Recycled concrete for foundation structure: LCA case study

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Abstract. Concrete containing primary raw resources such as sand and gravel can be replaced by recycled aggregate concretes (RAC). But recycling processes are energy-consuming and thus energy resources are consumed. To investigate the resource consumption and overall environmental impact related to the life cycle of RAC, Life Cycle Assessment (LCA) was used to compare ten RAC foundation structures with two foundation structures containing just natural aggregate (NA). This paper presents the characteristics of two types of RAC for the foundation with various replacement rates of NA (30\%, 50\%, 100\%). Various concrete mixtures were designed with the three replacement ratios of natural gravel, the two amount of cement and the two effective water-cement ratios. Unsurprisingly, the NA foundation structures have smaller crude oil consumption. The NAC I 16/20 foundation consumed 84 kg of crude oil. Contrarily, this foundation has the biggest consumption of natural aggregate (7.6 t). Moreover, the RAC foundation structures have beneficial impacts in the Metal depletion category. For example, the impact of the RAC I C30_V1 foundation is -31.7 kg Fe eq. Most of the RAC foundation structures demonstrated the overall environmental impact lower than NA foundation structures, suggesting that RAC could be suitable replacements for standard concretes.

1. Introduction

Concrete is the second most used material after water, which is dependent on primary natural resources such as virgin aggregate, cement and 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. For this reason, reusing recycled aggregate concrete (RAC) as an aggregate for a new concrete mix follows crucial importance. Simultaneously, there will be an increase in the amount of demolished concrete structures and the need for the recycling and reuse of RAC. 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 RAC dates back to the 1940s [1].

Due to the suitable characteristics of concrete, it is the most used material for foundation structures. Furthermore, the foundation structures usually consume a large volume of materials, because it is necessary to carry the load from the building to the subsoil. Given these facts, the foundation structures have been one of the structures, which represented the highest environmental impact in nearly every impact category analyzed by LCA [2–4].
The environmental assessment of RAC for structural use and its comparison with natural aggregate concrete (NAC) has been published [5–17]. The LCA method is one possible way to compare the environmental impacts of concrete structural elements [18]. Few studies have been published on the comparison of different types of natural aggregate (NA) and recycled aggregate (RA) e.g., river NA, crushed NA, and course RA [5,9,19,12,20]. The RA with NA production for the production of lower-grade concrete products was studied [19]. The utilization of the RA as a replacement of NA in concrete mixtures mostly leads to decreasing the properties of concrete and its durability [6,21]. Due to this fact, in some studies [7,22] the decline of RAC properties was compensated with additional cement.

The main aim of this paper was to optimize the RAC mixture for structural utilization according to the examined properties and environmental impacts. This paper presents the characteristics of RA and RAC and their comparison with conventional materials. Two types of recycled aggregate prepared by different recycling processes were used to find the optimal way how to get the suitable quality of RA with the lowest environmental impact. The concrete was optimized according to the exposition class of concrete and future use as the structural element for foundations.

2. Materials and methods
To compare the environmental impact of several new concrete mixtures with recycled aggregates, a holistic approach taking into account a whole product system should be used. The Life Cycle Assessment (LCA) was selected as the most suitable method for this purpose. This method was performed following the ISO 14040:2006 [23]. According to these requirements, LCA consists of four main parts: the goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and life cycle interpretation [24].

2.1. Materials
Ten RAC mixtures and two NAC mixtures were designed to optimize the use of RA for the same structural use. The different replacement ratios of aggregate with two different amounts of cement and the two different effective water-cement ratios were designed to examine the impact of the proposed technique. Mechanical and physical properties of manufactured mixtures are investigated. According to previous researches, higher water absorption and lower density of RA have been identified [11,25]. Water absorption of RCA after 24 h for fraction 4/8 mm was 7.0% for both types of RA and for fraction 8/16 mm varies from 6.0% (RA 2) to 9.0% (RA 1). The oven-dried density varied from 2380 kg/m³ (RA 1) to 2420 kg/m³ (RA 2) for fraction 4/8 mm and it was 2420 kg/m³ for fraction 8/16 mm of both types of RA. The results of the RA properties correspond with the results of previous studies. Twelve concrete mixtures with two types of RA, various replacement ratios, two different amounts of cement CEM I 42.5 R (OPC) and different water-cement ratios were used for experimentation. The considered exposition classes were X0 and XC1 according to the Czech European Standard [26]. The cement content was kept constant, i.e. 260 kg/m³ (NAC I, RAC I) and 300 kg/m³ (NAC II, RAC II). The effective water/cement (w/c) ratio was kept constant, i.e. 0.65 (NAC I, RAC I) and 0.55 (NAC II, RAC II). The replacement ratio of coarse aggregate for RAC I was 30%, 50% and 100% (RAC I C30, RAC I C50, RAC I C100) and for RAC II was 30% and 100% (RAC II C30, RAC II C100). The composition of concrete mixtures per cubic meter is shown in Table 1.

