

THE GEOTECHNICAL PROPERTIES OF RECYCLED CONCRETE AGGREGATE WITH ADDITION OF RUBBER CHIPS DURING CYCLIC LOADING

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ABSTRACT: The following paper presents the results of tests performed on the reclaimed waste, namely the Recycled Concrete Aggregate (RCA). Geotechnical study was undertaken, in order to obtain physical and mechanical properties of RCA improved with rubber grains. Such a mix could exhibit increased elastic strain development during load cycles, which are typical for traffic. For better understanding of its exceptional behaviour under repeated loading, cyclic CBR tests were conducted in various stages of loading. For the purpose of bearing capacity analysis, uniaxial test was also conducted. While the cyclic loading and mechanical stabilization are a cause of aggregates crushing, another particle size distribution could occur and may not fulfil quality requirements. Determination of resilient modulus M_r on the basis of a repeated loading test and development of displacements during the tests have also been presented. The M_r value for pure RCA was equal to 495.6MPa. The addition of rubber chips in amount 0.5% and 1% results in rise of resilient modulus value, equal to 632.4MPa and 698.0MPa respectively. During the tests the plastic strain abate was recognised. The plastic displacement analysis shows increase of the permanent settlement due to cyclic loading in case of 0% and 1% rubber chips content. The 0.5% rubber chips addition results in smaller plastic displacement. The plastic and elastic displacement was later analysed in order to characterize the deformation behaviour of RCA. The paper proposes also a possible guideline for using the RCA mix as a material in pavement subbase construction.

Keywords: Cyclic loading, cCBR, rubber chips, recycled concrete aggregate

1. INTRODUCTION

The development of car industry results in an increase of cars. One of the waste types produced both during the car exploitation of a vehicle and after its utilization are rubber tires. Among many geo-engineering methods of recycling, rubber retaining walls, so-called rubber chips and tire shreds are only some of many possible ways in which this source [1]. Lately, a series of intensive studies aimed at finding the possible application of rubber chips (RC) mixed with natural aggregates have been conducted.. Takano et al. [1] tested shear behaviour of RC and silica sand mix using micro focus X-ray CT scanner. Results of this test shown, that under direct shear (for the mix of sand and RC) the shear stress level rises monotonically and no peak stress is observed. Dilatancy effect was also not as significant when compared to tests conducted on pure sand. It is also interesting that RC additions can decrease shear strain propagation. This fact is important for road engineering, as shear stress causes many structural damages. A mix of gravel, fly ash and waste fibres was also studied by [2]. Series of CBR tests and direct shear tests have shown an increase of CBR characteristics; optimal addition of waste tyre

rubber is ranges between 0.2 to 2.0% of dry unit weight of soil. [3] used shredded waste rubber to reinforce soft clay with different percentages of rubber content and cement as a binding medium to. Series of CBR and unconfined compressive strength tests have shown an improvement of bearing capacity, strength and high compressibility of the material.

Recycled Concrete Aggregate (RCA) is an anthropogenic material which is a product of demolishing of exploit constructions. Research conducted on the recycling process of RCA has led to the establishment of many possible ways of application in bound and unbound form. Important fact is that for sustainable development to be achieved, non-renewable resources, such as sand, gravel etc., should be replaced by renewable resources, such as RCA [4]. Application of renewable materials can reduce green-house gas emission simply by avoiding the mining process [5].

Cyclic loading is phenomenon which can be observed in many constructions. Characterization of the material subjected to repeated loading is required mostly by road and foundation engineers, during the construction of industrial settlements. Wind plants foundation engineering constitutes a

new area in which this issue is also present, as the wind can cause a the gravity centre to move and create cyclically changing stresses over subgrade soils [6]

In order to understand cyclic loading phenomenon, proper tests must be conducted for each material. The most common method to obtain such data is performing cyclic triaxial tests. Unfortunately, these tests are expensive and not used commonly, especially in road laboratories.

In their previous article, [7] the authors presented a new method of dealing with the cyclic loading phenomenon. The cCBR method was presented as an equivalent of standard cyclic triaxial tests. The cCBR method has many advantages, its cost is low due to a common standard of CBR tests, which means that no new equipment is needed. Procedure of the cCBR test is based on the CBR method. It can easily be performed by an experienced laboratory crew.

