazardous leachate, whereas incineration can result in non-desirable gasses and heat. Their recycling and reutilization are, therefore, preferred due to environmental benefits and potential cost reductions ensuing from reduced use of raw natural resources [3]. Tire recycling is the process of converting end-of-life or unwanted waste tires into materials that can be utilized in new products or applications [4]. Tire wastes (whole tires, tire shreds, or tire chips) provide many unique properties that are significant for engineering applications, particularly in geotechnical engineering [5]. These include low density, low earth pressure, good insulating properties, good drainage capability, good long-term durability, and high compressibility [6].

Another waste of growing concern, resulting from the rapid urbanization of society, is refuse from demolition and construction work. Many particles constitute such a waste, for example, wood, bricks, steel, humus, and asbestos, although 85% of its content is aggregates [7]. As illustrated in Fig. 1, Arabani and Azarhoosh [8] reported that up to 75% of construction and demolition (C&D) wastes are concrete composites. By crushing demolished concrete, aggregates can be recovered or reclaimed, and later reused in the same construction ground or other building activities [9]. Such aggregates are referred to as recycled concrete aggregates (RCA) [10]. Depending on the quality of the aggregate, RCAs produced from C&D waste can be used in various construction sites [7]. The use of modified RCAs has been proven effective in various aspects of geotechnical engineering, such as construction substrates or a replacement for natural aggregates [2].

The question then becomes, what will the combination of two recycled materials look like? What will be the result

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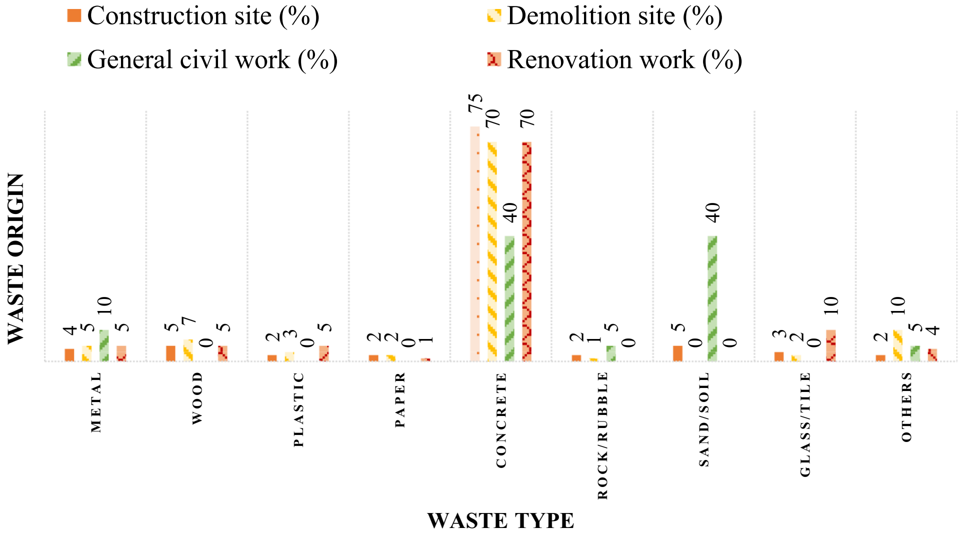
Fig. 1 A typical composition of construction wastes, based on [8]



of modifying RCA and enriching it with recycled tire waste (RTW)?

The literature survey shows that most studies to date concerning RTW have dealt with the engineering properties of sand-rubber mixtures (mainly tire scrap—shreds and/or chips) [11]. It was found that the addition of scrap rubber waste to the sand improved the shear strength of the sand, while granulated rubber reduced it, due to its significant ductility. In contrast, mixtures of sand with scrap tire waste were reported to undergo large deformations without any apparent peak or failure. In addition, they are characterized by low shear modulus and high damping coefficient, low liquefaction potential, and excellent damping and seismic isolation properties. Studies in recent years have shown that compaction effort has a negligible effect on the shear strength of sand-tire chip mixes. It has been observed that the behavior of the mixture changes from sandy to rubbery as the proportion of waste rubber in the composition increases [6]. Determining the behavioral zones (sand, sand-rubber, rubber) of the tested mixes is fundamental to their use in engineering projects.

However, when selecting the type of soil and size of recycled rubber to create soil–rubber mixtures for geotechnical applications, the availability, and cost-effectiveness of both materials must be carefully considered. [4]. An alternative to RTW mixtures is the employment of locally available RCA in place of sandy soil. Such compositions have a definite advantage of having, in theory, properties independent of location (rubber chips and concrete are standardized materials). Such RCA–RTW mixtures, however, lack throughout characterization [5]. Although a good indication, the knowledge acquired from studies on sand-rubber compounds cannot be directly applied to recycled concrete aggregate–rubber blends. Therefore, detailed studies providing insights into the physical properties, compaction characteristics, and mechanical behavior of the RCA–RTW mixtures are instrumental for their large-scale applications.

To address this issue, the present research deals with the compressibility characteristics of modified RCA by shredded rubber tires. Some physical and mechanical properties of the same or similar geocomposites have been studied by the authors of this paper from the year 2015 [5, 12, 13]. This article will present a series of oedometer tests on eight loose mixtures of variable grain-size distribution, rubber inclusion (RC), and fine fraction (FF) content. Oedometer tests are carried out to explore the influence of rubber particles on the compressibility parameters of the RCA–RTW mixtures. These parameters are of great importance in the mechanical behavior of rubberized soil mixtures. Fully dried RCA–RTW specimens, prepared at different percentages of rubber content of 5%, 10%, 15%, and 20%, are subjected to different vertical stress under no lateral displacement. Based on the obtained results, an attempt is made to investigate the deformation mechanisms of the mixture of two recycled materials. It is believed that such studies can be very useful in designing the reuse of shredded tires as structural and general fill material.

Materials and methods

Materials and mixtures

The anthropogenic material used in this work as a basic material for the preparation of composites is recycled concrete aggregate, wherein the concrete elements are derived from concrete floors, especially concrete curbs from the demolition of roads, of the strength class between C16/20 and C30/35. A presentation of RCA employed in the recent research, along with its selected physical, geometric, and chemical properties can be found in the authors' previous publications [5, 13]. The recycled concrete particles have a rounded, spherical shape, with smooth edges (Fig. 2), with a specific gravity (G_s) between the values of 2.60–2.61 g/cm^3. The more rounded and spherical shape of RCA improves its workability, in comparison to the original aggregates, which have generally an angular shape [14].

