MIDDLE POMERANIAN SCIENTIFIC SOCIETY OF THE ENVIRONMENT PROTECTION
ŚRODKOWO-POMORSKIE TOWARZYSTWO NAUKOWE OCHRONY ŚRODOWISKA

Annual Set The Environment Protection
Rocznik Ochrona Środowiska

Volume/Tom 16. Year/Rok 2014 ISSN 1506-218X 627–638

Effectiveness of the Use of Recycling Aggregate Concrete for Sustainable Building Structures

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1. Introduction

Rapid economic development processes began to bring attention to recycling of construction waste. After demolition of building structures the construction wastes can be recycled and can again "change" for a new type of energy-saving building materials. Recovery of construction waste after it is dismantled in the crushing process, will create special material production out of the building materials.

One of the possible use of recycling is to replace natural aggregate with the recycled aggregate in the concrete constructions. It is estimated, that the global world concrete construction industry needs a huge volume of natural aggregates (about 10 billion ton per year). It is very harmful to the environment unless some drastic action is taken to make widespread use of recycled aggregates. For several years construction debris has been put to use, usually as a road base or for levelling the ground. It seems that a better solution would be to use such an recycling aggregate to produce concrete structures [5, 8].

From an economic point of view, there is no better construction material like concrete. For example, the environmental impact of a reinforced concrete beam and a steel I-beam designed for the same engineering function was estimated using a computer program, see Rahal [10] or Struble and Godfrey [14]. Based on this estimation, production of the concrete beam required much less energy and had a lower net environmental impact than production of the steel beam.

Content of coarse aggregate in concrete mix is about 60-80% amount of all the aggregate. The best concept would be to replace the natural aggregate with recycled aggregate. The biggest problem is however the lack of guidelines concerning the use of secondary aggregates for construction and the lack of principles of segregation of materials already at the stage of demolition. Such debris, even after being processed into aggregates is most often contaminated with parts of bricks, wood and tar paper, which significantly hinders its reuse. In western countries, such as, the USA the segregation process is started in the place of building demolition. Construction industry waste in the form of demolition debris, because of its volume is a significant problem for environmental protection.

The problems arise mainly due to:

- Total or partial demolition of existing buildings,
- Construction of new buildings,
- Modernization and renovation of existing buildings.

It is estimated that European Union produced about 120 million tons of construction waste annually of which the largest share falls on Germany (60 million tons), Britain (30 million tons) and France (14 million tons). According to European statistics on an inhabitant of the EU has a ton of construction and demolition waste annually, which is becoming a serious concern. In among the construction waste constitutes the largest part of concrete – 40%, mortar 30%. Estimated percentage composition of construction waste in Europe is presented in Fig. 1.

It is expected that soon will overtake ceramic concrete in the amount of construction waste, because nowadays it will demolish more and more buildings [2, 4].

Building materials may retain a structural or aesthetic value beyond their lifespan in a given building. This value is captured through material reuse, a practice that can occur independently from or in conjunction with deconstruction and other lifecycle construction activities. The concept of "Reduce, Reuse, Recycle" identifies reuse as midway between initial reduction of resource use and resource recycling in a hierarchy of limiting environmental impact. Similar to deconstruction, the major benefit of material reuse is the resource and energy use that is avoided by reducing the production of new materials.

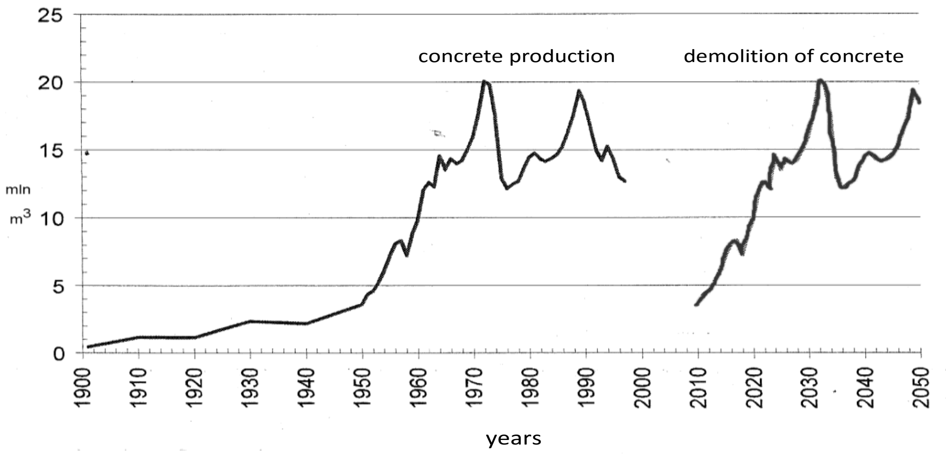

Fig. 1. Amount of produced concrete and the estimated amount of concrete subjected to demolition in million m^3 by Hoffmann [5]
Rys. 1. Ilość wyprodukowanego betonu oraz szacunkowa ilość elementów z betonu poddanych rozbiórce w mln m^3 wg Hoffmanna [5]