Table 1. Concrete mixtures of NAC and RAC, per cubic meter.

|                | NAC I | RAC I C30_V1 | RAC I C30_V2 | RAC I C50_V1 | RAC I C50_V2 | RAC I C100_V1 | RAC I C100_V2 |
|----------------|-------|--------------|--------------|--------------|--------------|---------------|---------------|
| **CEM 42.5 R** | 260   | 260          | 260          | 260          | 260          | 260           | 260           |
| **Water**      | 169   | 201          | 184          | 206          | 206          | 179           | 211           |
| **NA (0-4 mm)**| 736   | 632          | 632          | 611          | 611          | 415           | 588           |
| **NA (4-8 mm)**| 533   | 0            | 0            | 0            | 0            | 0             | 0             |
| **NA (8-16 mm)**| 570 | 656          | 656          | 311          | 311          | 0             | 0             |
| **RCA (4-8 mm)**| 0    | 485          | 485          | 506          | 506          | 239           | 526           |
The results of the basic examined mechanical and physical properties are shown in Table 2. The target concrete strength class was examined due to the characteristic compressive cube strength according to the Eurocode and ISO 12491. The target strength class for the NAC mixture was C25/30 (characteristic compressive cube strength equal to 30 MPa) and C30/37 (characteristic compressive cube strength equal to 37 MPa). The target concrete strength classes for RAC mixtures ranged from C8/10 to C25/30. This method of determination of strength class of concrete is chosen due to the consideration of the number of samples to eliminate their influence.

Based on these results, the foundation structural elements were designed to carry an equal load and had the same effective loading area [m²]. The element is designed from plain concrete without reinforcement. The element made of lower-strength-class concretes were designed to maintain the same utility properties which led to a greater element height. It followed that for the same utility properties the structural element with the lower strength class had a larger volume, which means a larger amount of concrete must be used to obtain the same utility properties. The volume of concrete elements for foundations is shown in Table 2. These volumes were used as referential flows for environmental analysis.

| Type of concrete | Density [kg/m³] | Water absorption [%] | Compressive strength [MPa] | Flexural strength [MPa] | Static elastic modulus [GPa] | Target strength class | Volume of element [m³] |
|------------------|-----------------|----------------------|-----------------------------|-------------------------|-----------------------------|----------------------|----------------------|
| RAC C30_V1       | 2143            | 7.6                  | 21.9                        | 4.1                     | 23.6                        | C12/15               | 4.62                 |
| RAC C30_V2       | 2199            | 5.6                  | 32.4                        | 5.6                     | 28.9                        | C25/30               | 3.74                 |
| RAC C50_V1       | 2023            | 13.4                 | 22.1                        | 3.8                     | 18.0                        | C16/20               | 4.40                 |
| RAC C50_V2       | 2168            | 6.1                  | 33.5                        | 5.0                     | 25.4                        | C25/30               | 3.74                 |
| RAC C100_V1      | 1977            | 15.0                 | 15.2                        | 3.6                     | 14.2                        | C8/10                | 5.06                 |
| RAC C100_V2      | 2054            | 11.8                 | 22.3                        | 3.3                     | 18.0                        | C16/20               | 4.40                 |
2.2. Goal and scope definition, functional unit and system boundaries

The primary goal of this study was to determine the concrete mixture with the lowest environmental impact in the comparison, where the mixtures are used for the same function in building foundation structure. The secondary goal is to describe the influence of the type of recycled aggregate on the environmental impact of concrete mixture, or concrete strength class classification, respectively.

