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USE OF ECOLOGICAL LIGHTWEIGHT AGGREGATES IN REINFORCED CONCRETE STRUCTURES

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ABSTRACT: The article discusses the possibility of utilising both wastes from CHP plants (Combined heat and power plants), i.e. fly ash, and PET plastic waste (polyethylene terephthalate), through processing into lightweight aggregate used construct reinforced concrete beam elements to protect the natural environment. Properties of the utilised lightweight artificial aggregates are presented. Selected results of experimental tests in load-bearing capacity and deformability of reinforced concrete beams made in the model scale are presented. An analysis of the test showed that, despite their lower resistance to crushing, artificial aggregate beam elements have the same load-bearing capacity as reinforced concrete beams made with recycled aggregate, with better flexural strength properties in some cases.

KEYWORDS: bendable elements; artificial aggregates; PET aggregate; recycling; lightweight concrete

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Introduction

In 2013 the production of plastic waste worldwide amounted to close to 300 million tonnes and is steadily increasing. The largest quantities of plastic waste are produced on the Asian continent, amounting to 40% of the global production, connected with high population density. Next, the USA, Canada, and Mexico have 19.4%, with the European countries producing 20%. The lowest waste production occurs in Japan and amounts to as little as 4.4%. Analyses show that 40% of plastic waste is sent to landfills, 32% lands in seas and oceans, with only 14% undergoing recycling (Valavanidis, 2016).

By-products, i.e. fly ash and boiler slag, are produced in power plants and CHP plants as a result of coal combustion processes. Waste connected with electricity and heat production has been an environmental concern for decades because they largely end up in landfills. For example, in 2017, bituminous coal consumption in Poland was 74.6 million tonnes, and in 2019 was 68.8 million tonnes. As a result of combustion processes of such amounts of coal, leftover fly ash totalled 3.4 million tonnes (Rolka, Ślęzak, 2012; Statistical information, 2018; Statistical Yearbook, 2018, Statistical Yearbook, 2020).

Fly ash is one of the most important by-products of coal combustion, with years of work put into its utilisation. It is currently utilised to the largest extent in the building materials industry. The chemical and mineral composition of fly ash enables its application as a mineral additive in cement and concrete production as well as lightweight fly ash-based aggregates (figure 1). Its properties depend on multiple factors, including the type of combusted coal, the type of coal combustion installation, the method of preparation, and methods of capture, removal, and storage of ashes. In the case of cement, aggregate and concrete, the fly ash that is utilised to the largest extent is fly ash produced in bituminous coal combustion, i.e. silica fly ash (Rolka, Ślęzak, 2012; Giergiczny, 2007).

The diminishing natural resources are another factor contributing to the development of green construction, as well as to the production of aggregate from waste material. Each year the mining of natural aggregate exceeds 200 million tonnes, with a record level in 2011 when as much as 311 million tonnes of natural raw materials were produced. The decrease of natural resources results from high consumption, but it is also affected by increasing environmental protection requirements that block access to new resources.

Due to the diminishing amounts of natural aggregates and the increasing amounts of waste produced, as well as waste deposited in landfills and oceans, efforts are put into finding possibilities for its processing and reuse. In addition, the construction sector is big enough for it to be able to utilise newly produced raw materials to a large extent. This results in increasing numbers of studies using waste and recycled materials.

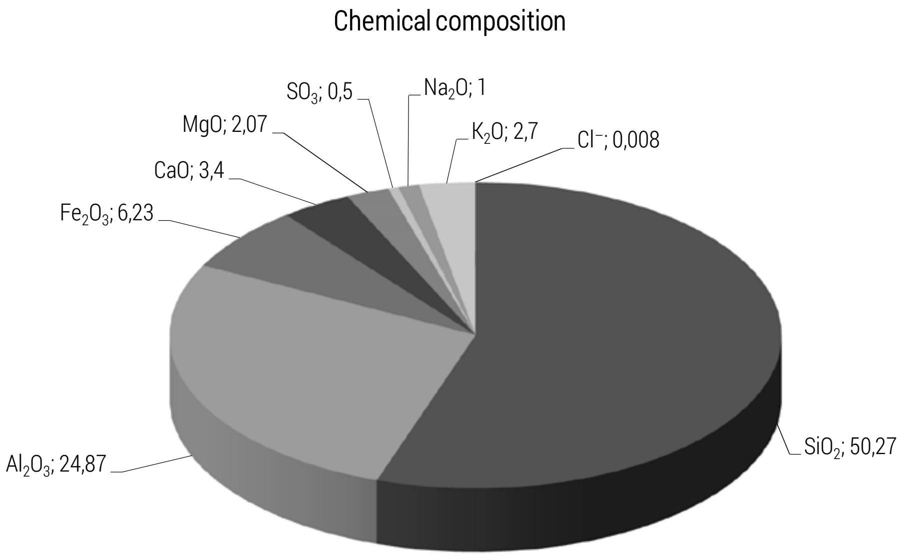


Figure 1. Chemical composition of fly ash [% mass]
Source: author's work.

