

BEHAVIOR OF RECYCLED CONCRETE AGGREGATE IMPROVED WITH LIME ADDITION DURING CYCLIC LOADING

Wojciech Sas¹, Andrzej Głuchowski¹ and Alojzy Szymański¹

¹Faculty of Civil and Environmental Engineering, Warsaw University of Life Sciences, Poland

ABSTRACT: In this paper, study on the use of reclaimed waste in Recycled Concrete Aggregate (RCA) was conducted. Reclaimed concrete problem has increased over the past decade, due to the replacement of the old concrete parts, such as rail substructures or pavement curb. The main idea of this article was the introduction of recycled materials to pavement engineering, which in Poland were usually deposited on waste landfills. Geotechnical study was undertaken to obtain physical and mechanical properties of RCA. For better understanding of its exceptional behavior under repeated loading, cyclic triaxial test was conducted in various stages of loading. For the purpose of bearing capacity analysis, uniaxial tests were made. Moreover, RCA improvement of mechanical properties was proposed. Chemical stabilization with lime and gypsum was undertaken in order to ameliorate mechanical characteristics. While the mechanical stabilization is a cause of aggregates crushing, created fine fraction could be a stabilizing medium. Stabilization process in this study demonstrates existence of free pozzolanic compound in crushed concrete. Determination of resilient modulus M_r from repeated loading test for non-stabilized and stabilized material was also presented for non-stabilized and stabilized RCA. M_r value was 543.2MPa and 816.5MPa respectively. In this article, plastic strains occurrence was also analyzed. As a brittle material, RCA can response to cyclic loading by crushing. Repeated excitations can cause another mechanism of plastic strains development, not present in natural aggregates, where main causes of plastic strains are frictional forces occurring during contact between particles.

Keywords: Recycled Concrete Aggregate, cyclic CBR, Stabilization, Lime

1. INTRODUCTION

Recycled Concrete Aggregate (RCA) is a product of crushing process of concrete waste left from demolished constructions. Due to development of civil engineering and limited place for construction sites, old buildings are replaced by new structures. Such events are the cause of increasing of concrete debris on waste landfill. In order to stop this unpleasant situation, many studies on possibility of recycling crushed concrete were made. In transportation geotechnics, for example, an application of RCA as sub-base and improved subgrade was proposed. Interesting possibility of use RCA as noise barrier embankment is promising, moreover rehabilitation of old landfills with waste product is developed [1, 2].

For RCA to be applied in pavement design as parts of road structures, its mechanical properties need to be described well. Many studies carried out over past decades, point out with a doubt that as artificial aggregate, RCA needs special tests in order for to obtain accurate strength properties. Most obvious property which lights out problem of RCA is the greater angularity with comparing to natural aggregate. Moreover, surface of RCA is much rougher and aggregates display an unusual build. Voids in RCA are divided into two parts: accessible for water on surface, termed "surface pores", and those that are isolated, namely "internal pores" [3]. This occurrence of the voids results in higher degree of water absorption. This fact makes existing standards inaccurate for RCA testing. These problems eliminate the possibility of using RCA as

building material in the nearest future. Many tests conducted nowadays - for example direct shear test, triaxial tests and uniaxial compression tests - have shown that RCA is reliable and that this material shows good performance [4].

In case of pavement design it is important to obtain data about material cyclic loading. Among traditional cyclic triaxial tests, dynamic hollow cylinder tests are used for this purpose. Nevertheless, those methods are highly sophisticated and cannot be applied for such material like RCA. Applying this apparatus in pavement laboratories is expensive and simply too complicated. In order to simplify the tests and shorten their time, another manner was proposed. Replacing empirical methods, such as the CBR test, is the greatest advantage in utilizing this procedure [5]. Repeated loading CBR or cyclic CBR (cCBR) methods use common CBR apparatus and similar procedures to obtain resilient modulus M_r , characteristic for cyclic phenomena.

