ISSN 1644-0633
www.acta.media.pl

ACTA SCIENTIARUM POLONORUM *Acta Sci. Pol. Architectura 14 (1) 2015, 29–41*

EXPERIMENTAL STUDIES ON CRUSHING OF RECYCLED CONCRETE AGGREGATES

Wojciech Sas, Andrzej Głuchowski, Emil Soból, Monika Kulkowska
Warsaw University of Life Sciences – SGGW

Abstract. This paper presents the results of studies on crushing phenomena during the Proctor compaction test on Recycled Concrete Aggregate (RCA). Increase in demand for materials in road construction industry creates the need for new materials which can replace natural aggregates (NA). Moreover, it should be noted that NA are a non-renewable resource in opposite to, for example RCA which could be recycled and become a part of road construction. There are many material properties, which need to be clarified and crushing phenomenon is one of them. The following article analyses the issue of crushing. Selected blends which differs by gradation curves were tested. Tests have been made according to Proctor's method in various moisture conditions. The paper ends with final remarks for practical application of the RCA.

Key words: subgrade, recycled concrete aggregate, Proctor test, crushing, fractal

INTRODUCTION

Increasing demand for materials used for road network development in Poland creates a need for new materials, which could replace Natural Aggregates (NA). The process of introducing such substitutes needs to be preceded by studies on wide spectrum of physical and mechanical properties. Among many such properties, crushing phenomenon is one of most important, because grain crumble is still not fully understood. One of the materials which could be replace NA properly, is Recycled Concrete Aggregate (RCA). However, this material – which is classified as lightweight aggregate – is characterized by the more intensive crushing process in comparison to NA. RCA proved to be a reliable material during field tests in Melhus, Norway [Aurstad et al. 2006] or during numerous tests in

Corresponding author: Wojciech Sas, Warsaw University of Life Sciences – SGGW, Faculty of Civil and Environmental, Water Centre Laboratory, 6 Ciszewskiego St. 02-776 Warszawa, e-mail: wojciech_sas@sggw.pl

USA [Shull et al. 1998] and in Poland [Sas et al. 2014]. Many countries introduced practical codes for using such materials.

The crushing process described above is complex and its course depends on many random effects. This randomness is caused by unrepeatable soil grain distribution in soil skeleton and random contact surfaces between grains and particles. Therefore a simple model which could describe crushing of grains is still desired. In industry, a number of simplified explanations of crushing phenomena has been proposed, among them an energy hypothesis, which is employed to approximate effects of crushing. This method is based on dependence on external work done on some elements and the size of those elements, grain surface newly created after grain decomposition and other properties [Zawada 1998, Dańko 2007, Zawada and Chochoł 2009, Wesołowski and Bochat 2010, Macko 2011, Skrzyński and Dańko 2014).

RCA is anthropogenic soil which was recognized as capable to excess crushing material [Sas et al. 2015]. Previous studies of the phenomenon of crushing as occurrence connected with the process of suffusion and the impact of crushing on CBR test results are presented in the following paper. Nevertheless, scope of this work was to present threats which accompany the crushing phenomenon and how this fact can impact structures.

Proper identification of the amount of external work done on soil volume could be useful information. Recently, researcher came up with a more suitable proposition of solving the crushing problem, such as example models or experimental tests. Structural loading on mixed sediments can cause more damage to weak grains than to stronger ones [Leleu and Valdes 2007]. In constructions, where part of soil base was replaced by RCA, or in road engineering, where one of layers is compacted RCA, increased rate of crushing can occur.

Most intensive crushing occurs in a loose state, when contact surfaces between particles are small. Compacted soil mass decreases its volume and thus density rises. Important observations made during compaction of granular materials show that crushing of grains contributes to volume contraction by reducing dilation in shear [Yamamuro and Lade 1996]. During one-dimensional loading, soil mass experiences first a small strain caused by rearranging of particles under a relatively high stress. Later, a large strain occurs, followed by the crushing of the grains and classic yielding [McDowell and Bolton 1998, Guimaraes et al. 2007].

It should also be noted that during one dimensional loading when soil yields and crushes, particle size distribution approaches a linear trend on a log-log scale which suggests a fractal distribution of grain sizes [McDowell 1999, Lobo-Guerrero and Vallejo 2005].

