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The influence of the demolition process on the environmental impact of reinforced concrete structures based on recycled aggregate

Wpływ procesu rozbiórki na oddziaływania środowiskowe konstrukcji żelbetowych z kruszywem pochodzącym z recyklingu

Abstract

The article presents an analysis of the influence of the demolition process on the environmental impact of a reinforced concrete structure, based on recycled concrete aggregate (RCA). Two aggregate production scenarios, varied in terms of the scope, were adopted and the contribution of RCA to the total environmental impact as well as the influence of demolition on the environmental performance of RCA were determined. The NONROAD model was used in the research as a tool for calculating the emissions generated by the equipment used for the processing of construction debris. Environmental impacts were assessed on the basis of the Ecopoint value. Despite the large quantity of aggregate in the concrete mixture, it did not constitute a significant environmental impact. However, demolition was the dominant process in the production of recycled concrete aggregate and it is reasonable to consider this process in an environmental analysis.

Keywords: environmental impact, recycled concrete aggregate (RCA), demolition, reinforced concrete structures

Streszczenie

W artykule przedstawiono analizę wpływu procesu rozbiórki na oddziaływania środowiskowe konstrukcji żelbetowej, do wykonania której zastosowano kruszywo z recyklingu betonu. Przyjęto dwa scenariusze produkcji kruszywa zróżnicowane pod względem zakresu i ustalono udział kruszywa w oddziaływaniach całkowitych konstrukcji oraz wpływ rozbiórki na efektywność środowiskową kruszywa. W badaniach wykorzystano model NONROAD jako narzędzie umożliwiające ustalenie emisji generowanych przez sprzęt służący do pozyskania i przetwarzania gruzu budowlanego. Oddziaływania środowiskowe oceniono na podstawie wartości wskaźnika Ecopoint. Pomimo przeważającej w stosunku do pozostałych składników ilości kruszywa w mieszance betonowej nie generuje ono istotnych oddziaływań środowiskowych. Sama rozbiórka jest natomiast procesem dominującym w produkcji kruszywa i zasadne jest uwzględnianie jej w analizie środowiskowej.

Słowa kluczowe: oddziaływania środowiskowe, kruszywo recyklingowe, rozbiórka, konstrukcje żelbetowe

1. Introduction

As concrete production is one of the main uses of natural raw materials, the use of concrete within construction significantly influences the demand for aggregates. This is a major challenge for the European mineral aggregates industry, which, in order to satisfy the demands of concrete production, should ensure an annual production of 2,700 million tonnes [21]. Due to the depletion of primary resources and energy-intensive extraction, excessive exploitation of aggregates is becoming a threat to the environment and a global economic problem [18]. However, the increasing amount of construction and demolition waste (C&D) requires the implementation of new waste-management concepts. An effective solution is the promotion of reverse logistics models based on a circular economy, in which the highest possible recovery of materials for re-use is promoted. In this way, debris that is a waste product from the demolition of structures can be used after mechanical processing as an aggregate in concrete production.

Research on the environmental aspects of the recycled concrete aggregate is most often based on the *cutoff* principle. This means omitting the impact of the primary aggregate production process and only considering the processes directly related to C&D waste management. The demolition phase is usually excluded from the analysis [9, 20]. However, research is also performed in which demolition is considered as the first step of recycled aggregate production, prior to the transport of debris to the processing plant or to the landfill as well as mechanical treatment processes [8]. This approach seems to be appropriate if it is considered that the concrete structure to be demolished plays the same role in the production of recycled aggregate as the mine in the case of natural, primary aggregates.

Despite the above-discussed, after the period of technical suitability for use, the demolition of a structure is conducted regardless of the possibility for the recovery, reuse or recycling of materials. According to the standard concept of the building life cycle [5], the demolition process belongs to the end of life stage, within the system boundary. Reconsideration of this phase in the analysis of environmental impacts generated during the production of recycled aggregate may therefore arouse controversy. However, the standard assumptions according to which the transport, waste processing and disposal are also within the boundaries of the previous system, the validity of the analysis of environmental impacts associated with the production of recycled aggregate may be in question.

The lack of consistency in the determination of the boundaries of the recycled aggregate production system observed in the research, encourages the conducting of comparative analyses; such analyses were performed in the article. This was carried out using the example of a beam as the basic structural element of a reinforced concrete structure.

2. Method

2.1. Subject of the research and assumptions

The three-span reinforced concrete beam which was the subject of the previous research of the authors was analysed. It is a beam with a rectangular cross section of dimensions $b = 0.25$ m, $h = 0.85$ m loaded with a permanent load of $g = 24$ kN/m (above the dead load), uniformly distributed over the beam length and a live load of $q = 30$ kN/m. The analysis of the structure was based on the linear elasticity theory and the calculation of the beam was performed in accordance with European Standard [4] for 5 load combinations with consideration to ultimate and serviceability limit states (ULS and SLS). A characteristic value of concrete strength of $f_{ck} = 40$ MPa was assumed. It was found that for the adopted diameter of Ø = 20 mm in the left and right spans ($l_1 = 5$ m) two bars should be applied whereas in the middle span ($l_2 = 7$ m) and supports, three bars should be applied. The total mass of steel was determined to be $m_s = 227.17$ kg.