The purpose of performing cCBR test is to find a key factor which characterizes cyclic loading - the resilient modulus M_r .

Resilient modulus is a characteristic value of cyclic loading, taking resilient strain into consideration as a design factor. The M_r value is calculated as follows:

$$M_r = \frac{\Delta\sigma_d}{\Delta\varepsilon_r} \quad (1)$$

where, $\Delta\sigma_d$ stands for deviator stress pulse $\Delta\sigma_d = \Delta\sigma_1 - \Delta\sigma_3$; σ_1 stands for major principal stress; $\sigma_3 = \sigma_2$ stands for minor principal stress and $\Delta\varepsilon_r$ stands for resilient strain over deviator pulse $\Delta\sigma_d$ [8].

2. MATERIAL AND METHODS

2.1 Material

Material for tests was obtained from demolished concrete, which was present in a building demolition site. Concrete aggregates were an element of construction, whose strength class was estimated, as ranging from C16/20 to C30/35. Aggregates were in 100% composed from broken cement concrete. Grain gradation curve was adopted, according to EN ISO 14688: 2a [9] and positioned between upper and lower grain gradation limits.

For estimation of physical properties, a series of tests was conducted. The sieve analysis led to classifying this material as a sandy gravel (saGr), in reference to [9, 10]. Test results are shown in Fig. 1. This distribution of particles from 12.0mm to 0.063mm is typical for soils used for sub-base and supporting other structures.

The Proctor test results are presented in Fig. 2. The test procedure involved compaction in the

Proctor mold, whose volume equalled 2.2dm^3 , by using standard energy of compaction, being equal to 0.59J/cm^3 . Optimum moisture content for sandy gravel was $m_{opt} = 9.54\%$ and maximum dry density of optimum moisture content was 1.97g/cm^3 . For RCA with 0.5% RC addition, $m_{opt} = 8.47\%$ and $\rho_{max} = 1.94\text{g/cm}^3$. For RCA with 1% RC addition, $m_{opt} = 8.02\%$ and $\rho_{max} = 1.91\text{g/cm}^3$. Addition of RC caused a decrease of ρ_{max} and correspondingly of m_{opt} . This phenomenon is caused by the density of RC being smaller than in the case of RCA. Decrease of moisture content seems to prove that a larger amount water filled inner pores, than it was in the case of open pores, due to the influence of greater capillary forces [11].

2.2 Methods

After the optimum moisture content has been estimated, the cCBR tests on samples with 0, 0.5 and 1% RC content were performed.

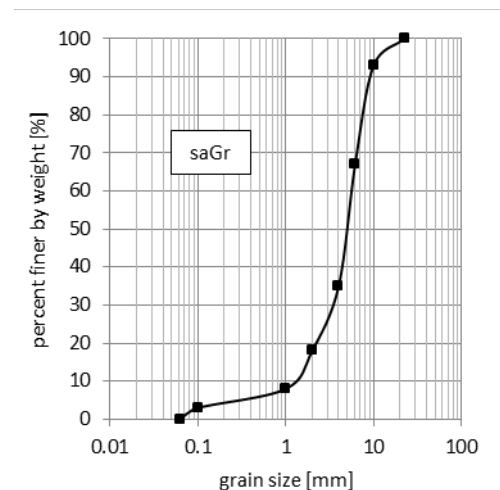


Fig. 1 Particle size distribution of tested soil

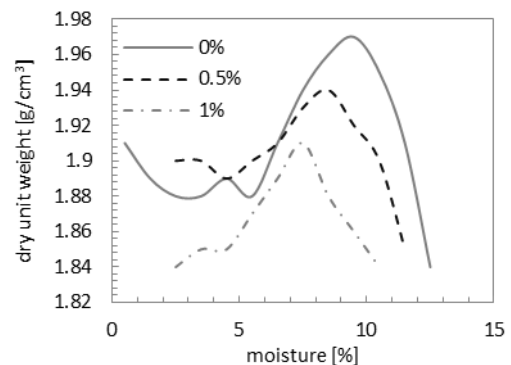


Fig. 2 The Proctor test results for sandy gravel

The Proctor test observations concerning the high water absorption of the RCA resulted in proper sample curing before compaction. RCA

was compacted, after leaving moist material in a hermetic box for 24h to prevent moisture loss. Material conditioned in such way provides more accurate data concerning physical properties repetition.

