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Environmental Assessment of Two Use Cycles of Recycled Aggregate Concrete

Tereza Pavlů [1,*], Vladimír Kočí [2] and Petr Hájek [1]

1 University Centre for Energy Efficient Buildings, Technical University, Prague, Trinecka 1024, 273 43 Bustehrad, Czech Republic; petr.hajek@fsv.cvut.cz

2 Department of Environmental Chemistry, Faculty of Environmental Technology, University of Chemistry and Technology, Technicka 5, 166 28 Praha 6—Dejvice, Prague, Czech Republic; Vlad.Koci@vscht.cz

* Correspondence: tereza.pavlu@cvut.cz; Tel.: +420-724-507-838

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Abstract: The main goal of this study was to compare two use cycles of natural aggregate concrete and recycled aggregate concrete, which is another way to compare the environmental impacts of recycled materials. A series of concrete mixtures with various replacement ratios of primary resources with recycled ones were prepared for this study. The mechanical properties of concrete mixtures were examined and were used for the design of structural elements in the same utilized properties. The two use cycles of a structural element were compared using life cycle assessment (LCA). In the first use cycle, the LCA of the structural element containing only primary raw materials was assessed. In the second use cycle, the LCA of a structural element in which primary materials were partially replaced by recycled ones was assessed. The obtained results confirm the potential use of high-quality recycled aggregate originating from local sources in some applications in building structures. Furthermore, the environmental assessment indicates the benefits of using recycled materials, such as environmental savings, especially the reduction of primary resource use, embodied energy, and embodied emissions, as well as reduction of the pressure on landfill sites.

Keywords: construction and demolition waste; recycled concrete aggregate; recycled aggregate concrete; recycled concrete powder; LCA; environmental savings; raw material savings

1. Introduction

The key hierarchy of sustainability goes through the three "R"s: the first is reduce, then reuse, and finally recycle. When the materials have been used in construction and there is no way to reuse them, recycling is the best possible way to reduce primary sources. The research in the field of recycled aggregate concrete dates back to the 1940s [1]. The crucial importance of reusing recycled concrete as an aggregate for a new concrete mix follows from the fact that concrete is the second most used material after water. It is evident that, due to its physical properties, concrete will remain a key construction material in the future. According to this prediction, its global use will continue to increase in the future. Simultaneously, there will be an increase in the amount of demolished concrete structures and in the need for the recycling and reuse of recycled concrete.

The aim of this paper was to contribute to increasing the use of recycled concrete in a more environmentally responsible way. The effective use of recycled concrete aggregate (RCA) in new concrete mixes can reduce waste dumping and simultaneously decrease the need for virgin aggregate—both important environmental aspects to be considered in responsible sustainable management. This also represents an important contribution to the solution of one of the core objectives of the 2030 UN Agenda for Sustainable Development: Goal 12 (SDG12)—Ensure sustainable consumption and production patterns [2]. This goal is focused on economic growth based on efficient resource use and low environmental degradation while improving the well-being of people. This can be done by a shift towards a more sustainable consumption of resources and improved production processes. Sustainable consumption and production policies are key to improving living standards without compromising the resource needs of future generations. These policies aim to decouple economic growth from environmental degradation.

Mineral resource depletion is a very real problem, not only from a local/regional perspective but especially from a global point of view. The per-capita material footprint of developing countries almost doubled in the past eight years, representing a significant and necessary improvement in material standard of living [2]. Most of this increase is connected with a rise in the consumption of non-metallic minerals, due to the growth of infrastructure and construction in these areas. This also covers the environmental impact of concrete structures, which are still growing in number. For this reason, concrete reuse and recycling represent important tasks in this process and are a promising challenge for the future.

1.1. Literature Review of the Environmental Assessment of Recycled Aggregate Concrete

In terms of sustainable material consumption (SDG12), effective construction depends on several factors, including optimization of materials use, reuse and recycling of materials, energy savings, control of emissions, and increasing the durability and lifespan of materials. Cement production is responsible for 83% of total energy use in the production of non-metallic minerals [3], and represents around 90% of the total embodied energy of concrete [4]. Cement production is a major global source of greenhouse gases. It was estimated that the cement industry was responsible for 5–7% of global anthropogenic CO_2 emissions in 2009 [5,6], and the newest data shows that it accounts for about 8% of total global CO_2 emissions [7]. Overall, it is evident that the contribution of cement production is the highest in all assessed impact categories and ranges between 75% to almost 94% of the total impact, depending on the impact category indicator [8]. The highest contribution of cement production is in the case of global warming potential, which causes climate change and is responsible for 74% to 81% of the total CO_2 emissions of concrete [9]. In contrast, the contribution of aggregate production is very small compared to cement production. The different energy consumption in the production of various types of natural aggregate (NA) (river NA and crushed NA) and recycled aggregate (RA) has no significant effect on the total results [4,8,10]. Aggregate production represents only 13% to 20% of the total CO_2 emissions of concrete. Nevertheless, the sand extraction from seaside or riverbed has a negative environmental impact on local fauna and flora ecosystems [11]. However, the utilization of RA as a replacement of NA in concrete production reduces primary resources consumption by up to 44% [10]. Furthermore, the concrete production is responsible for emissions of SO_X, increasing the acidification of the environment. Finally, the type and distance of aggregate transportation also influence the life cycle analysis (LCA) of concrete [4,12–14].

Research has been published on the environmental assessment of recycled aggregate concrete (RAC) for structural use and its comparison with natural aggregate concrete (NAC) [4,6,8–24]. The comparison of the environmental impacts of RA with NA production for the production of lower-grade concrete products was studied [15]. Few studies have been published on the comparison of different types of aggregate (e.g., river NA, crushed NA, and coarse RA) [4,12,15–17]. In [3,11,13], aggregate transportation scenarios were compared to determine the impact of the transportation phase (type and distance). Furthermore, in some studies [8,10] the decline of RAC properties was compensated with additional cement. Some studies were published on how to separate attached cement mortar from the aggregate surface from waste concrete (e.g., via heat treatment and abrasion or separation by microwave heating) [25,26]. The LCA method is one possible way to compare the environmental impacts of concrete structural elements [27].

1.2. Literature Review of Mechanical Properties and Durability of Recycled Aggregate Concrete

The quality of recycled aggregate concrete is lower than that of conventional concrete with NA prepared using the same mix design. The reason for the reduction in quality is mainly related to the quality of the recycled aggregate. The research of the replacement of NA by RA has become very complex over the past four decades. Recycled aggregate characteristics and their influence on concrete properties have been investigated during this time. Mechanical, physical, and durability properties of recycled aggregate concrete have been examined and described in many studies [6,28–48]. The properties of recycled aggregate concrete are influenced by the replacement rate of RCA, as well as by its quality and composition [29,30]. Further, the decline of mechanical properties depends on the presence of two interfacial transition zones, which is normally between aggregate and new cement mortar, but in the case of RAC, it is also between attached old mortar and new cement mortar [31–33,49]. The maximal replacement ratios of coarse NA by RCA in the concrete mixture without seeing a degradation in compressive strength have been presented [34–36]. It was found that the maximal replacement rate of NA by RCA is 30% [35,36] or 50% [34,35], which is also defined in the European Standard [50]. Recycled aggregate concrete could also be used for structural elements [51].

The use of fine RA replacement as a partial or full replacement of natural sand is mainly complicated by the higher mortar and impurity contents of the fine RA as compared to coarse RA [35]. This is one of the main reasons that the replacement of sand in concrete mixtures by secondary raw materials has not yet been defined in Standards. The previous research has indicated different maximal replacement rates. In one study, the maximal replacement rate of sand by fine RCA in concrete mixtures without significant effect on the mechanical properties was up to 30% [28]. In another study where the natural sand was fully replaced by fine RCA, a positive impact on mechanical properties was seen. The increase in compressive strength was 10% [52]. The fines content (particles finer than 75 µm) of aggregate has a larger surface area, which leads to higher water consumption. Nevertheless, the fines content fills pores between larger particles for a better aggregate skeleton in the concrete mixture [53]. Particles size between 125 and 500 µm contain a high proportion of cement mortar [11]. This could lead to better mechanical and permeability properties of the concrete. The use of fine and coarse RCA also influences the strength development of RAC [42].