For several years, scientists have been researching new types of lightweight aggregates. One of the ideas is to combine two types of waste materials of expanded polystyrene (EPS) and unprocessed fly ash (FA) on different properties of concrete (Moayyeri et al., 2016; Bengin, 2017; Ganesh Babu et al., 2005; Petrella et al., 2020). Most research on concrete containing unmodified expanded polystyrene (EPS) has revealed a decrease in concrete's durability and mechanical properties, increasing the amount of EPS particles in concrete. Some studies have reported the importance of using fly ash in concrete, saving a significant amount of energy and cost in cement manufacturing. It can also improve the engineering properties of concrete by replacing it with normal cement. In recent years researchers working in civil engineering have been engaged in investigations about the reuse of waste plastic in concrete construction (Geyer et al., 2017; Pacheco-Torgal et al., 2019; Czarnecki, 2019; Grygo, Łapko, 2012). Some publications focus on the production and performance of concrete with different types of recycled plastic as an aggregate or binder replacement or properties of concrete with recycled plastic fibres.

Materials and Methods

Properties of aggregates used in concrete mixtures

For the purpose of the tests, innovative lightweight recycled aggregate with a fraction of 16 mm was designed and used (figure 2). First, the aggregate was produced by processing used plastic bottles made from polyethylene terephthalate. In the next stage, aggregate adhesion to the cement matrix was improved by covering sand with a grade of 0-2 mm. The production process was carried out using a single-screw extruder equipped with four heat zones, presented in figure 3.

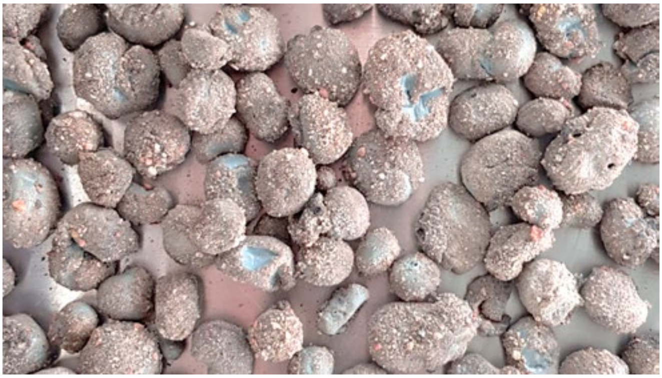


Figure 2. PET aggregate with a fraction of 16 mm obtained by processing used plastic bottles

Source: author's work.

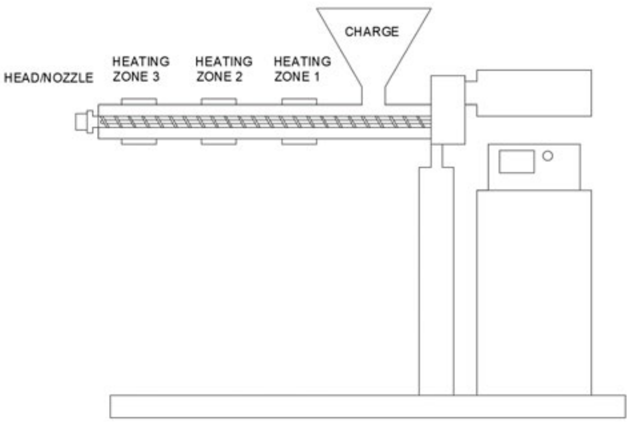


Figure 3. Scheme of the single-screw extruder used for the production of PET aggregate

Source: author's work.

Table 1. Properties of the aggregate obtained from PET bottle recycling (according to PN-EN 1097-6:2002, PN-EN 1097-3:2000, PN-76/B-06714/09, PN-76/B-06714/08)

Aggregate	Water absorption WA24	Density of dried grains	Saturated grain-density	Volume density	Lose bulk density	Voids	Porosity	Tightness
	%	Mg/m³	Mg/m³	Mg/m³	Mg/m³	%	%	%
PET	5.47	1.00	1.05	0.93	0.66	33.60	6.53	1.07
	3.67	1.00	1.04	0.97	0.65	35.02	3.04	1.03
	4.52	1.01	1.05	0.99	0.65	36.02	2.28	1.02
PET + fillers	3.18	0.97	0.97	0.86	0.46	49.14	10.75	1.12
	5.63	0.99	0.99	0.87	0.46	52.66	12.71	1.15

Source: author's work.

PET aggregate is characterised by very low bulk density at low grain porosity. The bulk density of non-foamed grains is at a level of 660 kg/m^3. In contrast, foamed aggregate deviates significantly from those available on the market, as the density value is 460 kg/m^3, maintaining low levels of absorbability (table 1). Another advantage of the plastic used for lightweight aggregate production is its thermal conductivity, whose value is 0.29 W/m·K.

Figure 4. Certyd aggregate with a grain diameter of 2-4 mm and 4-8 mm

Source: author's work.

Table 2. Properties of aggregates used for the tests

Type of aggregate	Unit	Certyd	Recycled aggregate
Fraction	mm	4/8	4/8
Shape	-	circular	crushed
Bulk density	kgm^3	700	2130
Compressive resistance	MPa	>5	-
Frost resistance	%	<2	< 3.3
Water absorption WA24	%	20	7.2
Radioactivity	Bq/kg	f1 ≤ 1.2 f2 ≤ 240	-

Source: author's work according to PN-EN 1097-6:2002; www.certyd.pl.

The paper also uses fly ash-based aggregate Certyd (figure 4), manufactured in the LSA – Lightweight Sintered Aggregate – technology using an innovative autothermal process of fly ash sintering from electro filters ash-slag mixtures. The main characteristic of aggregates of this type is their bulk density at a level of 620-725 kg/m^3, which results in the possibility to produce lightweight concrete with a density of 1400 kg/m^3. Apart from the low density, it is also characterised by good thermo-insulating properties, frost resistance as well as resistance to fungi, mould and pests.

Figure 5. Aggregate from concrete recycling

Source: author's work.