When the process of material curing and compaction in CBR mold, with respect to Proctor's energy of compaction, was finished, the cCBR tests were performed. The cCBR method was based on a standard CBR test, while the CBR method served as a basis for the cCBR test. Procedure of performing the cCBR test is simple and based on the standard CBR test procedure. Previous studies on cyclic loading, performed on porous material, were conducted with the use of a cyclic triaxial apparatus.

In recent years, the mechanistic-empirical pavement design has been gaining on popularity, replacing traditional empirical methods of design. CBR value method of road construction design was replaced by a mechanistic approach, which employs resilient modulus and Poisson ratio layer thickness calculations. The cCBR method is uses reliable CBR equipment together with new standards of designing.

The cCBR test method is consists of two stages, first one being a standard CBR test, in which loading is conducted until the degree of plunger penetration reaches 2.54mm, with velocity equal 1.27mm/min. Next step is the beginning of the second phase. After loading, the maximal stress level is noted at 2.54mm. Unloading is conducted until 10% of maximal stress level is reached. This value is called 'minimal stress'. Loading and unloading constitutes the first cycle of the cCBR test. Next step is a repetition of loading to maximal, and unloading to minimal, stress level. cCBR test is terminated, when plastic strains, which occur in one cycle, are less than 1% of total strain in one cycle. Commonly, the number of repetitions for non-cohesive soils can reach approximately 50 cycles. The number of cycles required to obtain this condition usually oscillates around 50 [12, 13].

After the cCBR test has been completed, the last hysteresis loop is then used for into calculate the value of a resilient modulus M_r . Resilient strain $\Delta\varepsilon_r$ stands for the amount of strain during unloading, where elastic response to decreasing stress is observed. Deviator stress is a difference between maximal stress level, at which the elastic strains occurs, and minimal stress level.

Because of CBR test standards, the specimen's upper area is not loaded in its entirety. Therefore, the correct strain cannot be measured. In order to calculate the M_r value, another equation was proposed [8] (2):

$$M_r = \frac{1.513(1-\nu^{1.104})\Delta\sigma_p \cdot r}{\Delta u^{1.012}} \quad (2)$$

where: ν –Poisson's ratio [-] (in this study, its

value was equal 0.35 in case of granular materials), $\Delta\sigma_p$ – change between maximal and minimal axial stress levels in one cycle [MPa], r – radius of the plunger [mm], Δu – recoverable displacement in one cycle.

3. RESULTS

Tests conducted on the RCA have shown good performance of this material. Detailed cCBR test results for the RCA with the RC content being equal 0% are presented in Figs. 3 to 5.

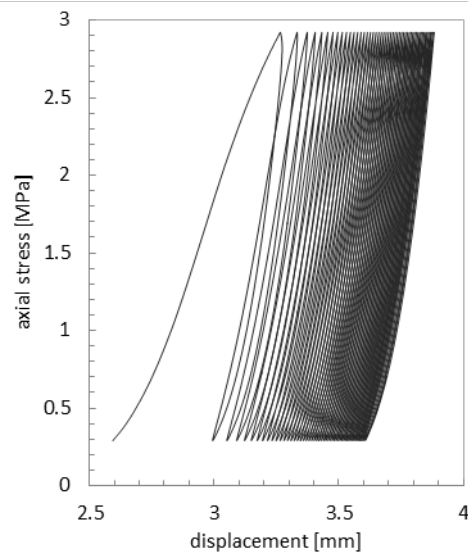


Fig. 3 Stress – displacement curve from cCBR test for RCA with the RC content being equal 0%