There are some possible ways to replace cement in concrete mixtures with industrial by-products and waste materials, such as fly ash [54], silica fume [55], granulated blast-furnace slag [56], ceramic powder [57–59], volcanic powder [60], recycled cement powder from waste concrete [61–63], and recycled gypsum (from recycled waste gypsum boards) instead of natural gypsum for cement production [64]. The use of recycled cement powder from waste concrete is a potential way to use the finest fraction from recycled concrete. The major constituent of the fines content of recycled concrete is cement paste, which can be used as a clinker raw material because it contains a high concentration of CaO [65]. It was verified that recycled cement powder could replace 10% of the cement in a concrete mixture [26].

This paper presents the characteristics of recycled aggregate concrete and its environmental evaluation using the life cycle assessment method. Three concrete mixtures containing recycled material were compared with a conventional concrete mixture (NAC): (1) RAC with full replacement of natural gravel; (2) RAC with full replacement of natural gravel and partial replacement of natural sand; (3) partial replacement of natural sand and partial replacement of cement by recycled concrete powder (RCP). The functional unit of the comparison was two cubic meters of concrete used for the structural element. In the first use cycle, the LCA of a structural element containing only primary raw materials was assessed. In the second use cycle, the LCA of structural elements in which the concrete mixtures have different partial replacement ratios are experimentally and environmentally assessed. Results showed that the addition of recycled concrete aggregate as a replacement for gravel negatively influenced the performance of RAC mixtures. However, the utilization of RCA and RCP for newly produced concrete leads to environmental savings.

2. Materials and Methods

A comparative environmental assessment of four different concrete mixes was performed using LCA. An assessment was carried out according to a typical scenario for the Czech context. The assessed scenarios included two use cycles considered as open-loop systems. The first scenario covered the production of NAC and the second one covered the production of RAC. The system boundaries of both of the assessed scenarios covered cement production, concrete production, use in structure and landfill, and natural coarse aggregate and natural sand (NA) or recycled concrete aggregate (RCA) production, respectively. The production processes and use (including concrete production, construction phase, and operation phase) and demolition were considered the same for all types of concrete (Figure 1).

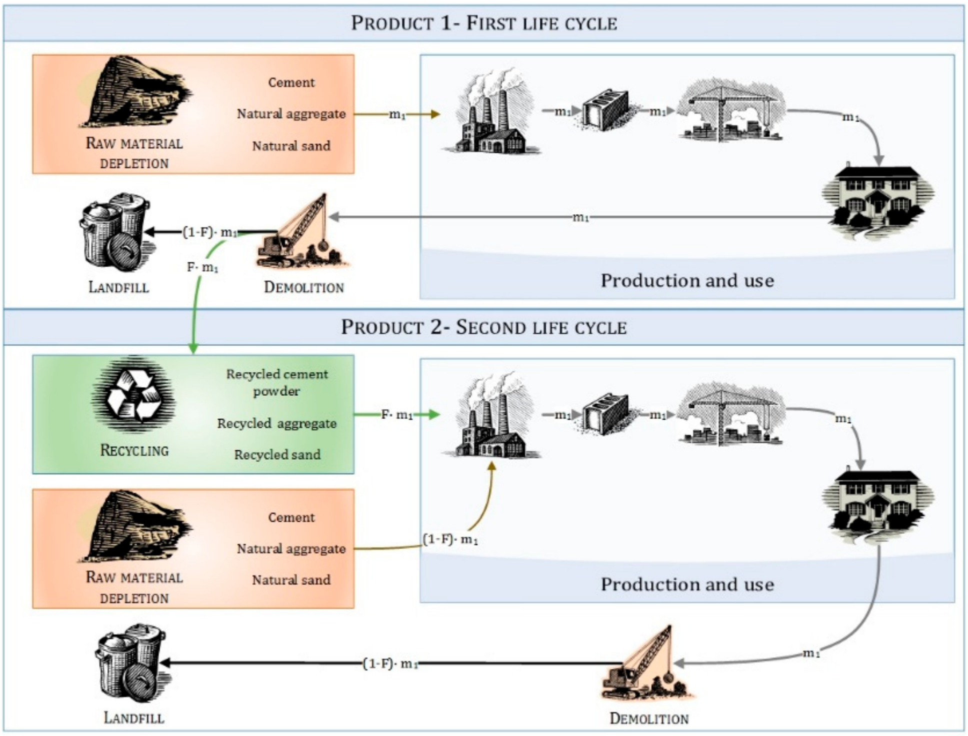


Figure 1. The use cycles of two concrete elements and system boundaries in the case study, where m_1 is the mass of the primary raw materials and F is the replacement ratio of primary raw materials.

All four concretes were designed for the same structural use, with the same amount of cement and the same effective water–cement ratio in order to examine the impact of the proposed technique. In one mixture, ordinary Portland cement (OPC) was replaced with recycled cement powder (RCP). The mechanical and physical properties of the manufactured mixtures were investigated. In the following, the tests of concrete properties are described.

Life cycle assessment (LCA) is a comparative methodology that evaluates the environmental impact of processes and products during their life cycle. This method compares various solutions with the same functional unit and boundaries. Commonly, one use cycle of a product or material is used for LCA. Two use cycles are assessed in this case study. The main reason for this is that it is necessary to produce ordinary concrete (NAC) in order to get RAC in the future.

Figure 1 shows the study flow diagram. For the simplification of this method, the same processes were not included in the comparison. These phases are shown in Figure 1 as "Production and use". There are studies [3,11,13] where aggregate transportation scenarios were compared to find the impact of the transportation phase. In this paper, the transportation phase was considered to be the same. The reason for this consideration is that in the Czech Republic the transport distances and transport types of natural and recycled aggregate are similar.

2.1. Materials

An experimental design was carried out to obtain the mix proportions of four different concrete mixtures with different aggregate types, where all of them were designed for the same structural use:

- NAC: Natural aggregate concrete made entirely with NA and OPC;
- RAC C100: Recycled aggregate concrete with natural sand and coarse RCA (100% replacement ratio) and OPC;
- RAC C100 F30: Recycled aggregate concrete with coarse RCA (100% replacement ratio), fine RCA (30% replacement ratio), and OPC;
- RAC C100 F30 P5: Recycled aggregate concrete with recycled coarse aggregate (100% replacement ratio), recycled fine aggregate (30% replacement ratio), and with partial replacement of OPC with RCP (5% replacement ratio).