The research concerned environmental impacts generated during the production of materials necessary to prepare the three investigated beams. The analysis covers two scenarios of the recycled aggregate production process (Fig. 1). The S1 scenario includes basic processes such as: demolition of the building, initial debris crushing, transport of aggregate and re-crushing in the plant using an impact crusher as well as the auxiliary processes of debris loading into the jaw crusher and aggregate loading onto the truck. The S2 scenario excludes only the demolition stage from the analysis, taking all other processes into account. Neither of the scenarios takes into account the potential for reusing materials without processing, waste disposal, transport of ingredients to the concrete plant and production of the concrete mixture as well as the subsequent life cycle stages of the new structure. For both scenarios, the processes are the same and do not affect the result of the comparative analysis.

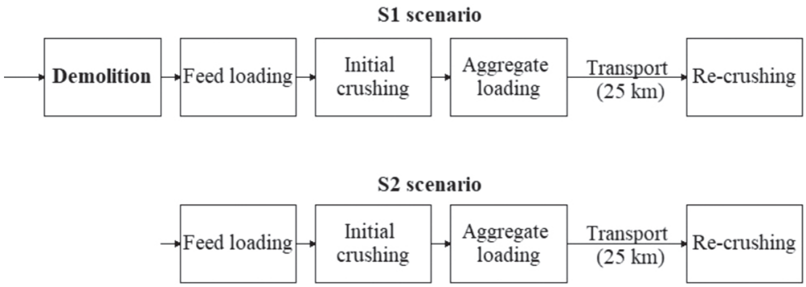

Fig. 1. Scope of the analyses within the considered scenarios of RCA production

2.2. Design of the recycled aggregate concrete mixture

The composition of the concrete mixture in which the natural aggregate was completely replaced with recycled concrete aggregate was analytically determined based on the recommendations included in [12]. It has been taken into account that the physical and mechanical properties of the recycled concrete aggregate are different from the properties of natural aggregate. The analysis considered the influence of the characteristic value of primary concrete strength on crushing strength correlated with recycled aggregate concrete properties (Fig. 2).

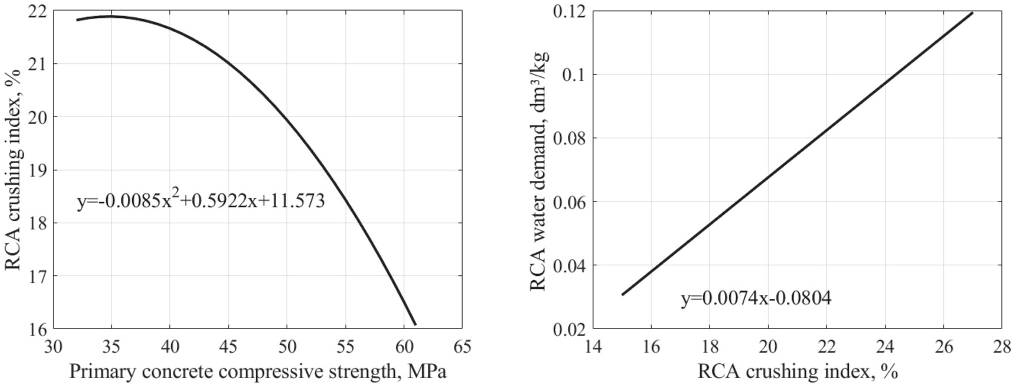

Fig. 2. Effect of primary concrete strength on the crushing strength (2a); the water-demand of RCA as a function of the crushing index (2b) [12]

It was assumed that the characteristic value of primary concrete strength was 55 MPa and using the relationships shown in Fig. 2, the crushing strength expressed by the crushing index $w_r = 18.43\%$ and the water demand of aggregate $w_{RCA} = 0.056$ dm³/kg were determined. On the basis of these parameters, the set of equations presented in Table 1 combining the content of individual components with the properties of a concrete mixture and hardened concrete was solved. It was assumed that the characteristic value of obtained concrete strength should be $f_{ck} = 40$ MPa and for this strength, the composition of the concrete mixture was determined. Apart from cement, water, fine aggregate (sand) and coarse aggregate, the concrete mixture did not contain admixtures or additives.

Table 1. Equations for designing the composition of a concrete mixture with recycled concrete aggregate according to the analytical method

Strength equation	$f_{cm} = A_{RCA} \cdot [(c/w) - 0.5]$
Robustness equation	$C/\rho_C + P/\rho_P + K_{RCA}/\rho_{RCA} + W = 1000$
Water demand equation	$W = C \cdot w_C + P \cdot w_P + K_{RCA} \cdot w_{RCA}$
Characteristic equation	$P_p = P/(P + K_{RCA})$
Symbols according to [12]: f_{cm} – mean strength, MPa; $f_{cm} = f_{ck} + 8$, Mpa, A_{RCA} equivalent of the coefficient A in the equation describing the strength according to Bolomey, $A_{RCA} = 49.14 - 34.46 \cdot (w/c) + 88.20 \cdot (w/c)^2 - 2.42 \cdot (w/c) \cdot w_r$; C, W, P, K_{RCA} amount of cement, water, fine aggregate (sand) and recycled concrete aggregate in the concrete mixture, kg/m³; P_p share of sand in aggregate, $P_p = 0.35$; w_C, w_P, w_{RCA} water demand of cement, sand and recycled concrete aggregate respectively, dm³/kg; w/c water to cement ratio; w_r – crushing index, %; $\rho_C, \rho_P, \rho_{RCA}$ density of cement, sand and recycled concrete aggregate, respectively, kg/dm³.	

