Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 108 (2015) 63 – 71

Procedia Engineering

www.elsevier.com/locate/procedia

7th Scientific-Technical Conference Material Problems in Civil Engineering (MATBUD'2015)

Water demand of concrete recycled aggregates

Jacek Kubissa[a], Marcin Koper[a], Włodzimierz Koper[a], Wojciech Kubissa[a], Artur Koper[a]*

[a]*Warsaw Uniwersity of Technology, Faculty of Civil Engineering, Mechanics and Petrochemistry (Płock), Łukasiewicza 17, 09-400 Płock, Poland*

Abstract

The procedure of designing the composition of concrete with the method of three equations demands to accept the assumptions regarding the consistence of concrete mixture. For the assumed consistency the water demand of aggregates and water demand of concrete is specified. In case of natural aggregates (NCA) the formulas, among others, of Sterne's of Bolomey's are used conditioning the water demand of aggregates from its granulation, kind and consistence of concrete mixture. There is lack of such dependencies in case of water demand of recycled aggregates (RCA). In such case there remains the empirical determination of the water demand, which in practice disqualifies the usefulness of the method of three equations to specify the concrete composition of on RCA aggregates. A way to solve this problem is looking for the relations between RCA water demand and its other qualities which are easy to specify in laboratory conditions in short time. The quality which gives such a chance to achieve this relation is the aggregates resistance to crushing whose measure is crushing indicator. This paper has made an attempt at specifying the manner of empirical definition of RCA water demand.

Peer-review under responsibility of organizing committee of the 7th Scientific-Technical Conference Material Problems in Civil Engineering

Keywords: Concrete; recycled aggregates (RCA); water demand of aggregates; aggregates resistance to crushing

1. Introduction

The most beneficial, but at the same one of the most difficult method of utilising construction waste materials is the use of the construction debris as the aggregates to produce the concrete. It requires, however, a careful selection of the waste and its crushing. The problem of crushing with the immediate use of concrete debris was

* Corresponding author.
E-mail address: artkop1@wp.pl

Peer-review under responsibility of organizing committee of the 7th Scientific-Technical Conference Material Problems in Civil Engineering
doi:10.1016/j.proeng.2015.06.120

solved through the introduction of professional, mobile combined crushers. Fractioning can be performed already at the site of demolition works. Usually it is done a division of granules into fractions 0/4, 4/8, 8/32 mm.

Proper segregation allows for the selection of adequately dispersed waste which can be used directly as aggregates to new concrete or as recycled aggregates used for various bedding. The recycled aggregates of the higher class concrete and including significantly large amount of concrete can benefit to achieve fully valuable constructive concrete [1, 2, 3, 4, 5]. The concrete mixture can be made using completely the aggregates form recycling or combining it with natural aggregates in particular fractions.

European Community aspires to standardise the directives related to the qualities and method of research of recycled aggregates. The issue of the adaptation of concrete debris was in the 1970s of the interest of Technical Committee “International Union of Testing and Research Laboratories for Materials and Structures” (RILEM). In 1994 the Committee RILEM TC-121-DRG issued “Specification for concrete with recycled aggregate” [6]. PN-EN 933-11:2009 defined the method of researching the thick aggregates of recycling in order to identify and value the various kinds of contamination. The present directives of RILEM to use the recycled aggregates are regulated by the specification of 2003 [7]. Thick aggregates (of diameter above 4mm) coming from the concrete recycling was there separated as the aggregates RCA II. For the recycled aggregates the requirements were contained also in PN-EN 206:2014. For the aggregates RCA II the requirements, characteristics and the condition of use for the concrete were defined (table 1).

Table 1. Characteristics of recycled aggregates of type RCA II according to RILEM [7].