The used RCA is a granular material categorized by granulation, which allows for its classification as a non-cohesive soil. The size of the soil particles varies between less than 0.063 mm (up to even 30%) and 2.0 mm (around 1%) with an average grain size characterized by d_{50} of about 0.16 mm. It can be seen that it is a material with a high proportion of fine fraction, zero proportion of gravel fraction, and predominantly sand fraction. According to PN-EN ISO, 14,688-2:2006 [15] specification the 'parent' granular materials are classified as poorly graded sand and well-graded sand with silt, with a coefficient of uniformity (C_u) in a range of 2.86–5.60 and a coefficient of curvature (C_c) in a range of 0.91–1.29. Using sieve analysis, this 'parent' material is separated into individual fractions with particle sizes as follows: < 0.063 mm, 0.063–0.125 mm, 0.125–0.25 mm, 0.25–0.50 mm, 0.5–1.0 mm, and 1.0–2.0 mm. Then, four new compositions of RCA, namely M1, M2, M3, and M4, are created. These mixtures have different, increasing, the content of fine fraction (FF), from 0 to 30%, in the increment of 10%. In Fig. 3 the grain size distribution curves of the mixes M1–M4 are depicted. Tested mixtures are of uniform grain size.

In the current research, to optimize the anthropogenic soil properties, two uniform rubber materials were used as synthetic parts of the mixtures, namely powder (*P*) 0.5–1.0 mm and granulate (*G*) 1.0–2.0 mm (Fig. 4). According to ASTM specification [16], these materials are classified as granulated or powdered rubber, exhibiting a mean grain size (d_{50}) in a range of 0.65–2.5 mm, with a coefficient of uniformity (C_u) in a range of 1.97–2.46 and a coefficient of curvature (C_c) in a range of 0.79–1.14. The specific gravity (G_s) of rubber solids was approximately 1.19 g/cm^3. In Fig. 5, the grain size distribution curves of 'parent' rubber materials are presented.

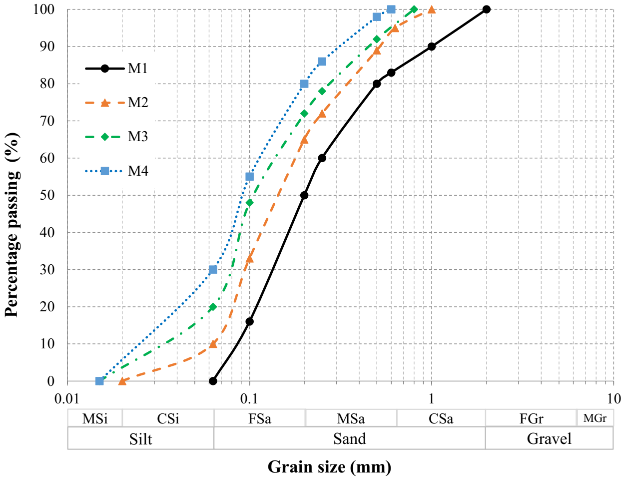
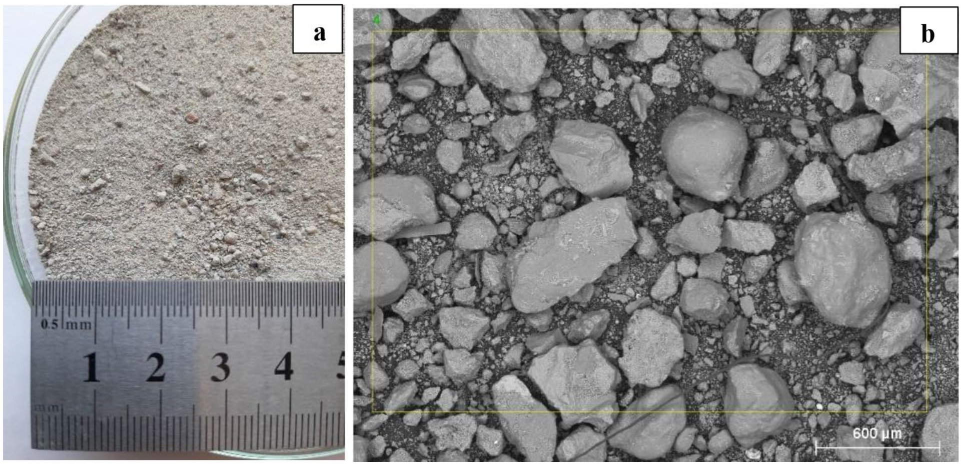


Fig. 3 Grain size distribution of tested pure RCA mixtures

The applied rubber comes from waste tires. It was shredded and processed in the local tire manufacturing plant. The use of rubber waste from worn vehicle tires was intentional. First, recycling used tires will cause serious negative effects on the ecosystem [6]. Second, based on the natural geotechnical properties of tire rubber, it can be mixed with soil to form rubber-reinforced soil, a new type of geotechnical material that can improve some selected properties of soil [17]. The main chemical components of used waste tires are natural rubber and synthetic rubber, as well as sulfur, carbon black, silicon oxide, iron oxide, calcium oxide, and other additives [5].

For test purposes, recycled tire wastes of two sizes, viz. powder and granulate, were mixed with previously prepared M1–M4 compositions with different mass rubber content,

Fig. 2 Recycled concrete aggregate used in this study: **a** natural dimensions and **b** microscopic view



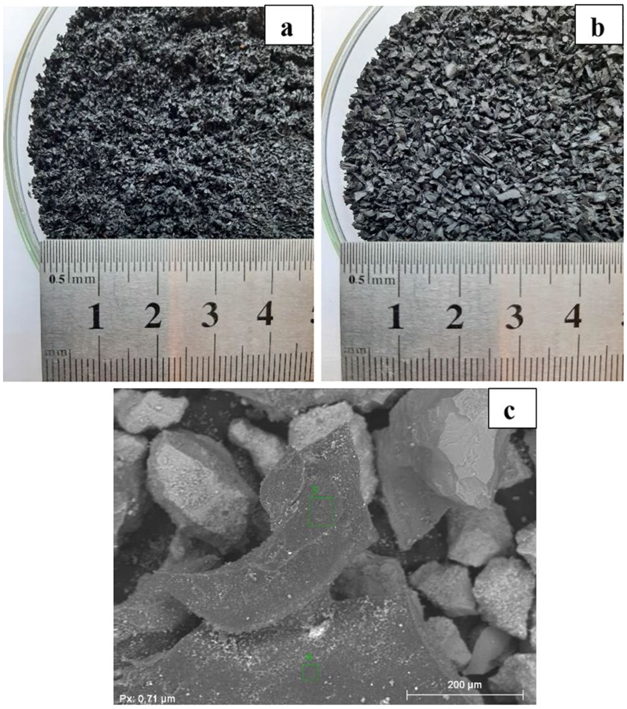


Fig. 4 Recycled tire waste: **a** powder 0.5–1.0 mm, **b** granulate 1.0–2.0 mm, and **c** microscopic view