Based on the above calculations, it was found that to achieve the assumed compressive strength, 1 m^3 of concrete mixture should contain 336.7 kg of cement, 187.5 kg of water, 639.9 kg of fine aggregate (sand) and 1,188.4 kg of recycled coarse aggregate. The use of recycled material as a fine aggregate was not taken into account because it is not recommended due to its high absorption [20].

2.3. Environmental impacts of cement, water, fine aggregate and reinforcing steel

Environmental performance was expressed using a set of indicators proposed by standard [5], for six environmental categories: global warming potential (GWP), acidification potential of soil and water (AP), eutrophication potential (EP), abiotic depletion potential for non-fossil resources (ADPE), formation potential of tropospheric ozone (POCP) and abiotic depletion potential for fossil resources (ADPF). Ozone depletion, which can be significantly affected by the processes of RCA production, especially the demolition process, was not taken into account. Due to the uncertainty of the data and the desire to present reliable analysis results, this category was omitted. In the study, only the environmental impacts of the first stage of the structure life cycle (product stage) relating to the production of the concrete mixture components and reinforcing steel are analysed.

Table 2 presents the values of the environmental impacts per unit of cement, water, fine aggregate (sand) and reinforcing steel amount, determined on the basis of Environmental Product Declarations (EPD).

Table 2. The values of environmental indicators in individual categories per unit of materials amount based on EPD

Environmental indicator	Cement [1 t]	Water [1 kg]	Fine aggregate [1 t]	Steel [1 t]
GWP [kg CO_2eq.]	8.98E+2	5.70E-4	3.10E+0	7.67E+2
AP [kg SO_2 eq.]	1.48E+0	8.58E-7	4.33E-2	3.50E+0
EP [kg$(PO_4)^{3-}$ eq.]	2.11E-1	2.48E-7	3.67E-3	9.00E-1
ADPE [kg Sb eq.]	1.10E-3	2.44E-10	2.11E-7	4.20E-4
POCP [kg Ethene eq.]	1.42E-1	8.53E-8	6.64E-3	1.10E+0
ADPF [MJ]	3.44E+3	5.38E-3	3.99E+1	1.16E+4

2.4. Environmental impacts of recycled concrete aggregate

The environmental profile of recycled concrete aggregate is determined on the basis of how it is obtained. The source of environmental impact is primarily equipment used for the demolition of structures and machines used for the crushing of feed, sorting, screening, rinsing and removing impurities, as well as the transportation of aggregate to the concrete plant. For the purpose of this study, it was assumed that the demolition of the structure is performed using hydraulic hammers that constitute excavator equipment. The initial crushing of debris is performed on the construction site using a mobile jaw crusher. The obtained aggregate is then transported to the processing plant and re-crushed using an impact crusher. The loading of the feed into the crusher and the crushed aggregate onto the truck is performed using a wheel loader. It was assumed that the recovery potential of the aggregate is 60% [15] and that the remaining debris is disposed at a landfill site and is not used for construction purposes. Taking this assumption into account, an appropriately increased amount of demolished concrete with respect to the required aggregate content in the concrete mixture was adopted.

Table 3 summarises the characteristics of the construction equipment used in the RCA production process. It was assumed that the machines were equipped with diesel engines that met Tier 4 Final assumptions requiring the maintenance of a specific level of particulate matter and a significant reduction of nitrogen oxides (NOx) emissions relative to pre-existing regulations.

Table 3. The assumed characteristics of the equipment used in the production of recycled aggregates

Production stage	Demolition	Feed crushing	Aggregate loading	Aggregate re-crushing
type of equipment	hydraulic hammer	jaw crusher	wheel loader	impact crusher
power [KM/kW]	160/118	117/86	139/102	136/100
capacity [t/h]	45.5	80	330*	100
age [year]	6	6	6	6
type of propulsion	diesel	diesel	diesel	diesel

* While determining the capacity of the loader, it was assumed that the duration of the duty cycle including loading and discharge as well as manoeuvring with a full and empty bucket is 30 seconds and the bucket is filled to the maximum capacity.

Using the NONROAD model [6], which is a tool for estimating air pollution generated by construction equipment engines, the emission factors EF_{adj} of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx), carbon dioxide (CO_2), sulphur dioxide (SO_2) and particulate matter (PM) for selected construction machines were determined. In the case of HC, CO and NOx emissions, the following relationship was used:

$$Ef_{adj}(\mathrm{HC,CO,NOx}) = Ef_{ss} \cdot TAF \cdot DF,\ \mathrm{g/hp\text{-}hr} \quad (1)$$

where:

- A, b – constants for a given pollutant/technology type, for compression-ignition engines (Diesel) b = 1;
- A_{act} – machine annual activity, h;
- A_f – age factor, fraction of median life expended, $A_f = \frac{t_s \cdot i}{T_{\dot{z}}}$;
- DF – deterioration factor; $DF = 1 + A \cdot A_f^b$ for $A_f \le 1$, for $DF = 1 + A$ for $A_f > 1$;
- EF_{ss} – zero-hour, steady-state emission factor, g/hp-hr;

TAF – transient adjustment factor; for Tier 4 Final: TAF = 1.0;
$T_{ż}$ – median life at full load, h;
a – equipment age, years;
i – load factor;
t_s – cumulative hours;
$t_s = A_{act} \cdot a$, h.