The research concerning concrete made with the use of secondary aggregates has been conducted for years in many countries. In 1977, Japan developed the first standard for concrete made of recycled aggregates. In 1985, the first international conference on problems with production of this concrete was organized in Rotterdam. The problems with the use of secondary aggregates for constructions were noticed in the available literature, see e.g. [10, 13, 15].

There are also several publications concerning the properties of concrete made of aggregates from recycling of concrete for production of structural elements, such as beams, walls or slabs, [10, 15]. Some of this research was conducted in Poland by Ajdukiewicz and Kliszczewicz [1] at the Silesian Technical University and by the research team from Bialystok University of Technology [6, 7, 9, 12]. The problem of application of coarse ceramic waste from construction industry for structural concrete members was analysed in the papers of Correira et al [2, 3] and recently in Poland by Domski and Katzer [4]. The authors of this paper dealt with the issue of evaluating the suitability of recycled aggregates for structural concrete. One of the ideas is to use concrete waste directly on site [8].

2. Investigation on deformability and carrying capacity of RC beams made of RAC

The research team of Building Structures Department of Bialystok University of Technology (Poland) conducted studies on the behavior of model RC beams made of recycling aggregate concrete (RAC). Some results of experimental studies conducted by authors on the model RC beams made of RAC under short time as well as long term load were presented previously in the papers [6, 7].

In this paper there are presented the results of experimental investigation on large-scale RC beams made of RAC under short time load compared to results of reference beams made of similar concrete class with natural coarse aggregate. More detailed data about this research the authors presented in [9].

Two Series of RC beams were prepared with the effective span of 2950 mm and the cross-section 120×200 mm. In each Series the following two types of large-scale beams were prepared:

- RC beams type R (made of coarse recycled aggregate concrete),
- RC control beams type N (made of natural aggregate concrete).

Table 1. Data of concrete compositions used in the tested large scale beams
Tabela 1. Skład mieszanki betonowej użytej w belkach w skali naturalnej

Concrete type	Ratio w/c	Cement [kg]	Water [*l*]	Sand [kg] (0–2 mm)	Coarse aggregate [kg]	
					2–4 mm	4–8 mm
RAC	0,70	270	189	575	481 recycl.	759 recycl.
Normal Concrete	0,70	270	190	575	480	760
Recycling aggregate concrete ($f_{cm,cube}$ = 32,5 MPa), Modulus of elasticity: $E_{cm,rec}$ = 27,2 GPa)						
Natural aggregate concrete ($f_{cm,cube}$ = 34,2 MPa), Modulus of elasticity ($E_{cm,n}$ = 30,8 GPa)						

The data of concrete compositions and properties of hardened concretes used in research are presented in the Table 1. The main assumption was to keep the same concrete compression strength for recycling aggregate concrete (RAC) and natural aggregate concrete.

Table 2. Characteristics of beams of Series 1 and 2
Tabela 2. Charakterystyka belek w seriach 1 i 2

Type of beam		Beam cross-section [mm]	Bottom flexural rebar RB500	Reinforcement ratio [%]
Series 1	S1-N1, S1-N2	120x200	2Ø10+1Ø8	1,00%
	S1-R1, S1-R2			
Series 2	S2-N1, S2-N2	120x200	2Ø14+1Ø12	2,00%
	S2-R1, S2-R2			

The RC beams were tested in four point bending scheme. The loading force was exerted by the hydraulic device gradually every 5 kN until the failure. During the tests the following structural parameters of the beams were recorded:

- Beam deflections measured in the mid-span of the beam and on the two supports,
- Concrete strains measured at three levels in the three verical cross sections (see Fig. 2).
- Flexural steel strains in the centre of the beams.
- Crack widths at the whole beam span.