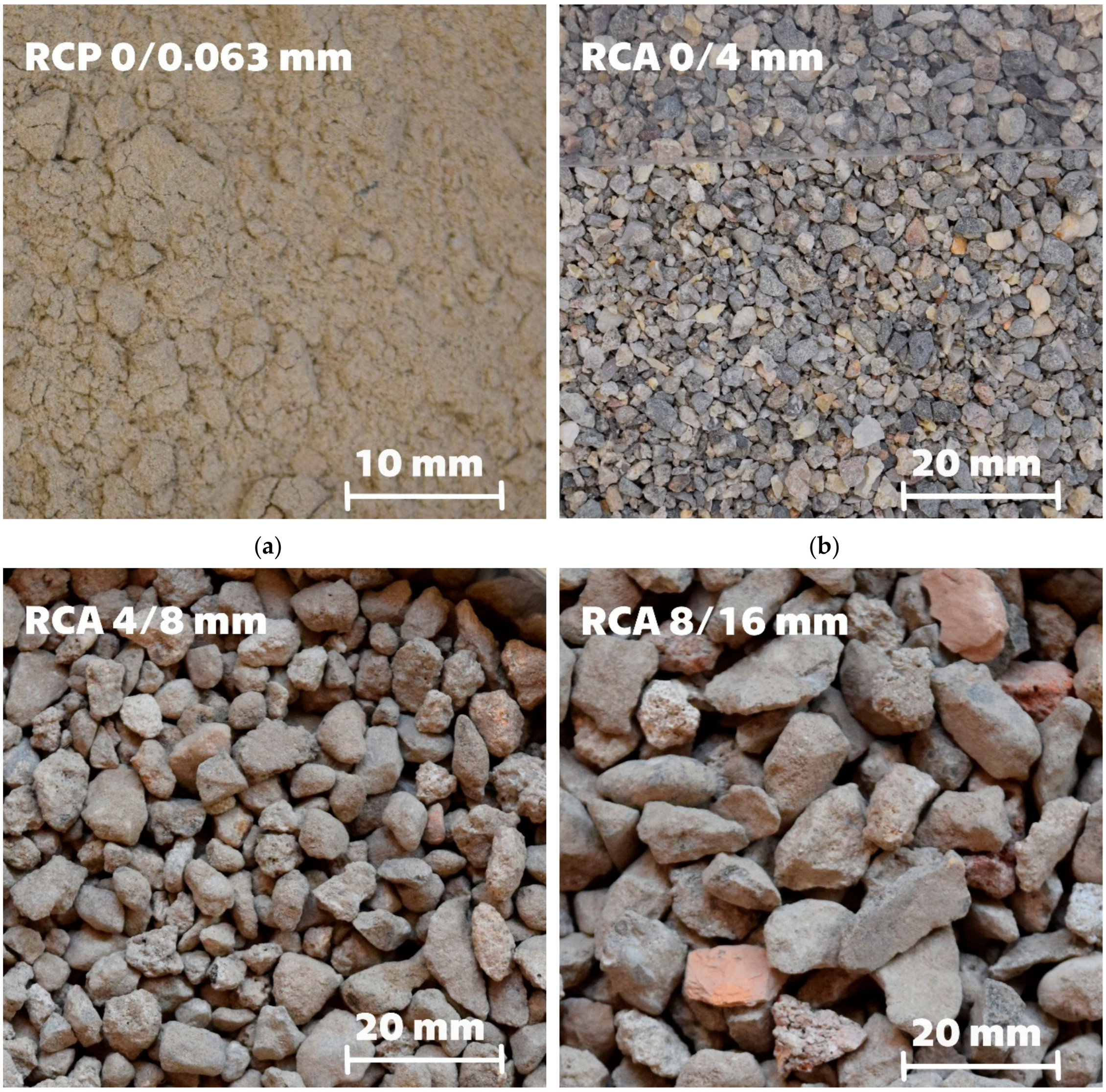
2.1.1. Recycled Concrete Aggregate Properties

Previous research has verified the higher water absorption and lower density of RCA. According to the previous studies, the water absorption of coarse RCA ranges between 0.5% and 14.75%, and the dry density of coarse RCA ranges from 1900 to 2700 kg/m^3 [35]. The water absorption of fine RCA ranges between 4.3% and 13.1% and the dry density of fine RCA ranges from 1900 to 2360 kg/m^3 [66]. The higher water absorption and lower density of RCA is caused by old mortar attached to the surface of original aggregate; for this reason the mortar is more porous and less dense than the aggregate particles [35]. This leads to a higher water absorption of recycled aggregate, which influences the effective water–cement ratio and has negative impact on the workability of the concrete mix.

The recycled concrete aggregate originated from a recycling center in the Czech Republic. The steel reinforcement was separated by a magnetic separator, which is one part of the mobile recycling plant. Further, the crushing of the concrete fragments was performed in the same mobile recycling plant to the fraction 64/128 mm, which were crushed and sieved to fractions 0/4, 4/8, and 8/16 mm (see Figure 2) in the second step, while the natural aggregate was quarry sand and crushed quarry aggregate. All types of aggregate were used in natural humidity conditions. An additional water amount was calculated on the basis of the water absorption of RCA after 10 min in concrete mixtures containing RCA. Basic properties of RCAs and NAs are shown in Table 1, while their particle size distributions are presented in Figure 3. Limits are defined in CSN EN 12620. Water absorption and density were verified by the pycnometric method according to CSN EN 1097-6. The water absorption of RCA after 24 h varied from 4.2% (fraction 8/16 mm) to 6.0% (fraction 4/8 mm), and the oven-dried density varied from 2350 kg/m^3 (fraction 4/8 mm) to 2500 kg/m^3 (fraction 8/16 mm). Due to its properties and composition, the RCA can be classified, for instance, as class A according to the Czech standard CSN EN 12,620 + A1 [50]. The results of the RCA properties correspond with the results of previous studies.

Table 1. Oven-dry density and water absorption of aggregate according to CSN EN 1097-6.

	Oven-Dry Density (kg/m^3)	Water Absorption (%)
NA (0/4 mm)	2600	2.9
NA (4/8 mm)	2650	1.1
NA (8/16 mm)	2650	0.8
RCA (0/4 mm)	2300	8.3
RCA (4/8 mm)	2350	6.0
RCA (8/16 mm)	2500	4.2

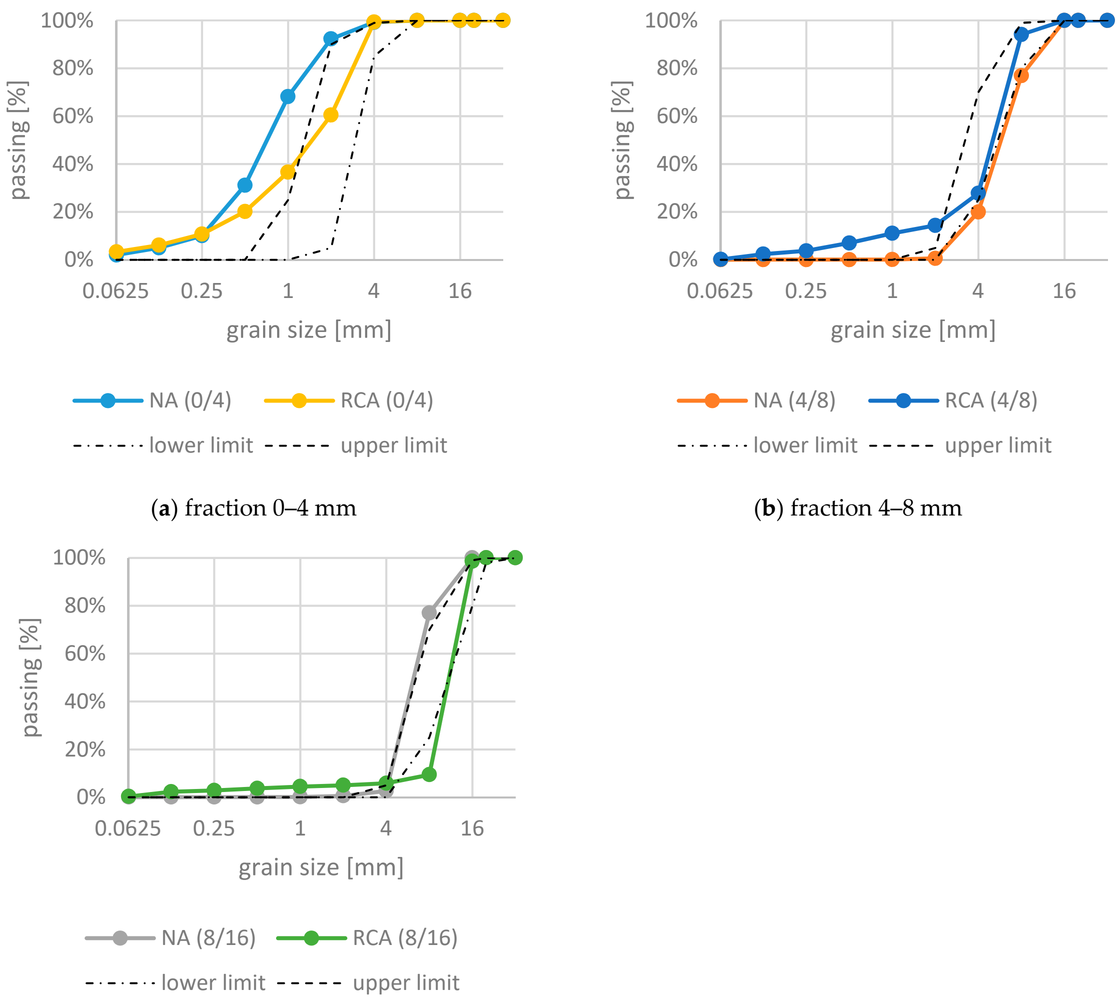


(**a**) (**b**) (**c**) (**d**)

Figure 2. RCA used for concrete mixture RAC: (**a**) sample of RCP (0/0.063 mm); (**b**) sample of RCA 0/4 mm; (**c**) sample of RCA 4/8mm; (**d**) sample of RCA 8/16 mm. RCA, recycled concrete aggregate; RAC, recycled aggregate concrete; RCP, recycled cement powder.