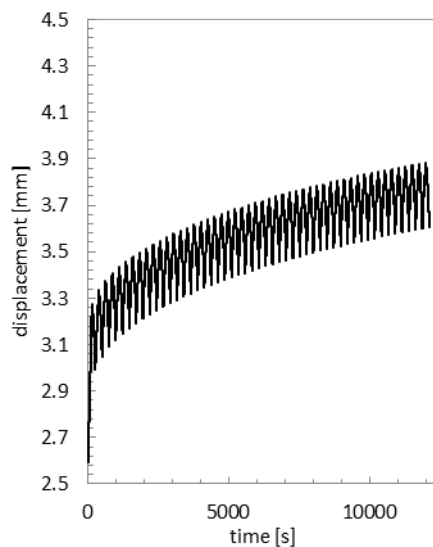


Fig. 4 Displacement – time curve from cCBR test for RCA with the RC content being equal 0%

Plots present the results of the cCBR test regarding the axial stress and displacement in Fig. 3. Figs. 4 and 5 present respectively, how the e displacement and axial stress changed in time during. During the test, the RCA exhibited a resilient response.

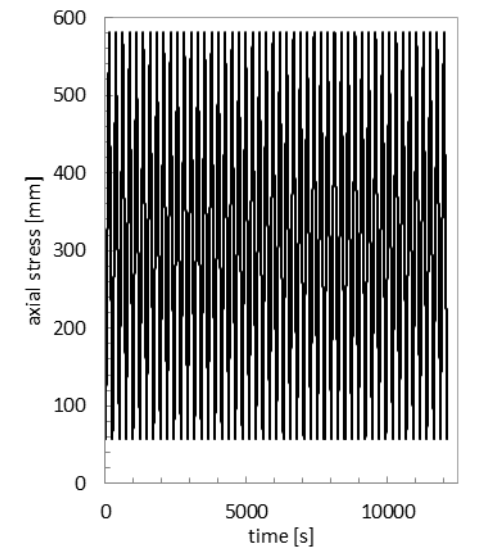


Fig. 5 Axial stress – time curve from cCBR test for RCA with the RC content being equal 0%

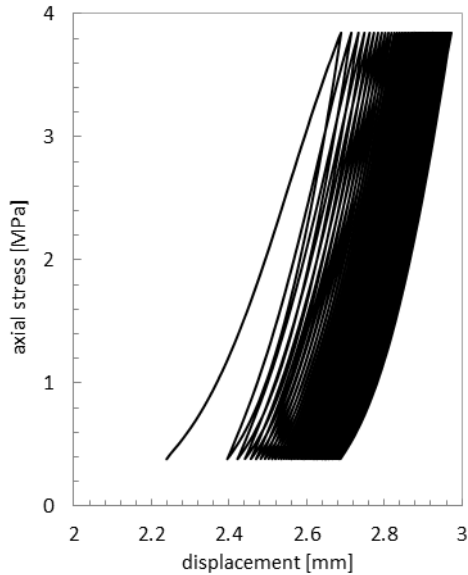


Fig. 6 Stress – displacement curve from cCBR test for RCA with the RC content being equal 0.5%

After 50 repetitions, resilient modulus value reached $M_r = 495.6 \text{ MPa}$. Elastic (resilient) displacement was equal 0.275 mm , which is 99.5% of total displacement in cycle. In terms of the shakedown concept [14], the material has reached a steady point, called ‘plastic shakedown’, during

which plastic displacements do occur, but constitute small amount of total displacements.

The cCBR test results for RCA with 0.5 and 1% of RC content are presented in Figs. 6 to 9. Plots present the results of cCBR test in function of axial stress and displacement in Fig. 6 and 8. Figs. 7 and 9 present, how displacement of RCA with 0.5 and 1% of RC content, changed in time.