The view of tested beam is presented in the Fig. 2 and the details of inductive indicators after the failure of the beam are shown in the Fig. 3.

The measurement of beam deflections were performed using inductive indicators produced by Megatron Muenchen having the measuring base 25 and 50 mm and the accuracy 0,001 mm (see Fig. 3). The registration was done continously using diagnostic registrator type KSR-32 produced by *Sensor* with the frequency sampling equal to 2s. For the configuration system and the preliminary data processing the program LAB-View was used and then the results were catalogued and processed in the program Microsoft Excel. Flexural steel strains were measured using electric resistance gauges with the base 12 mm type EA-06-240LZ-120 done by Micro-Measurements Division.

Fig. 2. The view of tested large scale beam made of RAC
Rys. 2. Widok badanej belki z betonu recyklingowego w skali naturalnej

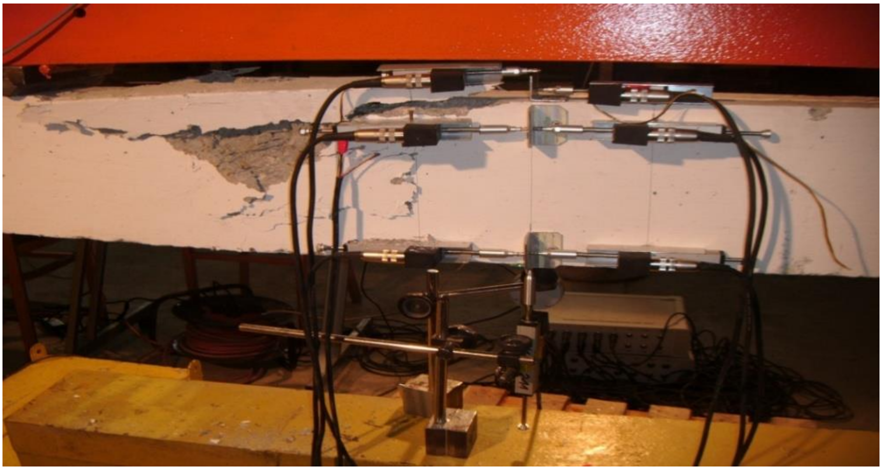

Fig. 3. Inductive indicators measuring concrete strains
Rys. 3. Czujniki do pomiaru odkształceń betonu

The registered deflections of the all the tested beams of Series S1 for the chosen values of loading forces are presented in the table 3 and for the beams for Series S2 are given in the table 4. The diagrams of beam deflections for the Series S-2 are presented in the Fig. 4.

Table 3. Deflections of the beams for Series S1
Tabela 3. Ugięcia belek serii S1

Loading force F [kN]	Deflections of tested beams [mm]			
	S1-N1	S1-N2	S1-R1	S1-R2
0	0,00	0,00	0,00	0,00
5	5,20	6,18	7,58	7,32
10	7,10	7,84	10,77	10,26
15	9,21	12,88	14,04	13,72
20	12,87	15,15	17,58	18,25
25	17,57	19,34	22,18	24,19
30	21,46	29,40	–	–

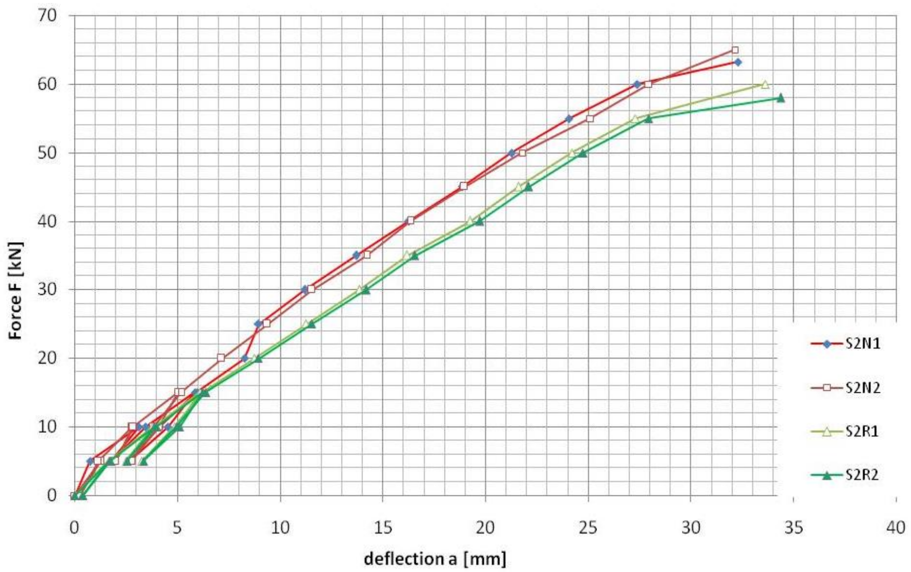

Fig. 4. Loading force versus beam deflections for the beam Series S2
Rys. 4. Zależność: obciążenie – ugięcia belek serii S2

