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The Fundamental Geotechnical Characteristics of Recycled Concrete Aggregates of Various Fractions

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Abstract
The purpose of this study is to determine the fundamental characteristics of a recycled concrete aggregate for its utilization in geotechnical constructions. Minimum and maximum bulk densities, the shear strength properties, and the deformation properties were tested in the laboratory. The tests were performed on recycled concrete aggregates of basic fraction, i.e., 0-16 mm, and separated fractions, i.e., 0-4 mm, 4-8 mm, and 8-16 mm. The laboratory tests on the recycled concrete aggregate were compared with the results of the natural aggregates sorted into comparing fractions with the recycled concrete aggregate. The bulk density of the recycled concrete aggregate was either less or equal to that of the natural aggregate. The shear strength properties of the recycled concrete aggregates were greater than the shear strength properties of the natural aggregates except for the fraction of 8-16 mm, where it was the opposite. The one-dimensional compression modulus of the recycled concrete aggregate is slightly lower than that of natural aggregate for the fractions of 4-8 mm, 8-16 mm, and 0-16 mm. However, for the fraction of 0-4 mm, which is not typically used in the creation of recycled concrete (because it is replaced by the natural aggregate), the recycled concrete aggregate has a higher shear strength and compression modulus than natural aggregate.

Keywords
recycled concrete aggregate, natural aggregate, geotechnical properties, shear strength, bulk density, compression modulus

1 Introduction

Solid waste materials are increasingly being generated worldwide. As a result of the demolition of old buildings, concrete structures, and road pavements, construction and demolition (C&D) waste is created, which often has no new or further use. To minimize greenhouse emissions and decrease carbon footprints, this waste material can be recycled and reused in various civil engineering projects. Recycling also reduces the consumption of virgin materials, such as fine-grained soil, coarse-grained soil, and quarry stones, and can significantly reduce waste disposal in landfills, e.g., [1–3]. Typical examples of C&D materials that can be recycled and reused are, e.g., recycled concrete aggregate (RCA), recycled waste aggregates (RWA), and recycled asphalt pavement (RAP), see, e.g., [4–6]. These materials can be used again as an aggregate to create "new" concrete for the construction of various types of concrete structures [7–12], but they can be widely used in different civil engineering projects, such as, e.g., pavement bases/subgrades, permeable pavements, light duty pavements, structural fill in highway embankments, and backfill for retaining walls and structures, see e.g., [6, 13, 14]. Slovakia produces over 5 million tons of C&D waste annually, with mineral C&D waste accounting for almost 22%. These materials are gradually starting to be reused for concrete structures, but they also have a good potential for use in geotechnical construction, see e.g. [15–17]. The study presented in the article reflects on the present situation of practical use of the RCA in the western part of Slovakia. After demolishing a structure, a landfill from the construction waste material is created on-site. Initially, bigger blocks of concrete material are separated and crushed to create RCA that is between 0-16 mm. To reuse the material in creating a concrete mixture, it is necessary to obtain a suitable granularity of the aggregate. For this reason, the basic fraction 0-16 mm is always divided in the concrete plant into three separate reservoirs, which contain the fractions 0-4 mm, 4-8 mm, and 8-16 mm. The concrete plant sources indicate that the primary focus is on

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reusing the 4-8 mm and 8-16 mm fractions. The interest in the reuse of the fraction 0-4 mm is only minimal. This fine fraction is often replaced by natural aggregates for the production of recycled concrete, and thus its excess is created in the concrete plant. In geotechnical engineering, there is almost no interest on the side of civil engineering implementation companies in the use of these materials due to concerns about their strength and deformation parameters.

This study aims to analyze the bulk densities, shear strength, and deformation properties of RCA for each fraction used in concrete plants. The individual parameters of RCA are compared and analyzed with those of natural coarse-grained aggregates (NA) of the same fractions. It can be assumed that knowing the "basic" geotechnical parameters of RCA for individual fractions will contribute to its greater use in geotechnical engineering. It can be also assumed that the presented results can lead to greater use of RCA of the 0-4 mm fraction in geotechnical engineering as it is not commonly used in recycled concrete.

2 The literature background for the study presented

The properties of the RCA for geotechnical engineering applications have been analyzed by many researchers, see, e.g., [4, 14, 17–20]. The density of RCA can be lower than that of NA. This is mostly caused by mortar that is part of the RCA structure and is less dense than the solid grain [12, 21]. The density can vary depending on the specific aggregate and binder in question.

