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# APPLICATION OF RECYCLED CONCRETE AGGREGATE IN ROAD ENGINEERING

Wojciech Sas
Warsaw University of Life Sciences – SGGW

**Abstract.** The development of road investments during past years results in an increasing demand for natural aggregates (NA) which x become a part of the road construction subbase in the form of an unbound mix. In order to decrease investment costs, the Construction and Demolition (C&D) materials, such as fly ash, steel slag or recycled concrete aggregates (RCA), were applied as a subbase fill. The advantage in using these materials, besides the reduction of costs, is a possibility of C&D material recycling and sustainable development, due to replacing the NA, which is a non-renewable source. Among many properties influencing the quality of road material, the California Bearing Ratio (*CBR*) is the one representing the mechanical properties of unbound mix. This article presents the results of *CBR* tests on RCA with various moisture and compaction properties, in order to characterise the *CBR* bearing capacity. The results were then used to form conclusions about *CBR* tests on RCA. The conclusion can be drown that the C&D materials can be successfully applied in road engineering when more strict regulation will be applied.

**Key words:** Recycled Concrete Aggregate, *CBR*, Bearing capacity, moisture, compaction

## INTRODUCTION

The Recycled Concrete Aggregate (RCA) is an anthropogenic material. As a Construction and Demolition (C&D) material, it is characterised by certain properties, such as mechanical performance or physical characteristics, which are different from those of Natural Aggregates (NA) [Sas et al. 2015a, 2016]. The utilisation of C&D materials takes many different forms. It can be used as a pipes backfilling, in embankments, or as a roads subbase [Li 2008, Vegas et al. 2011, Jimenez et al. 2012, Rahman et al. 2014]. One of the incentives to apply C&D materials is the European Parliament Waste Framework Directive, which states that until 2020, the minimum by weight of non-hazardous materials,

Corresponding author: Wojciech Sas, Warsaw University of Life Sciences – SGGW, Faculty of Civil and Environmental Engineering, Water Center Laboratory, St. Ciszewskiego 6, 02-787 Warsaw, e-mail: wojciech_sas@sggw.pl

the 70% of C&D wastes shall be prepared for re-use and recycling [EU Council Decision 2003/33/EC]. The demand on new materials for road constructions in Poland has led to an increase in the unbound NA exploitation [Kabziński 2012].

The C&D debris consists of a larger portion of concrete rubble, as well as bricks, sand, timber and metal. After separation of concrete rubble from the rest of C&D debris, the crushing process can be performed, its result being the RCA which canstill be utilised as a road construction material [Sherwood 2001, Safiuddin et al. 2010].

For the RCA to be utilised better, distinct set of requirements for technical specifications, which can help engineers with successful application of this material, is needed. A number of publications concerning C&D materials covers various properties displayed by said materials, includes results different from those achieved via the NA test.

The California Bearing Ratio (*CBR*) test is the most common strength properties test performed in road material quality laboratories providing the ability to identify the relative strength of soil used mostly in road constructions and embankments [Rico et al. 1988, Brown 1996, Arulrajah et al. 2012, Sas and Głuchowski 2014, Zabielska-Adamska and Sulewska 2015]. The *CBR* test is usually preceded by physical properties tests, such as optimal moisture content and sieve analysis.

In case of tests concerning the feasibility of the RCA, crushed brick and unbound road subbase application reports mention that the density of C&D materials is lower than the one of NA. Regarding the water absorption rate, the RCA was placed between crushed brick and NA. One the most important features of the C&D materials is the difference between soaked and un-soaked test conditions. In case of the NA, the saturation conditions did not impact the test results. The RCA *CBR* test results present the *CBR* value as being equal to 66%. The difference between the levels of optimum moisture content, observable during the compaction of C&D materials grows with an increase in the aggregates' water absorption [Poon and Chan 2006]. Despite the laboratory tests, field test reports show a comparable resilient response of subbase made from NA and RCA. The resilient response in these studies was found to be dependent on the strength of the original concrete [Nataatmadja and Tan 2001].