METHODS AND MATERIAL

Granalogy – analysis of crushing

In the work of McDowell et al. [1996], a proposition of highly simplified two-dimensional numerical model called Granalogy was presented. This theory concerns the uniformly sized grains which are allowed to split probabilistically. In the model, grains are seen as triangular laminate, but represent real soil particles. The value of energy absorbed into the creation of new surfaces can be calculated by Granalogy model. Finally, curves resulting from model simulation can be fit for experimental data and thus energy used crushing can be calculated.

For a fractal distribution of *L*-sized particles, which are greater than d-sized ones, a following equation was created:

$$N(L > d) = Ad^{-D} \tag{1}$$

where: *D* is fractal dimension and *A* is a constant of proportionality [Turcotte 1986, McDowell et al. 1996]. Figure 1 presents the logarithm for a number of particles larger than *d* to the logarithm of *d*.

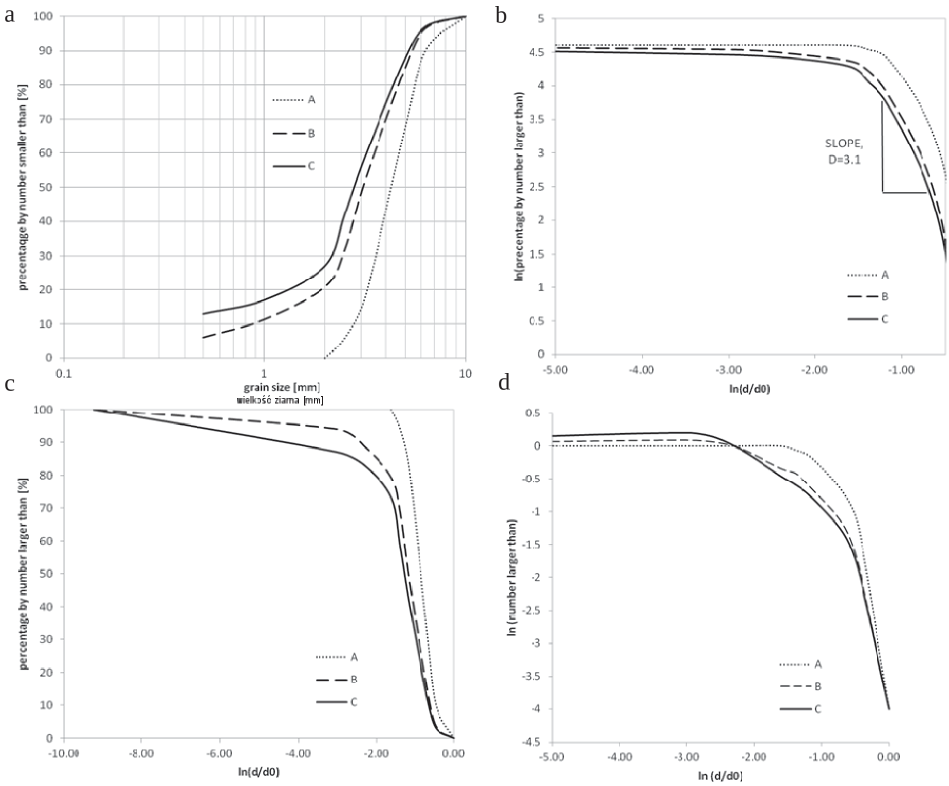

Fig. 1. Presentation of exemplary particle size distribution for fractal model of grain crushing: a – regular soil distribution curve, b – plot of natural logarithm percentage by number and natural logarithm of quotient of the particle size *d* to the largest particle size d_0, *D* is fractal dimension, c – percentage of particles larger than number to quotient of the particle size *d*, d – logarithm of percentage larger than number to quotient of the particle size *d*

In reference to the equation (1), soil distribution should become more exponential with the increase of crushing energy. Figure 2 presents such relationship, which was present, for example, in Figure 1 on log-log scale. On the basis of this relationship, this theory can be adjusted to describe evolution of soil gradation curve under compaction.

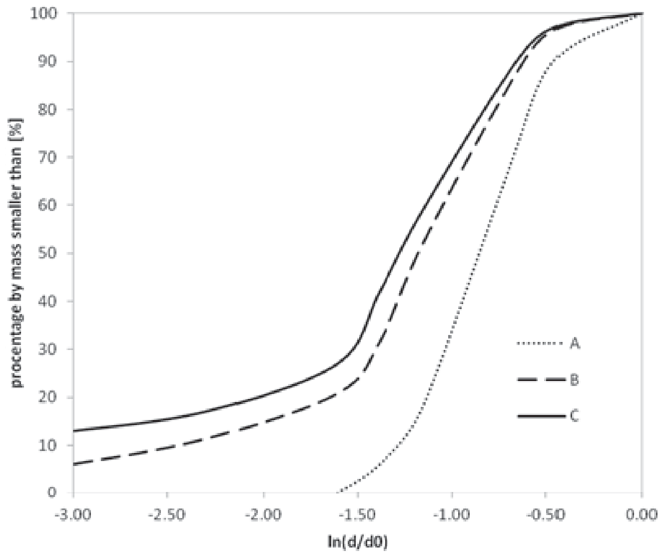

Fig. 2. Presentation of exemplary particle size distribution, evolution of size distribution to exponential form