The shear strength properties of RCA depend on its size, shape, and type. RCA is a typical example of a coarse-grained material for which the shear strength properties can be determined by a large-size direct shear test apparatus [22–25]. The shear strength of river gravel (pebbles) that has round grains is defined mostly by the angle of the shear strength; however, in the case of crushed gravel as well as quarry stone, the shear strength can be defined by the angle of the shear strength and the initial shear strength, see, e.g., [26, 27]. The initial shear strength has also been reported by other authors; however, they presented this parameter as the cohesion or the apparent cohesion of the soil, see, e.g., [15, 17]. Calling it the initial shear strength instead of cohesion is preferred because this effect is mostly caused by the interlocking effect of the soil particles, as first stated by [28]. A nonlinear failure envelope can provide a more accurate interpretation of the peak and critical shear strengths in these materials than a linear Mohr-Coulomb failure line [27, 29, 30]. This effect is caused by the crushing of the grains, which can be significant in poorly-graded materials, see, e.g., [31]. However, for normal stresses up to 200 kPa, a linear failure envelope can be accepted, see, e.g., [27].

The compressibility of RCA has been analysed by [14–17, 32]. Soleimanbeigi and Edil [15] presented a comparison of the 1D compression of sandy material and RCA. They noted that RCA has a lower degree of compressibility. Aqil et al. [17] stated that when RCA is compacted in the vicinity of optimum moisture content wopt, the compressive strength qmax becomes as great as well-graded gravel, which is considered the best type of backfill material. Topçu and Günçan [33] showed that the density, compressive strength, modulus of elasticity, and toughness values decrease with the increasing ratio of RA to NA. RCA has residual mortar adhering to the particles that can easily break off when subjected to loading, e.g., [15, 34, 35]. Hansen and Narud [36] noted that about 25% to 60% of the original mortar remains adhered to a given aggregate.

There are also some possible negatives of using RCA as subgrade materials, which were presented by [37]. They analyzed RCA recovered after 8 years and stated that its acid neutralization capacity and pH were higher compared to the original state. The application of RCA is also not suitable in an aggressive environment. These findings suggest that the use of RCA in geotechnical structures requires careful consideration.

3 Material samples preparation

Recycled aggregates were collected from various demolished structures in the western part of Slovakia. A total of four different RCA samples were used for the laboratory testing. In all the cases, an original RCA 0-16 mm fraction was also divided into separate fractions, i.e., 0-4 mm, 4-8 mm, and 8-16 mm, which was briefly described in the introduction. The process of creating and collecting samples for testing is depicted in Fig. 1 in a simple scheme. The grain-size distribution curves of all the fractions of the RCA material tested (from one demolished structure) are shown in Fig. 2. The grain-size curves of other RCA materials tested were nearly identical due to the samples being divided into identical fractions. The classification was done according to STN 72 1001: Classification of soil and rock [38], as follows:

- RCA sample of 0-4 mm fraction, classified as poorly-graded sand (SP);
- RCA sample of 4-8 mm fraction, classified as poorly-graded gravel (GP);
- RCA sample of 8-16 mm fraction, classified as poorly-graded gravel (GP);

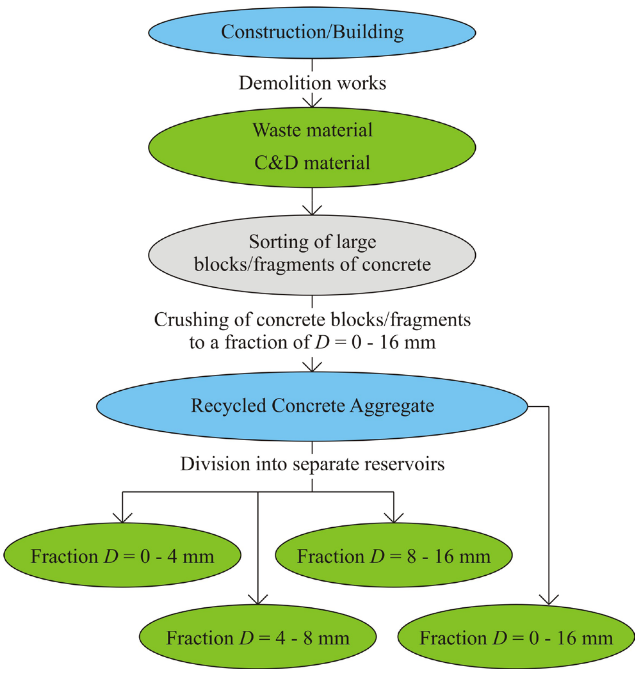

Fig. 1 Scheme of creating and collecting the recycled material samples

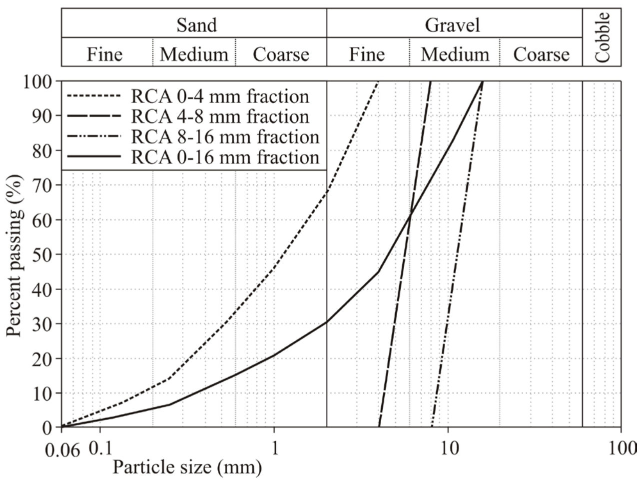

Fig. 2 Grain-size distribution curves of the tested materials

- RCA sample of 0-16 mm fraction (a basic fraction - before dividing it into 0-4 mm, 4-8 mm, and 8-16 mm fractions), classified as well-graded gravel (GW).