Aggregates/Concrete quality	RCA II	
Dry density in kg/m^3	min	2000
Absorbency in %	max	10
Material content of SSD*<2200 in kg/m^3	max	10
Material content of SSD<1800 in kg/m^3	max	1
Material content of SSD<1000 in kg/m^3	max	0.5
Material contamination in %	max	1
Metal content in %	max	1
Organic material content in %	max	0.5
Dust content < 0.063 mm in %	max	2
Sand content < 4 mm in %	max	5
Dissolved sulphates content in %	max	1
Destination		C50/60
Endurance to extension rate indicator f_{ctm}		1
Resilience module rate indicator E_{cm}		0.8
Concrete creeping rate indicator		1
Concrete shrinkage rate indicator		1.5

*SSD – water saturated surface dry conditions

Nationwide and international experiences [1, 8, 9, 10, 11] related to concrete of recycled aggregates confirm that this type of aggregates can be a fully valuable substitute to natural aggregates. The research indicate that it is possible to achieve concrete of the bigger endurance than analogically concrete of natural aggregates. Comparing concretes of recycled aggregates to natural aggregates, what can be noted is generally lower endurance to pressing (10-30%), fairly lower endurance to extending (10%), lower modules of resilience (10-40%), greater creeping (50-100%) and absorbency (25-50%) [4]. The research indicate a great increase in absorbency and decrease of frost resistance of concrete. It is due to the influence of 3,5-4 times bigger absorbency of recycled aggregates and almost 3 times bigger loss of the mass in the frost resistance researching. There are also some technical problems (shorter time of concrete setting, faster loss of workability). The data achieved through the research are often inconsistent, which, according to the authors, results from the freedom of assumed research conditions.

2. The aim and the range of this paper

The results of research on the physical and mechanical qualities of concrete made of the aggregates owing to the crushing of concrete debris available in the following literature [9, 5, 12, 13, 14] as well as the results of the research allow to formulate a thesis that in some defined conditions of availability of aggregates coming from crushing the demolition constructive concrete, it is possible to influence intentionally the physical and mechanical qualities of concrete made of it and to achieve the assumed qualities of such concrete, especially the qualities deciding on the possibilities of their defined usage, also substituting the use of constructive concrete on natural aggregates [16].

In many research works there are claims that designing of the composition of concrete mixture on recycled aggregates is similar to designing concrete on natural aggregates, there is however a necessity of experimental correction of batched water amount [1, 4]. Presently, there is no a verified method allowing for designing the composition of concrete mixture on recycled aggregates considering RCA bigger water demand as well as their worse endurance parameters.

Performed research confirmed a bigger water demand of concrete mixtures including RCA. Assuming that compared mixtures only differed with the aggregates types (NCA or RCA), the increase in water demand of concrete mixture must have been caused by bigger water demand of RCA. There is no enough knowledge on the course of water demand change, depending on quality, origin, kind and other characteristics of recycled aggregates. The ability to define the water demand of recycled aggregates depending on their qualities would simplify the process of designing concrete mixtures, including the prediction of the optimal water content in the mixture above all. This paper has made an attempt to define the method allowing for determining RCA water demand depending on the aggregates resistance to crushing indicator. Defining such relation may ease the process of designing concrete mixtures on recycled aggregates.

3. Recycled aggregates research

3.1. Aggregates preparation

In the first phase there were prepared recycled aggregates coming from 11 concretes of various characteristics. The weakest of the aggregates (RCA11) came from the laboratory concretes of pressing endurance within the range 10-15 MPa, the aggregates of the best quality (RCA1) was performed through crushing of concretes of pressing endurance at least 50 MPa. Analogically, there performed a series of aggregates (from RCA2 to RCA10) of concretes of endurance from 15 to 50 MPa. All the concretes designed to crushing were performed on the basis of iron-ore cement CEM I 32.5R, in accordance with PN-EN 206. Samples were crushed and stored in airy-dry conditions. Due to the fact that the aggregates came from crushing the pure laboratory concrete, there were no contamination nor materials of different characteristics. To achieve proper granulation, concrete samples underwent the double process of crushing. It allowed for reception of fraction 0-16 mm with a little amount of over-granulation (<5%) out of which the fraction 4-16 mm was separated. Participation of tiny fraction in recycled aggregates was 30%. To simulate the natural conditions, possible during industrial crushing of concrete, between crushing and creating concrete there was introduced about 2-month technological break. Apart from recycled aggregates, for the comparative purpose the research also included natural aggregates and the sand from the Vistula river.