Table 4. Deflections of the beams for Series S2
Tabela 4. Ugięcia belek serii S2

Loading force F [kN]	Beam deflection a [mm]			
	S2-N1	S2-N2	S2-R1	S2-R2
5	2,69	2,77	3,26	3,30
10	4,14	3,85	4,85	4,96
15	5,93	5,18	6,23	6,37
20	8,26	7,14	8,74	8,94
25	8,95	9,37	11,26	11,52
30	11,20	11,55	13,85	14,17
35	13,69	14,21	16,18	16,55
40	16,25	16,35	19,25	19,69
45	18,85	18,98	21,60	22,10
50	21,26	21,78	24,19	24,75
55	24,07	25,10	27,30	27,93
60	27,39	27,95	33,60	–

Table 5. Quantitative comparison of deflections for the beams for Series S1
Tabela 5. Ilościowe porównanie średnich wartości ugięć dla belek serii S1

	P=5 [kN]		P=10 [kN]		P=15 [kN]		P=20 [kN]		P=25 [kN]	
Beams S1-R	7,45	1,31	0,52	1,41	3,88	1,26	7,91	1,28	3,18	1,26
Beams S1-N	5,69		7,47		1,05		4,01		8,45	

The mean values of tested beam deflections are presented in the table 5 (for Series S1) and in the table 6 (for Series 2). As we can see, for each level of loading force the deflections are greater for the beams made of recycling aggregate concrete (RAC) compared to the deflections of the beams made of natural aggregate (type N). The mean value of magnifying deflection coefficient for the beams S1 (reinforcement ratio 1%) is equal to 1,30, whereas for the S2 (reinforcement ratio 2%) the magnifying coefficient equals to 1,18. These results clearly shows the stiffness decrease of beams made of RAC. This effects was probably caused by reduced value of RAC modulus of elasticity (see table 1), by about 13%.

Table 6. Quantitative comparison of deflections for the beams for Series S2
Tabela 6. Ilościowe porównanie średnich wartości ugięć dla belek serii S2

	P=10 [kN]		P=20 [kN]		P=30 [kN]		P=40 [kN]		P=50 [kN]	
Beams S2-R	3,30	1,21	8,84	1,15	14,01	1,23	19,47	1,19	24,47	1,14
Beams S2-N	2,73		7,70		11,37		16,30		21,52	

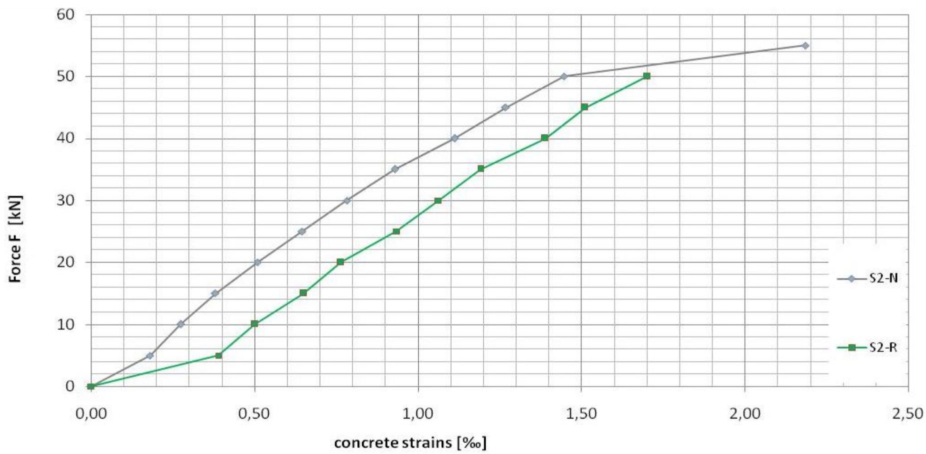

Fig. 5. Loading force versus concrete compressive strains for the beam Series S2
Rys. 5. Zależność obciążenie – odkształcenia betonu ściskanego w belce serii S2

The comparison of mean values of compressive concrete strains for the beams from Series S1 are presented in table 7. It can be seen visible differences between strains measured for the beams made of RAC and control beams with natural aggregate. The differences become larger for smaller levels of loading. The concrete strain magnifying coefficients vary from 1,30 (for the initial cracks) up to 1,25 (for the state of failure).