The natural aggregates were collected while constructing different types of geotechnical structures, such as e.g. roadbeds, reinforced earth structures, roads and railway embankments, base layers for foundations, and stone columns. Some of these samples were investigated in individual geotechnical problems presented by authors [26, 27, 39]. A total of 39 natural coarse-grained aggregates were used for the presented analysis. The samples were divided into the same fractions used in the case of RCA, i.e., 0-4 mm, 4-8 mm, 8-16 mm, and 0-16 mm.

4 Testing methodology

The first step involved determining the natural moisture content of all collected samples. The moisture content was determined according to the STN EN ISO 17892-1 (Laboratory testing of soil: Part 1-Determination of water content) standard [40]. Subsequently, the grain size distribution of the sample was determined using approximately 5 to 8 kg of dried sample. The tests were executed in the usual way using a set of standard nets (range of 0.063-16 mm) respecting the STN EN ISO 17892-4 (Laboratory testing of soil: Part 4-Determination of particle size distribution) standard [41]. Determining the minimum and maximum bulk densities fulfilled the requirements given by the STN EN ISO 17892-2 (Laboratory testing of soil: Part 2-Determination of bulk density) standard [42]. The tests were executed using a container with a volume of 5.93 dm^3 and repeated three times to minimize errors in the testing procedure. The bulk densities of some natural coarse-grained aggregates have already been presented by authors [43].

The shear tests were performed using a large-size direct shear test apparatus, which has dimensions of 300 × 300 × 200 mm (width × length × height). Each sample was tested under three normal stresses, i.e., 50, 100, and 200 kPa. The horizontal movement speed was equal to 0.25 mm/min for samples of 0-4 mm, 4-8 mm, and 0-16 mm fractions, and 0.50 mm/min for a sample of 8-16 mm fraction. The maximum horizontal movement achieved during the test was about 60 mm. A sample of the given weight (about 25-30 kg, depending on the grain sizes of the material tested) was compacted into the shearing box in 5 layers. The samples were compacted to their highest possible density by using a rubber hammer. Based on the known weight and the volume of the sample tested, the bulk density and the density index were determined. The first step of testing was the "consolidation phase". Because only dry coarse-grained materials were tested, this phase represented only a quick compaction/compression of the sample for the normal stress used without any time-consuming consolidation. The time of this "consolidation phase" was accepted to be about 30-60 minutes, and after it ended, the bulk density and density index were determined again.

Afterwards, shear testing was carried out. The tests were executed according to the requirements of the STN EN ISO 17892-10 (Laboratory testing of soil: Part 10-Direct shear test) standard [44]. In the case of dense coarse-grained soils, the shear strength consists of both peak and critical shear strengths. The peak shear strength is clearly defined by the maximum shear stress determined (point P in Figs. 3(a) and 3(b)). In the case of the