3.2. Researching the physical properties of aggregates

For the comparative purposes RCA was tested and used to create comparative concrete NCA. There was performed research of aggregates compliance with the standards in the area of: absorbency in accordance with PN-EN 1097-6, frost resistance in accordance to PN-EN 1367, apparent density in accordance with PN-76/B-06714, dust content in accordance with PN-78/B-06714/13 as well as alkaline reactivity in accordance with PN-92/B-06714. The results of the physical conditions of aggregates is presented in table 2.

Table 2. Results of researching the physical conditions of aggregates.

	Absorbency [%]	Frost resistance Mass lose [%]	Apparent density [kg/dm^3]	Dust content [%]	Alkaline reactivity
Natural aggregate					
Fraction 0-4 mm	2.15	0.95	2.61	-	not reactive
Fraction 4-16 mm	2.06	0.73	2.67	0.21	not reactive
Recycled aggregate (fraction 4-16 mm)					
Aggregate RK1	5.59	2.86	2.62	0.30	not reactive
Aggregate RK2	6.13	2.77	2.60	0.41	not reactive
Aggregate RK3	6.43	2.88	2.57	0.39	not reactive
Aggregate RK4	6.18	2.73	2.58	0.44	not reactive
Aggregate RK5	7.02	2.84	2.55	0.49	not reactive
Aggregate RK6	8.60	2.89	2.53	0.69	not reactive
Aggregate RK7	7.95	2.94	2.55	0.97	not reactive
Aggregate RK8	7.78	3.16	2.52	1.13	not reactive
Aggregate RK9	8.98	3.07	2.51	1.34	not reactive
Aggregate RK10	9.65	3.37	2.48	1.67	not reactive
Aggregate RK11	9.52	3.45	2.50	1.89	not reactive

3.3. Researching the mechanical properties of aggregates

According to the authors, the most important RCA sampling allowing to define its mechanical properties but also the usefulness of application in concrete is the testing its resistance to crushing, measured with crushing indicator w_r in accordance with PN-78/B-06714/40. The results of the research can be used to RCA qualification. As indicated further, it also allows for empirical defining of water demand of RCA.

The method of testing aggregates resistance to crushing is to define the percentage loss of aggregates granulates due to crushing with the force 200 kN of a sample placed in a inflexible cylindrical container (figure 1). Out of the sample prepared for testing through sieving there are fractions separated 4-8, 8-16 and 16-32 mm.

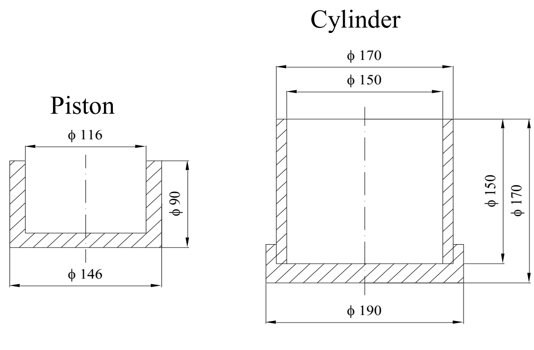

Fig. 1. Appliance to research the resistance to crushing.

Crushing indicator w_{ri}, as measure of resistance to crushing of a single aggregates fraction is calculated in percentage according to the following formula:

$$w_{ri} = \frac{m - m_1}{m} \cdot 100\% \tag{1}$$

where:
m and m_1 – masses of samples respectively before and after testing [g].

Crushing indicator of multi-fraction aggregates w_{rm} is calculated as weighted mean of crushing indicators of individual fractions undergoing the testing (w_{ri}), in accordance with the formula:

$$w_{rm} = \frac{w_{r1} \cdot f_1 + ... + w_{ri} \cdot f_i + ... + w_{rn} \cdot f_n}{f_1 + ... + f_i + ... + f_n} \tag{2}$$

where:
$w_{r1...n}$ – crushing indicators of individual aggregates fractions %,
$f_{1...n}$ – percentage of sampled fraction in sample mass.

The results of testing RCA crushing indicators are presented in table 3.

Table 3. Results of researching RCA crushing indicators.