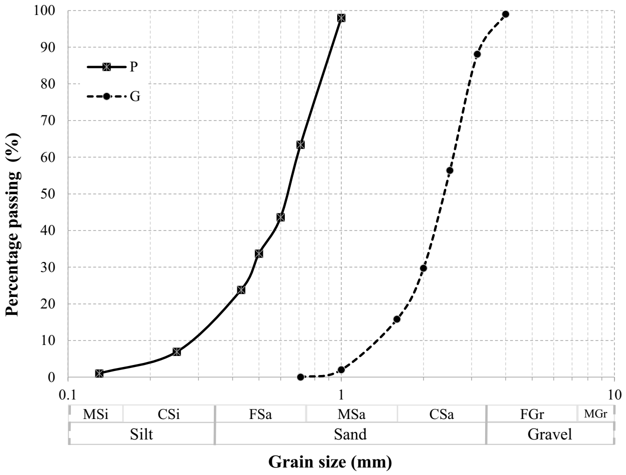


Fig. 5 Grain size distribution of 'parent' recycled tire waste (P-powder, G-granulate rubber)

appropriately 5%, 10%, 15%, and 20% of mixture weight. According to the literature [18], the maximum rubber content is equal here to 20% by weight, which corresponds to about 35–40% rubber content by mixture volume (VRC = 0.35–0.4). The new blends (mixtures named M1-R, M2-R, M3-R, and M4-R, where the letter R stands for rubber) were created in a slightly different way than the traditional mixing of two materials. The new compositions were prepared in such a process that the corresponding RCA fraction, with grain sizes ranging from about 2.0 mm or 1.0 mm to 0.5 mm, was eliminated and replaced with rubber waste. The final result was as follows soil grains smaller than rubber particles ($d_{50\mathrm{R}} > d_{50\mathrm{S}}$). However, it is difficult to determine the relative particle size between RTW and RCA, known as the aspect ratio ($\mathrm{AR} = \frac{\mathrm{D}_{50,\,\mathrm{RTW}}}{\mathrm{D}_{50,\,\mathrm{RCA}}}$, where $D_{50,\,\mathrm{RTW}}$ is the median diameter of recycled tire waste, and $\mathrm{D}_{50,\,\mathrm{RCA}}$ is the median diameter of recycled concrete aggregate). It is worth noting that as the content of the fine fraction (FF), i.e., < 0.063 mm, increases, the content of waste rubber decreases.

A major problem with this type of mixture, i.e., granular mixtures, is material segregation. In this study, to reduce segregation, the vibration was minimized and granular flow during specimen preparation was eliminated.

In Table 1, the general information about RCA–RTW resulting mixtures is summarized.

The variation of dry density (ρ_d) and void ratio (e) against rubber content (RC) are presented in Fig. 6. Since rubber particles are much lighter than recycled concrete aggregates (i.e., the $\mathrm{G_s}$ of rubber particle is around 40% less than of the RCA), dry density (both minimum and maximum) of the RCA–RTW mixtures decreases linearly by increasing RC as demonstrated in Fig. 6a. The decrease is within 7% for $\rho_{\mathrm{d,\,max}}$, and within 3% for $\rho_{\mathrm{d,\,min}}$. However, in terms of the void ratio, as shown in Fig. 6b, the void ratio slightly increased by about 7.5% up to RC = 20%. For e_max, it is a linear increase in value with increasing rubber waste content. In the case of e_min, on the other hand, a break in the upward trend is observed for rubber contents of 15%. In general, the reported increase in the void ratio values is related to the way the mixtures were prepared, namely by replacing RCA particles with rubber particles in the mixtures. In the research presented here, although the dimensions of rubber waste applied in the new specimens are usually small, as it has been used rubber powder and granulate, up to 2 mm in size, there are not small enough to fit in the voids between RCA grains. The dimensions of the rubber materials correspond to the dimensions of the soil removed; in this case, there is no possibility of filling. Soil separates the rubber contacts.

Shear strength characteristics of all RCA–RTW mixtures are included in the other manuscript by the author [5], where the results of friction angle and cohesion are indicated. Young's modulus values are reported to be in the range of approx. 160–33 MPa. In this research, the higher the content of waste rubber in the mixture, the lower the modulus. Although, it is important to keep in mind that the maximum content of rubber waste in the mix was 20%. With such a low rubber content, the RCA skeleton controls the behavior of the mixtures. A summary of rubber–soil interaction in

Table 1 Parameters of the tested RCA-RTW mixtures

No.	Code name of RCA-RTW mixture	Composition	Classification of rubber	Percentage of fine fraction	d_{50} (mm)	C_u[a]	C_c[b]	e_{min} (–)	e_{max} (–)
1	M1-R	RCA_20R_0FF	10% powder, 10% granulate	0	0.20	2.91	0.91	0.863	1.091
2	M2-R	RCA_15R_10FF	15% powder	10	0.16	2.86	1.27	0.719	1.077
3	M3-R	RCA_10R_20FF	10% powder	20	0.14	5.15	1.29	0.784	0.955
4	M4-R	RCA_5R_30FF	5% powder	30	0.12	5.60	1.17	0.699	0.882

[a] Coefficient of uniformity $C_u = d_{60}/d_{10}$

[b] Coefficient of curvature $C_c = d_{30}^2/(d_{10} \times d_{60})$

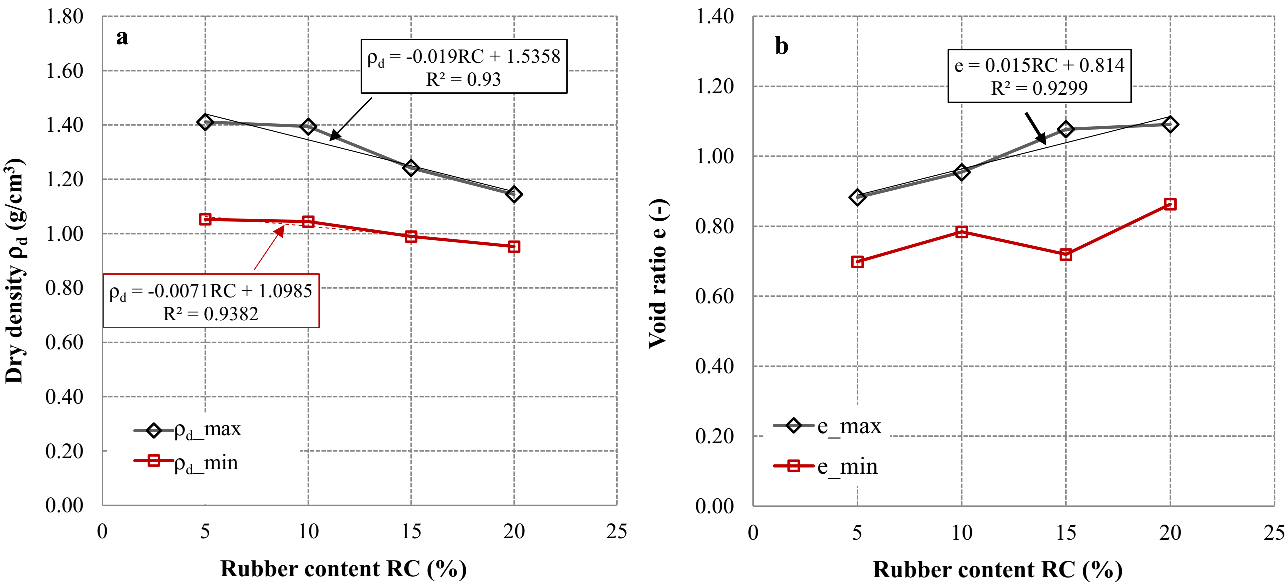


Fig. 6 Variation of: **a** minimum and maximum dry density, **b** minimum and maximum void ratio with weight rubber content

mixtures with different gravimetric and volumetric rubber content can be found in Kim and Santamarina [19].