Parameters *A* and *D*, obtained from the equation (1), can be used to calculate mass of particles finer than a particle size *d*, $M(L < d)$ (2) and a total sectional area for particles size *d* and greater $S(L > d)$ (3), respectively:

$$M(L < d) = \frac{ADd^{-D}}{2(2-D)} \tag{2}$$

$$S(L > d) = \frac{\beta ADd^{-D}}{D-1} \tag{3}$$

where: $\beta = 2 + \sqrt{2}$.

The model presented above is based on Weibull statistics of fracture [Weibull 1951, McDowell 1996]. By assuming that particles have similar geometry and the same number of contact points withother particles, survival probability $P_s(d)$ of particle with diameter *d* can be established with the following equation (4):

$$Ps(d) = \exp\left\{-\left(\frac{d}{d_0}\right)^w \left(\frac{\sigma}{\sigma_0}\right)^m\right\} \tag{4}$$

where σ_0 is stress under which 37% of block in diameter d_0 remains untouched, while *m* and *w* parameters are called ‘Weibull modulus’ and ‘dimension number’ respectively.

Material

Tests were conducted on anthropogenic material – RCA, which was collected from concrete debris through an industrial process, in which the debris was crushed to a 0–63 mm fraction. Concrete aggregates were a part of concrete wall, whose strength class was estimated as C16/20. Aggregates were in 100% composed from cement concrete. Grain gradation curve was adopted for Polish technical standard and placed between upper and lower grain gradation limit. Table 1 presents basic physical properties of RCA used in these studies.

Tests were performed for RCA samples, which were prepared in two blends. Grain diameter for Blend 1 was in range 2–10 mm and 0–31.5 mm for Blend 2.The material was formed by mixing respective fractions of the source material with assigned grain diameter, by sieving the 0-63mm fraction. After that, the Proctor test was performed in reference to PN-88/B-04481, with the use of a hammer weighting 4.5 kg in Proctor mould, whose volume was equal 2.2 dm^3. Tests were conducted in optimal moisture content $w_{\mathrm{opt},}$ whose value for each blend is presented in Table 1.

Table 1. Properties of RCA in this study

Parameters	Blend 1	Blend 2
Optimal moisture, w_{opt} [%]	7.95	7.49
Dry density [g·cm^{-3}]	1.8	1.94
Porosity ratio, e [–]	0.47	0,37
Porosity, n [–]	0.32	0,27
Compaction index, I_d [–]	≈1.00	≈1.00
Coefficient of curvature, C_C [–]	0.95	1.07
Coefficient of uniformity, C_U [–]	1.87	38.7

Laboratory tests

Soil blends differed with respect to their grain diameter composition, Blend 1 was created as a soil mix, characterised by uniform soil gradation curve (no voids), but poorly graded. All grains consist of gravel fraction boundaries. In opposition to Blend 1, Blend 2 is well graded. Uniform distribution of the grains should prevent particles from undergoing intensified breaking. Nevertheless, curvatures for both blends are similar. This helps to understand the impact to of this phenomenon on soil grains crushing, by focusing on non-uniformity of the soil.

In accordance with PN-EN 1997-2:2009 and PN-EN ISO 14688-2:2006, blend 1 was recognized as gravel (Gr) and blend 2 was recognized as sandy gravel (saGr).

Blends were compacted and later dried. Dried RCA, whose dry weight was around 400 g, was utilised to determine grain size distribution by performing sieve analysis. Before advancing with the compaction process, dried RCA sample was again soaked in water to restore previous conditions and was reconstituted to initial grain size distribution by applying weight. Also eventual loss of mass during sieve analysis was taken in to account. Compaction was repeated six times. Sieve analysis was performed with respect to PKN-CEN ISO/TS 17892-4:2009.

View of initial soil gradation curve is presented in Figure 3 for blend 1 and in Figure 7 for blend 2.