Aggregates type	Granulation [mm]	Crushing indicator of aggregates fraction w_{ri} [%]	Mean indicator of aggregates mixture crushing w_{rm} [%]
NCA	0-4/4-16	6.60/8.90	7.90
RCA1	4-8/8-16	17.02/16.12	16.46
RCA2	4-8/8-16	18.15/17.19	17.55
RCA3	4-8/8-16	19.49/18.46	18.85
RCA4	4-8/8-16	19.96/18.90	19.30
RCA5	4-8/8-16	20.35/19.65	19.92
RCA6	4-8/8-16	21.40/20.27	20.70
RCA7	4-8/8-16	22.32/21.55	21.85
RCA8	4-8/8-16	22.99/21.77	22.23
RCA9	4-8/8-16	24.40/23.11	23.60
RCA10	4-8/8-16	25.75/24.39	24.90
RCA11	4-8/8-16	26.17/24.57	25.10

3.4. Researching aggregates water demand

Water demand of recycled aggregates w_{RCA} was determined with the use of calculation method basing on quantity compositions of individual sampling concrete mixtures presented in table 4. For this purpose there was also used the following equation of water demand:

$$w_{RCA} = \frac{W - C \cdot w_c - P \cdot w_p}{K_{RCA}} \tag{3}$$

where:
C, W, P – cement, water and sand content in 1 m^3 of concrete mixture [kg],
K_{RCA} – RCA content in 1 m^3 of concrete mixture [kg],
w_c, w_P – water demand indicators of cement and sand in accordance with Bolomey's [15] [dm^3/kg].

The range of research included performing 41 series of concrete mixtures including one comparative series on natural aggregates and 40 experimental series on recycled aggregates. Due to big differences of RCA absorbency, it was impossible to ensure a stable rate *W/C* to all performed concretes. Moreover, there assumed a stable consistency of concrete mixtures (F2 in accordance with PN-EN 206, without plasticising addictions) and cement

CEM I 32.5R in accordance with PN-EN 206. Concrete mixtures on recycled aggregates were performed with the use of the sour-dough method with the constant sand point at the level 0.3-0.35 and assumed rate *W/C*. In the experimental manner there was determined the amount of cement sour-dough necessary to achieve the assumed consistence.

Table 4. Compositions of experimental concrete mixtures.

No.	Concrete marking	Aggregates crushing indicator w_{rm} [%]	*W/C*	Cement [kg/m^3]	Water [kg/m^3]	Natural sand [kg/m^3]	Aggregates 4-16 mm [kg/m^3]
1	NCAC-1	7.90	0.40	473	190	582	1163
2	RCAC1-1	16.46	0.41	440	181	537	1253
3	RCAC1-2		0.59	252	149	611	1427
4	RCAC1-3		0.70	202	141	632	1474
5	RCAC2-1	17.55	0.40	540	216	564	1048
6	RCAC2-2		0.50	382	191	635	1178
7	RCAC2-3		0.60	296	177	673	1249
8	RCAC2-4		0.75	221	166	706	1311
9	RCAC3-1	18.85	0.52	381	197	655	1143
10	RCAC3-2		0.60	311	186	679	1207
11	RCAC3-3		0.70	254	178	705	1252
12	RCAC4-1	19.30	0.47	458	214	563	1127
13	RCAC4-2		0.55	364	200	596	1209
14	RCAC4-3		0.60	323	194	612	1243
15	RCAC4-4		0.70	266	185	636	1291
16	RCAC5-1	19.92	0.42	522	218	481	1142
17	RCAC5-2		0.50	409	204	527	1230
18	RCAC5-3		0.60	317	190	562	1312
19	RCAC5-4		0.70	260	182	583	1361
20	RCAC6-1	20.70	0.49	453	223	557	1115
21	RCAC6-2		0.55	389	214	576	1170
22	RCAC6-3		0.60	347	209	594	1205
23	RCAC6-4		0.65	313	203	607	1233
24	RCAC6-5		0.70	285	199	619	1256
25	RCAC7-1	21.85	0.42	595	248	444	1036
26	RCAC7-2		0.60	365	219	526	1229
27	RCAC7-3		0.70	301	210	550	1284
28	RCAC7-4		0.92	214	198	582	1358
29	RCAC8-1	22.23	0.58	419	242	616	1031
30	RCAC8-2		0.61	376	229	639	1079
31	RCAC8-3		0.65	344	222	713	1045
32	RCAC9-1	23.60	0.50	492	246	551	1024
33	RCAC9-2		0.60	387	232	595	1105
34	RCAC9-3		0.75	294	220	634	1177
35	RCAC9-4		0.90	236	213	658	1222
36	RCAC10-1	24.90	0.50	510	256	536	996
37	RCAC10-2		0.60	404	242	580	1078
38	RCAC10-3		0.75	307	230	621	1153
39	RCAC11-1	25.10	0.50	518	259	531	987
40	RCAC11-2		0.60	411	247	574	1067
41	RCAC11-3		0.75	312	234	616	1144