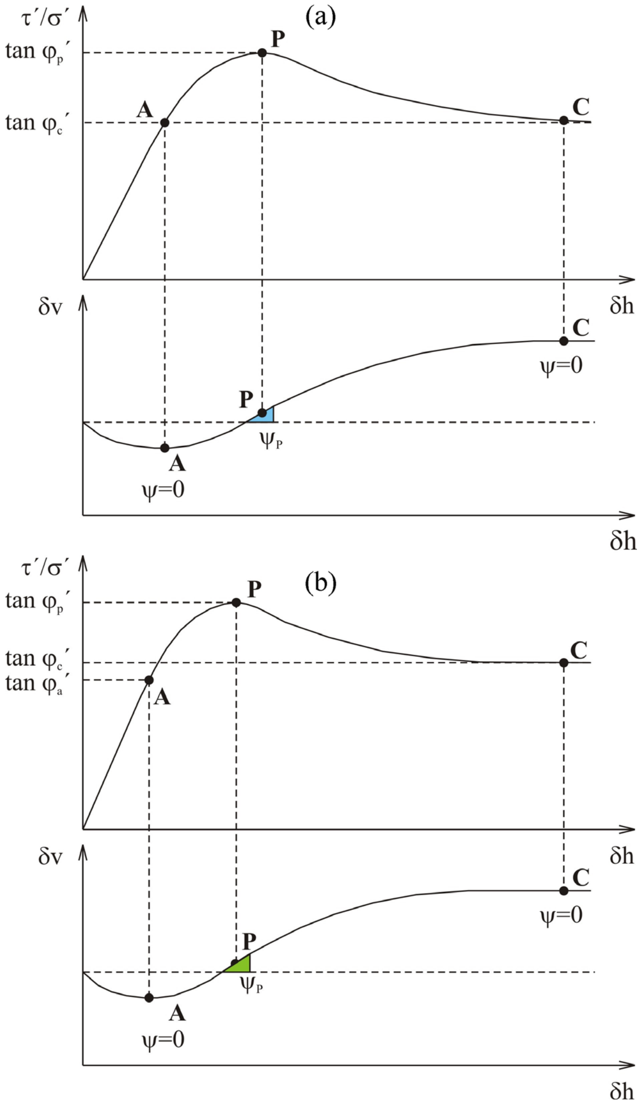

Fig. 3 A typical dilation and shear strength curve: (a) sandy soil, (b) poorly graded gravely soil (right)

fine coarse-grained soil (sandy soil), the critical shear strength can be determined at two states, i.e., when the maximum density of the sample tested is reached (point A in Fig. 3(a)), and for a large horizontal movement when the sample exceeds its peak stress state and a critical void ratio is reached (point C in Fig. 3(a)).

For coarse-grained materials consisting of sharp-edged grains, the shear strength at point C is greater than the shear strength at point A (Fig. 3(b)), which was investigated by the authors [27]. This effect can also be seen in the results presented by, e.g., [20, 29]. It is mostly caused by the interlocking effect of the sharp-edged soil particles. In this case, the shear strength τ'_a at point A is defined by Eq. (1), while the peak shear strength τ'_p (point P) is given by Eq. (2) and the critical shear strength τ'_c (point C) is given by Eq. (3).

$$\tau'_a = \sigma \cdot \tan \varphi'_a \tag{1}$$

$$\tau'_p = \sigma \cdot \tan \varphi'_p + \tau_{0,p} \tag{2}$$

$$\tau'_c = \sigma \cdot \tan \varphi'_c + \tau_{0,c} \tag{3}$$

where φ'_a is the angle of the shear strength at point A, φ'_p is the peak angle of the shear strength, $\tau'_{0,p}$ is the initial shear strength in the peak stress state, φ'_c is the critical angle of the shear strength, and $\tau'_{0,c}$ is the initial shear strength in the critical stress state. The angle of dilatancy was determined for the peak shear strength according to [28] using the following equation:

$$\tan \Psi' = \delta_V / \delta_h \tag{4}$$

where δ_v is an increment in the vertical direction and δ_h is an increment in the horizontal direction.

In the study presented, a nonstandard large-size compression test was used. The sizes of the consolidation box for the sample were 300 × 300 × 200 mm (width × length × height) - the tests were executed using the container for the shear strength test. The tests were carried out in the same way as standard oedometer tests according to the STN EN ISO 17892-5:2023 (Laboratory testing of soil: Part 5-Incremental loading oedometer test) standard [45]. The results were interpreted as 1D compression modules instead of oedometer modules because the dimension of the square consolidation box did not fulfill the requirements for the circular dimension of the oedometer cell; however, all the tests (recycled and natural) were executed using the same principle which allowed for direct comparison of the results.

In the first step of the test, a sample of a given weight (about 30-35 kg) was compacted in 5 layers into the consolidation box. The compression tests were carried out in the following way:

- initial sample compression (compensation to a sample reconsolidation used in a standard oedometer test),
- compressibility test - consisting of primary and cyclic loading.

The initial sample compression was done at a normal stress of 50 kPa. The purpose was to achieve compactness of the sample and eliminate the effects of manual compaction. The compressibility test was executed for the normal stresses σ = 0-100, 100-200, 200-400, and 400-800 kPa in the loading path and the normal stresses σ = 800-400, 400-200, 200-100, and 100-0 kPa in the unloading path. The cyclic loading consisting of 9 cycles was done right after the primary loading, so the testing procedure for each sample consisted of a total of 10 loading cycles.

5 Results of laboratory testing

5.1 Index properties

Table 1 presents the basic index properties of a typical RCA material. The results are given for a single RCA material (of different fractions). The division of the sample into separate fractions, i.e., 0-4 mm, 4-8 mm, 8-16 mm, and 0-16 mm causes, that the grain size distributions of all RCA materials tested to be identical. The minimum and maximum bulk densities are also presented for given fractions of this RCA material.

The ranges of minimum and maximum bulk densities of a given fraction of RCA material are presented in Figs. 4 and 5. The results are directly compared to the minimum and maximum bulk densities of natural aggregates of the given fraction. The minimum bulk densities of RCA were smaller than the minimum bulk densities of NA for all samples and fractions tested. The maximum bulk densities of RCA were less than those of NA. A small overlap between the values of 1692-1729 kg.m^{-3} was noted in the case of the fraction 0-4 mm. For all other fractions, there was no overlap in the results, so the maximum values of maximum bulk densities of RCA were smaller than the minimum values of maximum bulk densities of NA.