2.1.2. Recycled Concrete Powder

Ordinary Portland cement was used as the reference material to compare conventional binder with RCP. Recycled cement powder was formed during the crushing of RCA of the fraction 64/128 mm. The chemical composition as analyzed by the SPECTRO XEPOS energy-dispersive X-ray fluorescence (ED-XRF) spectrometer, as well as physical properties including density and specific surface area are shown in Tables 2 and 3. Figure 4 shows the particle size distribution of the powder as measured by a HELOS (H1922) laser particle size analyzer. The RCP had a similar particle size distribution to cement, thus enabling high pozzolanic reactivity in concrete mixes containing RCP.



(**a**) fraction 0–4 mm (**b**) fraction 4–8 mm

(**c**) fraction 8–16 mm

Figure 3. The particle size distributions of natural aggregate (NA) and RCA (grain sizes 0/4 mm, 4/8 mm, and 8/16 mm) according to CSN EN 933-1.

Table 2. Chemical composition of ordinary Portland cement (OPC) and RCP % (*w/w*).

	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	Na_2O	SO_3	LOI
OPC	20.2	4.7	61.9	3.0	2.6	0.2	3.9	3.5
RCP	34.6	10.5	28.8	5.0	5.8	1.7	1.8	11.8

Table 3. Physical properties of ordinary Portland cement (OPC) and RCP.

	Density (g/cm^3)	Specific Surface Area (cm^2/g)
OPC	3.044	3.630
RCP	2.585	3.635

2.1.3. Concrete Mixes

Recycled aggregate concrete mixtures were designed according to the Czech standard [50]. According to this standard, for structural applications a maximal replacement rate up to 30% without loss of the concrete's compressive strength is recommended with this RCA type. Different RAC mixing procedures have been published in previous studies. One such method is to use additional water before mixing to pre-soak the RCA [67,68]. This technique was used in this study due to its simplicity as well as economic and time benefits. This solution is suitable for use in practice where it has been verified.

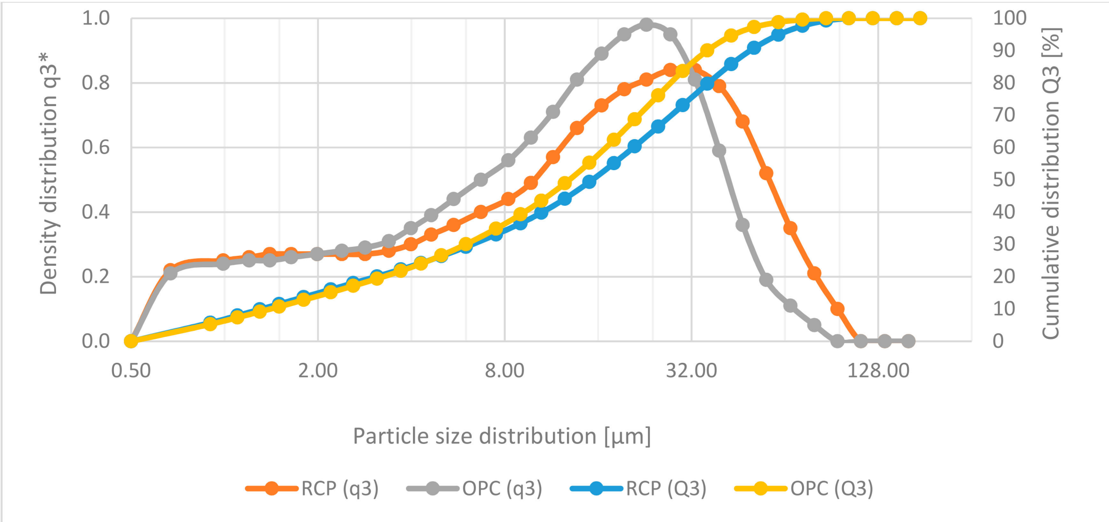


Figure 4. The particle size distributions of OPC and RCP.

The composition is given in cubic meters. With the aim of reaching a concrete compressive strength class of C30/37 and exposition class XC1, CEM I 42.5 R OPC was used for experimentation. The cement content was kept constant at 320 kg/m^3. The constitution of the granular skeleton was established according to the Bolomey particle size distribution curve. The parameter A was equal to 16 for the design of RAC mixtures, due to particle shape and roughness [69]. The properties of aggregates were used for mixture design. Due to the high water absorption of RCA, it is necessary to add a certain amount of water to saturate the RCA before or during mixing to obtain the desired RAC workability. In this case, RCA with natural air humidity was used for RAC mix production, and additional water quantity was calculated on the basis of RCA water absorption after 10 min. The effective water/cement (w/c) ratio shown in Table 4 refers to the free water content, excluding the amount of additional water. No water-reducing admixtures were used.

Table 4. Concrete mix C30/37 proportions for NAC (natural aggregate concrete made entirely with natural aggregate and OPC) and RAC per cubic meter. w/c: water-to-cement.

Type of Concrete	NAC	RAC		
		RAC C100	**RAC C100.F30**	**RAC C100.F30.P5**
NA 0/4 mm (kg)	767	784	603	603
NA 4/8 mm (kg)	458	0	0	0
NA 8/16 mm (kg)	726	0	0	0
RCA 0/4 mm (kg)	0	0	216	216
RCA 4/8 mm (kg)	0	364	310	310
RCA 8/16 mm (kg)	0	710	714	714
OPC CEM I 42.5 R (kg)	320	320	320	304
RCP (kg)	0	0	0	16
Effective w/c ratio (-)	0.50	0.50	0.50	0.50

2.1.4. Tests of Concrete Properties

Laboratory tests with various mix proportions of NAC and RAC were tested on Controls MCC8 50-C8422/M according to the following standards to obtain the target values: compressive strength EN 12390-3 (2003); flexural strength EN 12390-5 (2009); static modulus of elasticity EN 12390-13 (2014); dynamic modulus of elasticity EN 12504-4 (2005). For each concrete mix, three samples were tested, the average values of concrete properties are shown in Table 5 and Figure 5.

Table 5. Mechanical properties of NAC and RAC concretes.