During the production of concrete mixtures there was accepted the rule of limiting the maximal content of cement in 1 m^3 of mixture to the level of 550 kg. This limitation eliminated the possibility of producing concrete mixtures on "poor" recycled aggregates (high crushing indicator w_{rm}) and low rate of *W/C*. The calculated content of cement necessary to get concrete mixtures of $W/C < 0.4$ and recycled aggregates of $w_{rm} > 22$ would be in the extreme cases even 900 kg/m^3, which due to technological and economical issues is not to be accepted. The experimentally established water demand indicators of particular RCA mixtures [16], counted as means out of the determined ones for particular concrete mixtures from table 4, are presented in table 5.

Table 5. Results of water demand researching.

Aggregates type	Granulation [mm]	Aggregates mixture water demand w_{NCA} i w_{RCA} [dm^3/kg]
NCA	0-4/4-16	0.068/0.024
RCA1	4-16	0.041
RCA2	4-16	0.051
RCA3	4-16	0.057
RCA4	4-16	0.063
RCA5	4-16	0.067
RCA6	4-16	0.073
RCA7	4-16	0.087
RCA8	4-16	0.092
RCA9	4-16	0.093
RCA10	4-16	0.101
RCA11	4-16	0.106

RCA mixtures were composed out of fraction 4-8 mm and 8-16 mm in the ratio ensuring the receive the grading curves of aggregates mixture placing within the bordering standard curves for aggregates of fraction 4-16 mm with over-granulation. The achieved results indicate that the RCA water demand indicator is diversified and it expands along with the loss of quality of recycled concrete aggregates. Water demand of recycled concrete aggregates of highest quality (RCA1 – lowest crushing indicator) is almost three times smaller than the water demand of the weakest aggregates (RCA11). Figure 2 presents the comparison of NCA and RCA water demand indicators with their identical granulation.

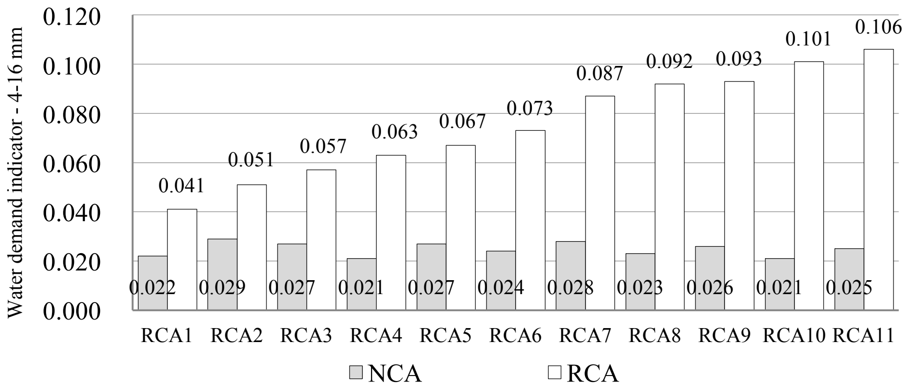

Fig. 2. Comparing the water demand indicators of natural and recycled aggregates of identical fraction granulation.

Basing on the research results presented in tables 3 and 5, the relation between recycled aggregates water demand and its crushing indicator was analysed.