Resilient modulus is calculated as follows:

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

where, $\Delta\sigma_d$ is deviator stress pulse $\Delta\sigma_d = \Delta\sigma_1 - \Delta\sigma_3$, σ_1 is major principal stress, $\sigma_3 = \sigma_2$ is minor principal stress, and $\Delta\varepsilon_r$ is recoverable or resilient strain over deviator pulse $\Delta\sigma_d$ [6].

Pozzolanic compounds which cause the grains combine with cement cannot be entirely exploited and part of them can be activated after crushing. Because of that, efforts to stabilize RCA, by adding lime have been made. Calcium hydroxide induces reaction with pozzolanic compounds, as well as with siliceous or aluminous material.

The biggest advantage of using the repeated loading test is the possibility of gaining data relating to the permanent strain. This information can be used in the design of pavement and shallow foundations [7]. Information about stress levels and performance of material during cyclic phenomena can also be obtained. This knowledge can be better utilized simply because of ready to use results.

2. MATERIAL AND METHODS

2.1 Material

Tests were conducted on material obtained from demolished concrete from building demolition site. Concrete aggregates were an element of concrete walls and floor, whose strength class estimated from C16/20 to C30/35. Aggregates were in 100% composed from broken cement concrete. Grain gradation curve was adopted according to Polish technical standard [8] and placed 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 sandy gravel (saGr), in reference to [8, 9]. Test results are shown in Fig.1. This distribution of particles from 31.5mm to 0mm is typical for soils used for sub-base and support structures.

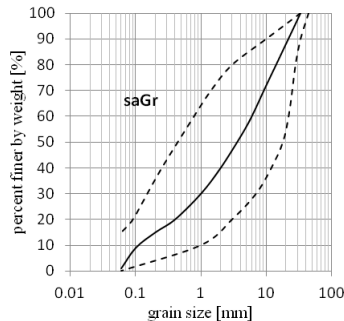


Fig. 1. Particle size distribution of tested soil.

Results of the Proctor test are presented in Figure 2.

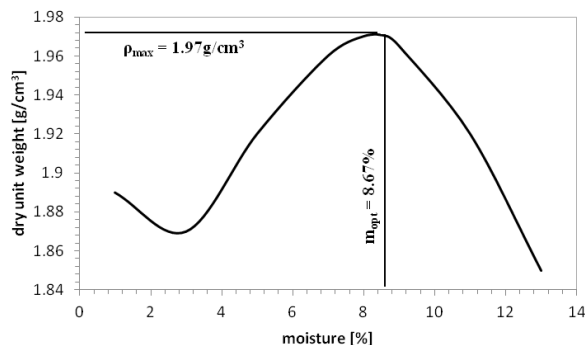


Fig. 2 The Proctor test results for sandy gravel.

The test was conducted by compaction in the Proctor mold, whose volume equaled 2.2dm^3 , by using standard energy of compaction, equal to 0.59J/cm^3 . Optimum moisture content for sandy gravel was $m_{opt} = 8.67\%$ and maximum dry density of optimum moisture content was 1.97g/cm^3 .

2.2 Methods

After the optimum moisture content has been estimated, the calculation of peak dry density ρ_{max} for tested samples relative density was performed. Observations during the Proctor tests show high water absorption of the material. Soil was compacted in three repetitions and registered data have been different each time. After 24 hours, tests were repeated on grains conditioned in constant moisture. After three repetitions, the recurrent results were obtained.

When marking of material physical properties and preparation of the samples were done, cCBR tests were performed. cCBR method was based on common CBR test. Main idea behind using this equipment came from its popularity. On the other hand, cyclic load triaxial apparatus is treated as a piece of advanced machinery. Long existence of CBR method and its usefulness in pavement design, resulted in its worldwide spread. Although for mechanistic-empirical design CBR test becomes too empirical. By using CBR mould and repeated loading apparatus, cCBR test method was established. The main principle of this test approach is to use standard CBR test procedure as a reference in order to study the later cyclic loading stage.

As was mentioned above, the first step is standard CBR test loading to 2.54mm. After reaching desired displacement with the use of plunger, unloading procedure was attempted, with the use of up to 10% of force obtained at 2.54mm. Loading and unloading is treated as the first cycle of cCBR test. Next cycles are determined by maximal and minimal force from the first loading. Test was carried out with standard 1.27mm/min. velocity. Number of cycles is determined by the percentage of plastic strain in one cycle. cCBR method assumes that the test can be stopped, when 1% or less of plastic displacement in one cycle will occur. Amount of the cycles to obtain this condition usually oscillates around 50 [10, 11].