Recycled aggregate was produced by crushing rubble leftover from the demolition of Fabryka Przyrządów I Uchwytów (machine and tool manufacturer) in Bialystok (figure 5). The crushing was carried out on a Tamel S.A. crusher with an optimised size reduction ratio. Then the obtained aggregate was subjected to sieving in order to separate particular fractions.

Study design

Reinforced concrete beams 8×12×110 cm were produced from 6 mm and 8 mm B500A and BFRP (Basalt Fibre Reinforced Polymer) steel rebars, whereas pull reinforcements were produced from smooth 3 mm rebars in three series (figures 6 and 7). The first series comprises elements made with recycled aggregate marked "R". In the second series, marked "P", fly ash based aggregates Certyd were used. In the third series, marked "PR", aggregate produced by processing used PET bottles were used. Beams P-1, P-4, and R-1, with a degree of reinforcement of ρ = 0.67%, had 2×6 mm top and 2×6 mm bottom reinforcements. Beams P-2, P-3, and R-2, with a degree of reinforcement of ρ = 1.21%, had 2×6 mm top and 2×8 mm bottom reinforcements. In model beams, PR-1 2×8 mm and 4×8 mm bottom steel reinforcements were used, whereas series PR-2 contained basalt (BFRP) 2×8 mm and 4×8 mm bottom reinforcements (figure 8). Beams PR-1 and PR-2 had a degree of reinforcement of ρ = 2.37%.

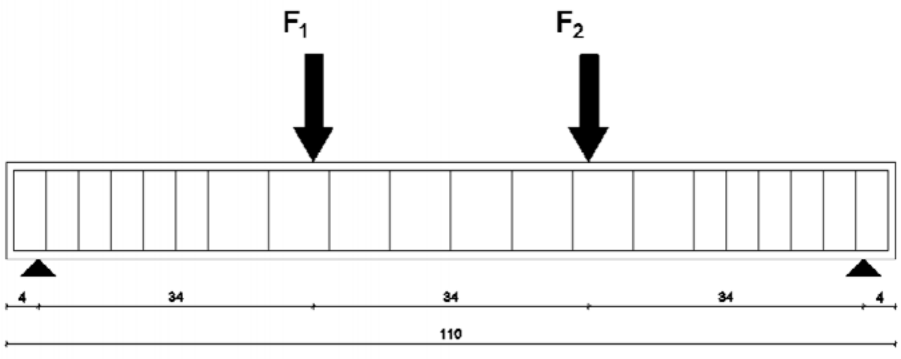


Figure 6. Scheme of the tested beams with load

Source: author's work.

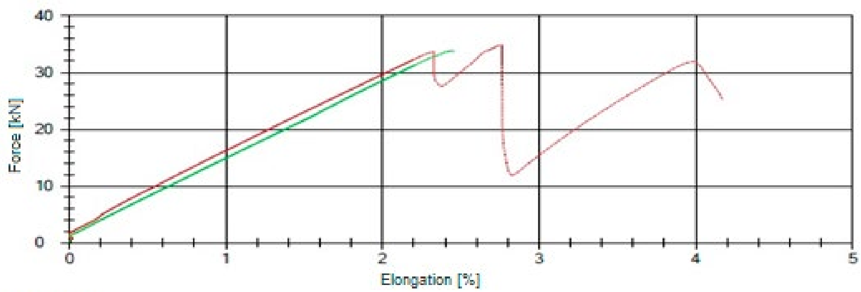
Figure 7. Reinforcing frames of reinforced concrete beams – top basalt rebars, bottom steel rebars

Source: author's work.

Basalt rebars are a composite product with a wide range of uses in construction. They are characterised by considerable resistance to the action of aggressive chemical environments and corrosion, as well as durability and low weight. Basalt rebars (BFRP) consist of fibres with diameters ranging from several to several tens of micrometres and a polymer matrix. They are manufactured in the pultrusion technology, ensuring the repeatability of the produced rebars, production continuity, and lower energy expenditures. The main ingredient is basalt fibres produced as a result of remelting of basalt rock, also called volcanic lava, at a temperature of 1400°C. The role of fibres is to ensure adequate, appropriate tensile strength of rebars, whereas resin is responsible for protecting the surface from damage, maintaining the appropriate distance between fibres, and transferring tensile stresses to them. According to (ACI 440.1R-15 Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRB) Bars), proper cooperation between FRP reinforcement and concrete can be achieved through three methods of rebar surface finishing. The first method is coating with modelling sand, the second – producing ribs in the same way as in the case of steel reinforcement, while the third – wrapping around rebar from the additional fibre layer (Grygo, Kosior-Kazberuk, 2017).

Test result:

Nr	Sample	m_E GPa	R_m MPa	A_{gt} %	$t_{badanie}$ s	d_0 mm	S_0 mm^2
1	1	47,2	1180	2,8	349,71	6,14	29,61
2	2	47,9	1200	2,5	339,27	6	28,27



Statistics:

Series n = 2	Sample	m_E GPa	R_m MPa	A_{gt} %	$t_{badanie}$ s	d_0 mm	S_0 mm^2
x	2	47,6	1190	2,6	344,49	6,07	28,94
s	1	0,505	14,3	0,2	7,38	0,09899	0,94
v [%]	47,14	1,06	1,21	8,27	2,14	1,63	3,26

Figure 8. Graph showing the tensile strength of BFRP rebars

Source: author's work.