The comparison studies, during which the *CBR* of RCA was confronted with the *CBR* test results of limestone, show similar values [O'Mahony and Milligan 1991]. The analysis of RCA and NA mix performance shows that blended mix consisting in 25% of RCA and in 75% of NA would exhibit the same resilient response and permanent displacement properties, as a subbase constructed from dense-graded material [Bennert et al. 2002]. Studies on blends, in which different C&D materials were mixed with NA, show lower toughness than in case of pure NA, which may lead to an increase of fines during the exploitation phase of unbound base. Nevertheless, as long as the fines content satisfy the requirements, they can be used as an unbound mixture for road applications [Taherkhani 2015].

The properties of RCA, especially the bearing capacity, result in the material having many practical applications, such as being used as an unbound subbase [Aurstad et al. 2006, Li 2008, Edil et al. 2012]. The RCA is recommended to be applied as a subbase, improved subgrade and drainage layer or as a noise barrier embankment [Krezel and McManus 2000, Petkovic et al. 2004, Poon and Chan 2006]. Nevertheless, the same laboratory tests can give results different from what was previously pointed out in case of C&D materials [Zabielska-Adamska and Sulewska 2009]. This phenomenon, related to the RCA properties, may be caused by puzzolanic activity after the crushing process, which causes active cement compounds on the surface of crushed concrete to produce new hydrated bounds upon the addition of water. This could be the cause of higher water absorption and diversity of material quality level [Gee 2007, Paranavithana and Mohajerani 2006].

The following paper is a study of the physical and mechanical properties of the RCA. The crushed concrete with a specified strength was tested, while for the material with different soil gradations CBR tests were performed.

## MATERIALS AND METHODS

### Materials and Sample Preparation

The Recycled Concrete Aggregate was obtained from the crushed walls of an industrial building. Prior to the geotechnical examination, the strength class of concrete was estimated. The results show that the strength class of the building material is B20 (C16/20). The RCA consists in 100% of crushed concrete. No other materials, such as parts of glass and bricks, were observed in the RCA ($\Sigma$(Rb, Rg, X) $\leq$ 1% m/m) in accordance with EN 933-11:2009 which establish criteria and procedures for the acceptance of waste and landfills.

### Physical Properties Analysis

In order to estimate physical properties, a series of tests was conducted. The sieve analysis was done during the first stage of physical tests. The tests were performed with respect to PKN-CEN ISO/TS 17892-4:2009.

The Proctor test was performed with respect to a standard Proctor's method guidelines according to ASTM D698-12e2. The selected method is marked as 'II', characterised by the use of a 2.5 kg hammer and large mould (2.2 $dm^3$). A 3-layer Proctor test was performed, with 55 blows to each layer. This procedure creates constant energy of compaction, whose level is equal to 0.59 $J \cdot cm^{-3}$ and refers to the Proctor's normal energy of compaction.

### CBR Bearing Capacity Analysis

The laboratory bearing capacity analysis was conducted to determine the engineering properties of RCA used in road applications, by using the California Bearing Ratio (*CBR*) [ASTM D1883-14].

*CBR* tests used large samples of RCA, with respect to standard guidelines for Proctor's method, where preliminary tests highlighted the maximum dry density and optimum moisture content. The *CBR* tests were performed according to applicable standards. Using this method, the RCA was studied three times for each moisture content level, which were equal to 6.05%, 9.51%, 10.02% 10.74% and 11.53% respectively to blend numeration. The distinct moisture contents refers to optimum moisture contents for each blend of RCA.