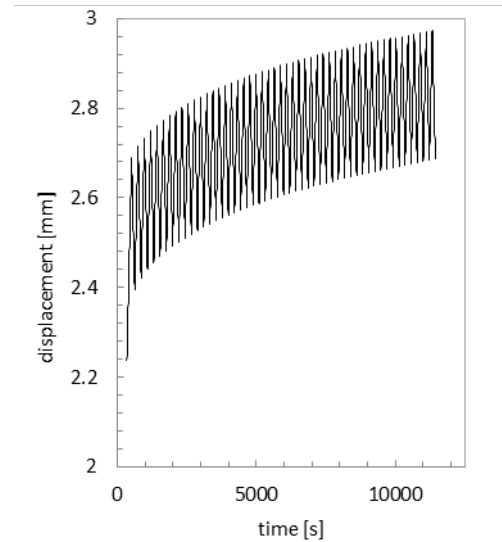


Fig. 7 Displacement – time curve from cCBR test for RCA with 0.5% RC

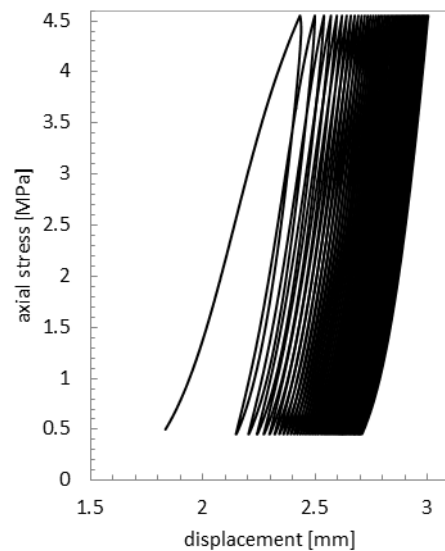


Fig. 8 Stress – displacement curve from cCBR test for RCA with 1% RC

Addition of 0.5% RC increased the CBR bearing capacity from 47% (RCA with 0% RC) to 56%. Calculations of resilient modulus have shown the increase of M_r . In case of RCA whose RC content was equal 0.5%, the M_r value was established as $M_r = 632.4 \text{ MPa}$ and was 137 MPa

greater than for the RCA without the RC addition.

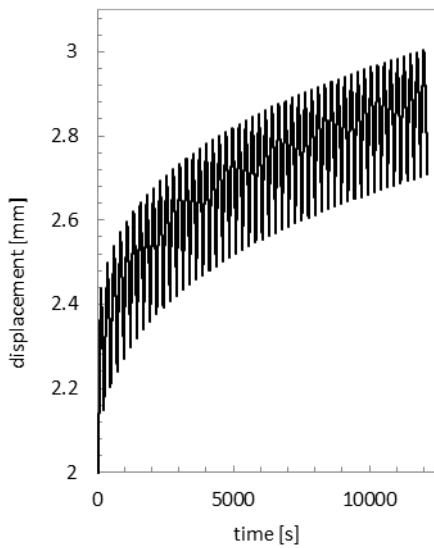


Fig. 9 Displacement – time curve from cCBR test for RCA with the RC content being equal 1%

The bearing capacity is not the only value, which is described by the resilient modulus ratio. Therefore a rise in CBR value was equal 19%, but a rise in M_r value was equal 27%. This means that a greater improvement of plastic strain dissipation was observed.

In case of a sample containing the 1% of RC addition, the CBR bearing capacity was equal 66%, which constituted 19% rise in comparison to the RCA with 0% RC content. The resilient modulus has shown an increase in the M_r value. In case of 1% RC content, the $M_r = 698.0 \text{ MPa}$, which was 202 MPa greater than in case of the RCA without the RC addition. The detailed view of results was presented in Fig. 10. The resilient modulus value rises more, when compared to the CBR value. This phenomenon is connected with the plastic strain increase. Lack of the RC addition results in the increase of the plastic strains. The amount of plastic strain is greater, in case of the RCA containing 0% of the RC.

The addition of RC seems to improve the resilient properties of the material. The RCA containing the RC has the ability to cause faster dissipation of the. This may be caused by the elastic properties of rubber. The stress resulting from the contact between individual grains may be avoided by using rubber chips. The above-mentioned statement is showcased in details in Fig. 11.

Properties of the RCA as an anthropogenic soil material need to be studied further for the better understanding of its mechanical properties, but the overall mechanical characterization proved that

this material is appropriate for construction of the unbound sub-bases. Eurocode 7 EN 13286-7:2004 [15] classifies the RCA by a mechanical performance parameter M_r . This material has reached the highest class, which is C1.