Testing method

In this study, an experimental laboratory program containing a series of oedometric tests was carried out. In the first step, soil and rubber parts were dried and mixed in a selected percentage of crushed pieces of recycled tire waste ranging from 0% (clean recycled concrete aggregate) to 20% by mixture weight to prepare uniform mixtures of specific rubber content. In the second step, 50 × 20 mm (diameter × height) specimens were constructed in dry conditions in three/four small layers directly in the metal ring of the oedometer, already in the oedometer cell. Each layer was compacted by a small hand tamper, from the bottom to the top of the metal ring. Densification was attained by tamping. The vibratory compaction is not suitable for granulated rubber samples [20]. All specimens were built at about the same construction energy (standard Proctor energy, 0.59 J/cm^3), although the energy level has little effect on the compatibility of rubber waste mixtures [21]. After each specimen was finished, its surface was leveled and capped with filter paper and permeable stone. The details regarding the ratio of soil to rubber, as well as the justification for RTW maximum content, are included in [5].

Each RCA–RTW blend was saturated, enclosed in a circular metal ring, and sandwiched between porous stones [22]. Vertical increments of static load were applied at regular time intervals (e.g., 24 h). The load was doubled with each increment, starting at 12.5 kPa, up to the required maximum, equal to 800 kPa. Once full consolidation was achieved, the unloading process was initiated. Each specimen was unloaded in four steps, in the sequence of 800, 400, 200, and 100 kPa with a load decrement ratio of 2. Afterward, the same specimen was reloaded (as well in four steps) up to a load of 1600 kPa. After the end of each test, the specimen was removed, and its thickness and water content were determined. In this study, one-dimensional consolidation tests on the RCA–RTW mixtures were carried out under repeated unloading and reloading conditions to investigate the effect of the addition of recycled tire rubber aggregate on the compressibility parameters of the mixtures.

All experimental tests were performed on freshly composed mixtures, without creep analysis. It can be expected that soil–rubber creep is significant, and this is an idea for future original research. Tire rubber has a remarkable ability to absorb oil and has been used to remove oil contaminants [23, 24]. The oil absorption translates into swelling of the rubber particles, thereby altering and potentially manipulating the mechanical response of the material. Based on the further literature review, it was concluded by Ngo and Valdes [25] that the initial and creep strains are proportional to the rubber content.

As for the temperature dependency, all experiments were conducted at room temperature (i.e., 22 °C). The tests were not performed at a different temperature, because according to the literature review [25] soil–rubber creep is temperature independent within the range of temperatures pertinent to typical civil engineering works.

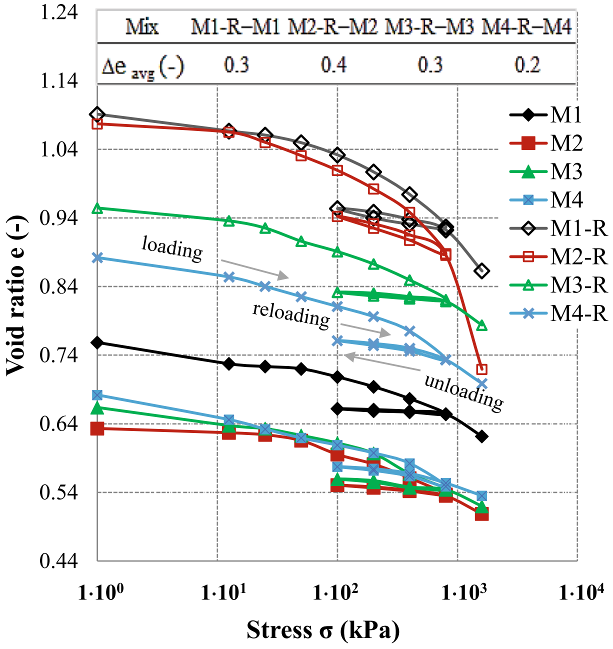


Fig. 7 Compressibility curves for pure RCA mixtures (compositions M1 to M4) and RCA–RTW mixtures (compositions M1-R to M4-R)

Test results and discussion

Compressibility behavior

Compressibility is one of the most important parameters required in design considerations. For natural pure soils such as sand and gravel that have rigid particles, any volume change is caused by the movement, rotation, and rearrangement of non-compressible particles [26]. The compressibility of soil–rubber mixture, however, is completely different due to inter alia significantly lower elastic modulus of soft rubber particles in comparison with the rigid particles of the host soil [27]. The Poisson's ratio of pure rubber is close to 0.5 [28], causing high bulk modulus, low shear modulus, and consequently, when subjected to an applied load, easy distortion of rubber specimens.

This section presents the compressibility results of tests carried out in the oedometer apparatus on loose mixtures of composite materials that consist of recycled concrete aggregate (RCA) and crushed pieces of recycled tire waste (RTW). The consolidation curves on the void ratio–stress ($e-\sigma$) the plot is shown in Fig. 7. The process of creating a consolidation curve is included in Sect. Testing Method of this article.

The results of various tests show that the compressibility of mixtures with rubber addition is higher than that of mixtures without rubber addition. Furthermore, the compressibility of the RCA–RTW mixtures generally increases with an increasing proportion of rubber waste. The highest compressibility is characteristic of the sample with 20% of rubber content (the M1-R mixture). The lowest compressibility is, on the other hand, characteristic of the M2 mixture, which is a composition without rubber waste but with a 10% of fine fraction. It was expected that the rubber would act as a solid grains binder, which will appropriately reduce the void ratio. The way the composites were designed had a big effect on this. As mentioned earlier, a rubber additive of a similar size to the initial soil was used, without the possibility to fill the voids. The effect of decreasing the compressibility could be achieved with smaller aspect ratio values. In Fig. 7, additional information about the average increase in void ratio values between corresponding soil–rubber blends and initial soil mixtures is included. It can be noticed that changes in Δe are similar, on average it is an increase of 0.3.