Figures 3, 4 and 5 present exemplary cCBR test result. In this case, the tested material is RCA with 6% moisture content, compacted with normal Proctor energy. Figure 3 presents the relation of plot axial stress [kPa] to displacement [mm]. Figs.4 and 5 present plot of axial stress and displacement against time. Cyclic wave propagated in one axis stress state results in displacement, which is divided into two components: elastic - recoverable and

plastic - irrecoverable displacement.

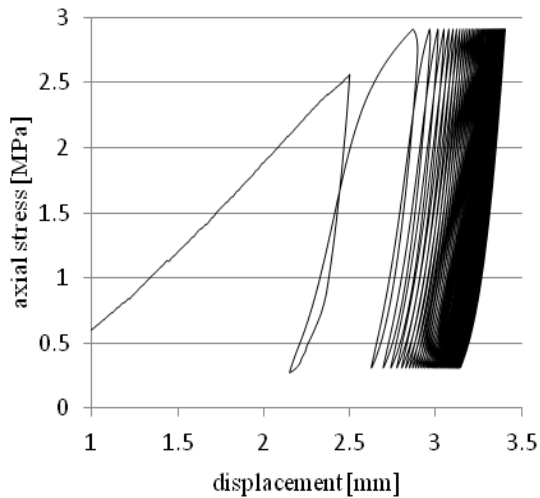


Fig. 3. Stress – displacement curve from cCBR test.

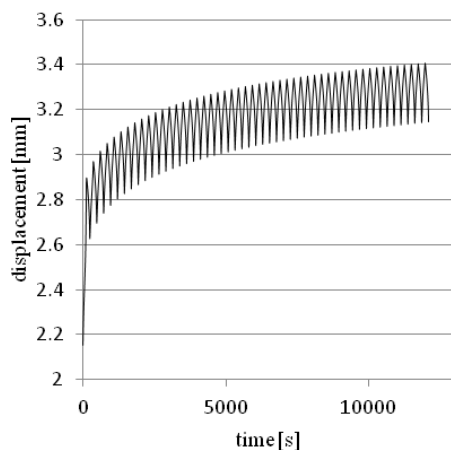


Fig. 4. Displacement – time curve from cCBR test.

These constitute the basis of numerous cyclic loading analyses. Fig.4 presents this phenomenon. At the end of every cycle, difference of displacement between analyzed test and cyclic test constitute the plastic displacement. Recovered displacements are represented by a difference between peak maximal strain and peak minimal strain in one cycle. In other words, the total plastic displacement increment is the value of minimal strain in each cycle.

2.3 Stabilization

Stabilization of non-cohesive soils - especially coarse grained soils, with greater content than 50 percent by weight of 75 μ m grains diameter - is beneficial, if chemical stabilization could occur. Improvement can be much higher up to ten times

when compared to untreated material [12]. Soil stabilization of cohesive soils impacts on their strength properties. Studies have shown that cohesion of this materials and resilient modulus M_r distinctly increase [13, 14].

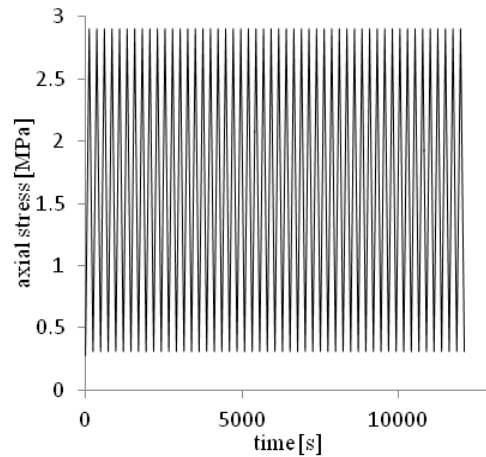


Fig. 5. Plot of cyclic wave from cCBR test.