RESULTS

Results of the Proctor tests for blend 1 are presented in Figure 3. After 6 repetitions, material yielded clearly to crushing phenomenon. During the test, amount of fines constantly increased and during the 6th repetition of the compaction process, maximal diameter of grains decreased from 10mm to 6.3 mm. This means that all of the larger grains became crushed and nevertheless the course of this phenomenon was changed slightly for the rest of fraction compositions. This was caused by the steady process of 10 mm diameter fraction decrement. Crushed grains constitute 20% of growth fines fraction smaller than 2 mm. Soil gradation curves present a picture of evolution from one-faction material to more uniformly graded mix. Coefficient of uniformity C_U for sixth curve is equal 3.84 and coefficient of curvature C_C is equal 1.76. Lack of fines in this blend caused a characteristic inflection point of the curve on 2mm grain size diameter. If soil-crushing process creates fractals, for such mix this would mean that initial curve became better graded, by aiming share of greater than smallest initial grain diameter and creates fines – smaller than the initial grain diameter. This process could be completed after mixing fines and grains with uniformly graded material, which can be seen on plot of grain size distribution in the form of straight line or a slight inflection around point of smallest grain diameter in initial material mix.

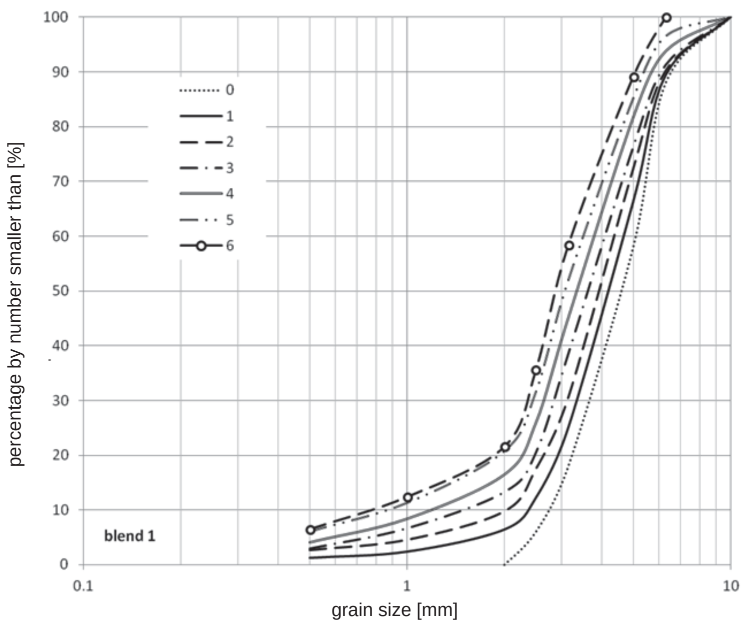

Fig. 3. Soil gradation curve for blend 1 after 6 repetitions of the Proctor test

Figure 4 presents results of the soil gradation curve parameters calculation. Slope estimation lead to establishing the *D* parameter, which describes fractal distribution and which could be used in equations (1), (2) and (3).

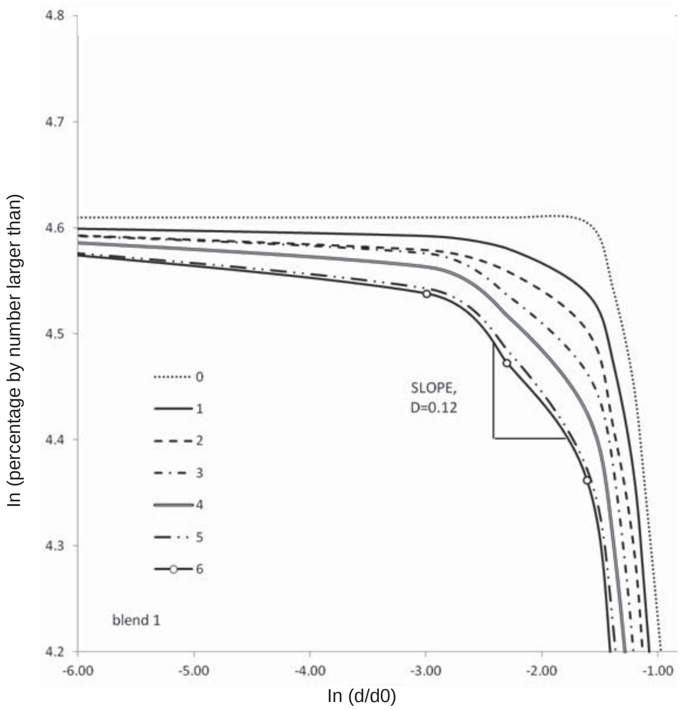

Fig. 4. Estimation of fractal gradation slope of RCA for blend 1

Figure 5 presents a cumulative mass fraction curve. Here we can also see the exponential movement of the of curve, which represents fractal distribution.