In Fig. 8, the void ratio as a function of rubber content and fine fraction content is presented. It may be seen as an increase in the average void ratio with an increase in the rubber additive content in the mixture. The increase of the average void ratio for the tested mixtures M1-R–M4-R has been developed in the power function. The obtained *e* values are similar to those characterizing loose even-grained sands. These results might be related to the fact that the addition of RTW reduces the density of the material, providing an increase in the void ratio of the soil and consequently increasing the compressibility of the composite. The lack of rubber addition results in a lack of ordering of the obtained void ratio values (see the mixtures M1–M4). The *e* values are smaller but also have less variation. They are similar

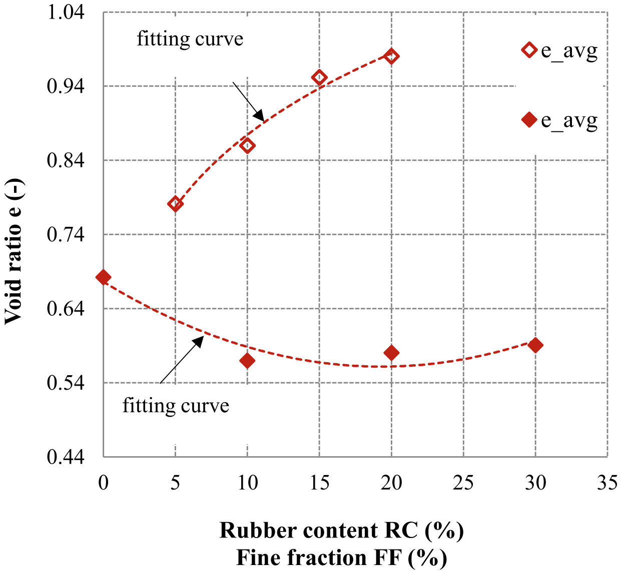


Fig. 8 Void ratio vs rubber waste content (blank symbols, compositions M1-R to M4-R) and fine fraction content (filled symbols, compositions M1 to M4)

to those characterizing loose well-grained sands. The void ratio of mixtures with rubber is higher than those without rubber inclusion. This is due mainly to the higher angularity of rubber particles and the lower specific gravity (G_s). It is worth mentioning that the smaller the rubber particles are, the higher the e_{max} value of the pure rubber is.

Compressibility parameters

The compressibility of soils, along with their strength, is one of the most important soil characteristics considered at the stage of designing engineering structures founded on the ground. Compressibility is defined as the change in soil volume toward increasing loading. Among the basic parameters characterizing compressibility is the compression and recompression index. They are usually obtained using the graphical analysis of compression curve in void ratio—effective stress (e – log σ) plots in Fig. 9. This curve consists of two basic fragments with an approximately linear course [29]. The slope of the straight-line portion of the virgin part of the compression curve on a semi-logarithmic plot is the compression index (C_C) and the slope of the recompression or swelling curve is the recompression index (C_r) [30], as shown in Fig. 9a. The swelling index (C_S) used as well for settlement calculation can be obtained also from the one–dimensional consolidation test. It represents the estimated slope of the decompression curve, the second branch of the compression curve as shown in Fig. 9b.

In Fig. 10, the variations of different compressibility parameters of tested soil–rubber mixtures as a function of the percentage of rubber waste addition and a fine fraction are presented. In the case of rubber-enriched recycled concrete aggregate (mixes M1-R-M4-R), the highest values of compression index, equal to 0.07, were obtained for first loading, in the first load range from 12.5 to 800 kPa. The values of the other two parameters, C_S and C_r, are very similar,

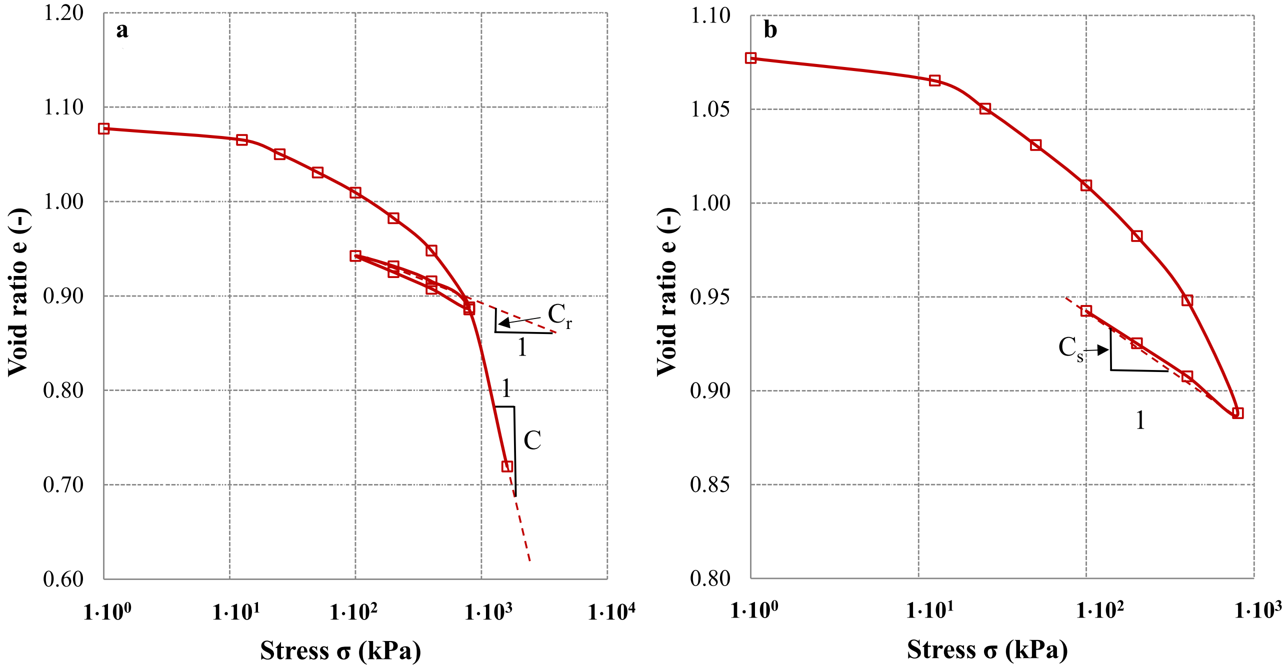


Fig. 9 Definition of: **a** C_c, C_r, and **b** C_s from the compression curve of the M2 blend

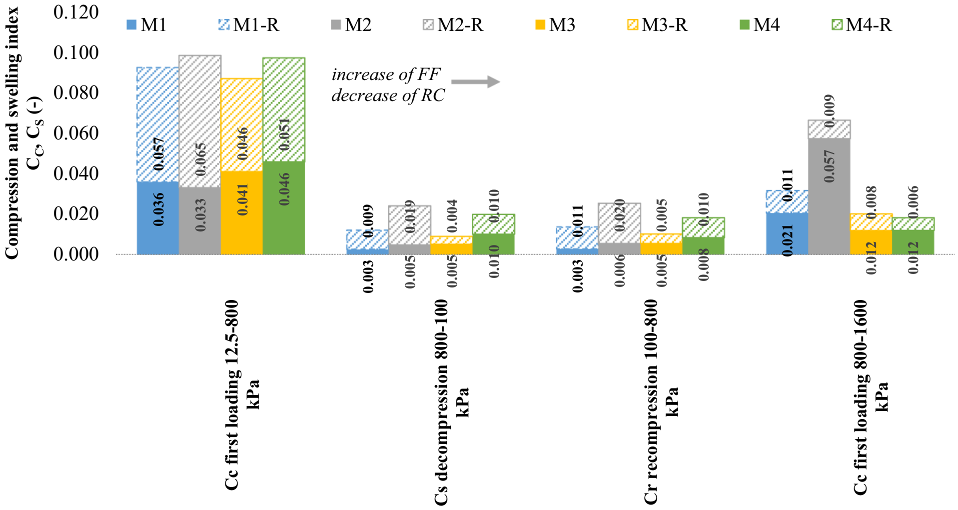


Fig. 10 Variation of the compression parameters versus rubber content (RCA–RTW mixtures) and fine fraction content (pure RCA mixtures). Solid rectangles indicate pure RCA mixtures, and hatched rectangles indicate RCA–RTW mixtures. The arrow indicates the direction of change in the fines (FF) or rubber waste (RC) content

almost overlapping, ranging from around 0.01 to 0.02. Based on the data presented, it is seen that the M3-R mix, with 10% of RC, is characterized by the highest values of the investigated parameters.