	Density	Compressive Strength	Flexural Strength	Static Modulus of Elasticity	Dynamic Modulus of Elasticity	Target Strength Class
Type of Concrete	**(kg/m^3)**	**(MPa)**	**(MPa)**	**(GPa)**	**(GPa)**	**(-)**
NAC	2340	49.5	5.0	34.0	48.0	C30/37
RAC C100	2210	33.6	4.5	25.7	40.0	C20/25
RAC C100 F30	2210	33.6	3.8	24.2	39.0	C20/25
RAC C100 F30 P5	2210	35.0	4.1	25.2	41.6	C20/25

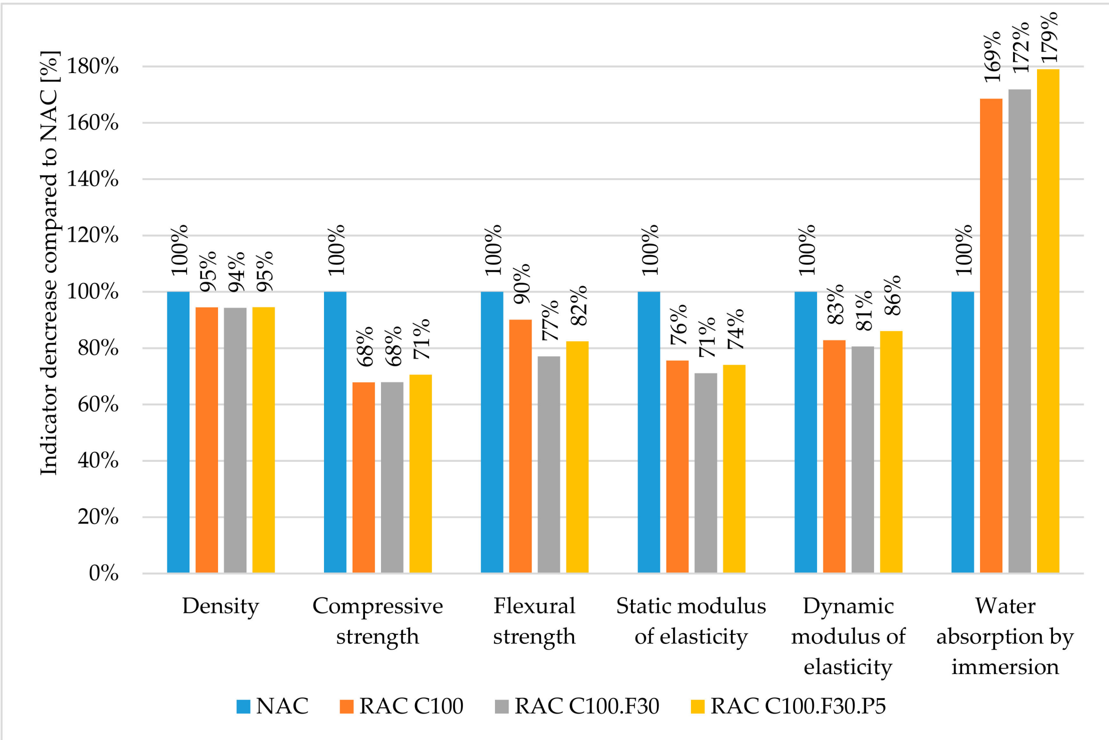


Figure 5. Mechanical properties of NAC and RAC concrete mixtures.

The decline of concrete compressive strength with the full replacement of coarse NA with RCA ranged from 10% to 35% [6,28]. Furthermore, the flexural tensile strength decreased by up to 10% and the highest decline was mostly for modulus of elasticity which ranged up to 45% [20]. All these results correspond with results of RAC C100, with full replacement of coarse aggregate. Previous research showed the different influences of fine RCA on the properties of concrete. Results have shown that replacement up to 30% had no significant effect on the mechanical properties [28], which was also verified in this study. It was verified in a previous study [26] that RCP could replace cement in a concrete mixture up to 10% of cement. In this study, the RCP replaced 5% of the cement in the concrete mixture and no significant declines of concrete mechanical properties were observed.

The target concrete strength class for NAC mixture is C30/37, nomenclature according to Eurocode and ISO 12,491 (characteristic compressive cube strength equal to 37 MPa) and the target concrete strength class for RAC mixtures is C20/25, nomenclature according to Eurocode and ISO 12,491 [70] (characteristic compressive cube strength equal to 25 MPa). This method of determining the strength class of concrete was chosen considering the number of samples in order to eliminate their influence. Based on these results, we designed the structural element (beam) which carried an equal load and had the same reinforcement and the same width. The beams made of lower-strength-class concretes were designed to maintain the same utility properties which led to a greater beam height. To compensate for the lower strength, a larger amount of concrete must be used to obtain the same utility properties. The total amount of RAC was about 4% higher than that of the NAC used for environmental analysis.

The durability of reinforced recycled aggregate concrete was not significantly influenced if the replacement rate of aggregate by RCA was less than 30% [43]. However, in this study, the replacement rate of NA by RCA was greater than 30%, and according to the previous studies, higher replacement rates lead to faster corrosion of steel bars. The durability properties of concrete are essential for its usage in structural applications. Concrete structures are very often exposed to the effects of thermal changes. Generally, the frost resistance of saturated RAC is not satisfying, and its use in structures exposed to severe climate is not recommended [38]. The durability and rheological properties were not verified in this study. Therefore, the analysis was limited to a structural element (beam) for which non-aggressive environmental conditions (e.g., indoor environment) were applied.

2.2. Environmental Assessment Methodology

Life cycle assessment (LCA) is a comparative methodology that evaluates the environmental impact of processes and products during their life cycle. This method compares various solutions with the same functional units and boundaries. LCA consists of four steps according to ISO standards ISO 14,040 [71] and ISO 14,044 [72]: goal and scope definition, creating the life cycle inventory (LCI), assessing the environmental impact (life cycle impact assessment, LCIA), and interpretation of results. For the comparison of the environmental impact of different concrete types, it is necessary that all concrete types fulfil similar functional requirements. LCA methodology is often used for the environmental assessment and comparison of aggregate (natural and recycled aggregate) and concrete (ordinary concrete and recycled aggregate concrete). Many comparative studies using this methodology have been published [4,8,13,16,20,23,24,60,73–86].

In previous studies, two ways to compensate the lower mechanical properties of concrete beams made of RCA have been mentioned. The decrease of compressive strength can be compensated by additional cement, and worse workability can be compensated by additional mixing water. Both of these compensations negatively influence the environmental impacts of concrete production. However, as written earlier, the impact of additional cement is not significant, due to the increase by up to 10% of additional cement in concrete mixture with full replacement of natural aggregate [37]. The decline of the mechanical properties of RAC can be also reduced by using steel fiber reinforcement [39]. In this case study, the third approach was chosen, which means that the strength decline of RAC mixtures was compensated by a higher beam height—the beam height was increased by 4%.

2.2.1. Goal, Scope, and Functional Unit

The goal of this study was to compare the environmental impact of the production of four types of concrete with different replacement rates of coarse aggregate, fine aggregate, and cement which were designed for the same structural use: NAC, RAC C100, RAC C100 F30, and RAC C100 F30 P5.

The system boundaries for natural and recycled aggregate were considered as cradle to gate. The environmental assessment of recycled aggregate depends on the type of recycling equipment used and the complexity of recycling process, which is related to fuel consumption. The production of recycled aggregate in this case study included processes of crushing, separating, and transporting in machines powered by diesel. The impact of the recycling process was evaluated in terms of the production and combustion of diesel. The functional unit of NA or RCA used for LCI in this study was 1 kg of aggregate (see Table 6).

Table 6. Environmental impacts of 1 kg of natural and recycled aggregate. ADP: abiotic depletion (fossil fuel); GWP: global warming potential; AP: acidification potential; EP: eutrophication potential; POCP: photochemical ozone creation potential.

	Natural Aggregate	Recycled Aggregate
ADP fossil (MJ)	0.0314	0.0160
GWP (kg CO_2-Eq.)	0.0024	0.0012
AP (kg SO_2-Eq.)	1.53E-05	8.91E-06
EP (kg Phosphate-Eq.)	5.32E-06	2.04E-06
POCP (kg Ethene-Eq.)	2.82E-10	5.56E-15

The assessment included two use cycles of concrete, which were considered as an open-loop system. The first use cycle consisted of natural aggregate and cement production and transport, the production and transport of concrete from the concrete plant to the construction site, demolition, and landfill. The second use cycle included natural aggregate, recycled aggregate, and cement production and transport; production of concrete and transport of concrete from the concrete plant to the construction site; demolition; and landfill. The processes of concrete production, construction phase, operation phase, and demolition were considered to be the same for all types of concrete (see Figure 1).

The functional unit of NAC and RAC used in this study was 2 m^3 of the produced structural element (beam). One cubic meter was from the first life cycle of NAC and the second cubic meter was from the second life cycle of the NAC or RAC, respectively.