Figure 6 presents the result of calculation with equation (1) for fractal distribution for slope of curve obtained during the tests. Calculations were performed for $D = 0.12$ and $A = 13$. It can be recognised that for fractal distribution the curves have a bigger number of fines and the slope of bigger grains is greater.

It can be expected that further evolution will impact grains around inflection – this conclusion was drawn on the basis of the increase in a number of fines and decrease in a number of biggest grains in this comparison.

Figures 7, 8, 9 and 10 present relationships mentioned before for blend 2. In this case, material was well graded and fines as well as grains were also present in the mix. After the sixth process of compaction, the soil gradation curve seems to not differ much from initial one. But if coefficients $C_U = 23.07$ and $C_C = 0.92$ are be taken to consideration, properties of this mix would change, as soil mix turn from well graded to poorly graded material. Curvature of this soil degenerates and becomes straighter, While its uniformity decreases which lead to conclusion that grains become more uniform. This phenomenon could lead to the conclusion about compaction: it seems that RCA with well graded composition turns loses its properties during compaction. Figure 8, slope of fractal gradation for this mix was recognised and Figure 9 presents fractal distribution for all seven gradation curves. It can be observed that curves evolve into straight lines, analysis of fractal distribution which is presented on Figure 10, which also presents the comparison of test results and calculations, could provide explanation to this occurrence. It seems that this soil blend has to many particles in the middle of its gradation – between 1 and 10 mm. Loss of fines in this test was low in comparison to blend 1.