The data necessary for calculations is presented in Tables 4 and 5.

Tables 4–5. Data for calculating of factors for emissions generated during equipment operation, based on [6].

Type of equipment	$BSFC_{ss}$	EF_{ss}				A_{act}	$T_{ż}$	i
		HC	CO	NOx	PM			
hydraulic hammer	0.367	0.1314	0.087	0.276	0.0092	1092	4667	0.59
jaw crusher		0.1314	0.087	0.276	0.0092	955		0.43
wheel loader		0.1314	0.087	0.276	0.0092	761		0.59
impact crusher		0.1314	0.087	0.276	0.0092	955		0.43

Type of equipment	A			
	HC	CO	NOx	PM
hydraulic hammer	0.027	0.151	0.008	0.473
jaw crusher	0.027	0.151	0.008	0.473
wheel loader	0.027	0.151	0.008	0.473
impact crusher	0.027	0.151	0.008	0.473

A similar approach [6] was applied while determining the PM emissions:

$$EF_{\mathrm{adj}(PM)} = EF_{ss} \cdot TAF \cdot DF - S_{PM\mathrm{adj}},\ \text{g/hp-hr} \tag{2}$$

taking into account the change in the sulphur content in the fuel by means of a correction factor :

$$S_{PM\mathrm{adj}} = \cdot\ 453.6 \cdot 7 \cdot soxcnv \cdot 0.01 \cdot (soxbas - soxdsl);\ \text{g/hp-hr} \tag{3}$$

where:

$BSFC$ – in-use adjusted brake-specific fuel consumption (lb fuel/hp-hr);
$S_{PM\mathrm{adj}}$ – adjustment to PM emission factor to account for variations in fuel sulphur content, g/hp-hr;
$soxbas$ – default certification fuel sulphur weight percent, $soxbas = 0.33\%$;
$soxcnv$ – grams PM sulphur/grams fuel sulphur consumed, $soxcnv = 0.02247\%$;
$soxdsl$ – episodic fuel sulphur weight percent (specified by user), $soxdsl = 0.25\%$;
7.0 – grams PM sulphate/grams PM sulphur;

453.6 – conversion from lb to grams.

CO_2 and SO_2 emissions were determined on the basis of relationships:

$$CO_2 = (BSFC \cdot 453.6 - \mathrm{HC}) \cdot 0.87 \cdot 44/12;\ \mathrm{g/hp\text{-}hr} \tag{4}$$

$$SO_2 = (BSFC \cdot 453.6 \cdot (1 - soxcnv) - \mathrm{HC}) \cdot 0.01 \cdot soxdsl \cdot 2;\ \mathrm{g/hp\text{-}hr} \tag{5}$$

where:

0.01 – conversion from percent to fraction;
0.86 – carbon mass fraction of diesel;
2 – grams of SO_2 formed from a gram of sulphur;
44/12 – the ratio of CO_2 mass to carbon mass.

The output stream for the aggregate transport to the processing plant was determined on the basis of the Ecoinvent database, adopting a transport vehicle with a maximum payload of 17.3 t and assuming a transport distance of 25 km. The emissions were classified into relevant environmental impact categories and then subjected to a characterisation procedure that reflects the impact of each compound on environmental performance within the categories. The characterisation procedure consists of converting the emissions into the impact indicators of individual categories by multiplying the emissions volume with the corresponding characterisation factors (Table 6).

Table 6. Factors characterising the potential of given chemical compounds for environmental impact within categories

Compound [1 kg]	**Characterisation factors, c_f**			
	GWP [kg CO_2-eq.]	**AP [kg SO_2 eq.]**	**EP [kg$(PO_4)^{3-}$ eq.]**	**POCP [kg Ethene eq.]**
HC	28	–	0.075	0.11
CO	–	–	–	0.027
NOx	265	0.5	0.13	0.028
CO_2	1	–	–	–
SO_2	–	1.2	–	0.048

‘-’ – no factor for the compound

Hydrocarbons (HC) are a group of compounds, among which methane has a particularly significant influence on global warming [10, 11]. The impact of methane on the environmental effect within the global warming category is much greater than that of carbon dioxide; therefore, a factor corresponding to methane as the appropriate representative of the HC was used for characterisation. The NOx group includes nitrogen oxides and expresses the total emission of NO and NO_2. In the process of fuel combustion, it is mainly nitrogen oxide NO that is formed and as a result of its oxidation in the atmosphere, nitrogen dioxide NO_2 is formed. However, the research [7, 14] also indicates the presence of N_2O in the exhaust, which is a greenhouse gas and significantly affects the destruction of the ozone layer. Therefore, the influence of NOx on the environmental effect within the global warming category was assessed using a characterisation factor for N_2O, indicating an almost 300-times greater impact of this gas than carbon dioxide. It should be noted that for the assumed power and capacity of machines, these assumptions do not significantly affect the result of the analysis, but to a large extent, reflect the significance of methane and nitrous oxide with regard to the environment. The most significant factor is the impact of carbon dioxide and considering the available data, the analysis in this case can be limited only to carbon dioxide. For other categories, characterisation factors for HC and NOx groups were used. In the characterisation procedure, the CML environmental impact assessment method and the openLCA database were implemented.