The following scenarios were assessed:

- SCENARIO 1: Two natural aggregate concrete (NAC) elements which ended in a landfill; the cycle included natural aggregate production, cement production, concrete production, use in structure, and landfill for 100% of concrete; this cycle was counted twice.
- SCENARIO 2: One natural aggregate concrete element and one recycled aggregate concrete element in which 0.49 m^3 of the NAC element was used as partial replacement of primary sources; the cycle included natural aggregate production (sand), cement production, use in structure, landfill for part of concrete waste which was not recycled, recycled aggregate production, concrete production, use in structure, and landfill.
- SCENARIO 3: One natural aggregate concrete element and one recycled aggregate concrete element in which 0.56 m^3 of the NAC element was used as partial replacement of primary sources; the cycle included the same processes as SCENARIO 2.
- SCENARIO 4: One natural aggregate concrete element and one recycled aggregate concrete element in which 0.57 m^3 of the NAC element was used as partial replacement of primary sources; the cycle included the same processes as Scenarios 2 and 3.

2.2.2. Life Cycle Inventory (LCI) Data

This step of the LCA involves collecting data for each unit process regarding all relevant inputs and outputs of energy and mass flow, as well as data on emissions to air, water, and land. The production of ready-mixed NAC and RAC studied in this paper was located in the Czech Republic. So, the inventory data for recycled aggregate were collected from local recycling plants in the Czech Republic. Emission data for diesel production, combustion, and transportation were taken from the GEMIS database. Emission data for natural aggregate and cement production and transportation, concrete production, production and transport of concrete from the concrete plant to the construction site, demolition, and landfill were taken from the Ecoinvent 3.1 database (2015). GaBi 9 software (Thinkstep, Leinfelden-Echterdingen, Germany) was used for the assessment.

2.2.3. Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment finds a relation between inputs and outputs. The main analyzed inputs in this study were natural resources, fossil fuels, and water; the main outputs were emissions and energy. The problem-oriented (mid-points) methodology was chosen for the impact assessment. This method includes the environmental impacts related to abiotic depletion, global warming, change, acidification, eutrophication, photochemical oxidant creation, raw materials depletion, etc. The impacts can be evaluated using the CML method, which was chosen in this study [87].

The most common impact categories for concrete or aggregate production are abiotic depletion (ADP; fossil fuels) in MJ, global warming potential (GWP) in kg CO_2-equivalence, acidification potential (AP) in kg SO_2-equivalence, eutrophication potential (EP) in kg phosphate-equivalence, and photochemical ozone creation potential (POCP) in kg ethene-equivalence [20], where ADP fossil, GWP, and have global environmental impact and AP, EP, and POCP have local environmental impact [88]. These impact categories were determined in this study. The impact category mineral resources depletion was added. The new category refers to raw material depletion in tonnes. This category is based on the number of raw materials consumed by cement, natural aggregate, and sand production. Each component of concrete was multiplied by a unitless conversion factor. The conversion factor means the amount of raw material in tonnes used for 1 tonne of the concrete component. The conversion factor for cement was considered as 1.7, for natural sand and aggregate it was 1.0, and for recycled aggregate it was 0.

Table 6 shows the environmental impacts of all processes related to natural and recycled aggregate production.

3. Results

The comparative environmental impact assessment of two use cycles of two cubic meters (two structural elements) of concrete was performed for raw material extraction, recycling, and material production stages of the concrete life cycle (including transport), where the first life cycle was considered in terms of only primary resources and in the second one part of the aggregate was replaced by recycled concrete from the first life cycle.

Four scenarios of natural aggregate concrete and recycled aggregate concrete were assessed. Due to the similar transport distances of natural and recycled aggregate in the Czech Republic, only one transport scenario was analyzed. Table 7 shows the environmental impacts of all processes related to concrete production, such as cement, aggregate, concrete production, and transportation. The amounts of component materials (cement, natural and recycled aggregate) were according to tests performed for determining the mix proportions of NAC and RAC with the same structural utilization.

Table 7. Environmental impacts of each process per 2 m^3 of four scenarios of NAC and RAC.

	Cement (CEM I 42.5)	Natural Aggregate (NA)	Natural Sand	Landfill	Transportation	Diesel Consumption	Electricity Grid Mix
			SCENARIO 1				
ADP fossil (MJ)	1260	77	47	960	0	736	70
GWP (kg CO_2-eq)	561.5	5.9	3.9	73.6	48.6	4.8	7.0
AP (kg SO_2-eq)	0.700	0.038	0.018	0.446	0.183	0.049	0.049
EP (kg phosphate-eq)	0.074	0.013	0.004	0.061	0.048	0.011	0.002
POCP (kg ethene-eq)	0.094	0.005	0.002	0.042	0.000	0.007	0.003
			SCENARIO 2				
ADP fossil (MJ)	988	20	37	730	0	604	55
GWP (kg CO_2-eq)	440.0	1.6	3.1	55.9	38.5	5.3	5.4
AP (kg SO_2-eq)	0.548	0.010	0.015	0.339	0.145	0.050	0.038
EP (kg phosphate-eq)	0.058	0.003	0.003	0.047	0.038	0.011	0.002
POCP (kg ethene-eq)	0.074	0.001	0.002	0.032	0.000	0.007	0.002
			SCENARIO 3				
ADP fossil (MJ)	941	17	30	691	0	595	52
GWP (kg CO_2-eq)	419.0	1.3	2.5	52.9	37.7	5.4	5.2
AP (kg SO_2-eq)	0.522	0.008	0.012	0.321	0.142	0.051	0.037
EP (kg phosphate-eq)	0.056	0.003	0.002	0.044	0.037	0.012	0.002
POCP (kg ethene-eq)	0.070	0.001	0.001	0.030	0.000	0.007	0.002
			SCENARIO 4				
ADP fossil (MJ)	903	17	30	686	0	592	52
GWP (kg CO_2-eq)	402.0	1.3	2.5	52.6	37.5	5.4	5.2
AP (kg SO_2-eq)	0.501	0.008	0.012	0.319	0.141	0.051	0.036
EP (kg phosphate-eq)	0.053	0.003	0.002	0.044	0.037	0.012	0.002
POCP (kg ethene-eq)	0.067	0.001	0.001	0.030	0.000	0.007	0.002

Calculated total impact indicators per functional unit of four scenarios NAC and RAC are presented in Table 8.

Table 8. Environmental impacts per 2 m^3 of four scenarios of NAC and RAC.

	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4
ADP fossil (MJ)	3150	2434	2326	2280
GWP (kg CO_2-eq)	705.3	550.0	524.2	506.6
AP (kg SO_2-eq)	1.483	1.146	1.093	1.069
EP (kg phosphate-eq)	0.214	0.163	0.156	0.153
POCP (kg ethene-eq)	0.153	0.118	0.112	0.109

4. Discussion

The environmental assessment of recycled aggregate concrete (RAC) for structural use and its comparison with natural aggregate concrete (NAC) has been studied in previous research [4,6,8–24]. These studies evaluated the environmental impact of production of 1 m^3 of concrete with NA or RA, respectively. In contrast to these studies, in this study two use cycles of NAC or RAC were evaluated. The main reasons for this consideration were that ordinary concrete is necessary for every RA, and although the recycling process is similar to crushed aggregate production, in addition to recycling, inventory data in the previous studies also included mobile plant transportation to the demolition site and landfilling of recycling waste [4,12,16]. This study responds to the philosophical question of whether the demolition and recycling process is the end of the ordinary concrete life cycle or if it is the beginning of the recycled aggregate life cycle. The results of this consideration are discussed and compared in this chapter.

Figures 6 and 7 show the impact category indicator increase or decrease (in percentages) of Scenarios 2, 3, and 4 over the impact category indicators of Scenario 1. In these figures all category indicators for Scenario 1 are presented as a 100% value, while category indicators of other concrete types were calculated as percentages of increase or decrease compared to Scenario 1. The percentage of recycled materials in concretes is also mentioned in Figure 6.