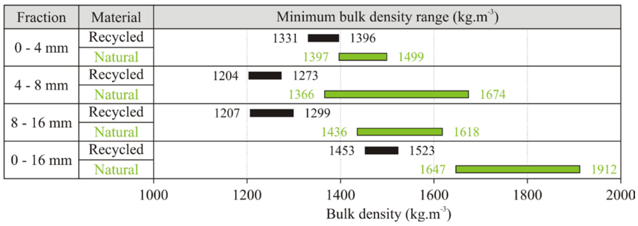

Fig. 4 Minimum bulk densities

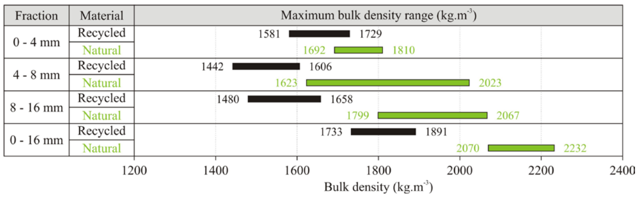

Fig. 5 Maximum bulk densities

5.2 Shear strength properties

The results of the peak and critical shear strength tests on different fractions of one RCA sample are presented in Table 2. This table shows the values for one sample from each fraction, i.e., 0-4 mm, 4-8 mm, 8-16 mm, and 0-16 mm. The initial shear strength was determined in both the peak stress state ($\tau'_{0,p}$) and the critical stress state ($\tau'_{0,c}$). Fractions 0-4 and 0-16 mm have higher values of the angle of the shear strength than fractions 4-8 and 8-16 mm. This is mainly caused by higher porosity in fractions 4-8 and 8-16 mm (due to the absence of fine grains). In the critical stress state, the differences between the angles of the shear strength are not as significant as in the peak stress state. The interlocking effect resulted in a significant increase in the initial shear strength for the fraction 8-16 mm when compared to the other fractions. The effective angles of the dilatancy are presented for all normal stresses applied, i.e., 50, 100, and 200 kPa (Table 2). The values of effective angles of the dilatancy decrease with increasing normal stress. The different behavior of the RCA and NA in shear strength is plotted in Fig. 6.

The shear strength distribution curves of RCA of given fractions are directly compared with the shear strength distribution curves of NA for normal stresses used, i.e., 50, 100, and 200 kPa. The shear strength curves of RCA are significantly higher than NA in the case of fractions 0-4 mm and 0-16 mm. RCA has a slightly higher peak and critical shear strength than NA, even for the fraction of 4-8 mm. The different behavior was determined in the case of the fraction 8-16 mm, where the shear strength of RCA is slightly higher than NA for small normal stresses; however, for a normal stress of about 200 kPa, the shear strength of RCA was significantly smaller than NA.

Each sample presented in Table 2 and Fig. 6 was simultaneously included in the sample set, for which the shear strength properties ranges are presented in Figs. 7–11. The ranges of the peak angles of the shear strength of different fractions of RCA and NA are presented in Fig. 7. In the case of the fraction 0-16 mm, the peak angle of the shear strength can be slightly higher for RCA than NA.

Table 1 Index properties of the recycled material tested

Sample	Classification	Fraction	d_{10}	d_{30}	d_{50}	d_{60}	c_u	c_c	$\rho_{d,min}$	$\rho_{d,max}$
		mm	mm	mm	mm	mm	-	-	kg.m^{-3}	kg.m^{-3}
Sample R1	SP	0 - 4	0.19	0.53	1.19	1.65	8.68	0.90	1353.1	1639.9
Sample R2	GP	4 - 8	4.40	5.20	6.00	6.40	1.45	0.96	1233.1	1495.4
Sample R3	GP	8 - 16	8.80	10.40	12.00	12.80	1.45	0.96	1224.7	1527.1
Sample R4	GW	0 - 16	0.35	2.00	4.55	6.00	17.39	1.93	1463.3	1756.5

Table 2 Shear strength properties of the recycled material tested

Sample	Fraction	φ'	τ_0'	φ_c'	$\tau_{0,c}'$	ψ_{50}'	ψ_{100}'	ψ_{200}'	ψ_{av}'
	mm	°	kPa	°	kPa	°	°	°	°
Recycled concrete aggregate	0-4	50.3	21.2	35.1	9.7	20.6	18.1	13.4	17.4
	4-8	44.7	17.2	36.4	4.9	18.8	14.3	9.1	13.7
	8-16	41.6	28.6	36.0	19.2	16.9	11.2	8.9	12.3
	0-16	50.8	24.4	38.6	7.3	23.6	18.9	13.1	18.5