Finally, the values of environmental impacts S_e (kg_{eqiv}/t) within the individual categories per unit of recycled concrete aggregate amount were determined based on the relationships:

$$EF_k = P \cdot \frac{EF_{adj} \cdot 0.7355}{c}; \text{ g/t} \tag{6}$$

$$S_e = \sum_{k=1}^{m} EF_k \cdot 0.001 \cdot cf_{ke}; \text{ kg}_{\text{equiv}}/\text{t} \tag{7}$$

where:

- C – machine's capacity, t/h;
- EF_k – emission factor of k^{th} compound for 1 t of RCA, g/t;
- P – machine's power, kW;
- cf_{ke} – characterisation factor for k^{th} compound within e^{th} environmental impact category (Table 6);
- e – number of environmental impact category;
- m – number of considered compounds;
- 0.7355 – conversion from hp-hr to kWh.

The analysis considers no impact of recycled concrete aggregate production processes on the depletion of abiotic non-fossil resources (ADPE) under the assumption that they do not require exploitation of natural resources. A similar assumption was made in relation to transport using the tank-to-wheel model and considering only fuel consumption, not its supply chain [19]:

$$F_{ON} = BSFC \cdot (0.4536 / 0.7355) \cdot P \cdot i; \text{ kg/h} \tag{8}$$

where:

- F_{ON} – fuel consumption, kg/h;
- P – power of engine, kW;
- i – load factor;
- 0.4536 – conversion from lb to kg;
- 0.7355 – conversion from hp-hr to kWh.

The abiotic depletion potential for fossil resources F_{ADPF} was determined by converting the amount of fuel needed to operate the equipment to the amount of consumed energy using a characterisation factor cf_{ON} = 42 MJ/kg, expressing the calorific value for 1 kg of diesel oil:

$$F_{ADPF} = \frac{F_{ON} \cdot cf_{ON}}{C} \text{ ; MJ/t} \quad (9)$$

The values of environmental impact within individual categories per unit of the concrete mixture components as well as of the reinforcing steel amounts are given in Table 2.

2.5. Environmental assessment

The result of the analysis conducted according to the presented procedure is the Ecopoint indicator E_p – a single value reflecting the environmental performance within all impact categories, calculated on the basis of the formula [2]:

$$E_p = \sum_{e=1}^{n} N_e \cdot w_e \quad (10)$$

where:

- E_p – Ecopoints;
- N_e – normalised value of environmental impact within e^th^ category, ;
- R_e – reference value for environmental impacts within e^th^ category;
- S_{ej} – characteristic value of environmental impact within the e^th^ impact category for j^th^ material;
- cj – the amount of j^th^ material;
- j – material (concrete mixture component or steel);
- e – environmental impact category;
- w_e – weight of e^th^ environmental impact category.

The reference values and weights of environmental indicators were adopted in accordance with [3, 17] and summarised in Table 7.

Table 7. Reference values and weights of environmental indicators according to [3, 17]

	GWP	AP	EP	ADPE	POCP	ADPF
R_i	4.6E+12	2.36 E+10	9.70 E+10	3.23 E+7	1.58 E+10	3.32 E+13
w_i	1.16	1.18	1.14	1.00	1.27	1.00

3. Results and discussion

3.1. Summary of the results and general interpretation

The environmental assessment was conducted for three beams. This decision was taken for logistical reasons; the amount of aggregate needed to produce one beam is much smaller than the effective payload of the transport mean (14.7 t by the 0.85% utilisation rate), the incomplete load is uneconomical and may adversely affect the results of the environmental analysis. Using the NONROAD model, the emission factors EF_{adj} of HC, CO, NOx, PM, CO_2 and SO_2 were determined for the production processes of recycled concrete aggregate. Taking into account the characterisation factors (Table 6), on the basis of relationships (6, 7) the environmental impact of the unit of aggregate amount within individual environmental impact categories were determined. On the basis of the concrete mixture composition and data in Table 2, the environmental impacts of three beams for S1 and S2 scenarios were then calculated. The results are presented in one table (Table 8) with highlighting of the demolition process, which is not covered by the scenario S2 (Fig. 1).