## RESULTS OF DISCUSSION

### The physical test results

The physical properties test results are presented as the sieve analysis in Table 1 and Figure 1. All five blends were recognised as sandy gravels (saGr) with respect to PN-EN 1997-2:2009 and PN-EN ISO 14688-2:2006. The coefficient of uniformity ($C_u$) in all blends was higher than 15. The coefficient of curvature ($C_C$) for blends from 3 to 5 was between 1 and 3, which means that the shape of the grading curve was multi-graded. The blend 2, whose $C_C$ was equal 0.49, which classifies this soil as gap-graded. The blend 1 was recognized as even-graded due to high $C_C$ factor, according to PN-EN ISO 14688--2:2006. The blends were confronted with upper and lower bound of sufficient soil gradation [WT-4, 2010]. The blends 3, 4 and 5 fulfil the requirements for soil blend 0–31.5 mm for main course of unbound sub-base. The blend 2 fulfils the requirements for soil blend 0–22.4 mm for main course of unbound sub-base. The blend 1 does not meet any of the requirements specified in the WT-4 document. The soils for sub-base course should display frost resistance and permeability resistance to suffosion. The ratio $d_{15}/d_{85}$ over 5 displays sub-base resistance to particle transportation in sub-base. All 5 blends fulfil the permeability requirements. The detailed results of calculations are presented in Table 1.

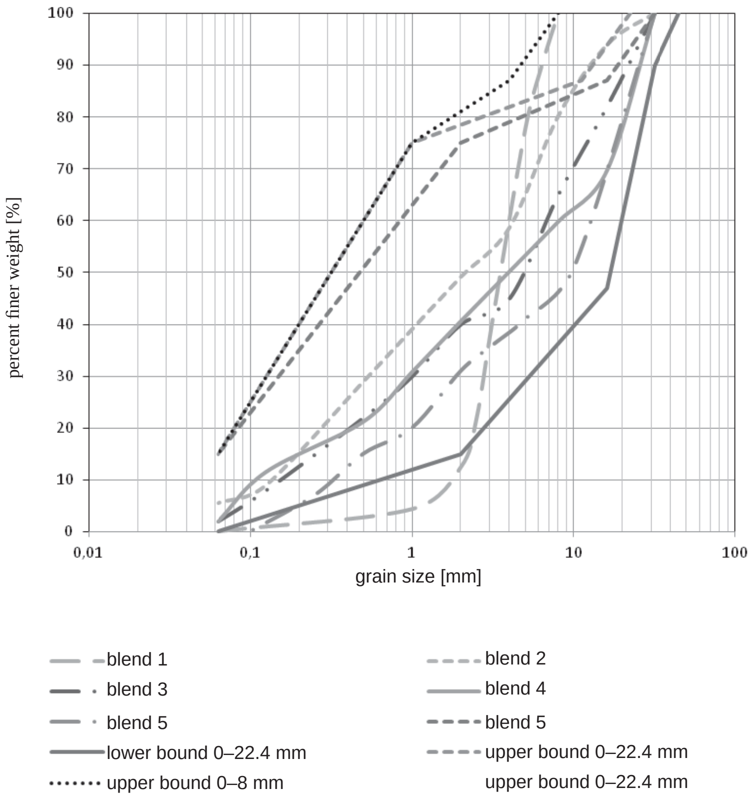


Fig. 1. Gradation curve of tested RCA

Table 1. RCA gradation properties

| Blend No. | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| $d_{10}$ | 0.19 | 0.13 | 0.14 | 0.10 | 0.33 |
| $d_{15}$ | 2.30 | 0.20 | 0.26 | 0.20 | 0.40 |
| $d_{30}$ | 2.90 | 0.51 | 1.00 | 1.00 | 2.00 |
| $d_{60}$ | 4.00 | 4.10 | 5.90 | 8.00 | 12.00 |
| $d_{85}$ | 5.70 | 10.00 | 10.70 | 22.00 | 22.00 |
| $d_{90}$ | 6.10 | 12.00 | 21.00 | 25.00 | 25.00 |
| $C_U$ | 21.05 | 31.54 | 42.14 | 80.00 | 36.36 |
| $C_C$ | 11.07 | 0.49 | 1.21 | 1.25 | 1.01 |
| $d_{15}/d_{85}$ | 0.40 | 0.02 | 0.02 | 0.01 | 0.02 |

The Proctor test results are presented in Figure 2. Presented test results show different optimal moisture content for each blend. The most visible difference is in the case of blend 1, in which gap-graded soil gradation curve was recognised [Bond and Harris 2008]. This phenomenon occurs with no clear optimum moisture point. The roughness of angular particles, which characterises the RCA grains, leads to compaction problems. The small amount of fines fills the even-graded gravel fraction.