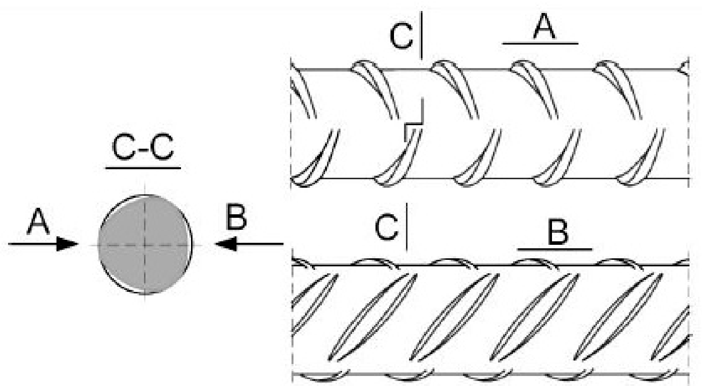


Figure 9. B500A ribbed reinforcing bars

Source: author's work based on PN-EN 12390-5:2009.

The yield strength of B500A steel is 500 MPa and has low malleability (figure 9). According to Polish Standards is A-IIIN steel, while according to Eurocode 2 – class A. It is characterised by parallel, transverse ribs, which may be placed in two rebar rows on both sides. The ribs are inclined in the same direction (PN-EN 12390-5:2009).

Three formulas for concrete mixture components were designed for the tests, using recycled concrete aggregate – series "R", fly ash based– series "P", and concrete produced by processing plastic from used PET bottles – series "PR". During the analysis, special attention was paid to the bulk densities of both aggregates, as they lead to differences in their contents as expressed in kilograms. The composition of concrete mixtures is presented in tables 3 and 4.

Table 3. Compositions of concrete mixtures in series "P" and "R"

Series Component	P-1	P-2	P-3	P-4	R-1	R-2
	Quantity [kg/m^3]					
Cement (CEM I 42,5 R)	270				260	
Water	221				170	
Sand 0-2 mm	680				585	
Aggregate 2-4 mm	336				528	
Aggregate 4-8 mm	168				712	
Admixture Chryso Omega	3.9				2.6	

Source: author's work.

Table 4. Formula of 1m^3 trial feed based on PET plastic waste aggregate

Series Component	PR-1	PR-2
	Quantity [kg/m^3]	
Cement (CEM I 42,5 R)	350	
Water	205	
Sand 0-2 mm	1032	
PET aggregate 16 mm	500	
Admixture Chryso Premia	7	

Source: author's work.

Measurements of deflection of the tested reinforced concrete beams were performed at the sample midspan using electronic sensors with an accuracy of 0.01 mm. Deflection values were recorded with the2 kN force stroke. The results were recorded and processed in Excel. Tests of the load-bearing capacity of beams were carried out on a Controls destructive machine with the span of the applied load equalling 1/3 of the beam span. Figure10 shows the test stand for the model beams.

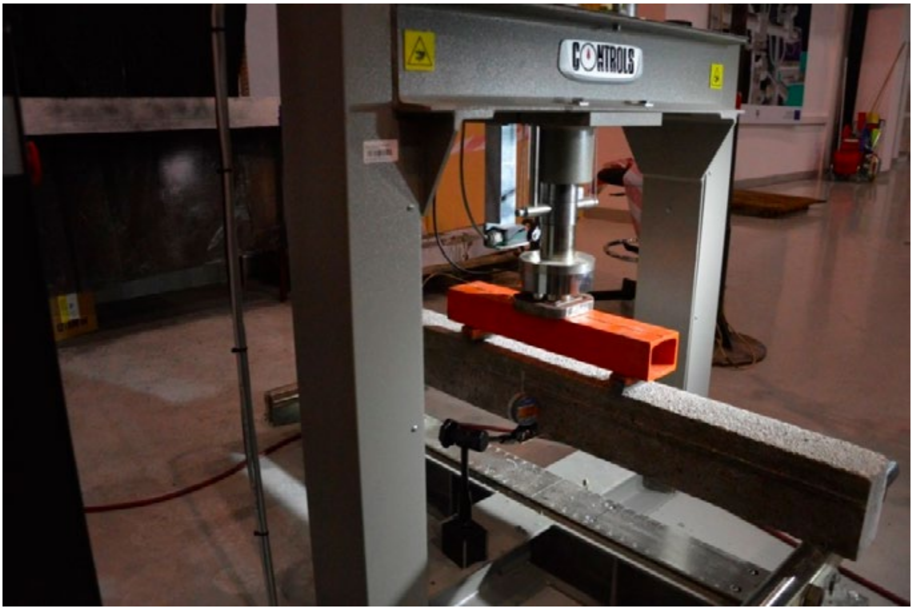
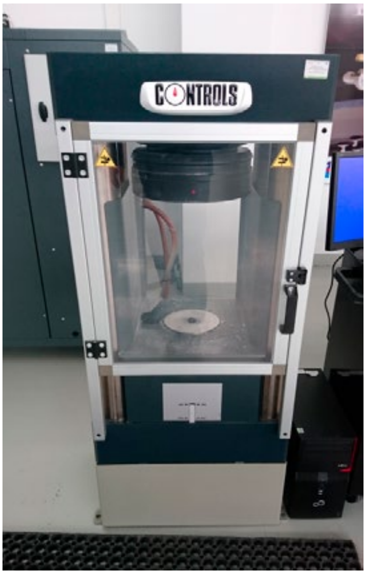


Figure 10. Test stand for reinforced concrete model beams
Source: author's work.