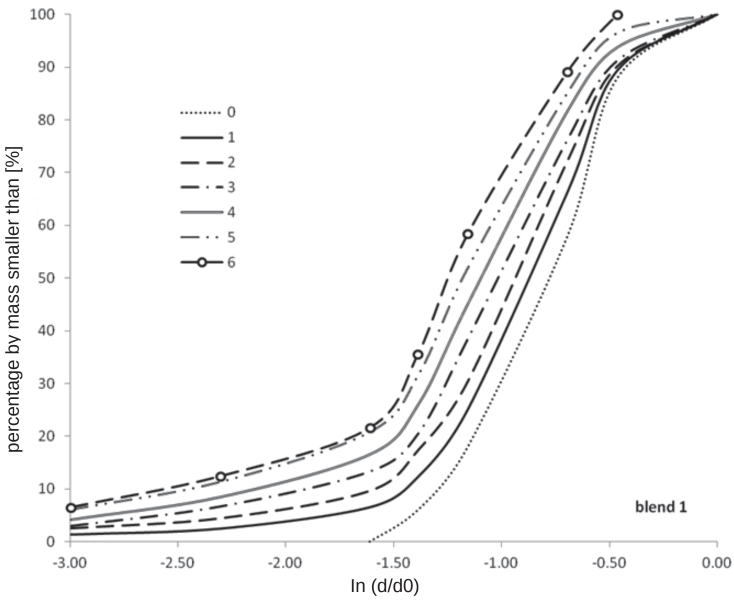

Fig. 5. Estimation of fractal distribution for RCA blend 1

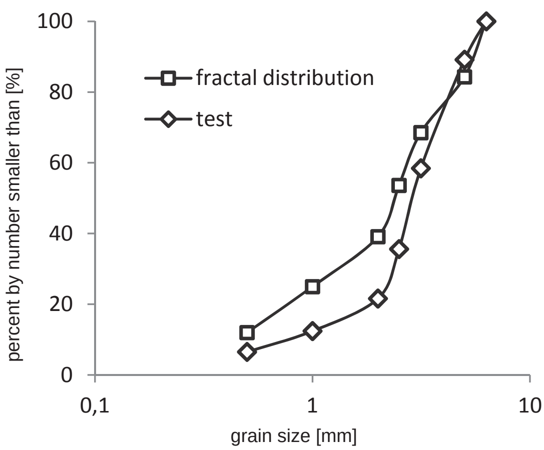

Fig. 6. Comparison of fractal distribution for RCA blend 1

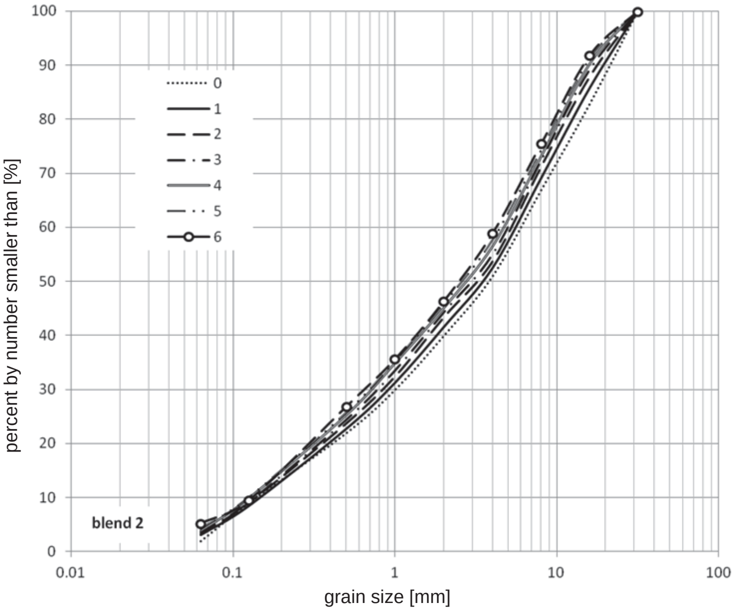

Fig. 7. Soil gradation curve for blend 2 after 6 repetitions of the Proctor test

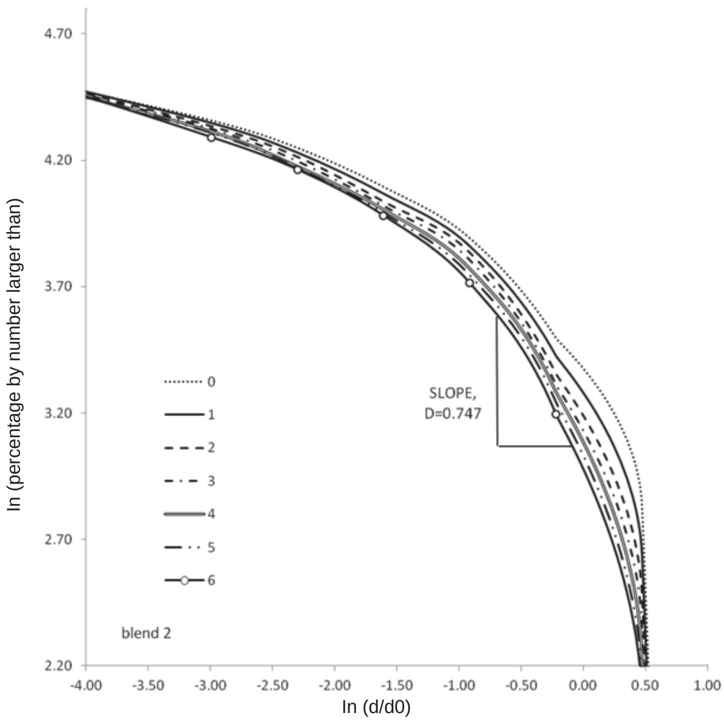

Fig. 8. Estimation of fractal gradation slope of RCA for blend 2

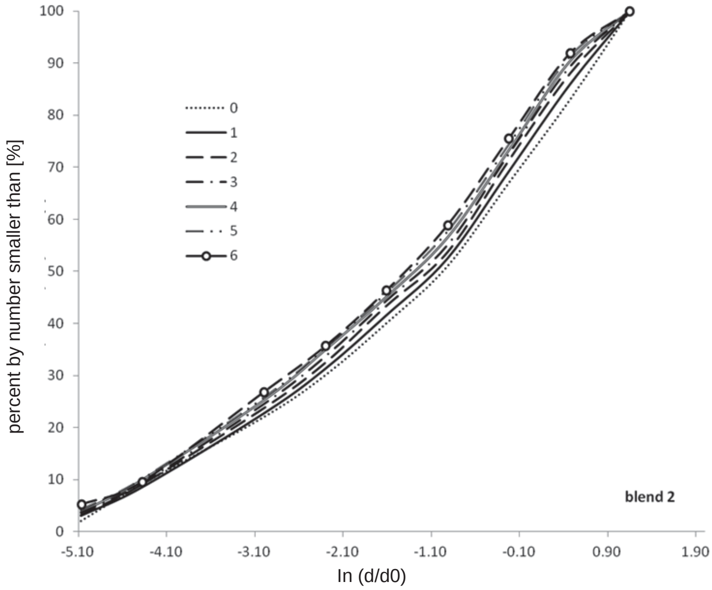

Fig. 9. Estimation of fractal distribution of RCA for blend 2

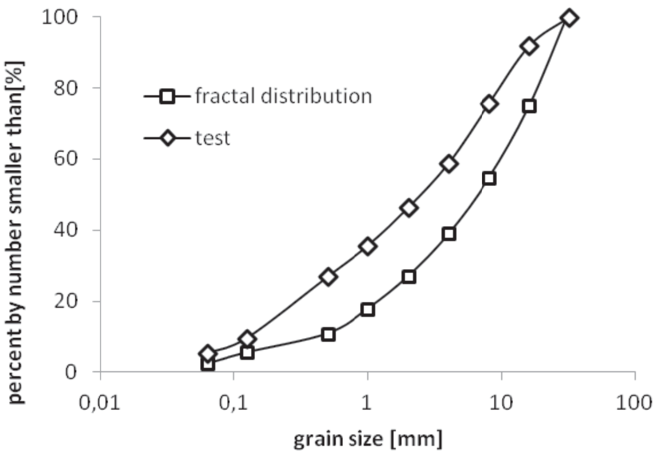

Fig. 10. Estimation of fractal distribution of RCA for blend 2

This could mean that crushing occurs mostly with respect to larger grains, which is correct, grains bigger than 10mm in initial conditions lose 10% of share after sixth compaction. This process can last until biggest fraction reduction will occur and curve will become distributed more fractal.

CONCLUSION

In this study, results of experimental test on Recycled Concrete Aggregate was presented. Crushing phenomenon was studied, by performing numerous repetitions of the Proctor test. Presented results and analysis of gathered data lead to the following conclusions:

1. RCA as light-weight material is exposed to excessive crushing process under excitations from compaction.
2. For RCA, fractal distribution of soil gradation curves was recognised and the development of crushing was studied.
3. Two blends were tested in this study. The first one was poorly graded and second one was well graded. For blend 1, evolution of gradation curve to fractal distribution which was followed by improvement of coefficient of uniformity and curvature was observed.
4. For poorly graded soil, characteristic inflection point was recognised. This point indicates the threshold for the increase in the number of fines and decrease in the number of grains. This phenomenon is seems to be connected with the occurrence of fractal distribution and should be studied further.