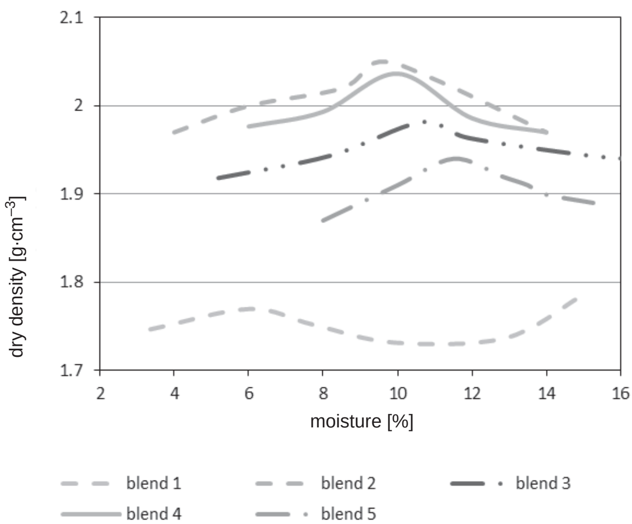


Fig. 2. Results of Proctor test

Therefore, overall dry density of this blend is clearly smaller, than in case of other 4 blends (1.73–1.77 g·cm$^{-3}$). For the rest of the blends, the optimal moisture content and maximal dry density obtained in these conditions are presented Table 2.

The optimum moisture content for blends 2 to 5 was between 9.51% and 11.53%. The dry density was between 2.05 g·cm$^{-3}$ and 1.94 g·cm$^{-3}$. The optimum moisture content and dry density was highest in the case of blend 2. This phenomenon means the highest dry density is obtained, when the coefficient of curvature is low. In case of blend 1 different shape of compaction curve was observed. The reason of that phenomena was the

Table 2. Optimum moisture content test results for various blends of RCA

| Blend No. | Moisture [%] | Dry density [g·cm$^{-3}$] |
|---|---|---|
| 1 | 6.05 | 1.78 |
| 2 | 9.51 | 2.05 |
| 3 | 10.02 | 2.04 |
| 4 | 10.74 | 1.98 |
| 5 | 11.53 | 1.94 |

behaviour of material which is more like non cohesive material with no distinct optimum moisture content (small difference of value of dry density). The tests were performed until 14.5% moisture content to ensure this phenomena. The results after 8% up to 13.5% of moisture content were in lower range of dry density, but the results in range between 13.5% and 14.5% may be random. The compaction of material in moisture greater than 14.5% was not possible due to full saturation of the material.

## The *CBR* Bearing Capacity Test Results

The typical *CBR* test results for RCA are presented in Figure 3. During the tests, the first step of loading disturbances was observed. The appropriate response to loads was achieved upon reaching the plunger penetration level equal to 0.25–1.0 mm. In order to find the right *CBR* result, the correction of results was made. The *CBR* value was calculated, by employing:

$$CBR = \frac{P}{P_s} \cdot 100 \tag{1}$$

where: $P$ – stands for force obtained at the depth of 2.5 mm and 5.0 mm,
$P_s$ – a characteristic value of CBR force at the depth of 2.5 mm and 5.0 mm.