The compressive strength of hardened concrete was determined on cubical samples with a side length of 100 mm. Figure 11 shows the Controls destructive machine used to perform the compressive strength tests of the concrete samples.

Figure 11. The Controls destructive machine
Source: author's work.

Results and Discussion

Compressive strength tests of hardened concrete

The tests of compressive strength of concrete samples were carried out after the concrete had cured for 28 days, according to PN-EN 12390-3:2011/AC:2012. Compressive strength of cubical samples was calculated according to the following formula:

$$f_c = \frac{F}{A_c} \cdot \eta \ ,$$

where:
f_c – compressive strength, in MPa (N/mm^2),
F – maximum force at destruction, in N,
A_c – cross-section area of the sample with compressive force, calculated based on the declared sample dimensions or based on its measurements, in mm^2,
η – ratio depending on the dimensions of the used forms; for cubical forms with a side length of 100 mm – η = 0.9.

The results for compressive strength for cubical samples in series P-1÷P-3, R-1÷R-3, and PR-1÷PR-3 are presented in table 5. Destruction of series PR is visualised in figure 12.

Table 5. Results of compressive strength tests of concrete after 28-day curing

Number	Series	Force	Compressive strength f_{ci}	Average compressive strength f_{cm}
		[kN]	[MPa]	[MPa]
1.	P-1	335.40	30.19	29.50
2.	P-2	317.20	28.55	
3.	P-3	330.60	29.75	
4.	PR-1	242.50	21.83	22.03
5.	PR-2	239.55	21.56	
6.	PR-3	252.20	22.70	
7.	R-1	533.50	48.02	47.81
8.	R-2	513.00	46.17	
9.	R-3	547.00	49.23	

Source: author's work.

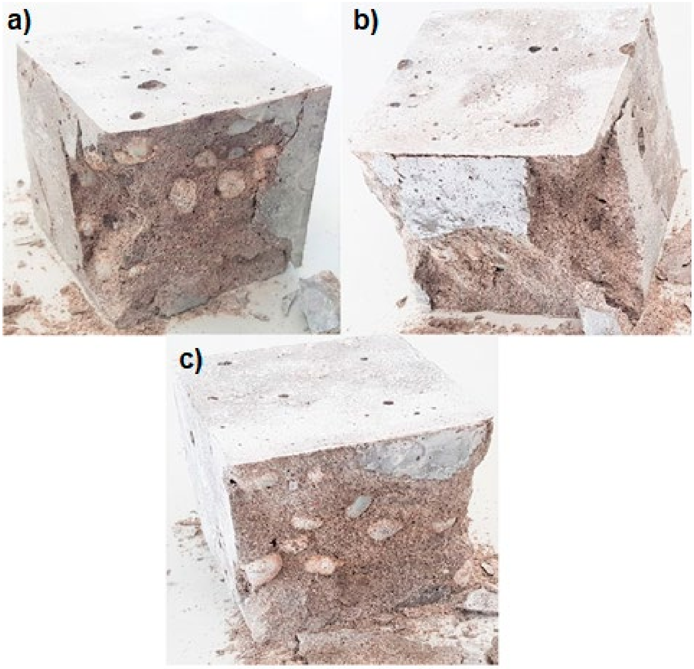


Figure 12. Destruction of concrete samples in series PR:
a) sample PR-1, b) sample PR-2, c) sample PR-3

Source: author's work.

After visual inspection of the destroyed cubes it must be noted that PET (PR) aggregate did not distribute evenly throughout the sample's cross-section. The bottom part contained plastic aggregate only in negligible amounts as a significant amount was present in the middle and top parts. This is a result of the low density of the aggregate.

Tests of tensile strength at splitting

The results of determinations of tensile strength at splitting according to EN 12390-6:2011 and the values of the splitting force for cylindrical samples with a diameter of 15 cm and a height of 30 cm are presented in table 6, whereas figures 13-15 show destruction of samples in the tested series.

When analysing the tested series "PR" sample, it can be noted that the crack only appeared at ¾ of the sample height, counting from its bottom part. The reason for such destruction is an uneven distribution of aggregate within the sample – a negligible part of coarse-grain aggregate was present in the bottom part, which resulted in the crack appearing precisely in that place. During densification, the aggregate moved upwards.

Table 6. Results of tests of tensile strength at the splitting of polymer-based, recycled, and fly ash-based aggregate samples

Series	Force	Tensile strength at splitting f_{ti}
	[kN]	[MPa]
PR	111.60	1.58
R	219.50	3.10
P	195.43	2.76

Source: author's work.

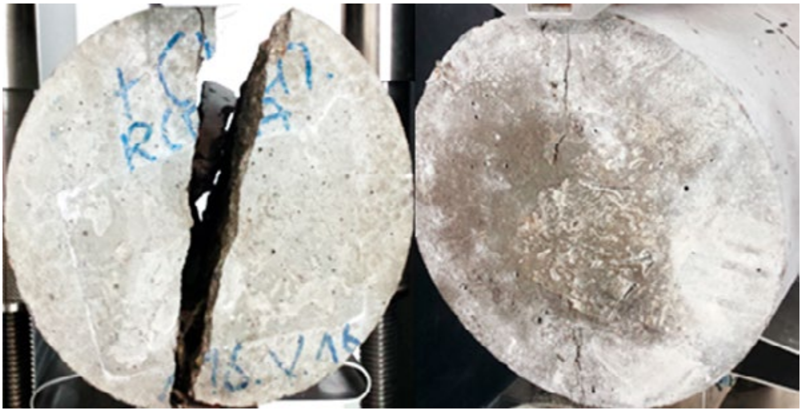


Figure 13. View of cylindrical samples in series R (left) and P (right) after the destruction

Source: author's work.