4. Appointing aggregates water demand indicators

In the phase of designing composition of mixtures on recycled aggregates there arises a problem related to accepting proper values of water demand indicators of individual RCA fractions. To determine them, a designer must define them beforehand empirically, after performing the trial batch of concrete mixture of assumed rate *W/C* and assumed consistence. A way to solve the problem would be to re-fill the formulas and tables created by Sterne or Bolomey [15] for natural aggregates with RCA water demand indicators, which simply and effectively would let them be defined.

An obstacle to define the theoretical water demand indicators of RCA is a big variety of their characteristics. Recycled aggregates are very non-uniform and their characteristics depend on the material used to produce them [1,16]. Thus, it is not possible only to define RCA water demand basing on the aggregates fraction and concrete mixtures consistence, as it is in case of NCA. Such a proceeding would omit the impact of RCA quality.

The authors made an attempt at defining the manner of theoretical determination of RCA water demand indicators on the basis of aggregates other properties. A relation was searched between RCA water demand and the property whose determination would be simple and allow for attributing to the whole party of aggregates. Such a property fulfilling the condition is crushing indicator as the measure of aggregates resistance to crushing. What was analysed was the dependency of RCA water demand indicator on crushing indicator to the aggregate made from crushing of concrete of pressing resistance 10 - 50 MPa. There was grading of fraction RCA 4-16 mm and concrete mixtures consistence F2 in accordance with PN-EN-206.

As a result of performed statistical analysis of results, a linear dependency between RCA water demand indicator and crushing aggregates indicator was achieved for consistence F2 of concrete mixtures, as follows:

$$w_{RCA} = 0.0074 \cdot w_{rm} - 0.0804 \tag{4}$$

Cohesion of the relation of both variables and good match between model and empirical data (the regression lines) can be seen in high: linear correlation indicator (0.989) and determination indicator (0.978). The dependency was presented in draft 3.

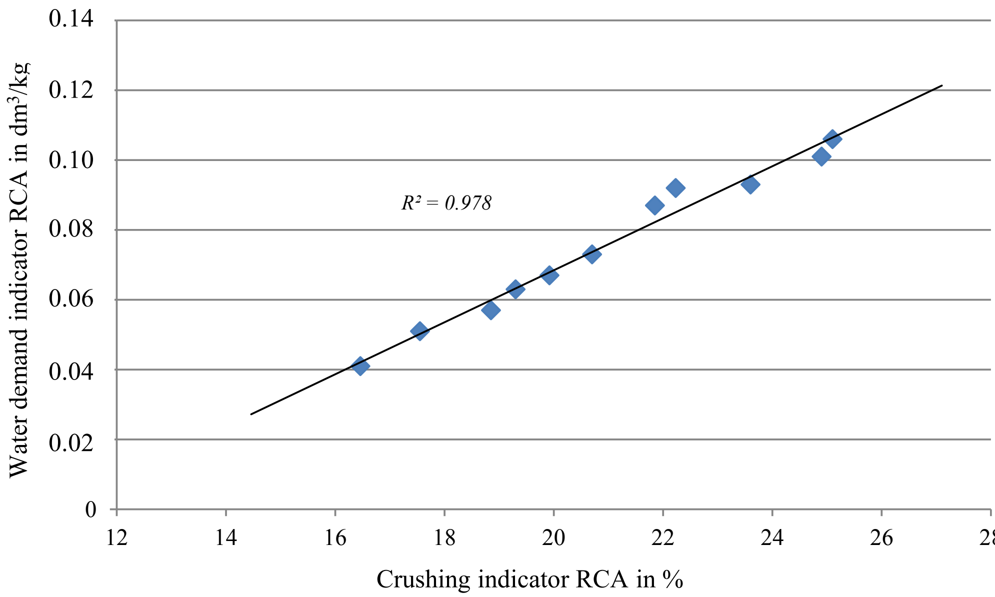

Fig. 3. The graph of dependencies of water demand indicator on recycled aggregates crushing indicator.

Comparing the achieved results with the analogical values determined for natural aggregates we can notice that the water demand indicator w_{NCA} of natural aggregate of fraction 4-16 mm, for consistence of concrete mixture F2, achieves values from 0.021 to 0.029 depending on aggregate composition and is fairly smaller than the water demand indicators w_{RCA} of recycled aggregate. Water demand of RCA of average quality (crushing indicator about 20%) is comparable to water demand of tiny natural aggregate of fraction 0 - 4 mm and equals about 0.07.