RCA containing cement could still possess some unreacted pozzolanic compounds. Crushing process uncovers active pozzolanic compounds and leading to a reaction. In order to improve this reaction, lime and gypsum addition was undertaken. Lime as a hydraulic binder immobilized by pozzolan and produced calcium silicate hydrate. Moreover, addition of gypsum triggered the increase in hydration rate due to presence of RCA lime and gypsum, Ca and Al ions, in the mixture [15, 16].

In this study, RCA was stabilized with addition of lime and gypsum in amount of 5% and 0.5% respectively. Material was stabilized in optimal moisture content, which was 8.7% for non-stabilized aggregate. This capacity was raised up to 10.7% due to water loses, caused by hydration. After 50 cycles, the material reached resilient response to applied load and test was completed.

3. RESULTS

Tests conducted on non-stabilized RCA have shown good performance of this material. During standard CBR test the CBR value reached from 36% for material compacted in 4% moisture content conditions, to 44% for RCA in optimal moisture content, although important feature of RCA performance under cyclic loading is characterized by displacement. It is easy to notice that the same penetration of plunger during the first load is the same as a tested value of overload to desired rut in pavement engineering in next cycles, but results in different plastic displacements. Lower moisture of RCA causes 3.5mm displacement with optimal moisture content conditions resulting in 3.0mm

displacement. This phenomenon is clearly caused by degree of compaction of this material. Fig.2 presents Proctor's test results and differences of dry unit weight between 4.5% and 8.7% moisture content seem to be rather low, but due to their irregular shape, the grains could reduce righty of RCA surface and create better conditions to assume better position of grains in skeleton. The problem of the RCA righty was observed in previous studies conducted in this research program. For example, direct shear tests friction angle results for 4% of moisture content and in optimal moisture content reached 44°, but in case of 4% moisture content, apparent cohesion was observed in quantity of 10kPa.

Stabilization process in details is presented in Figs. 6, 7 and 8. Plots present results of cCBR test in function of axial stress and displacement on fig. 6. Figs.7 and 8 present the changing in time of displacement and axial stress respectively. After 24 hours from stabilization process, cCBR test conducted on this material presents improvement in CBR bearing capacity. CBR value has reached 72% and is 28% higher than results in optimal moisture content for non-stabilized sample. During cCBR test, displacement reached during the 50th cycle equaled 2.47mm during the unloading phase, which is 0.53mm less than in case of non-stabilized sample. Detailed view is presented on Fig.9.

RCA and especially stabilized RCA exhibit very resilient response to cyclic loading and this phenomenon can be observed in first cycles. Fig. 10 presents results of cCBR test for stabilized RCA and an example of the second cycle of cCBR test for sandy clay. This plot picture presents RCA as the elastic displacement to cyclic load. In comparison to sandy clay tested by cCBR method, unloading path came back almost to beginning of load phase in single cycle. Sandy clay exhibits less resilient respond. Hysteresis loop did not close after the 50th cycle, which caused plastic displacement to increment.

In case of parallel stabilized and non-stabilized RCA, samples are more likely to exhibit resilient response as stabilized RCA, but this phenomenon occurs in a slighter manner. These properties result in fast customization of this material to new load conditions. Material recovers its elastic properties in first few cycles, and rut depth in case of pavement engineering will not proceed or growth will be small. Plot of this phenomenon is presented in Fig.10. The analysis of plastic displacement for RCA is presented in Fig.11. Average functions of plastic displacement growth show that for stabilized RCA, acceleration of plunger penetration will be smaller than for the non-stabilized RCA.

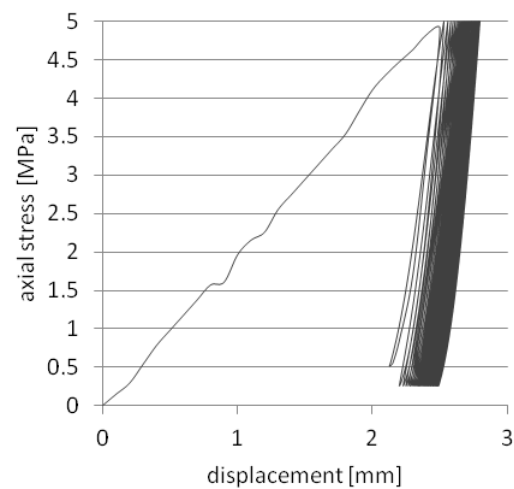


Fig. 6. Plot axial stress-displacement from cCBR test, for stabilized RCA.