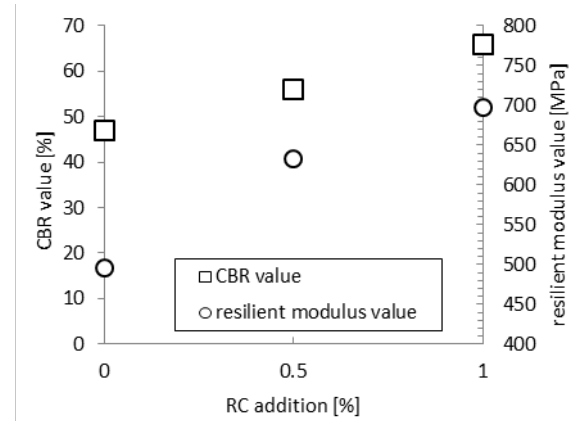


Fig. 10 CBR value and M_r value for different addition of RC from cCBR test

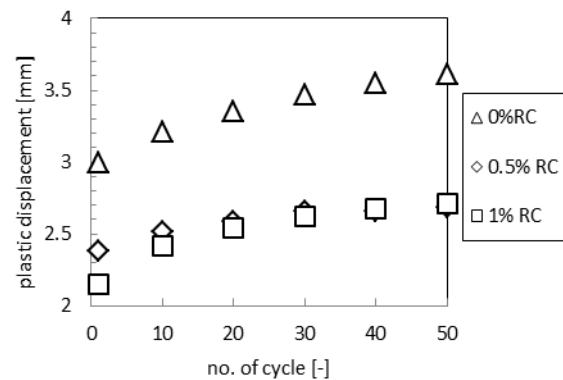


Fig. 11 Plastic displacement change during cCBR test for RCA with varying RC content

4. THE DEFORMATION CHARACTERISTICS

Deformation characteristics of the stabilized RCA are presented in Fig. 12, which displays the change in plastic displacement during a number of cycles using a log-log plot. The analysis of the log-log plot has led to distinguishing the exponential function of the displacement change. The exponential characteristics begin after the 9th cycle. The trend line was estimated for each of the samples.

In case of the RCA sample whose RC content was equal 0%, the Eq. (3) is calculated as follows:

$$\Delta u_p = 2.7946 \cdot N^{0.0652} \quad (3)$$

where Δu_p stands for a plastic displacement value [mm] and N stands for a number of cycles. In Eq. (3), the regression constant R^2 equals 0.9974.

For the sample containing 0.5% of RC, the Eq. (4) is calculated as follows:

$$\Delta u_p = 2.3175 \cdot N^{0.0377} \quad (4)$$

In Eq. (4), the regression constant R^2 equals 0.9973.

Finally, for the sample containing 1% of RC addition, the Eq. (5) is calculated as follows:

$$\Delta u_p = 2.0057 \cdot N^{0.0076} \quad (5)$$

for Eq. (5), the regression constant R^2 equals 0.9969.

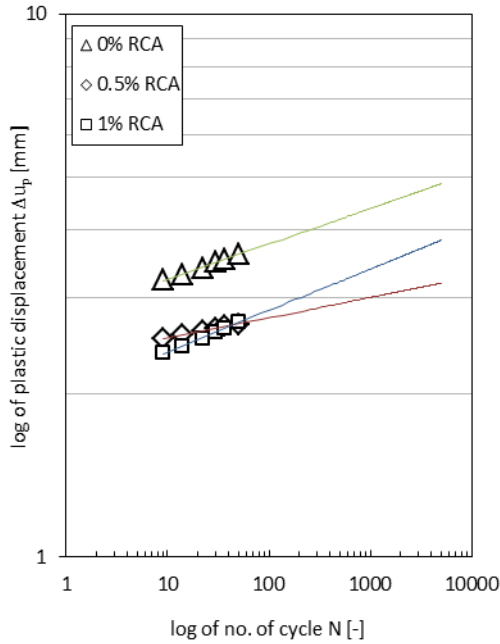


Fig. 12 The development of plastic displacement during the cCBR test versus a number of cycles shown on a log-log plot

Based on Eqs. (3) to (5), the calculation of the displacement in 3000th and 5000th cycle was made. Table 1 presents the results of plastic displacement calculation.

Table 1 The plastic displacement [mm] in the 50th, 3000th and 5000th cycle, based on the estimated exponential functions

	50 th	3000 th	5000 th
0% RC	3.61	4.71	4.87
0.5% RC	2.69	3.22	3.27
1% RC	2.71	3.68	3.83

The plastic displacement analysis shows that the increase of the permanent settlement due to cyclic loading is greater in case of the RCA with the 0% and 1% RC content. The trend is in both cases similar. When it comes to the RCA sample with the 0.5% RC content, the plastic displacement occurs in a less significant way, despite the fact

that in first cycle, the plastic displacement was greater, when compared to the RCA sample with the 1% RC content.