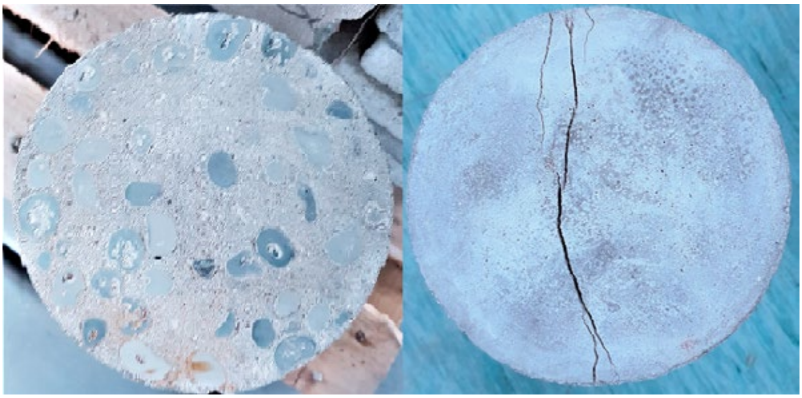


Figure 14. View of a series PR sample after destruction – top (left) and bottom (right) part of the cylinder

Source: author's work.

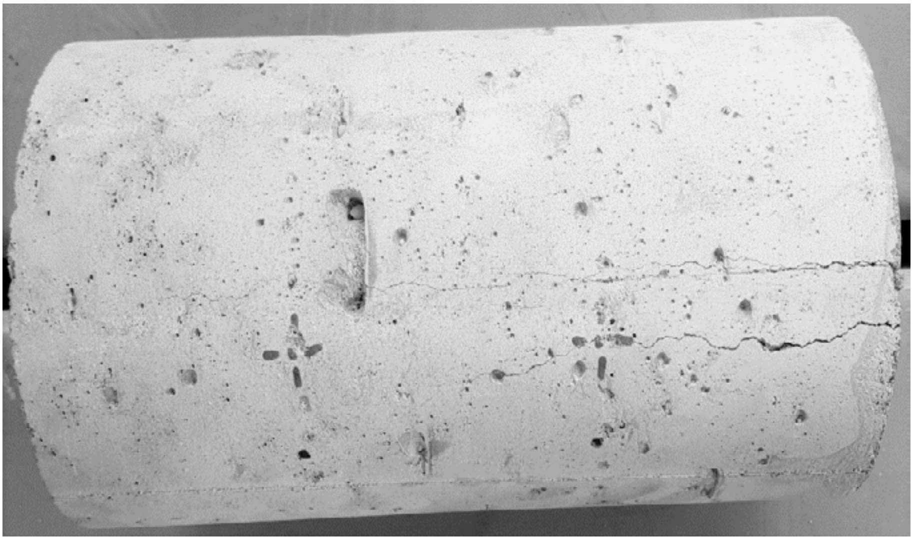


Figure 15. Side part of a PR series cylinder after the destruction
Source: author's work.

Tests of load-bearing capacity and deformability of reinforced concrete model beams

The load-bearing capacity and deformability tests were carried out after curing the concrete for 28 days. Below, the measured values of deflection, together with the calculated average values at given loads for beams with degrees of reinforcement ρ = 0.67% and ρ = 1.21%, series "PR", are presented in the form of tables and graphs. In both cases, beams made with recycled aggregate are characterised with higher deflection compared to reinforced concrete beams made with fly ash based aggregate. Steel-reinforced beam PR-1 is characterised with a considerably lower deflection than basalt-reinforced beam PR-2. The graphs in figure 16 illustrate the relationship between deflection and the applied load.

When analysing the deflection values for the tested model beams contained in table 7, it should be noted that series "P" beams made with fly ash based aggregate are characterised with lower deflections. At a loading force of 16 kN, the greatest difference occurs in the case of samples PR-1 and PR-2 and equals 4.47 mm, i.e. 64% less than the beam made with the use of basalt reinforcement.

Table 7. Deflection of series "P", "R" and "PR" beams

Applied load	Deflection [mm]										
[kN]	PR-1	PR-2	Average	P-1	P-4	R-1	Average	P-2	P-3	R-2	Average
0	0	0	0	0	0	0	0	0	0	0	0
2	0.03	0.42	0.42	0.28	0.26	0.40	0.40	0.33	0.36	0.40	0.36
4	0.54	0.92	0.92	0.75	0.47	1.08	0.77	0.52	0.66	0.65	0.61
6	0.83	1.85	1.34	1.36	0.96	1.81	1.38	0.71	0.86	1.01	0.86
8	1.13	2.81	1.97	2.13	1.58	2.49	2.07	1.03	1.24	1.35	1.21
10	1.46	3.73	2.60	2.58	2.21	3.12	2.64	1.36	1.67	1.69	1.57
12	1.80	4.74	3.27	3.17	2.89	3.71	3.26	1.72	2.09	2.00	1.94
14	2.15	5.72	3.94	3.77	3.47	4.33	3.86	2.08	2.47	2.34	2.30
16	2.52	6.99	4.76	4.42	4.10	4.95	4.49	2.43	2.87	2.66	2.65
18	2.87	7.73	5.30	5.18	4.94	5.88	5.33	2.81	3.28	3.03	3.04
20	3.25	8.72	5.99	9.56	8.28	9.60	9.15	3.18	3.70	3.42	3.43
22	3.66	9.77	6.72	12.94	12.53	13.29	12.92	3.57	4.21	3.83	3.87
24	4.07	10.93	7.50					3.98	4.68	4.25	4.30
26	4.50	11.99	8.25					4.42	5.20	4.70	4.77
28	4.94	13.05	9.00					4.89	5.68	5.23	5.27
30	5.44							5.56	6.23	5.64	5.81
32	5.99							6.24	7.14	6.28	6.55
34	6.75							7.18	10.38	7.08	8.21
36	8.06							10.25		10.21	10.23
38	9.87										
40	11.24										
42											
Critical load [kN]	40.21	28.10		20.86	21.32	21.24		35.30	32.85	35.84	

Source: author's work.