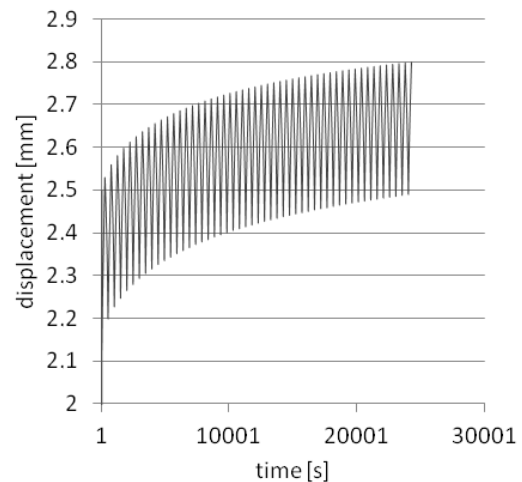


Fig. 7. Plot of cyclic wave from cCBR test for stabilized RCA.

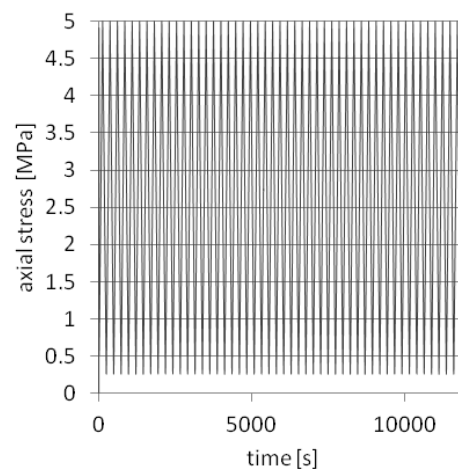


Fig. 8. Plot of cyclic wave from cCBR test for stabilized RCA.

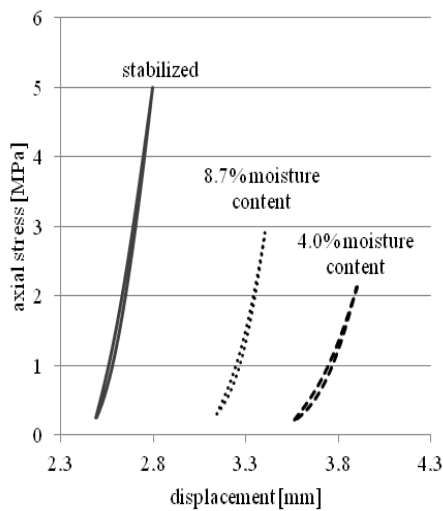


Fig. 9. Plot of last cycles from cCBR test for stabilized and non-stabilized RCA.

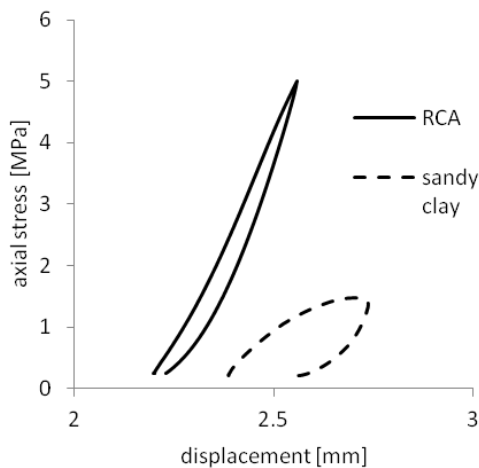


Fig. 10. Plot of results from cCBR test for stabilized RCA and sandy clay.