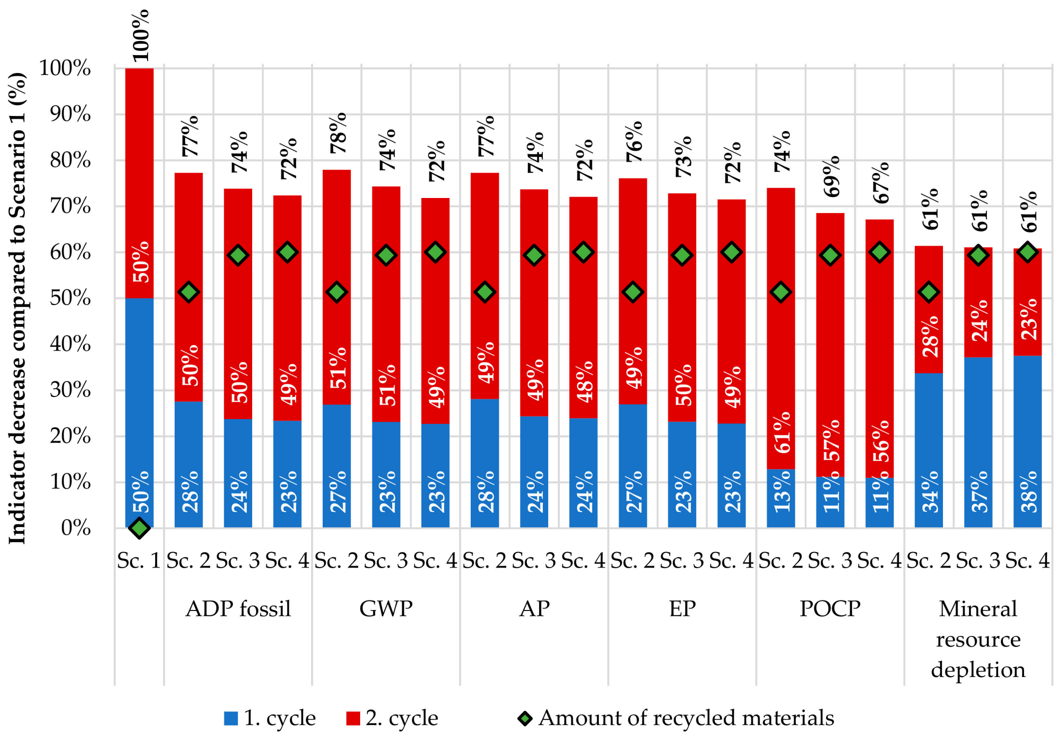


Figure 6. The comparison of two use cycles of scenarios in selected impact categories.

Figure 6 shows that Scenario 1, which is two use cycles of a concrete element with only natural aggregate (NAC + NAC), had the largest indicators for all impact categories, which is shown as 50% for each use cycle. Scenarios 2 and 3, where the natural aggregate is partially replaced by recycled aggregate in the second use cycle from the first use cycle of a concrete element with natural aggregate, had lower indicators for both use cycles. Scenario 4, which is two use cycles of concrete with full replacement of natural aggregate, partial replacement of natural sand, and partial replacement of cement (NAC + RAC C100.F30.P5), had the lowest indicators for all impact categories because it used the lowest amount of cement, which has mostly the highest environmental impact.

The increase in all category indicators of Scenario 1 compared to Scenarios 2, 3, and 4 ranged from 20% to 40%. There are a few reasons for this result: higher natural aggregate consumption, higher landfilling, and for Scenario 4, lower cement content. In Scenario 1, the landfilling was assumed for 2 m^3 of concrete and the natural aggregate consumption was a much more polluting process than the recycling of concrete, which was assumed in Scenarios 2, 3, and 4. However, this should be considered as realistic for the Czech Republic, since in this study the real data for the recycling process were collected from recycling centers in the Czech Republic to reproduce the real recycling process in Czechia.

The indicators for all impact categories of Scenario 2 (NAC + RAC 100), Scenario 3 (NAC + RAC C100.F30, and Scenario 4 (NAC + RAC C100.F30.P5) were similar—the difference was below 10%. The indicators for most impact categories (except POCP) of RAC mixtures in the second life cycle were similar compared to indicators of NAC (i.e., a decrease below 2%, which can be considered as negligible). The category indicator POCP showed the higher impact of the second use cycle for Scenarios 2, 3, and 4 in comparison with Scenario 1. Nevertheless, the summary of both use cycles showed lower total impacts in this category indicator. However, using part of the NAC from the first use cycle as a partial replacement of natural resources in the second use cycle could reduce the indicators for all impact categories in a total of two use cycles by nearly 40% in all impact categories. In the case of RAC concretes, it should be noted a clear benefit in terms of waste reduction and minimization of natural mineral resources depletion.

Figure 7 shows the contribution of different phases in the concrete production process to the total impacts, for all concrete types and calculated category indicators. The contribution of the cement production was by far the largest contributor to all of the category indicators and for all concrete types, and varied from 25% to 80%, depending on the category indicator and the concrete type. The largest contribution of cement production was for Scenario 1 (GWP), while the lowest was for Scenario 4 (EP). The main reason for this is the well-known fact that large CO_2 emissions are produced during the calcination process, in clinker production, and in the use of fossil fuels [19].