Resilient strain development of the RCA with the RC addition is presented in Fig. 13. The change of resilient displacement in a number of cycles in log-log plot shows previous correlations between varying displacement values at a given cycle. The exponential function of displacement was distinguished. The exponential characteristics occur in the same way, as in the case of plastic displacement phenomenon after the 9th cycle. The trend line was estimated for each sample.

In case of the sample containing 0% RC addition, the Eq. (6) is calculated as follows:

$$\Delta u_r = 3.0789 \cdot N^{0.0582} \quad (6)$$

where Δu_r stands for maximum/resilient displacement value [mm] and N stands for a number of cycles. For Eq. (6), the regression constant R^2 equals 0.9946.

In case of the sample containing 0.5% RC addition, the Eq. (7) is calculated as follows:

$$\Delta u_r = 2.5891 \cdot N^{0.0347} \quad (7)$$

for Eq. (7), the regression constant R^2 equals 0.9968.

For 1% RC addition, the Eq. (8) is calculated as follows:

$$\Delta u_r = 2.2862 \cdot N^{0.0697} \quad (8)$$

for Eq. (8), the regression constant R^2 equals 0.9977.

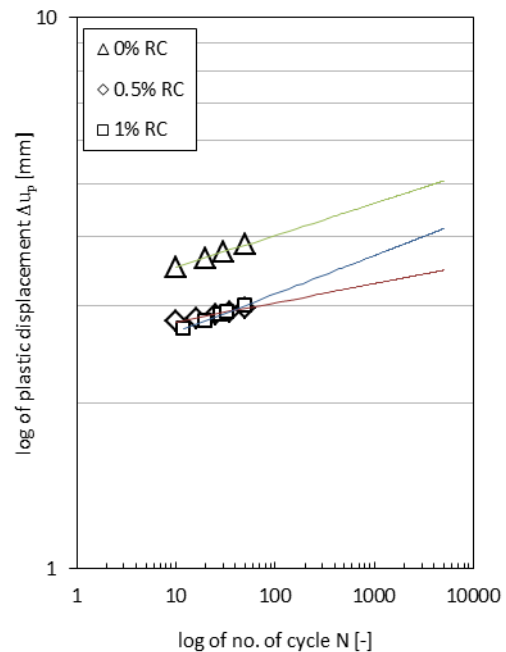


Fig. 13 Maximum/Resilient displacement development during cCBR test versus number of cycles on log-log plot

The prognosis of maximum (resilient)

displacement based on the Eqs. (6) to (8) during the 3000th and 5000th cycle was presented in Table 2.

The maximum displacement analysis highlights the same phenomenon as the plastic displacement calculations. The increase of maximum displacement due to cyclic loading is greater in case of the samples with 0%RC and 1% RC content. The trend is in both cases similar. In case of the RCA sample with the 0.5% RC content, the maximum displacement ratio is smaller and, as in the case of permanent displacement during the first cycle, the maximum displacement was greater, when compared to the RCA sample with 1% RC content RCA.

Table 2 The maximal displacement [mm] in 50th, 3000th and 5000th cycle, based on estimated exponential functions.

	50 th	3000 th	5000 th
0% RC	3.87	4.91	5.05
0.5% RC	2.97	3.42	3.48
1% RC	3.00	3.99	4.14

The plastic and elastic displacements rate can be calculated on the basis of Eqs. (3) to (8). The calculation of plastic displacement rate \dot{u}_p is calculated as follows (9):

$$\dot{u}_p = \Delta u_{pN} - \Delta u_{pN-1} \quad (9)$$

where Δu_{pN+1} is plastic displacement in $N-1$ cycle and Δu_{pN} is plastic displacement in N cycle, with N standing for a cycle number.

The calculation of elastic displacement rate \dot{u}_r is calculated as follows (10):

$$\dot{u}_r = \Delta u_{rN} - \Delta u_{rN+1} \quad (10)$$

where Δu_{rN} is maximal/resilient displacement in N cycle, with N standing for a cycle number.