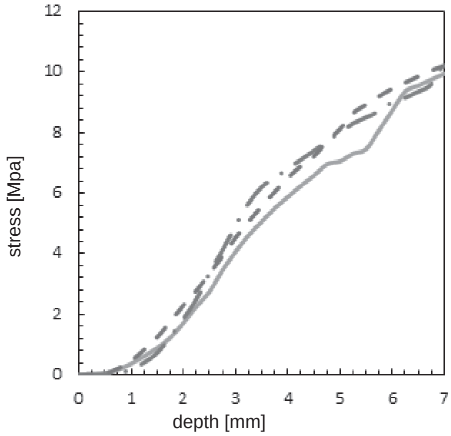


Fig. 3. Typical *CBR* test results for RCA

The disturbances during the *CBR* test may be caused by loose grains on top of the *CBR* cylinder and the crushing process. The crushing phenomenon was previously studied. The RCA tends to undergo crushing even during the Proctor tests [Sas et al. 2015a]. Therefore, the addition of a smaller fraction may prevent form this undesirable occurrence. This procedure was performed with the use of a steel slag, for which the same crushing phenomenon was observed. The proposed improvement, which includes the addition the smaller fraction on the top of the surface, provides better *CBR* values [Sas et al. 2015b]. The correction of *CBR* test results therefore was conducted to provide proper *CBR* values. The *CBR* values for each blend presents Table 3. The *CBR* test results shows different values for each blends. The highest *CBR* value was obtained for blend 3, for which the peak *CBR* was equal to 113% at 5.0mm depth. Closely similar results were observed in case of blends 4 and 5. The *CBR* value was oscillating between 90% and 73%. The gap-graded blend 2 performed slightly worse during the *CBR* test. The results for this blend was between 76% and 62% the *CBR* value. The even-graded blend 1 gave the lowest *CBR* test results. The *CBR* value for this blend ranged from 29% to 18%.

Table 3. Results of the *CBR* tests for various blends of RCA

| Specification | Blend | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| $CBR_{2.5}$ [%] | 22 | 71 | 83 | 90 | 78 |
| | 23 | 61 | 87 | 80 | 76 |
| | 18 | 62 | 68 | 73 | 84 |
| $CBR_{5.0}$ [%] | 27 | 76 | 110 | 87 | 86 |
| | 29 | 75 | 113 | 90 | 78 |
| | 24 | 74 | 110 | 84 | 79 |

The test results clearly indicate that blend 3, 4, and 5 can be applied in all layers as unbound mixtures. These blends are characterized by the relatively low content of sand fraction. Nevertheless, in accordance with the applicable regulations [WT-4, 2010], the lower and upper bounds of sufficient gradations need to be improved. The more restrictive bounds will prevent the possibility of the RCA bearing capacity decrease. In Figure 4 displays proposed new upper and lower bounds of sufficient gradation for tested RCA. Table 4 presents detailed particle distribution for lower and upper bound of sufficient gradation for RCA. High *CBR* values can be obtained, when the gravel fraction is dominating the mixture. The sand and fine fractions fill the pores, but do not disrupt the contact between gravel fraction grains. This distribution is beneficial, mostly due to the phenomenon of the RCA crushing. The smaller particles support the bigger grains. Most of the axial load is transmitted by gravel fraction. If the composition of the gradation contains less sand fraction, the lack of support will lead to an increase of the crushing power and therefore occurrence of plastic displacements. The high roughness of the RCA grains is an advantage, when friction forces appear. Nevertheless, the same property of the RCA causes problems with compaction; the Proctor's tests show lower dry density for blend 3 than for blends 2 and 4. This indicates that dry density should not be a factor of in case of RCA's bearing capacity value.

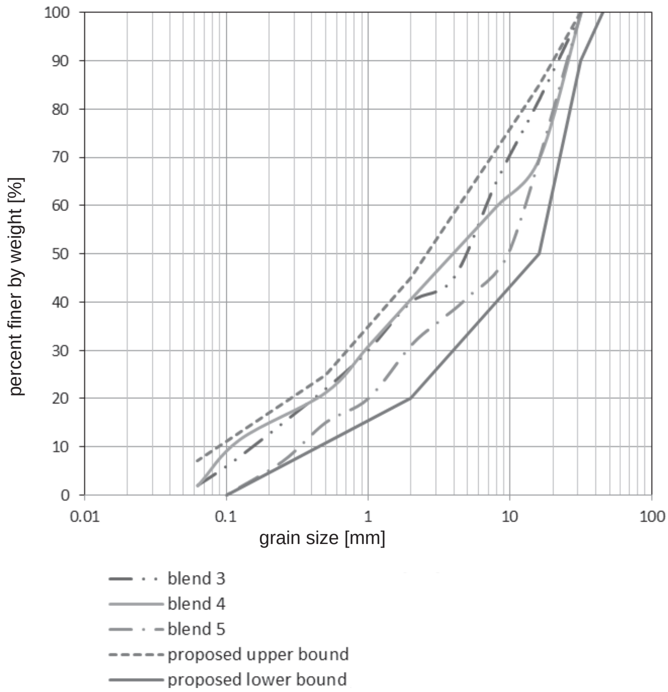


Fig. 4. The proposed new upper and lower bound of sufficient gradation for RCA

Table 4. Detailed description of upper and lower bound of gradation curve for RCA