Table 8. Characteristic values of the environmental impacts of materials for three reinforced concrete beams – scenarios S1 and S2 (in S2 scenario, the impacts resulting from the demolition process, included in the shaded column, are omitted)

	Cement	Water	Fine agg.	RCA					Steel
				Demolition	Feed crushing	Loading	Transport	Re-crushing	
GWP*	3.28E+3	1.16E+0	2.15E+1	4.65E+1	1.91E+1	3.32E+0	2.07E+1	1.06E+1	1.18E+3
AP	5.40E+0	1.74E-3	3.00E-1	8.51E-2	3.49E-2	6.08E-3	1.00E-1	1.95E-2	2.40E+0
EP	7.70E-1	5.04E-4	2.55E-2	3.50E-3	1.45E-3	2.50E-4	2.27E-2	8.07E-4	2.52E-1
ADPE	4.01E-3	4.96E-7	1.46E-6	0	0	0	0	0	1.94E-4
POCP	5.18E-1	1.73E-4	4.60E-2	4.93E-3	2.02E-3	3.51E-4	7.05E-3	1.13E-3	4.76E-1
ADPF	1.25E+4	1.09E+1	2.77E+2	3.16E+2	9.43E+1	2.26E+1	2.99E+2	5.27E+1	1.16E+4

*Indicator's units according to Table 2

Based on the results obtained for S1 and S2 scenarios, using the expression (10), the Ecopoint scores were calculated as the sum of the weighted, normalised environmental impacts of individual components. The Ecopoint indicator for the S1 scenario is Ep_{S1} = 2.5611E-9, and for the S2 scenario, Ep_{S2} = 2.5351E-9. Higher Ecopoint scores indicate higher environmental impacts; therefore, the S2 scenario is a more favourable variant from the environmental performance point of view. The difference between the Ecopoint indicators is insignificant and amounts to 1%, which reflects the minor influence of demolition on the total environmental impact generated in the production processes of all components of the concrete mixture and steel. Despite the fact that aggregate generally occupies 60% to 75% of the concrete volume (70% to 85% by mass) [1, 16] its environmental impact is dominated by the production processes of cement and, as in the present case, steel as well as other technological processes [13, 22] that require large amounts of energy and affect the depletion of abiotic resources.

3.2. S1 scenario analysis

Based on the performed calculations, the S1 scenario was analysed in terms of the influence of RCA on the total environmental impact resulting from the production processes of the concrete mixture components and reinforcing steel. Pie charts (3a and 3b) show the share of production processes of individual materials and the environmental impact categories respectively in total impacts expressed by the Ecopoint indicator.

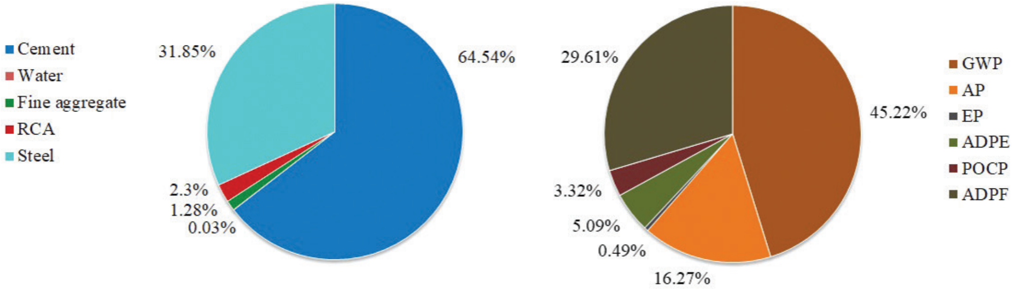

Fig. 3. Share of environmental impacts of individual materials production processes (3a) and categories (3b) in total impacts expressed by the Ecopoint indicator – S1 scenario

The greatest impact on the environmental performance of the product stage relates to cement (65%) and reinforcement (32%) production. This results from the energy intensity of clinker and steel production processes and the considerable amount of greenhouse gases, particularly CO_2, released into the atmosphere. The nature of the production processes simultaneously determines the significant contribution of global warming and abiotic depletion of fossil resources (3b) in the total environmental effect. The production of recycled concrete aggregate accounts for 2.3% of the total environmental impact. The results were obtained under the assumption that the equipment used for the production of recycled aggregates was produced in 2014 (Table 3). When considering the use of machines produced in 2011 and engines meeting Tier 3 requirements, the impact of recycled concrete aggregate increases to 3.3%.

The shares of the material production processes in environmental impacts within the individual categories for the S1 scenario are shown in the bar graph (Fig. 4). With regard to contributions to environmental impacts, cement clearly dominates and there is also a significant influence of reinforcing steel on the environmental performance within each category. Recycled concrete aggregate contributes the most to environmental impacts covered by the ADPF category (2.97%), which results from the energy-intensive processing of concrete debris.

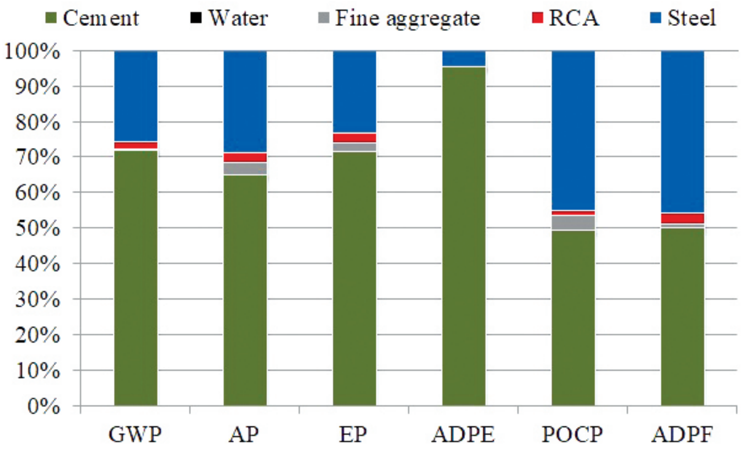

Fig. 4. Share of material production processes in the environmental impacts within individual categories – scenario S1

The results of the global analysis of the S2 scenario, in which the demolition process was omitted, do not differ significantly from the results of the S1 scenario analysis presented above. This is due to the minor contribution of demolition in the total impact generated by the components of the concrete mixture and steel (~1%). More pronounced differences between the S1 and S2 scenarios occur in the environmental analysis covering only the aggregate production processes presented in Section 3.3.