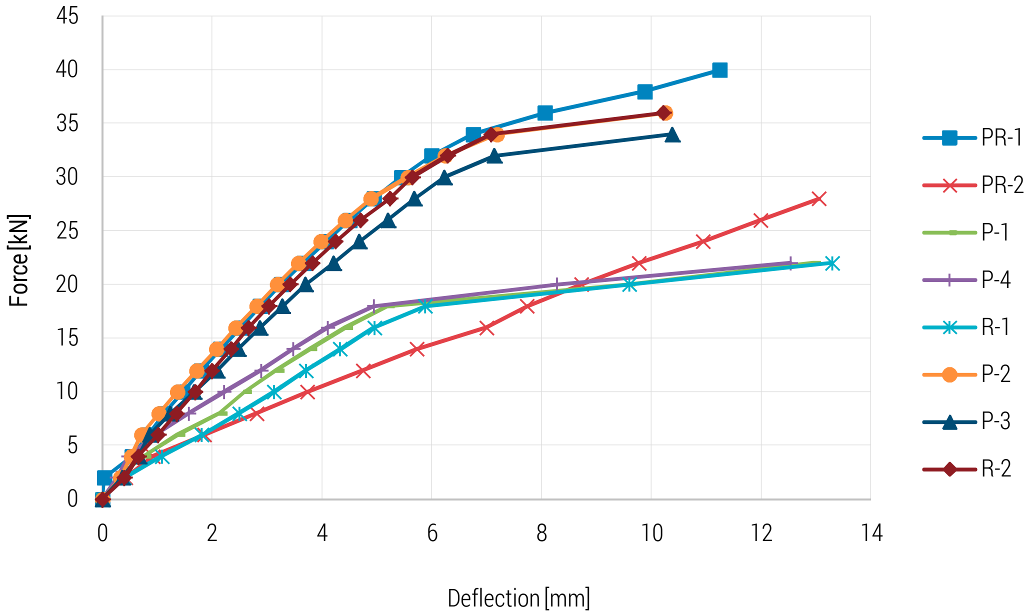


Figure 16. Load-deflection ratio plot – deflection for series "R", "P", and "PR"

Source: author's work.

The results of tests of the load-bearing capacity of reinforced concrete beams are summarised in figure 17 in the form of a bar chart. The breaking moment values for the particular beams were calculated according to the following formula:

$$M_{breaking} = \frac{P}{2} \cdot \frac{L}{3} = \frac{P \cdot L}{6},$$

where:
P – force [kN],
L – length of beam [m].

When analysing the presented results of flexural strength tests of model beams, series "R" is characterised with a slightly higher load-bearing capacity; however, the results are comparable with series "P", made with fly ash-based aggregate. Nonetheless, the highest load-bearing capacity occurred in the case of beam PR-1 made with PET plastic aggregate. The highest difference exists between beams P-3 and R-2, with the value for beam P-3 being lower by 8% compared to R-2. When comparing two types of reinforcement, it should be noted that sample PR-2 is characterised with a lower load-bearing capacity; this is, however, caused by the occurrence of shearing.

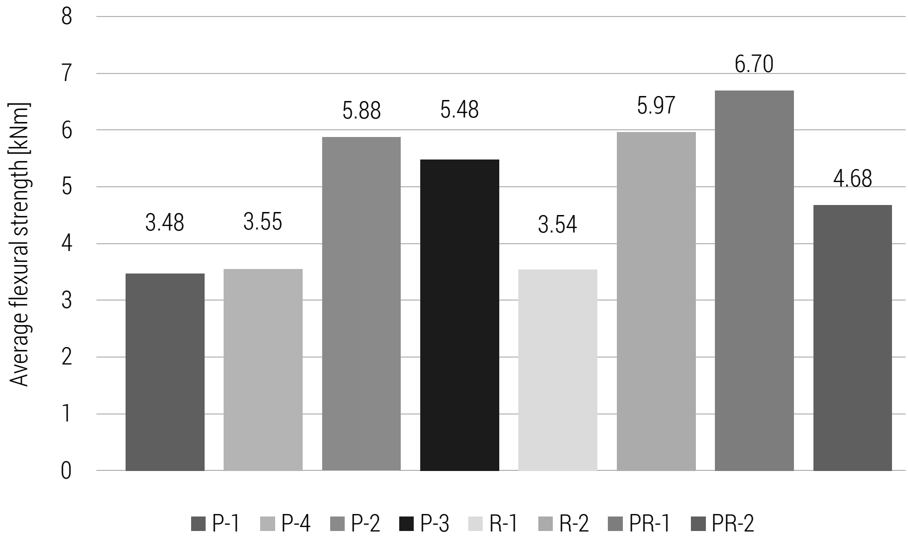


Figure 17. Average flexural strength of each of model beams [kNm]

Source: author's work.