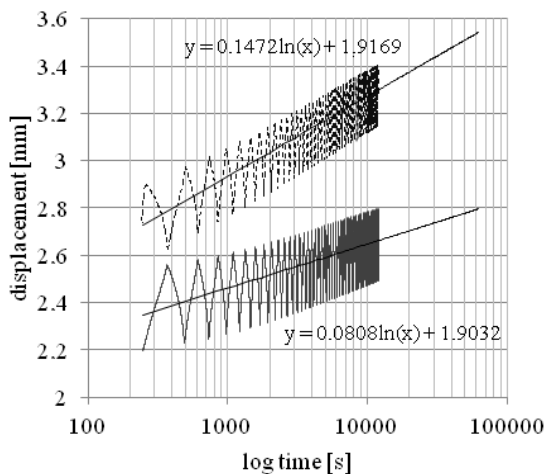


Fig. 11. Average functions of plastic displacement growth from cCBR test.

Stabilization process therefore became reason of stiffness increase in this material. This statement came from not only total displacement observation, but moreover from slope of the hysteresis loop, best seen in Fig. 9.

Resilient modulus which cannot be calculated directly from stress-displacement plot and is presented on Eq (1), needs to be recalculated. In literature, such recalculation was presented in figure [17]. Equivalent modulus from repeated loading CBR, which in this case is named resilient modulus M_r , can be obtain as follows:

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

where: ν – Poisson's ratio [-] (in this study 0.35 for granular materials), $\Delta\sigma_p$ – change between maximum and minimum axial stress in one cycle [MPa], r – radius of plunger [mm], Δu – recoverable displacement in one cycle.

Resilient modulus for non-stabilized RCA calculated in this manner is equal $M_r = 543.2\text{MPa}$ which is a reasonable result [18], and $M_r = 816.5\text{MPa}$ for stabilized RCA.

4. PLASTIC STRAIN DEVELOPMENT

Tests on RCA with constant stress ratio were performed after cCBR tests in standard procedures. Aim of these studies was to describe the yield stress of RCA and its dependence on water content. Maximal stress σ_{max} was equal 2.9MPa. Average stress ratio σ_{avg} was equal 2.61MPa. Samples were loaded 50 times. Moisture content was estimated as being equal 4, 6, 8 and 12%. Tests lead to characterizing the RCA performance under repeated loading. In opposition to regular cCBR tests, first loading was performed not until fixed displacement but fixed stress.

Figures from 12 to 16 present results of the cCBR test and yield criterion.

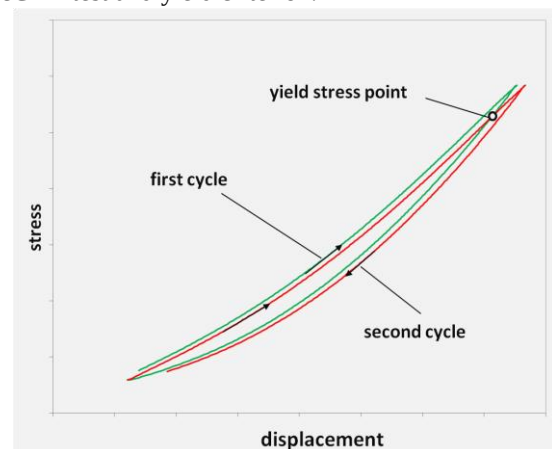


Fig. 12. Plot axial stress-displacement obtained on the basis of the cCBR test for 4% moisture content RCA.

Yield points were designated on the plot. Yielding occurred, whenever the stress level exceeded the stress path during previous unloading step. This relation is presented Fig. 12. If stress in the second cycle of loading does not exceed yield stress point, unloading phase in second cycle occurs in elastic manner. If during the test, yield point is equal to maximal stress, then no plastic strain or displacement appears [19].

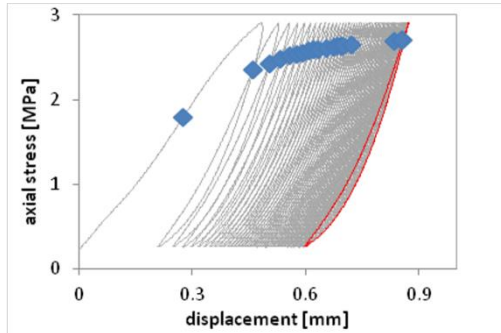


Fig. 13. Plot axial stress-displacement obtained on the basis of the cCBR test for 4% moisture content RCA.