3.3. Detailed comparative analysis of the scenarios

Analysis of individual processes indicates that the largest share of the environmental impact resulting from the recycled concrete aggregate production, according to the S1 scenario, relates to the demolition process (44%) and then the processes of transport, crushing and loading (Fig. 5a). Thus, in order to comprehensively characterise the impact of recycled aggregate on the environment, consideration to the demolition process seems to be necessary and it is suggested to treat this process as a source of material for the production of aggregates. In the case of the S2 scenario (Fig. 5b), which excludes the demolition of the structure, the transport process of aggregates from the construction site to re-crushing in the processing plant becomes increasingly important (61%).

Figure 6 shows the influence of recycled concrete aggregate production processes on the total environmental impacts related to this production within individual categories. Aside from the significant influence of demolition in the S1 scenario (Fig. 6a), transport has a particular importance and the intensity of its impact depends on the transport distance. The environmental effect of recycled concrete aggregate production according to the S2 scenario (Fig. 6b) is determined by this factor. As a result of increasing the transport distance to 50 km or 100 km, the share of transport in the environmental effect of RCA increases to 51% and 67% in the S1 scenario and 76% and 86% in the S2 scenario, respectively. Therefore, further research is planned to determine the sensitivity of the analysis results to factors such as transport distance and equipment age. It should be noted that in the case of the large-scale production of concrete mixture and the related greater demand for aggregate, it is additionally required to take into account idle runs and emissions generated during transport.

Comparing the share of individual processes in the environmental impacts of RCA, it is stated that depending on the adopted scenario, optimisation will be targeted at the transport process (S2) or the demolition and transport processes (S1).

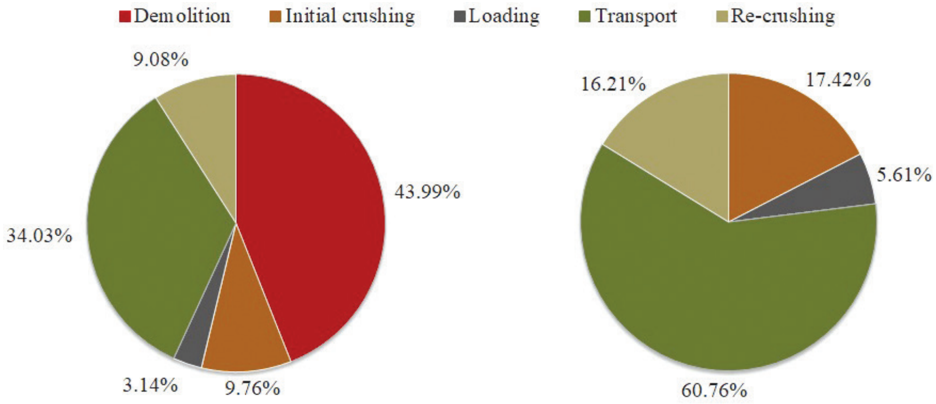

Fig. 5. Share of production processes in the total impact of recycled concrete aggregates: (5a) scenario S1, (5b) scenario S2

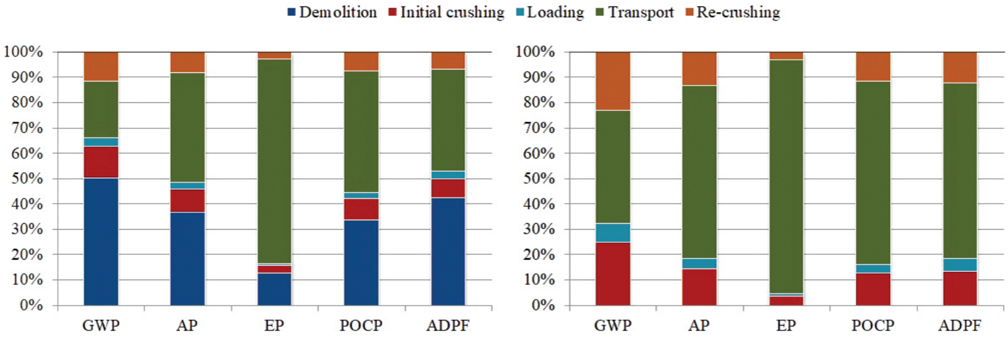

Fig. 6. The influence of aggregate production processes on environmental impacts within individual categories: (6a) S1 scenario, (6b) S2 scenario

The influence of recycled aggregates on ozone layer depletion requires additional analysis. Previous research [18] suggests that there are no significant changes to the results obtained; however, it do not provide exhaustive data on the aggregate production processes included in the analyses. Therefore, assuming that the recycled aggregate has a negligible influence on environmental impacts in this category could be over-simplifying the issue. The creation of the hole in the ozone layer is a consequence of the release of gases (including nitrogen oxides generated during fuel combustion) into the atmosphere, and for this reason, with an adequate quality of data, it should be included in the analysis.