The results of calculation of the plastic displacement rate are presented in Fig. 14.

The plastic displacement change shows that 0.5% RC addition results in smaller plastic displacements. Nevertheless the trend of plastic displacement ablation is similar in all three cases. Which may indicate that such RC addition has smaller impact on deformation characteristics.

The resilient displacement change presents the prognosis of 5000 cycles of cyclic loading. The RC addition has led to achieving a steady state of RCA, in which no softening and fatigue of the material may be observed. The resilient strain is larger in case of 1% RC material. This phenomenon may indicate that a larger RC addition can effect in more significant elastic strains during one cycle.

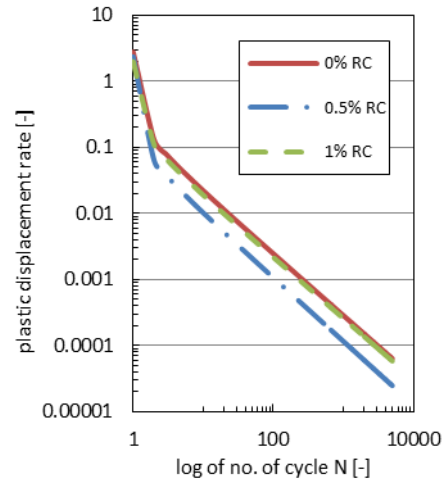


Fig. 14 The change of plastic displacement in cycles of repeated loading.

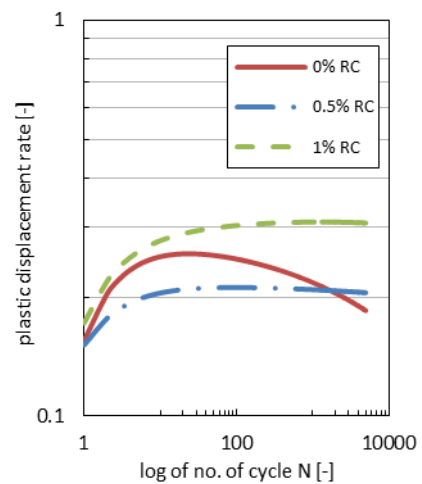


Fig. 15 The change of resilient displacement in cycles of repeated loading.

5. CONCLUSION

Results of the cCBR test on stabilized and non-stabilized RCA presented in this paper are as follows:

1. Optimal moisture content for RCA with the addition of RC is lower. Also maximal dry density decreases with the increase of RC addition.

2. The CBR value for tested samples rises with increase of RC addition. For pure RCA, the CBR value was equal 47%; for 0.5% and 1% RC content, the CBR value was 56% and 66% respectively.

3. The resilient modulus M_r value growth was observed with the increase of the RC content. For pure RCA, the M_r value was 495.6MPa; for 0.5% and 1% RC content, the M_r value was equal 632.4 and 698.0MPa.

4. Plastic displacements are decreasing upon the addition of the RC. For 0.5 and 1% RC content plastic displacements are smaller but

between these contents, differences are not so great.

5. Resilient modulus values in comparison with European standards classified this material as belonging to the highest class, which is C1, and the RCA with the addition of RC can be a part of road construction as sub-base.

6. The plastic displacement analysis shows an increase of the permanent settlement due to cyclic loading, in case of 0% and 1% RC content. In case of the RCA with the 0.5% RC content the plastic displacement which occurred, was smaller.

7. The maximum displacement analysis shows the same phenomenon as in the case of plastic displacement calculations. Increase of the maximum displacement is greater in the case of 0%RC 1% RC content. In case of 0.5% RC content RCA the maximum displacement occurs smaller.

8. The trend of plastic displacement ablation was recognized as being similar in all three cases, which may indicate that RC addition has smaller impact on deformation characteristics.

9. The RC addition has led to achieving a steady state of RCA, in which no softening and fatigue of the material may be observed. The resilient strain is bigger in case of the 1% RC material. This phenomenon may indicate that a larger amount of RC can result in bigger elastic strains during one cycle. This elastic strain may also lead to a bigger plastic displacement due to soil skeleton deformation.

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