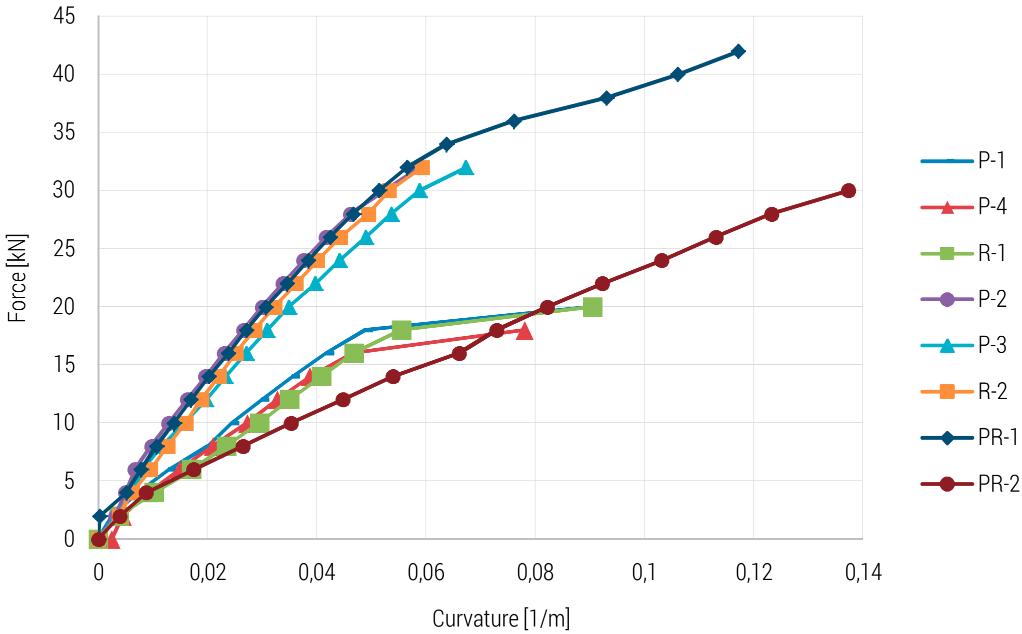


Figure18. Graph showing force P – curve X ratio for all beam series

Source: author's work.

Below, the values of stiffness B for all the tested reinforced concrete beams are summarised, while figure 18 shows a comparative plot showing the following ratio: force P – experimental curve X of the tested beams.

When analysing the tabular results presented above, as well as the graph showing experimental curves X and stiffness B of the tested reinforced concrete beams, it should be noted that although beam P-2, made with fly ash based aggregate, is characterised with the highest stiffness B compared to all the samples, series PR-1 beam is characterised with only marginally lower values of stiffness B than sample P-2, as the difference is only about 5%. At the same time, beams made with CERTYD and PET aggregates are characterised with lower values of experimental curves X for a given force, compared to reference beam REC, by 23% and 16%, respectively.

Conclusions

The tests of reinforced concrete model beams showed beneficial effects of using fly ash based aggregates for concrete. However, a comparative analysis of the measured values of deflections of model beams with degrees of reinforcement of ρ = 0.67% and ρ = 1.21% at bending enables to conclude that deflections of series "P" beams are characterised with lower values, from 9 to 17%, compared to series "R", made with recycled aggregate. When comparing the values of deflections of beams PR-1 and PR-2, on the other hand, using reinforcement of various types, i.e. steel and basalt, it should be noted that beams with composite reinforcement are characterised with values of deflections higher by as much as 177%.

Using fly ash based aggregates in the innovative LSA (Lightweight Sintered Aggregate) technology made it possible to reduce deflections of model reinforced concrete beams, while at the same time, load-bearing capacity remained at a level comparable to series "R" beams. When comparing the load-bearing capacity results for different beams, it can be noted that those in series "R" are characterised with values higher by as little as 1.5 to 8.2%. At the same time, they are characterised with higher deflection values, from 9.5 to 12%, at a particular force, compared to beams made with fly ash based aggregate. The highest value of load-bearing capacity was achieved in the case of beam PR-1 with aggregate produced from waste, i.e. plastic PET bottles, which equalled 6.70 kNm. The reason for the low strength of beam PR-2 made with composite reinforcement was the presence of shearing during sample loading.

When analysing the values of stiffness B for all the tested samples of reinforced concrete beams, it has been concluded that the highest values of stiffness B were achieved in the case of sample P-2 made with from fly ash aggregate; however, a virtually identical result was obtained for beam PR-2, as the difference was as little as about 5% in favour of P-2.

A very small bulk density characterises PET aggregate. In the case of non-foamed grain, its bulk density is similar to that of Certyd aggregate, which is a porous aggregate. On the other hand, when comparing both porous aggregates, PET aggregate, with a bulk density of 460 kg/m^3, has a significant advantage, producing a result lower by 26% compared to Certyd. An additional advantage of the innovative aggregate is its low absorbability, at a level of 4.5 % (PET plastic has low absorbability at a level of about 0.2%).

When analysing the properties of the innovative aggregate produced from processed, used polyethylene terephthalate bottles, it can be concluded that it is characterised with above-average parameters compared to the lightweight aggregates already available on the market. This leads to the willingness to conduct further research using the aggregate in question in concrete to reduce the amounts of waste deposited in landfills and protect the environment.

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The contribution of the authors

Robert Grygo: conception – 50%, literature review – 40%, experimental research – 50%, analysis and interpretation of data –40%.

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