5. Well graded soil in this study, denoted as blend 2, exhibits different response to compaction. Gradation curve properties, such as C_U and C_C, decrease during tests and soil mix tends to evolve into fractal distribution in another manner.
6. Excessive amount of grains with diameter in middle of soil distribution, tend to increase the number of greater grains undergoing crushing and decrease the accumulation of fines.
7. This study, as other pilot studies on the phenomenon of RCA particle crushing, cannot give a proper and clear resolution this problem. Nevertheless, findings pointed out in this study are promising and could lead to finding a practical application for the fractal distribution phenomenon. Further repetitions of compaction process and tests on soils with different gradation curves need to be performed to reach more detailed conclusions.

REFERENCES

Aurstad, J., Berntsen, G., Petkovic, G. (2006). Evaluation of unbound crushed concrete as road building material – Mechanical properties vs. field performance. 26th International Baltic Road Conference, Kuressaare.

Dańko, R. (2007). Development of energetic model for dry mechanical reclamation process of used foundry sands. International Journal of Cast Metals Research, 20(4), 228–232.

Guimaraes, M.S., Valdes, J.R., Palomino, A.M., Santamarina, J.C. (2007). Aggregate production: Fines during rock crushing. International Journal of Mineral Processing, 81(4), 237–247.

Leleu, S.L., Valdes, J.R. (2007). Experimental study of the influence of mineral composition on grain crushing. Geotechnique, 57(3), 313–317.

Lobo-Guerrero, S., Vallejo, L.E. (2005). Discrete element method evaluation of granular crushing under direct shear test conditions. Journal of Geotechnical and Geoenvironmental Engineering, 131(10), 1295–1300.

Macko, M. (2011). Badania i analiza sił i odkształceń w rozdrabnianiu jednokrotnym. Inżynieria i Aparatura Chemiczna, 50(3), 47–48.

McDowel, G.R. (1999). Macromechanics of classic soil. Proceedings of the International Workshop on Soil Crushability. Ube, Yamaguchi, Japan, 138–157.