The one-dimensional compression tests on RCA–RTW mixtures indicate that owing to the high compressibility nature of tire rubber, the compressibility increases with increasing rubber content by weight. There is, for example, a slight linear increase, of about 17%, in the compression index for the first loading, in the second load range from 800 to 1600 kPa.

For pure RCA compositions (M1–M4), the compression index is characterized by the greatest dispersion of results. Moreover, it is difficult to observe any dependency on the fine fraction content. The highest value, $C_C = 0.057$, was obtained for the specimen M2 (FF = 10%), for the first loading, in the second load range from 800 to 1600 kPa. This is an exception in comparison with other mixtures, where for all others, higher C_C was found for the first loading sequence, 12.5–800 kPa. The decompression and recompression index take similar values for M1–M4 blends, with an average of 0.005.

These studies show that all RCA–RTW blends tested are characterized by higher values of the compression index (C_C) and swelling index (C_S) compared to the pure RCA specimens, by around 26–27%. However, it must be emphasized that the C_C values are of the order of $5 \cdot 10^{-2} - 6 \cdot 10^{-2}$ for soil-rubber mixtures, and the order of $3 \cdot 10^{-2} - 4 \cdot 10^{-2}$ for pure soil samples, which corresponds to typical values of C_C for sands and indicates that all mixtures are low compressible soils. The recompression indexes (C_r) are between $\frac{1}{3}$ and $\frac{1}{6}$ of the virgin compression index, revealing that consolidation or compaction significantly improves the stiffness of the blends. The swelling potential was found in the range of $0 < C_S < 0.1$ for all investigated mixtures. This means that the specimens had a low degree of swelling. Similar conclusions were drawn by Benessalah et al. [31], who investigated the compressibility of natural soil, and sand, mixed with rubber under one-dimensional consolidation loading conditions.

The oedometric modulus is another parameter characterizing soil compressibility that can be obtained by the oedometric tests. If the results from the oedometric test are represented in terms of the oedometric curve $\left(\Delta\varepsilon = f\left(\Delta\sigma_{ef}\right)\right)$, it will be found that for each point on the curve a different ratio of $\frac{\sigma_{ef}}{\varepsilon}$, where σ_{ef} is the effective stress, $\Delta\sigma_{ef}$ is the reduction of effective stresses, ε is the strain, $\Delta\varepsilon$ the is the change in strain with a change in stress of $\Delta\sigma_{ef}$. If the stress–strain curve is replaced for a certain interval of two adjacent stresses $\sigma_{1ef} - \sigma_{2ef}$ by a secant line, the linear behavior of soil in this interval is allowed and represents the soil compressibility by $\frac{\Delta\sigma_{ef}}{\Delta\varepsilon}$. This ratio is called the oedometric modulus of deformation. The oedometric modulus of deformation (M) is, therefore, a secant modulus linked to a certain stress interval $\sigma_{1ef} - \sigma_{2ef}$ selected on the stress–strain diagram $\left(\Delta\varepsilon = f\left(\Delta\sigma_{ef}\right)\right)$:

$$M = \frac{\Delta\sigma_{ef}}{\Delta\varepsilon} = \frac{\sigma_{2,ef} - \sigma_{1,ef}}{\varepsilon_2 - \varepsilon_1}. \tag{1}$$

[32] Based on the curves of compressibility, values of oedometric modulus of deformation during primary consolidation (M_0), in the stress range 12.5–800 kPa and 800–1600 kPa, and secondary consolidation (M), in the stress range 100–800 kPa, are calculated and presented in Fig. 11. The difference between the oedometric modulus of pure anthropogenic soil and soil–rubber mixture is in the order of approximately 33%. By increasing rubber in the mixture (Fig. 11), the modulus M_0 decreases by an average of 8% for vertical stress from 12.5–800 kPa, and by an average of 37% for vertical stress from 800 to 1600 kPa. A similar trend of change in oedometric modulus for soil–rubber

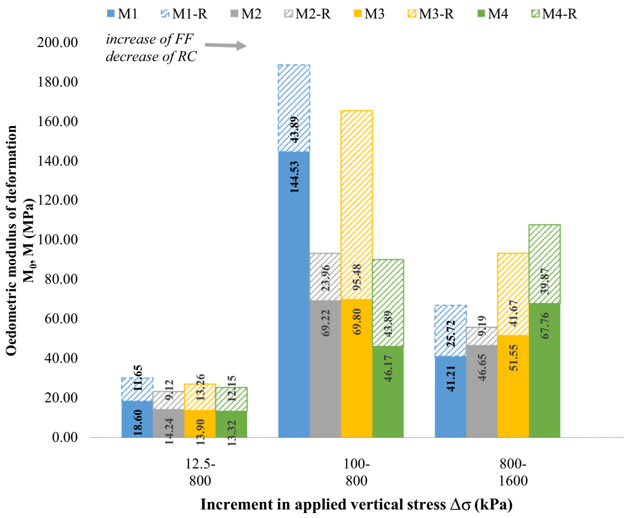


Fig. 11 Comparison of values of oedometric deformation modulus (M_0, M) for RCA–RTW mixtures and pure RCA mixtures

mixtures are reported in the literature [33]. From the data presented, it can be seen that when RC is small (up to 10%), the mixture transfers the load mainly through the soil skeleton. The increased rubber–rubber interaction gradually reduces the effective stiffness of the mixture, as well as the modulus of deformation, with an increasing fraction of rubber particles [19]. The values of modulus during reloading (M) decreased by more than 50% (see the M1-R and M3-R blends). In addition, for RCA–RTW mixtures the highest modulus values ($M_0 \cong 42$ MPa, $M \cong 96$ MPa) are obtained for the mixture with 10% of rubber content (M2-R).

Based on the results presented, it can be noted that the amount of the fine fraction affects the oedometric modulus of deformation at higher vertical stress levels (i.e., > 800 kPa) (Fig. 11). A linear gradual increase in M_0 values is observed (a coefficient of determination $R^2 = 0.91$). The highest value of M_0 ($M_0 = 67.76$ MPa) is found for the composition M4, with the maximum addition of FF, equal to 30%. At a lower vertical stress level (i.e., < 800 kPa), specimen No 1 (pure anthropogenic material) is characterized by the highest moduli. The addition of fine fraction (< 0.063 mm) generally causes M_0 and M to decrease by respectively 23% and 52%. Then, on the other hand, the amount of FF content alone does not have any significant impact on the modulus values. The scatter of these values is small, of the order of a few percent for the M_0 modulus and a dozen for the M modulus.