4. Conclusions

In the conducted research, two scenarios of recycled concrete aggregate production (S1, S2) were compared in terms of the impact of production processes, including the demolition process, on the total environmental impacts of reinforced concrete beams and the aggregate itself. Based on the results, it was found that:

- The demolition process accounted for just over 1% of the total environmental impact; with such a minor contribution, omitting the demolition in the analysis of the first stage of the life cycle (product stage) is not significantly imprecise.
- More pronounced differences between S1 and S2 scenarios occurred in the environmental analysis covering only the aggregate production processes.
- In the case of the S1 scenario, demolition is responsible for almost half of the environmental impacts generated during production.
- The exclusion of demolition (scenario S2) caused a significant increase in the contribution of transport in the environmental effect of recycled concrete aggregates (from 34% to 61%).
- Recycled concrete aggregate contributed the most to environmental impacts covered by the ADPF category (almost 3% of total category impact).
- Environmental impacts resulting from the aggregate production depended on the characteristics of the machine park, engine parameters and transport distance.
- Although the S1 scenario had higher Ecopoint scores, it is recommended for the comprehensive assessment of the influence of recycled concrete aggregate on the environmental effect.

References

[1] ACI Committee *Aggregates for Concrete*, ACI Education Bulletin E1-07, 2007.
[2] Building Research Establishment (BRE), [online] http://www.bre.co.uk (access: 02.2019).
[3] Castellani V., Benini L., Sala S., Pant R., *A distance-to-target weighting method for Europe 2020*, The International Journal of Life Cycle Assessment 21/2016, 1159–1169.
[4] EN 1992-1-1:2004 Eurocode 2: Design of concrete structures, Part 1–1: General rules and rules for buildings, 2004.
[5] EN 15643-2 Sustainability of construction works – assessment of buildings, part 2: framework for the assessment of the environmental performance, 2011.
[6] EPA Exhaust and crankcase emission factors for nonroad engine modeling – Compression-ignition, 2010.
[7] EPA Nitrogen Oxides (NOx), why and how they are controlled EPA-456/F-99-006R, 1999.
[8] Estanqueiro B.A.M, *Life cycle assessment of the use of recycled aggregates in the production of concrete*, Instituto Superior Técnico, Universidade Técnica de Lisboa-UTL, Lisboa 2011.

[9] Estevez B., Aguado A., Josa A., *Deconstruction and Materials Reuse CIB Publication 287,* Proceedings of the 11th Rinker International Conference, 2003.

[10] IIASA The Greenhouse Gas Methane (CH4): Sources and Sinks, the Impact of Population Growth, Possible Interventions. WP-92-042, 1992.

[11] Kirkinen J., Palosuo T., Holmgren K., Savolainen I., *Greenhouse Impact Due to the Use of Combustible Fuels: Life Cycle Viewpoint and Relative Radiative Forcing Commitment*, Environmental Management 42/2008, 458–469.

[12] Koper A., Koper W., *Projektowanie betonów konstrukcyjnych na kruszywach z recyklingu*, Materiały Budowlane 3/2017, 38–41.

[13] Marinković S., Radonjanin V., Malešev M., Ignjatović I., *Comparative environmental assessment of natural and recycled aggregate concrete*, Waste Management 30/2010, 2255–2264.

[14] Mollenhauer K., Tschoke H., *Handbook of diesel engines*, Springer, Berlin 2010.

[15] Nagataki S., Gokce A., Saeki T., Hisada M., *Assessment of recycling process induced damage sensitivity of recycled concrete* aggregates, Cement and Concrete Research 34/2004, 965–971.

[16] Okonkwo V.O., Arinze Emmanuel E., *A Study of the Effect of Aggregate Proportioning On Concrete Properties*, American Journal of Engineering Research 7/2018, 61–67.

[17] Sala S., Crenna E., Secchi M., Pant R., *Global normalisation factors for the Environmental Footprint and Life Cycle Assessment*, JRC Technical Reports, 2017.

[18] Serres N., Braymand A., Feugeas F., *Environmental evaluation of concrete made from recycled concrete aggregate implementing life cycle assessment*, Journal of Building Engineering 5/2016, 24–33.

[19] Silva C.M., Gonçalves G.A., Farias T.L., Mendes-Lopes J.M.C., *A tank-to-wheel analysis tool for energy and emissions studies in road vehicles*, Science of The Total Environment 367/2006, 441–447.

[20] Tošić N., Marinković S., Dašić T., Stanić M., *Multicriteria optimization of natural and recycled aggregate concrete for structural use*, Journal of Cleaner Production 87/2015, 766–776.

[21] UEPG (European Aggregates Association), [online] http://www.uepg.eu (access: 01.2019).

[22] Wałach D., Dybeł P., Sagan J., Gicala M., *Environmental performance of ordinary and new generation concrete structures – a comparative analysis*, Environmental Science and Pollution Research 26/2019, 2980–3990.

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