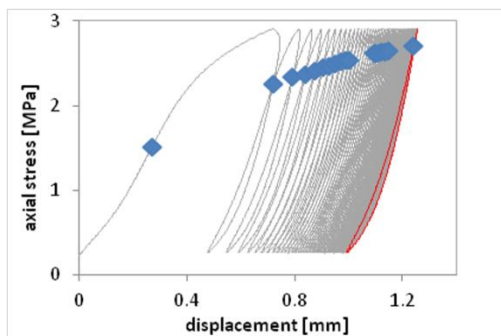


Fig. 14. Plot axial stress-displacement obtained on the basis of the cCBR test for 6% moisture content RCA.

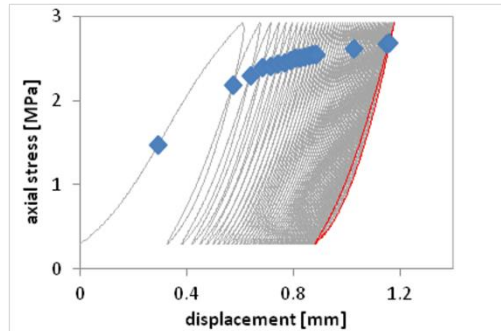


Fig. 15. Plot axial stress-displacement obtained on the basis of the cCBR test, for 8% moisture content RCA.

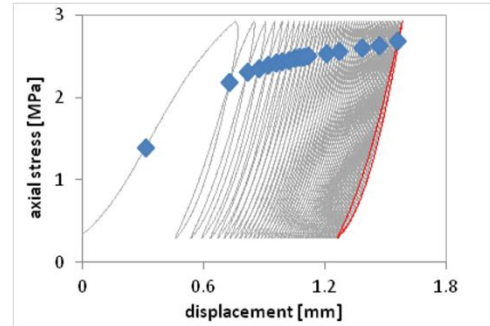


Fig. 16. Plot axial stress-displacement obtained on the basis of the cCBR test for 12% moisture content RCA.

Yield stress levels were also presented on a 3D plot (Fig. 17). For 4% moisture content, yield stress change was greater, than in the case of 6% moisture content. This phenomenon is caused by rough surface of RCA. Lower moisture content does not fill the grainy surface. This phenomenon vanishes, as soon as the degree of the water content reaches around 6%. Above this value, RCA exhibits behavior similar to those exhibited by the natural aggregate, yield stress reaches top values and this occurrence was the earliest.

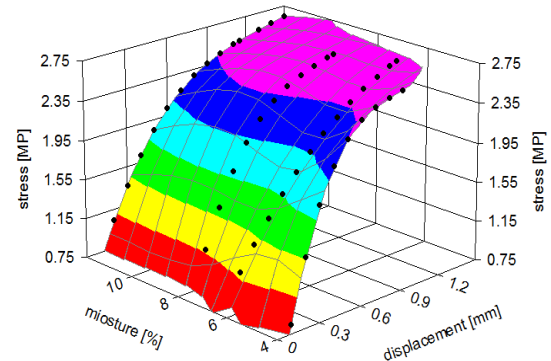


Fig. 17. Average functions of plastic displacement growth from cCBR test.

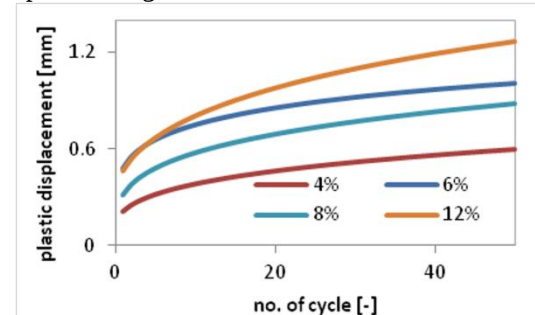


Fig. 18. Plastic displacement growth for RCA with various moisture contents.