McDowell, G.R., Bolton, M.D. (1998). On the mechanics of crushable aggregates. Geotechnique, 48(5), 667–679.
McDowell, G.R., Bolton, M.D., Robertson, D. (1996). The fractal crushing of granular materials. International Journal of Mechanics and Physics of Solids, 44(12), 2079–2102.
PKN-CEN ISO/TS 17892-4:2009 Badania geotechniczne. Badania laboratoryjne gruntów – Część 4: Oznaczanie składu granulometrycznego
PN-88/B-04481 Grunty budowlane. Badania próbek gruntu.
PN-EN 1997-2:2009 Eurokod 7. Projektowanie geotechniczne – Część 2: Rozpoznawanie i badanie podłoża gruntowego.
PN-EN ISO 14688:2006 Projektowanie geotechniczne – Część 1: Rozpoznawanie i badanie podłoża gruntowego.
Sas, W., Głuchowski, A., Szymański, A. (2014). Cyclic Behavior of Recycled Concrete Aggregate Improved with Lime and Gypsum Addition. Fourth International Conference on Geotechnique, Construction Materials and Environment, 1. Brisbane, Australia, 196–201.
Sas, W., Miszkowska, A., Głuchowski, A. (2015). Wpływ podatności destruktu betonowego na kruszenia oraz zmiany jego właściwości fizycznych i mechanicznych. Przegląd Naukowy Inżynieria i Kształtowanie Środowiska, 67, 40–53.
Shull, M., Allen, D.L., Fleckenstein, L.J., Graves, C. (1998). Performance evaluation of recycled PCC pavement used as a crushed stone base and dense grade aggregate. Research report KTC 97-3.
Skrzyński, M., Dańko, R. (2014). Assessment of the destruction degree of the quartz matrix in the REGMAS reclaimer. Archives of Foundry Engineering, 14(4/1), 17–22.
Turcotte, D.L. (1986). Fractals and Fragmentation. Journal of Geophysical Research, 91, 1921–1926.
Weibull, W. (1951). A statistical distribution function of wide applicability. Journal of Applied Mechanics 18, 293–297.
Wesołowski, L., Bochat, A. (2010). Próba modelowania bijakowego rozdrabniania materiałów ziarnistych. Inżynieria i Aparatura Chemiczna, 49(5), 127–129.
Yamamuro, J.A., Lade, P.V. (1996). Drained sand behaviour in axisymertic tests at high pressures. Journal of Geotechnical and Geoenvironmental Engineering, 122(2), 109–119.
Zawada, J. (1998). Wstęp do mechaniki procesów kruszenia. Wydawnictwo Technologii Eksploatacji, Radom.
Zawada, J., Chochoł, K. (2009). Doświadczalne badania energii kruszenia na przykładzie modelowej kruszarki dźwigniowej Blake'a. Górnictwo i Geoinżynieria, 33(4), 317–326.

EKSPERYMENTALNE BADANIA ZJAWISKA KRUSZENIA SIĘ DESTRUKTU BETONOWEGO

Streszczenie. W artykule zaprezentowano wyniki zjawiska kruszenia się destruktu betonowego (RCA) podczas badania wilgotności optymalnej metodą Proctora. Wzrost zapotrzebowania na materiały budowlane tworzy potrzebę zastosowania nowych, dotychczas niewykorzystywanych materiałów, które mogą zastąpić kruszywo naturalne (NA). Należy zaznaczyć, że NA jest źródłem nieodnawialnym w przeciwieństwie do RCA, który poprzez wbudowanie w konstrukcję jest recyklingiem. W przypadku materiałów antropogenicznych istnieje wiele niewyjaśnionych właściwości, jednym z nich jest zjawisko kruszenia się. W tym artykule przedstawiono opis tego zjawiska. Wyznaczone rodzaje gruntu różnią się pod względem właściwości uziarnienia. Badania wykonano za pomocą aparatu Proctora w różnych warunkach zagęszczania. Artykuł kończy się wnioskami dotyczącymi zjawiska kruszenia wraz z praktycznymi wskazówkami.

Słowa kluczowe: podbudowa, destrukt betonowy, badanie Proctora, kruszenie się, fraktal

Accepted for print: 28.04.2015

For citation: Sas, W., Głuchowski, A., Soból, E., Kulkowska, M. (2015). Experimental studies on crushing of recycled concrete aggregates. Acta Sci. Pol., Architectura, 14 (1), 29–41.