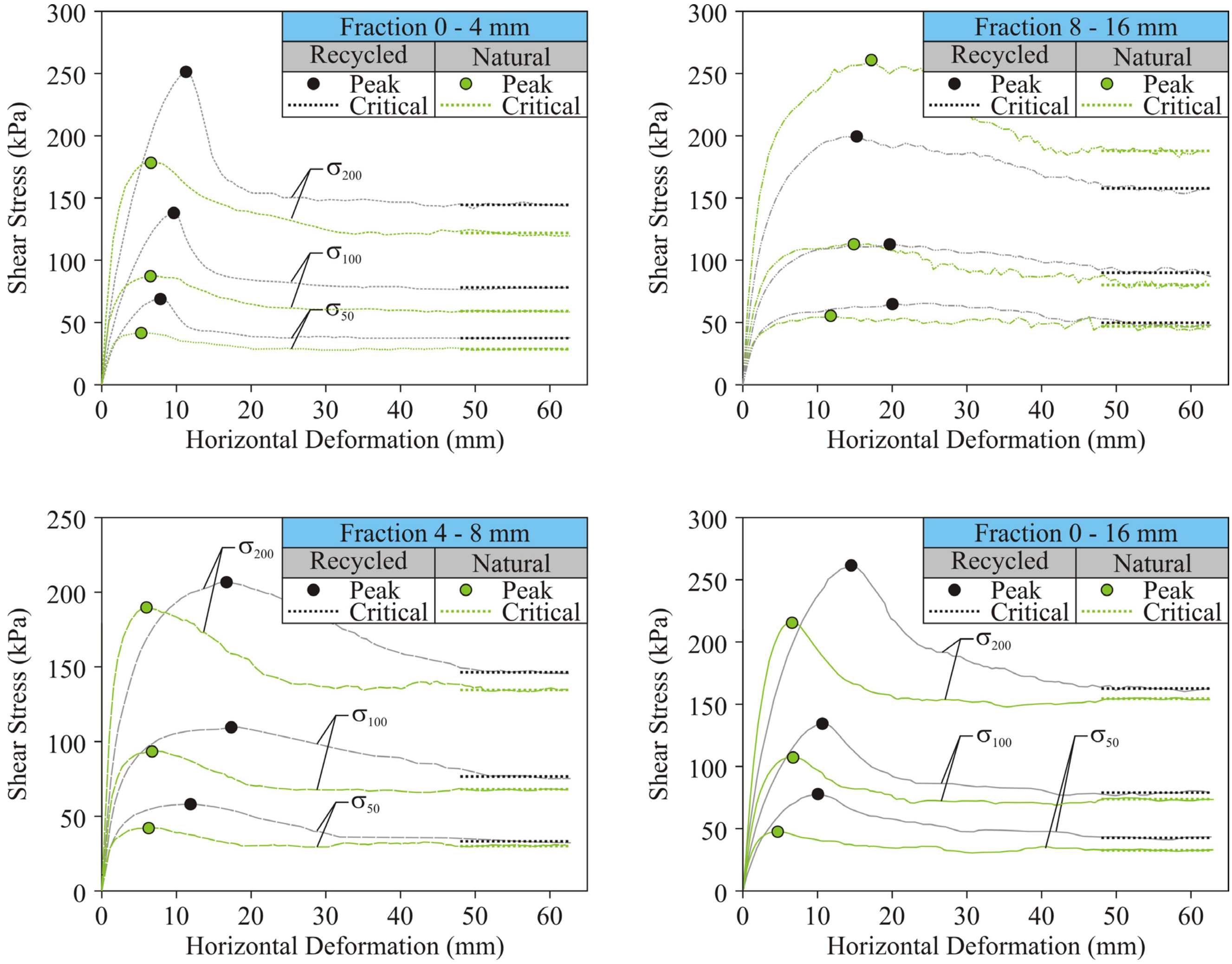

Fig. 6 Shear strength curves of RCA and NA materials

The different behaviors can be seen for fractions 0-4 mm, 4-8 mm, and 8-16 mm. While for the fraction 0-4 mm the angle of the peak shear strength is significantly higher for RCA than NA, in the case of the fraction 8-16 mm it is exactly the opposite. The values of the angle of the shear strength of RCA and NA are similar to each other in the case of the fraction 4-8 mm. The same evaluation can be applied to the comparison of the ranges of the critical angle of the shear strength of RCA and NA (Fig. 8).

In the following stage, the dilatancy angle values of the RCA and NA were compared (Fig. 9). The average values of the angle of the dilatancy for the normal stresses of 50 to 200 kPa were compared. The comparison of the values led to the same conclusions which were stated for the peak and critical angles of the shear strength if fractions 0-4 mm, 4-8 mm, and 0-16 mm. In the case of the fraction 8-16 mm, the average angle of the dilatancy of NA was in the range of 8.3° to 20°, while for RCA the range was only 12° to 12.6° (within the interval of NA).

The results of the shear strength testing showed that NA has no or neglected initial shear strength. The initial shear strength was significant only in the case of RCA.