Consolidation parameters

Using oedometer tests it is possible to quantify the effects of consolidation. The analysis of the settlement curves as a function of time, so-called consolidation curves, makes it possible to define the representative points of the bearing

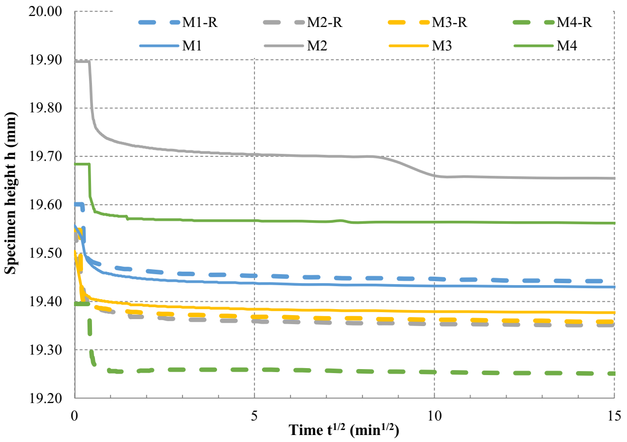


Fig. 12 Consolidation curves of a different mixture: RCA–RTW mixture and pure RCA mixture

in mechanical terms of vertical stress versus deformation. In Fig. 12, an example of consolidation curves under normal stress of 100 kPa for all investigated mixtures is presented. Based on the following figure, it can be concluded that the consolidation process in all analyzed mixes is fast; the consolidation curves have a similar path; the thresholds of change to subsequent phases of the consolidation process are clear.

From the time-settlement curve, the coefficient of consolidation (c_v) can be readily estimated. Of two commonly used methods to determine c_v, the Taylor method is implemented in this research. In this method, readings of a compression dial are taken up to a time corresponding to at least 90% of the primary compression of the test specimen under the increment of loading being considered. The 90% consolidation time varies with different specimens and with different thicknesses of specimens [33]. The Taylor method consists in determining the slope at the starting point in the plane of settlements as a function of the square root of the consolidation time. The slope multiplied by 1.15 intersects the consolidation curve at 90% of the deformations, which makes it possible to define the t_{90} value and thus the consolidation index (c_v) for the considered level. C_v is described by Eq. (2):

$$c_v = \frac{T_{v90} \cdot H^2}{t_{90}} \tag{2}$$

where H is the average longest drain path during consolidation (the thickness of specimen at 90% consolidation), t_{90} is the time to reach 90% deformation (consolidation) and T_{v90} is the time factor, which takes the value 0.848 [34].

In Table 2, the changes in c_v coefficients for all tested composites are summarized. Results show that in most cases, as the rubber content of the mixtures increases (mixtures

Table 2 Consolidation parameters of the tested mixtures

Mixture No.	Code name of mixture	t_{90} (min)	T_{v90} (−)	H (mm)	c_v (mm²/min)
1	M1	0.25	0.848	19.557	1297.36
2	M2	0.32	0.848	19.896	1049.00
3	M3	0.04	0.848	19.504	8064.61
4	M4	0.19	0.848	19.684	1729.29
5	M1-R	0.11	0.848	19.601	2961.83
6	M2-R	0.25	0.848	19.553	1296.83
7	M3-R	0.04	0.848	19.548	8101.04
8	M4-R	0.25	0.848	19.395	1275.96

M1-R–M4-R), the consolidation index (c_v) increases too. The composition with the highest rubber content, at 20%, results in higher c_v. This is an increase of over 50% compared to a composition with 15% rubber content. For subsequent soil–rubber samples, Δc_v is around 2%. However, the M3-R blend is an exception, the c_v value obtained is significantly different from the others. In the case of pure anthropogenic soil mixtures, there is a large scatter of results, with no clear trend in c_v change, and one mixture (here M3) significantly diverging from the others.

Conclusions

Previous studies on soil–rubber mixtures have mainly focused on sandy soils mixed with various rubber sizes. This paper presents one–dimensional compression test results for recycled concrete aggregate (RCA) mixed with recycled tire waste (RTW), as well as, for comparison, for specimens of pure RCA. The tests are performed on compositions prepared and air-dried by the tamping method. All blends are consolidated under normal effective stress in the oedometric device. The compressibility characteristics of eight loose mixtures of variable grain-size distribution, rubber inclusion (RC), and fine fraction (FF) content are shown and described here. The main conclusions of this research are the following:

- The inclusion of rubber particles in RCA–RTW blends increases the compressibility of the compound materials.
- Compressibility parameters (C_C and C_S) of rubber-reinforced mixtures are mostly about 27% higher in comparison to pure RCA mixtures.
- RCA blends are characterized by higher values of primary (M_0) and secondary (M) oedometric modulus than RCA–RTW mixes by an average of 33% and 26%, respectively.
- An increase in consolidation index (c_v) is observed when rubber content increases. The size and highly compressible nature of tire rubber may be responsible for the increased rate of consolidation.

In future studies, the experimental results of this work could be enriched with additional laboratory tests on the specimens with optimum moisture content prepared by under compaction method to avoid segregation of two–size soil–rubber mixtures. Moreover, an adaptation of water–saturated mixtures has more advantages from a geotechnical viewpoint. RCA is an excellent construction material and when enhanced with rubber waste can be successfully used in road construction. An interesting solution for many geotechnical applications may be the usage of coarser material in mixes, either coarser RCA or larger rubber. According to Hazarika et al. [35], the implementation of gravel-rubber mixtures in the layers under the foundation of residential buildings can provide sufficient bearing capacity and reduce earthquake-induced subsidence.

Finally, although RCA–RTW are great building materials from a geotechnical point of view, their final use should also be determined by environmental studies to ensure that there is no damage to the environment.