5. Summary

Recycle aggregates properties vastly depend on the quality of the material of which they were produced. Accepting simplicity – comparing recycled aggregates to natural aggregates, but only with the attention regarding bigger absorbency, would mean attributing recycled aggregates with the properties of natural aggregates, which, omitting easily spotted differences like density or absorbency, would not consider their quality variety. Thus, it is necessary at the phase of concrete mixture designing to condition the aggregate quality, which means that the designing methods of concrete mixtures on natural aggregates cannot be used without the implementation of proper modifications to designing the mixtures on recycled aggregates.

The authors claim that the most important property of RCA, defining its mechanical properties and deciding on the properties of concrete of which it was produced is the resistance to crushing measured with crushing indicator. This property was used at working with qualification of aggregates of recycling. It was defined the relation between recycled aggregates water demand and its resistance to crushing w_{RCA}. The analysis of achieved data indicates that the recycled aggregates water demand is diversified and it increases along with the loss of quality of these aggregates. Owing to this fact, conditioning water demand of recycled concrete aggregates with their quality is in case of designing concrete mixtures on RCA a must.

The defined dependency w_{REC} - w_{rm} can be used to define RCA water demand indicator and used in the process of designing the composition of concrete mixtures.

References

[1] Ajdukiewicz A, Kliszczewicz A. Influence of recycled aggregates on mechanical properties of HS/HPC, *Cement and Concrete Compsites*, Vol. 24, nr 2/2002.
[2] Barra M, Vazquez E. Properties of concretes with recycled aggregates: influence of properties of aggregates and their interpretation, UK Thomas Telford Publishing, 1999, 19–30.
[3] Kikuchi M. Application of recycled aggregate concrete for structural concrete, Part 1 – experimental study on the quality of recycled aggregate and recycled aggregate concrete, UK Thomas Telford Publishing, 1999, p. 55–68.
[4] Kliszczewicz A, High performance concrete with recycled aggregate (in Polish), Conference 'Dni Betonu – Tradycja i Nowoczesność', Polski Cement i Stowarzyszenie Producentów Cementu i Wapna, Szczyrk, 2002, Polski Cement, Cracow 2002.
[5] Pawluczuk E. Recycled aggregates influence on defined concrete properties (in Polish), Zeszyty naukowe Politechniki Białostockiej, Białystok 2009.
[6] RILEM, 121-DRG, Specification for concrete with recycled aggregates, Materials and Structures, Vol. 27, 1994.
[7] Recommendations for recycled aggregates, No 11/2003, Wydawnictwo BFT.
[8] ECCO: Recycling Concrete and Masonry. Environmental Council of Concrete Organizations, Skokie, Illinois 2002.
[9] Bretschneider A, Rühl M. The influence of recycled aggregate of the compressive strenght and the elastic moduluj of concrete. Aus dem Berichtsband zu Darmstadt Concrete, 1998.
[10] Zieliński K. Possibilities of using construction debris to produce cement concretes (in Polish), Politechnika Poznańska, Poznań 2005.
[11] Cichocka K, Małaszkiewicz D. Properties of concrete with recycled aggregate (in Polish), Zeszyty naukowe Politechniki Białostockiej, nr 25/2004.
[12] Padmini AK, Ramamurthy K, Mathews MS. Influence of parent concrete on the properties of recycled aggregate concrete, Construction and Building Materials 23, 2009, p. 829–836.
[13] Bołtryk M, Pawluczuk E. Modification of selected properties of cement concretes on recycled aggregates (in Polish), Inżynieria i Budownictwo, R.67, nr 6, 2011.
[14] Bołtryk M, Pawluczuk E. Method of determining effective water in concrete mixture on recycled aggregates (in Polish), 54 KN KILiW PAN „KRYNICA 2008", Krynica 2008.
[15] Jamroży Z. Concrete and its technologies (in Polish), PWN, Warszawa 2005.
[16] Koper M. Forming of properties of recycled aggregate concrete (in Polish), Warsaw University of Technology, Warsaw 2013.