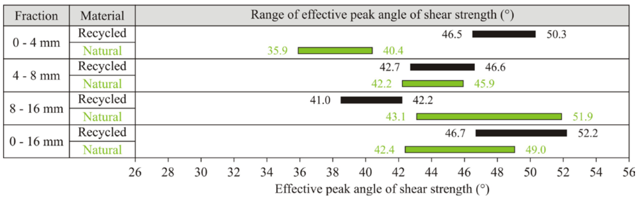

Fig. 7 Peak angles of the shear strength

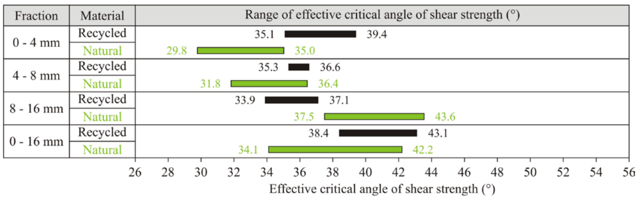

Fig. 8 Critical angles of the shear strength

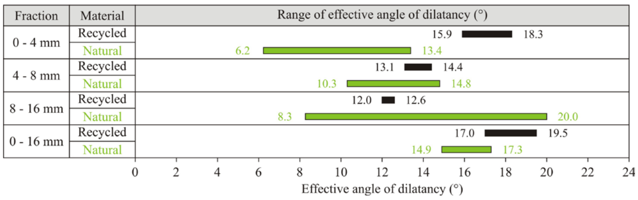

Fig. 9 The average angles of the dilatancy

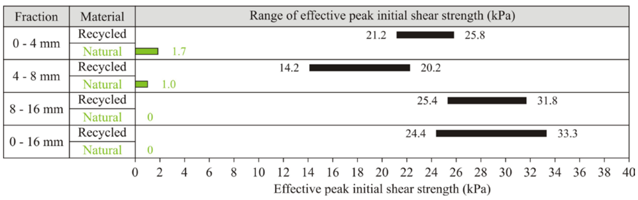

Fig. 10 The peak initial shear strengths

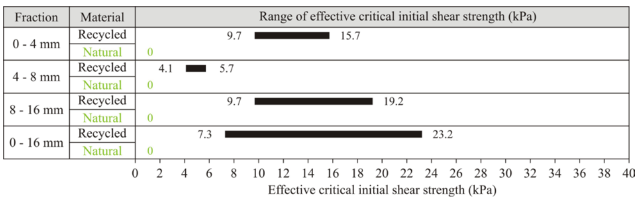

Fig. 11 The critical initial shear strengths

The ranges of the peak and critical initial shear strength of RCA are shown in Figs. 10 and 11. The results showed that for the fraction of 4-8 mm, the values of the initial shear strength (especially in the case of the critical stress state) were slightly smaller than for other fractions tested.

5.3 Deformation properties

The results of the compression tests showed that the differences between a one-dimensional deformation modulus (E_{1d}) determined for different samples of a given fraction are neglected. To make it easier to interpret the results, the E_{1d} values for one sample of RCA and the NA of the given fractions are given for clarity. The results of E_{1d} for the loading stages of 100-200 kPa, 200-400 kPa, and 400-800 kPa, and the unloading stages of 800-400 kPa, 400-200 kPa, and 200-100 kPa, are presented in Fig. 12.

The results showed that, under the same boundary conditions of testing, the values of E_{1d} for NA are similar or slightly higher than for RCA; however, no significant differences were noted. In the case of the fraction of 0-4 mm, the values of E_{1d} for RCA can also be higher than for NA.

6 Discussion

The minimum and maximum bulk densities of RCA were either less or identical to those of NA (Figs. 4 and 5.). This is in agreement with the results of other researchers, see, e.g., [12, 21]. For this reason, RCA has a higher potential for use in geotechnical constructions, where it is appropriate to reduce the weight of the material, e.g., backfills for gravity walls and retaining structures.

The values of the peak and the critical angle of the shear strength were equal to or higher than those of NA for the fractions of 0-4 mm, 4-8 mm and 0-16 mm in the case of RCA. The peak and critical angles of shear strength values for RCA were lower than for NA (Figs. 7 and 8) only for the 8-16 mm fraction. In the case of NA, the peak and critical angles of the shear strength increase with increasing fraction, while the opposite trend can be seen for NA. This effect is caused by the brittleness of the grains of the RCA material. The 8-16 mm fraction has large grains and high porosity and is prone to grain breakage. Crushing of grains occurs even with a fraction of 0-4 mm, but due to the size of the grains and porosity, there is no decrease in the shear strength. Compared to NA, the RCA has significant initial shear strength in the peak and critical stress states for all fractions tested. This is typical for coarsely crushed gravels and quarry stones [26, 27]. Except for the fraction