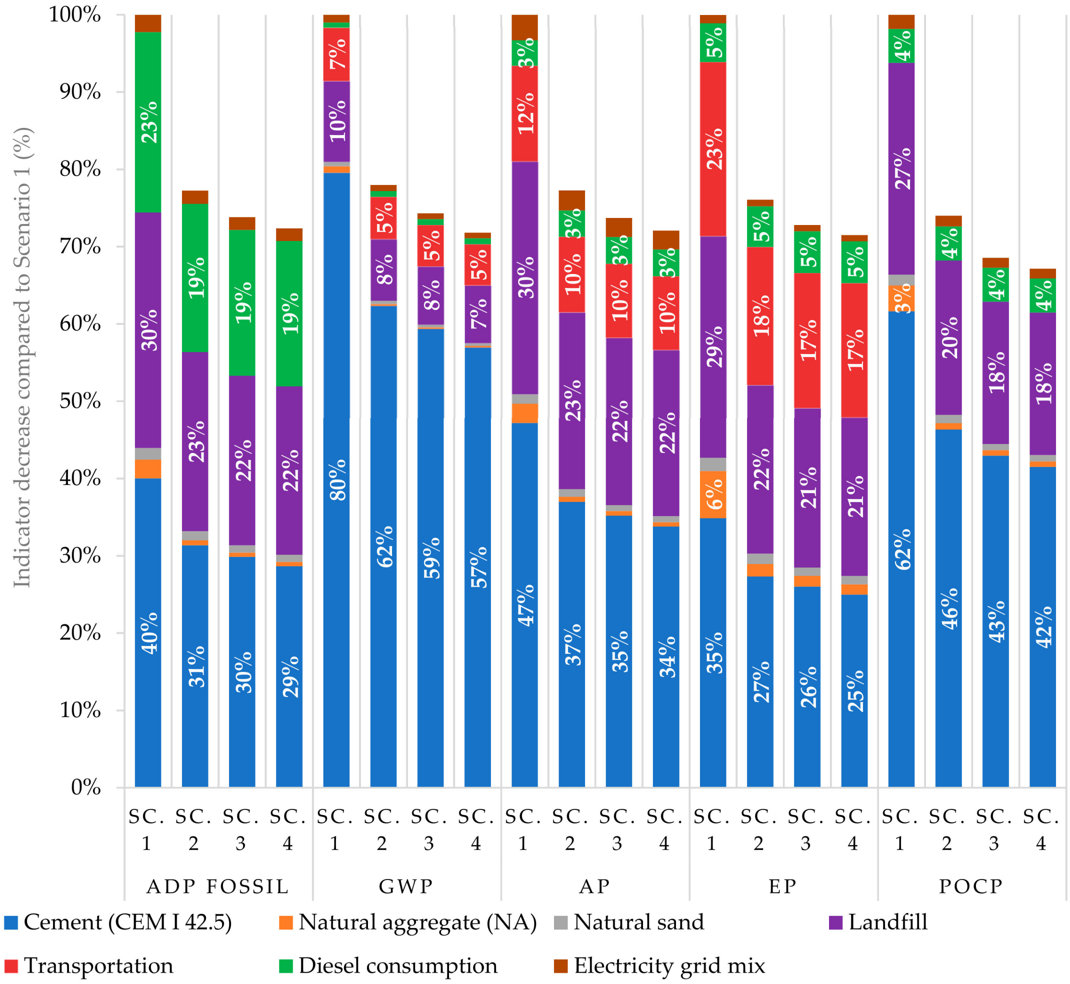


Figure 7. The comparison of processes of scenarios in selected impact categories. In [4,12,16], the LCIA was evaluated and the potential environmental impact was estimated in selected impact categories. It was found that the energy consumption potential was about 20% higher for crushed recycled aggregate than for natural river aggregate [16], and more than two times higher in comparison with crushed NA production [4]. Although the recycling process was similar to the crushed aggregate production, in addition to recycling, inventory data also included mobile plant transportation to the demolition site and landfilling of recycling waste, which had a high impact. The functional unit chosen was 1 tonne of NA or RCA, respectively. In contrast to these studies, this study showed a lower energy consumption and lower emissions for RA in comparison with NA (see Table 6). The main reason for this difference is the different consideration of transportation, which indicates its importance.

The contribution of the coarse natural aggregate (gravel) production phase was smaller for all category indicators and concrete types in comparison with the cement production phase. It varied from 0.6% to 6.1% depending on the category indicator and scenario. The largest contribution of natural aggregate production was for Scenario 1, where only natural aggregate was used for manufacturing of concrete mixtures. In other scenarios, the natural aggregate was partially replaced by the recycled concrete aggregate in the second use cycle. Moreover, more energy was consumed for the natural aggregate production than for the production of recycled concrete aggregates and, hence, category indicators based on emissions were higher in this case. Although the recycling process is similar to the crushed aggregate production process, LCI data for RCA include crushing, separating, and transport machines powered by diesel fuel. The impact of the recycling process was evaluated as the production and combustion of diesel fuel; the impact of the recycled aggregate production was lower in all impact categories in comparison with natural aggregate production (see Table 6).

The contribution of the natural sand production phase was also small and varied from 0.1% to 1.7%, depending mostly on the category indicator. It was largest for Scenarios 1 and 2 because natural sand was used in both use cycles.

Landfilling was the second greatest source of impacts. The contribution of the landfill phase ranged from 7% to 30%. It was largest for Scenario 1 because the NAC was fully landfilled after both of the use cycles of the concrete structural element. In Scenarios 2, 3, and 4, part of the NAC from the first life cycle was not landfilled but used as a partial replacement of primary sources in the second life cycle. Due to this fact, fewer waste materials were disposed to landfill. The highest impact (between 20% and 30% for all scenarios) of landfilling was for category indicators ADP fossil and AP compared to the lowest impact, which was for GWP and ranged between 7% and 10%.

The diesel consumption phase was one of the greatest sources of impacts for the ADP fossil category indicator, and it varied between 19% and 23% depending on the scenario. On the other category indicators, the diesel consumption ranged from 1% to 5%. The diesel consumption phase included diesel used for trucks and for the recycling process.

Transport was the third-largest source of impact for the AP, EP, and GWP indicators, ranging from 5% to 23%. The largest transport contribution was for Scenario 1 for all impact categories, as the NAC was assumed to be transported to landfill twice. In Scenarios 2, 3, and 4, on the other hand, only part of the first use cycle was landfilled, reducing the amount of transported materials.

These results show that the cement production phase was by far the largest contributor to the of all assessed category indicators. The contribution of gravel production was below 5%, and the contribution of natural sand production was below 2%. Even if there are some uncertainties regarding the quality of data, it would not affect the results significantly. The recycling process was included in the diesel consumption phase, which was crucial only in the ADP fossil category indicator. In the other category indicators, the diesel consumption was below 5%.

The LCA results for 1 m^3 of NAC or RAC showed that the impacts of aggregate production phases were slightly larger for RAC than for NAC in previous case studies [4,12,16]. On the contrary, some studies have presented a lower embodied energy and lower greenhouse emissions of RA compared with natural aggregate. In comparison with NA, the embodied carbon emissions are reduced by around 25% [18]. The reduction of emissions is also connected with the transportation of aggregate, especially where recycled aggregate is used near the demolition site [14].

The present study found that the impacts of aggregate production phases were lower for RAC in comparison with NAC. There are two reasons leading to this fact; the first is the consideration of recycling and transportation phases, and the second is the saving of primary material in the second use cycle. The highest impact in all studies was determined from cement production (which confirmed the well-known fact that cement production is the largest contributor to all category indicators for concrete production, due to its large energy consumption), the use of fossil fuels, and high CO_2 emissions during the calcination process in clinker production [19]. In comparison with the cement production phase, it can be said that the impact of the aggregate production phase is negligible for all impact categories, with no significant differences between all types of aggregate. In contrast to previous studies where two scenarios of aggregate transportation were compared and it was found that transportation had the second-highest impact and could influence the whole LCA of concrete [4,12], in this study transportation was considered to be the same for all aggregate types. This consideration is supported by the availability of both aggregate types in the Czech Republic.

In this case study, the higher beam height was designed to compensate for the lower strength class of concretes with RCA, which had no significant effect on the compared impact categories. Another way to compensate for the decline of RAC properties is to add cement to RAC mixtures. There are some studies [8,10] in which this solution is used. In the compared impact categories (e.g., energy use, climate change (global warming), acidification, respiratory effects, land use, and gravel use) no significant differences were found. For instance, the comparison showed differences in energy consumption and global warming potential between NAC and RAC of up to 3% [10].

The results indicate the positive impact of cement replacement by RCP in all impact categories. The RCP was separated during the second phase of the recycling process, where only pure concrete fragments were crushed and sieved to limit the soil content in RCP. In contrast, some studies have been published on different ways to obtain RCP. These procedures mostly separate attached cement mortar from the aggregate surface from waste concrete. Nevertheless, these procedures are not efficient for the reduction of CO_2 emissions. One such procedure involves heat treatment and abrasion [65]. In another method, the cement paste and aggregate can be completely separated by heat treatment between 300 and 500 °C, where the attached cement mortar is separated from aggregate during this process and then separated cement mortar is milled to cement powder [26]. Finally, another way of separating attached cement mortar from the aggregate surface is by microwave heating [25].

5. Conclusions

A case study on the environmental assessment of four scenarios with two use cycles of a structural element with the utilization of natural aggregate concrete (NAC) and recycled aggregate concrete (RAC) was performed using LCA methodology. Due to the different properties of concretes, the comparative environmental analysis was made on the structural unit (beam) with the same utility properties.

The results of this study indicate the following:

- The properties of concrete are negatively influenced by the full replacement of coarse aggregate by recycled concrete aggregate. The partial replacement of natural sand by fine recycled aggregate (up to 30%) and partial replacement of cement (up to 5%) has no further significant impact on the properties of concrete.
- If the lower strength class of concrete is used for the beam, the height of the beam has to be higher. However, the amount of added material is not significant and has no significant influence on the environmental assessment.
- The influence of cement production is the highest for all of the impact categories, as expected from many previous studies.
- The contribution of the aggregate production phase to the total impacts of concrete is rather small. The contribution of gravel production is below 5%, and the contribution of natural sand production is below 2%.
- The environmental impacts of RAC and NAC (with gravel aggregate) production are very similar. However, if part of the NAC from the first use cycle is used as partial replacement of primary sources in the RAC (the second use cycle), it is clear that all impact categories are improved.
- The importance of transportation and landfilling is verified. The influence of the landfill phase and the transportation showed a high impact for Scenario 1, where all the material was landfilled, indicating the benefits of recycling.

In conclusion, the utilization of recycled construction and demolition waste—especially recycled concrete—as an aggregate for new concrete could lead to environmental savings, especially the reduction of primary resources use, embodied energy, and embodied emissions, and could help to reduce the pressure on landfilling sites.

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