After crossing the yield stress value, plastic strains appear. If difference between maximal stress

and yield stress is low, than so is the increase of plastic displacement.

Fig.18 presents the growth of plastic strains during cCBR tests for RCA with varying moisture content.

Plastic displacements development increase for 12% water content has top value. This level of moisture content corresponds to soaked conditions. This behavior of RCA is similar to natural aggregates. Lowest increase of plastic displacement was noted for RCA with 4% moisture, which is 8%. The RCA specimen between the soaked and driest one, was close to optimal moisture content, which is 8%. The shape of the graph curves of the plastic displacement function is also interesting. Low moisture samples (4 and 6%) have similar shape. The same situation can be observed with RCA specimens whose water content is equal 8 and 12%. This can suggest that brittle nature of RCA is expressed mostly by plastic displacement development during cyclic loading.

After analysis of yield stress and plastic displacement, resilient modulus calculation for four tests was performed. Results are presented in Table 1. Calculations were conducted for the last, 50th cycle in each test. In Figures 12 to 15 a red-colored line presents the above mentioned hysteresis loop. In case of 4% moisture RCA sample, resilient modulus M_r was equal 510.72MPa. Maximal value of $M_r = 529.13$ have 6% water content RCA sample. This phenomenon could be caused by the greater plastic displacement accumulation during the cCBR test. Particle crushing and rearrangements could cause better adjustment to repeated loading.

Yield stress, which denotes plastic displacement, corresponds with results presented in Figure 16. The plastic displacement was greater for 6% moisture RCA sample than for 4% and 8%. Change of shape in yield stress function therefore can be important factor when searching for better mechanical performance of RCA.

When designing pavements, engineers deal with two problems. Mechanical characteristics should always meet high quality requirements. Moreover, plastic displacements are undesirable and most of them should be eliminated during the construction phase. Anthropogenic soil, such as RCA, behaves randomly, considering stress and strain characteristics. It is worth to note that the highest M_r value in this study was obtained for 6% water content sample, which is not the optimal moisture degree. Properties of RCA are still not fully understood but overall mechanical characterization proved that this material is appropriate for construction of the unbound sub-bases. Eurocode 7 EN 13286-7:2004 [20] classifies RCA by mechanical performance parameter M_r and this material reached the highest C1 class.

Table 1 Resilient modulus M_r values for varying water content during the cCBR test for RCA

moisture [%]	resilient modulus M_r [MPa]
4	510.72
6	529.13
8	460.77
12	430.77

5. CONCLUSION

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

1. RCA as artificial aggregate behaves different than natural aggregates. This phenomenon came from its irregularity and rough surface.
2. Value of M_r for non-stabilized samples in optimal moisture content was 44% and 72% for stabilized specimen. In case of resilient modulus, values were as follow: 543.2MPa and 816.5MPa respectively.
3. Displacements due to cyclic loading were the smallest in stabilized specimens. Non-stabilized samples exhibit higher total displacement and its value rose with the decrease of moisture content.
4. Resilient modulus describes resilient response tested material in one cycle. Therefore no data about total displacement is available.
5. Material such as RCA generates resilient response much faster than, for example, cohesive soils such as sandy clay. Mobilization of elastic properties was highest in case of stabilized RCA.
6. Stabilization process demonstrates existence of free pozzolanic compound in crushed concrete. Addition of lime and gypsum as stabilization media could trigger hydration reaction.
7. Future studies should concern estimation of optimal lime, water and gypsum content, evolution of displacements in more than 50 cycles and in other frequencies.
8. RCA exhibits different behavior in comparison to natural aggregates. Highest values of M_r were observed for 6% water content specimen, where optimal moisture content was 8.67%.
9. Properties of RCA need to be more recognized, mechanical characterization proved that this material is suitable for construction of the unbound sub-bases in accordance with the Eurocode 7 EN 13286-

7:2004, which categorizes RCA as a material belonging to the highest C1 class.

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Int. J. of GEOMATE, Feb., 2016, Vol. 10, No. 1 (Sl. No. 19), pp. 1662-1669.

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Corresponding Author: **Wojciech Sas**