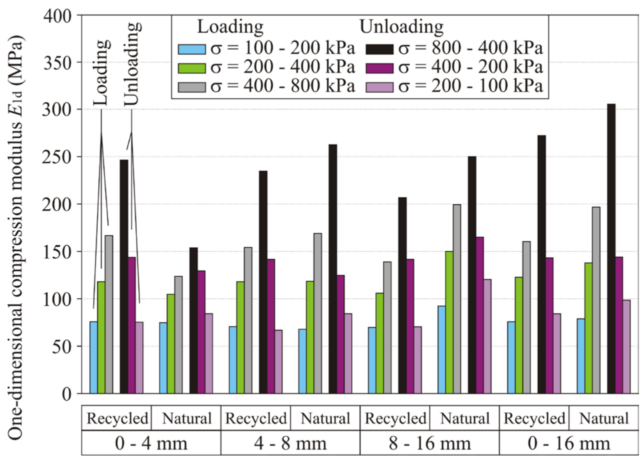

Fig. 12 The average values of one-dimensional compression modulus

8-16 mm, the shear strength of the RCA is greater than the shear strength of the NA in the peak as well as critical stress state. The compression tests revealed that RCA has a similar deformation property to NA. In the case of fractions 4-8 mm, 8-16 mm, and 0-16 mm, the values of E_{1d} of the NA were only about 1.095-1.43 greater than the values of E_{1d} of the RCA in the loading, and about 1.119-1.209 in the unloading. The values of E_{1d} of the RCA can be assumed to be potentially very good for geotechnical applications. In the 0-4 mm fraction, the values of E_{1d} for RCA were higher than those for NA. While at the normal stresses of 100-200 kPa, the values of the RCA and NA were similar to each other, for the normal stresses of 400-800 kPa, E_{1d} of the RCA was about 1.35 times greater than E_{1d} of the NA in the loading stage. In the unloading stage, the ratio between E_{1d} of RCA and NA increased from about 1.12 (normal stresses 100-200 kPa) to about 1.6 (normal stresses 400-800 kPa).

The testing results indicate that the NA can be replaced by the RCA for appropriate geotechnical structures. A good potential for practical geotechnical application also has the 0-4 mm fraction, which is usually replaced by natural aggregates in the creation of recycled concrete and thus its excess is created. The 0-4 mm fraction of RCA has a significantly greater angle of the peak shear strength, the angle of the dilatancy, and the angle of the critical strength than the NA. The shear strength properties of the 0-4 mm fraction (RCA) were significantly greater than those of fractions 4-8 mm and 8-16 mm (RCA). The E_{1d} parameters are equal to or greater than the values of E_{1d} of the NA material during the loading and unloading stages. The shear strength and deformation properties of the 0-4 mm fraction were similar to those of other fractions (RCA).

The study does not include an analysis of the long-term behaviour of RCA, as this is still ongoing. It can be assumed that the application of the RCA in an aggressive environment can lead to a negative effect on the material structure. The results of the presented study can be used for the application of RCA in geotechnical structures in a non-aggressive environment.

7 Conclusions

The recycling of construction materials is one of the most important topics in civil engineering worldwide. The use of recycled material in geotechnical structures is very rare in Slovakia. The recycled concrete aggregate (RCA) is produced in large quantities and has a good potential for use in suitable geotechnical structures. The laboratory testing presented in the paper was focused on determining the basic soil properties, e.g., the bulk density, the shear strength and the compression modules, which are required in the geotechnical design. Knowing about them can encourage their use in appropriate geotechnical structures. The recycled concrete aggregate fractions of 0-4 mm, 4-8 mm, 8-16 mm, and 0-16 mm were tested. This division resulted from the division of materials in the reservoirs of the concrete plant. The properties of the recycled concrete aggregate were compared with the properties of the natural aggregates of the same fraction. Based on the results of laboratory measurements presented, the following conclusions can be drawn:

- Both minimum and maximum bulk densities of RCA were less than or at most equal to those of NA;
- In cases of fractions 0-4 mm, 4-8 mm, and 0-16 mm, the recycled concrete aggregate had a peak and critical angles of the shear strength greater than the natural aggregate. Only in the case of the fraction 8-16 mm, larger brittle grains and high porosity resulted in the shear strength angle of the recycled material being smaller than that of the natural aggregate;
- While the natural aggregate has almost no initial shear strength, the recycled concrete aggregate showed significant initial shear strength at the peak as well as the critical stress state;
- The one-dimensional compression modulus (E_{1d}) of the natural aggregate was about 1.095-1.43 greater than that of the recycled concrete aggregate in the case of the loading stage and about 1.119-1.209 in the unloading stage for fractions of 4-8 mm, 8-16 mm, and 0-16 mm;
- The recycled concrete aggregate of the 0-4 mm fraction has greater E_{1d} than the natural aggregate by about 1-1.35 in the loading stage and about 1.12-1.6 in the unloading stage;
- The recycled concrete aggregate of the fraction of 0-4 mm has significantly greater shear strength and deformation properties than the natural aggregate of the same fraction. Because this fraction is not used for creating recycled concrete, it can be suitably applied in geotechnical structures;
- The results of the tests showed that the properties of the recycled concrete aggregate are comparable (in some cases even better) to the coarse-grained natural aggregates. Natural aggregate can be replaced by recycled concrete aggregate in suitable geotechnical constructions.

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