The comparison of loading critical forces for all the tested beams (for Series 1 and 2) under bending are presented in table 8.

As expected, the beams made of RAC revealed slightly lesser flexural capacity compared to the beams with natural aggregate. The mean value of reduction coefficient of critical force for the beams from Series 1 equals 0,84, whereas for the beams from Series 2 equals to 0,96.

Table 7. Comparison of concrete compressive strains for beams of Series S-2
Tabela 7. Porównanie odkształceń betonu w strefie ściskanej belek serii S-2

	P = 5 [kN]		P = 10 [kN]		P = 15 [kN]		P = 20 [kN]		P = 25 [kN]	
Beams S1-R	7,45	1,31	10,52	1,41	13,88	1,26	17,91	1,28	23,18	1,26
Beams S1-N	5,69		7,47		11,05		14,01		18,45	

Table 8. Critical loading forces for tested beams for Series 1 and 2
Tabela 8. Siły niszczące w badanych belkach serii 1 i 2

Type of beam	Critical loading forces P_R [kN]			
Series S1	S1-N1	S1-N2	S1-R1	S1-R2
	33,5	32,1	28,5	26,6
	Mean value: 32,8 kN		Mean value: 27,6 kN	
Series S2	S2-N1	S2-N2	S2-R1	S2-R2
	57,2	56,9	55,1	54,2
	Mean value: 57,1 kN		Mean value: 54,65 kN	

3. Conclusions

Demolition of old concrete constructions gives an opportunity for the use of crushed concrete wastes for recycling aggregate concrete (RAC), what is a new type of energy-saving building material, as it is required for environmental protection in the light of sustainable construction.

The result of tests conducted on large scale RC beams made of RAC revealed shape of failure and critical values of loading forces being similar to control beams made of natural aggregate concrete, however the deformability parameters (deflections, concrete strains and widths of cracks) in the two types of tested beams were differed.

The short time tests on beams made of RAC revealed an increase of beam deflections in the range of 18% to 30%. Also the concrete strains in the zone of compression were increased in about 30% compared to the beams made of natural aggregate concrete.

The results confirmed the possibility of application of good quality aggregate made of crushed concrete wastes for production of structural concrete used for construction like RC beams or slabs, what is very important for the needs of environmental protection.

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Acknowledgement

The authors are grateful for the financial support provided in the frame of Grant NCBiR NR04-0012-10/2010.

Efektywność zastosowania betonu recyklingowego w konstrukcjach budownictwa zrównoważonego

Streszczenie

W artykule przedyskutowano narastający problem zagospodarowania gruzu betonowego z rozbiórek budynków na potrzeby recyklingu betonów konstrukcyjnych, w świetle ochrony środowiska i wymagań budownictwa zrównoważonego. Przedstawiono wyniki badań doświadczalnych żelbetowych elementów belkowych wykonanych z betonów na kruszywach wtórnych. Omówiono wybrane wyniki badań doświadczalnych w zakresie doraźnej odkształcalności i nośności belek żelbetowych wykonanych w skali naturalnej o zróżnicowanym stopniu zbrojenia na zginanie. Wyniki badań porównano z rezultatami badań belek referencyjnych z betonów tej samej klasy. Wykazano, że zastosowanie betonu wykonanego z dobrej jakości kruszyw wtórnych, w porównaniu do elementów referencyjnych wykonanych z betonów tej samej klasy na kruszywach naturalnych, pozwala uzyskać elementy konstrukcyjne o podobnych parametrach wytrzymałościowych lecz nieco zwiększonych odkształceniach. Daje to szansę na zagospodarowanie olbrzymiej ilości gruzu budowlanego dla potrzeb wytwarzania nowych elementów konstrukcji spełniających wymagania budownictwa zrównoważonego.

Słowa kluczowe: beton na kruszywie z recyklingu, belki żelbetowe, nośność na zginanie, odkształcalność konstrukcji
Key words: recycled aggregate concrete, RC beams, flexural capacity, structural deformability