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Declarations

Conflict of interest The author declares that they have no conflict of interest. The funding organization has no role in the collection, analysis, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Akhtar A, Sarmah AK (2018) Construction and demolition waste generation and properties of recycled aggregate concrete: a global perspective. J Clean Prod 186:262–281. https://doi.org/10.1016/j.jclepro.2018.03.085
2. MaduabuchukwuNwakaire C, Poh Yap S, ChuenOnn C, Wah Yuen C, Adebayo Ibrahim H (2020) Utilisation of recycled concrete aggregates for sustainable highway pavement applications; a review. Constr Building Mater 235:117444. https://doi.org/10.1016/j.conbuildmat.2019.117444
3. Tajdini M, Nabizadeh A, Taherkhani H, Zartaj H (2017) Effect of added waste rubber on the properties and failure mode of kaolinite clay. Int J Civ Eng 15:949–958. https://doi.org/10.1007/s40999-016-0057-7
4. Tasalloti A, Chiaro G, Banasiak L, Palermo A (2021) Experimental investigation of the mechanical behaviour of gravel-granulated tyre rubber mixtures. Const Build Mater 273:121749. https://doi.org/10.1016/j.conbuildmat.2020.121749
5. Gabryś K, Radzevičius A, Szymański A, Šadzevičius R (2021) Shear strength characteristics of recycled concrete aggregate and recycled tire waste mixtures from monotonic triaxial tests. Materials 14(3):1–17. https://doi.org/10.3390/ma14237400
6. Mashiri MS, Vinod JS, Sheikh MN, Tsang HH (2015) Shear strength and dilatancy behaviour of sand–tyre chip mixtures. Soils Found 55(3):517–528. https://doi.org/10.1016/j.sandf.2015.04.004
7. Tam VWY, Soomro M, Evangelista ACJ (2018) A review of recycled aggregate in concrete applications (2000–2017). Constr Build Mater 172:272–292. https://doi.org/10.1016/j.conbuildmat.2018.03.240
8. Arabani M, Azarhoosh AR (2012) The effect of recycled concrete aggregate and steel slag on the dynamic properties of asphalt mixtures. Const Build Mater 35:1–7. https://doi.org/10.1016/j.conbuildmat.2012.02.036
9. Albayati A, Wang Y, Wang Y, Haynes J (2018) A sustainable pavement concrete using warm mix asphalt and hydrated lime treated recycled concrete aggregates. Sustain Mater Technol 18:e00081. https://doi.org/10.1016/j.susmat.2018.e00081
10. Sas W, Głuchowski A, Soból E, Kulkowska M (2015) Experimental studies on crushing of recycled concrete aggregates. Acta Sci Pol Arch 14(1):29–41
11. Nakhaei A, Marandi SM, SaniKermani S, Bagheripour MH (2012) Dynamic properties of granular soils mixedwith granulated rubber. Soil Dyn Earthq Eng 43:124–132. https://doi.org/10.1016/j.soildyn.2012.07.026
12. Sas W, Głuchowski A, Szymański A (2015) The geotechnical properties of recycled concrete aggregate with addition of rubber chips during cyclic loading. In Proceedings of the 5th International Conference—GEOMATE 2015 Géotechnique, Construction Materials and Environment, Osaka, Japan, 16–18 November 2015; pp. 193–198
13. Gabryś K, Sas W, Soból E, Głuchowski A (2017) Application of bender elements technique in testing of anthropogenic soil—recycled concrete aggregate and its mixture with rubber chips. Appl Sci 7:741. https://doi.org/10.3390/app7070741
14. McNeil K, Kang TH-K (2013) Recycled concrete aggregates: a review. Int J Concr Struct 7(1):61–69. https://doi.org/10.1007/s40069-013-0032-5
15. PN-EN ISO 14688–2:2006. Geotechnical investigation and testing—determination and classification of soils—part 2: classification rules; PKN: Warszawa, Poland, 2006
16. ASTM. Standard practice for use of scrap tires in civil engineering applications: D6270–98. In Annual book of ASTM standards, ASTM International, 1998
17. El-Sherbiny R, Razek AYA, Lotfy H (2013) Triaxial testing on saturated mixtures of sand and granulated rubber. Geotechnical Special Publication, Auburn, IN, USA
18. Senetakis K, Anastasiadis A, Pitilakis K (2012) Dynamic properties of dry sand/rubber (SRM) and gravel/rubber (GRM) mixtures in a wide range of shearing strain amplitudes. Soil Dyn Earthq 33:38–53. https://doi.org/10.1016/j.soildyn.2011.10.003
19. Kim H-K, Santamarina JC (2008) Sand−rubber mixtures (large rubber chips). Can Geotech J 45:1457–1466. https://doi.org/10.1139/T08-070
20. Ahmed I, Lovell CW (1993) Rubber soils as lightweight geomaterials. Transp Res Rec 1422:61–70
21. Moo-Young H, Sellasie K, Zeroka D, Sabnis G (2003) Physical and chemical properties of recycled tire shreds for use in construction. J Environ Eng 129:921–929. https://doi.org/10.1061/(ASCE)0733-9372(2003)129:10(921)
22. Gabryś K, Soból E, Sas W (2021) Physical, deformation, and stiffness properties of recycled concrete aggregate. Sustainability 13(8):4245. https://doi.org/10.3390/su13084245
23. Kershaw DS, Kulik BC, Pamukcu S (1997) Ground rubber: Sorption media for ground water containing benzene and O-xylene. J Geotech Geoenviron Eng 123(4):324–334. https://doi.org/10.1061/(ASCE)1090-0241(1997)123:4(324)
24. Ahmad AL, Bhatia S, Ibrahim N, Sumathi S (2005) Adsorption of residual oil from palm oil mill effluent using rubber powder. Braz J Chem Eng 22(3):371–379. https://doi.org/10.1590/S0104-66322005000300006
25. Ngo AT, Valdes JR (2007) Creep of sand-rubber mixtures. J Mater Civ Eng 19(12):1101–1105. https://doi.org/10.1061/(ASCE)0899-1561(2007)19:12(1101)
26. Lee C, Truong QH, Lee W, Lee JS (2010) Characteristics of rubber-sand particle mixtures according to size ratio. J Mater Civ Eng 22:323–331. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000027
27. Guler E, Enunlu AK (2009) Mechanical properties of granular rubber−sand mixtures determined by triaxial tests. 2nd International Conference on New Developments in Soil Mechanics and Geotechnical Engineering, 28–30 May 2009, Near East University, Nicosia, North Cyprus
28. Youwai S, Bergado DT (2003) Strength and deformation characteristics of shredded rubber tire – sand mixtures. Can Geotech J 40:254–264. https://doi.org/10.1139/T02-104
29. Stróżyk J (2011) Zastosowanie równań wskaźnika ściśliwości C_C do oceny ściśliwości iłów serii poznańskiej (In Polish) application of the compressibility index C_C equations to the evalution of compressibility of clays of the Poznan serie. Górnictwo i Geoinżynieria 35(2):549–556
30. Alptekin A, Taga H (2019) Prediction of compression and swelling index parameters of quaternary sediments from index tests at Mersin District. Open Geosci 11:482–491. https://doi.org/10.1515/geo-2019-0038
31. Benessalah I, Arab A, Sadek M, Bouferra R (2019) Laboratory study on the compressibility of sand−rubber mixtures under one dimensional consolidation loading conditions. Granul Matter 21:7. https://doi.org/10.1007/s10035-018-0860-8

32. Vanicek I (2000) Geomechanika 10: mechanika zemin. 3th edition, Prague, CTU, 229s., ISBN 80–01–01437–1
33. Tasalloti A, Chiaro G, Murali A, Banasiak L (2021) Physical and mechanical properties of granulated rubber mixed with granular soils-a literature review. Sustainability 13:4309. https://doi.org/10.3390/su13084309
34. Shukla SK, Sivakugan N, Das BM (2009) Methods for determination of the coefficient of consolidation and field observations of time rate of settlement – and overview. Int J Geotech Eng 3:89–108. https://doi.org/10.3328/IJGE.2009.03.01.89-108
35. Hazarika H, Pasha SMK, Ishibashi I, Yoshimoto N, Kinoshita T, Endo S, Karmokar AK, Hitosugi T (2020) Tire-chips reinforced foundation as liquefaction countermeasure for residential buildings. Soils Found 60:315–326. https://doi.org/10.1016/j.sandf.2019.12.013