| Specification | Grain size [mm] | Percentage finer by weight [%] |
|---|---|---|
| Upper bound | 31.5 | 100 |
| | 16 | 85 |
| | 2 | 45 |
| | 0.5 | 25 |
| | 0.063 | 7 |
| Lower bound | 45 | 100 |
| | 31.5 | 90 |
| | 16 | 50 |
| | 2 | 20 |
| | 0.1 | 0 |

## CONCLUSIONS

This article, presented the results of physical and *CBR* bearing capacity tests for Recycle Concrete Aggregate. The results lead to the following conclusions:

1. The RCA is an unbound mix, which can be utilized as an element of unbound layers of the road. The average *CBR* ratio for multi-graded material was over 80%. Therefore, the RCA can be applied as an improved subbase (medium-graded mix, for which the *CBR*

value is over 40%, can also be applied), support sub-base (*CBR* value over 60%) and as main sub-base (*CBR* value over 80% in refer to WT-4 [2010]).

2. RCA is sensitive to uneven gradation, the lack of gravel fraction support results in crushing. The uneven gradation also leads to problems during then compaction, during which low dry density and no sharp optimum moisture content was observed.

3. The successful utilization of C&D material as the RCA has to be preceded by more restrictive regulation in case sufficient gradation bounds. The uniform distribution of fraction can prevent crushing and results in high bearing capacity levels.

4. The upper and lower bounds of sufficient gradation of RCA have been proposed. These bounds were estimated, using the *CBR* test results analysis and ensure uniform distribution of the RCA.

5. During the *CBR* tests, the loose top surface of sample was observed in each test. This phenomenon occurs as a part of non-appropriate penetration response of sample during the loading. The improvement of top surface (1–2 cm) by finer fractions would prevent from this unpleasant occurrence.

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## ZASTOSOWANIE KRUSZYWA Z DESTRUKTU BETONOWEGO W BUDOWNICTWIE DROGOWYM

**Streszczenie.** Rozwój inwestycji drogowych na przestrzeni ostatnich lat spowodował wzrost zapotrzebowania na mieszanki niezwiązane, które są elementem podbudów drogowych. W celu zmniejszenia kosztów budowy zaczęto poszukiwać materiałów alternatywnych, takich jak popiół lotny, żużel, a także destrukt betonowy. Przewagą tych materiałów nad kruszywem naturalnym jest możliwość recyklingu dotychczasowych odpadów, a także zastosowanie zasady zrównoważonego rozwoju poprzez zmniejszenie wykorzystania materiałów naturalnych, jakimi są kruszywa naturalne. Jednym z kryteriów, które materiał wbudowany w podbudowę drogową musi spełnić, jest określona wartość kalifornijskiego wskaźnika nośności (*CBR*). Artykuł ten przedstawia wyniki badania *CBR* dla materiału pochodzącego z pokruszenia destruktu betonowego. Dla analizowanego kruszywa porecyklingowego – betonowego w celu scharakteryzowania właściwości materiału wykonano szereg badań *CBR* w różnych warunkach wilgotności i zagęszczenia. Wyniki badań zostały następnie przeanalizowane i omówione we wnioskach. Na podstawie wykonanych badań można stwierdzić, że istnieje możliwość aplikacji gruntów antropogenicznych, które mogą zastąpić naturalne kruszywa, jeśli zastosuje się w stosunku do nich bardziej restrykcyjne wymagania niż dla kruszyw naturalnych.

**Słowa kluczowe:** kruszywo betonowe z recyklingu, *CBR*, nośność nawierzchni drogowej, grunt

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