In this study, compared foundation structures were designed to have the same function. Therefore, the compared functional unit was one foundation structural element with an equal load and the same effective loading area. As compensation for the lower strength class, the higher element height was designed and a larger volume of concrete had to be used for the same utility properties of the structure. The referential flows of concrete mixtures, which were needed to reach defined FU are different and they are described as the calculated volume in Table 2. The system boundaries for each concrete mixture include all life cycle phases: production of materials, production of concrete and construction of foundation structure, deconstruction and EoL. Production of primary raw materials includes excavation and production of RCA as secondary raw material starts with unloading demolition and construction waste in a recycling plant.

Two types of aggregates were considered: V1 from the one-step recycling process and V2 from the two-step recycling process. The first step is the same. The demolition and construction waste is crushed and sorted. Also, steel scrap is separated. Through this recycling process, three fractions are produced. Two of them are used as filling into bed under infrastructure. The third is V1, which can be used as aggregate for concrete or it can be crushed and sorted again. In this second step, another three fractions are produced and one of them is V2 aggregate. The two-step process helps with the separation of clay particles and therefore V2 type is more suitable for concrete.

2.3. Life cycle inventory (LCI)

The Gabi 9 software was used to conduct the data. As a priority, specific data for the Czech Republic were used and also generic data from GaBi 9 database and Ecoinvent were used [27]. Specific data for modelling concrete production in the Czech Republic was assumed according to Fiala [28]. The EoL of foundation structures includes deconstruction, transportation and landfilling as a typical type of removal for construction and demolition waste.

2.4. Life cycle impact assessment, normalization and weighing

Environmental impacts were evaluated according to the ReCiPe characterization method (Goedkoop M., 2013). In this study, Hierarchist (H) perspective for this method was chosen. Version 1.08 of this method was used. For this study, considered indicators and their results are in Table 5. To compare the overall impact of each foundation structure, the results of the impact indicators were normalized and weighted. Normalization means relating the results to the global impact. The results are multiplied by global factors for each category (Guinee, 2001). In this case, normalization was carried out with factors from ReCiPe 1.08 (H), Mid-point Normalization, World, incl. biogenic carbon (person equivalents) (Dr. Thilo Kupfer, 2019). The weighing means adding specific value to each category. The results after normalization are multiplied by factors, which are based on the opinion of the scientific community. In this study, the
weighing was performed according to the thinkstep LCIA Survey 2012, Global, thinkstep LCIA Survey 2012, Global, ReCiPe 1.08 (H), incl. biogenic carbon (person equiv. weighted) (Dr. Thilo Kupfer, 2019).

3. Results

3.1. Life cycle inventory analysis

Table 3. shows chosen primary resources, which were consumed in the life cycle of compared foundations. Negative flows in this table represent the consumption of primary resources, which were avoided by the production of secondary raw materials or by waste materials recycling, respectively. For example, the negative flow of iron is caused by iron scrap recycling. In our production system, the construction and demolition waste is sorted and iron scrap is used again for the production of new steel. Production of recycled aggregate has a similar effect on natural aggregate flow, which is negative or significantly reduced in the case of foundations with recycled concrete.

Table 3. The chosen resources demand of concrete foundation structure with V1 and V2 recycled aggregate.

|            | RAC I C30_V | RAC I C50_V | RAC I C100_V | RAC II C30_V | RAC II C100_V | NAC I | NAC II |
|------------|-------------|-------------|--------------|--------------|--------------|-------|--------|
| Non renewable energy resources (kg) |             |             |              |              |              |       |        |
| Crude oil  | 103         | 97          | 116          | 128          | 109          | 84    | 81     |
| Hard coal  | 16.1        | 0.5         | -31.3        | -6.9         | -26.4        | 32.9  | 34.6   |
| Lignite    | 89.9        | 85.3        | 98.1         | 99.1         | 101.1        | 73.0  | 77.4   |
| Natural gas| 55.9        | 52.8        | 53.7         | 60.0         | 48.1         | 48.0  | 44.8   |
| Peat       | 0.0246      | 0.0189      | 0.0097       | 0.0203       | 0.0078       | 0.0268| 0.0252 |
| Uranium    | 0.0008      | 0.0007      | 0.000665     | 0.000874     | 0.000686     | 0.0008| 0.0008 |
|            | 87          | 34          |              |              |              | 55    | 77     |
| Non renewable elements (kg) |             |             |              |              |              |       |        |
| Copper     | 0.0038      | -0.0074     | -0.0302      | -0.0117      | -0.0274      | 0.0174| 0.0179 |
| Iron       | -12.7       | -31.3       | -77.8        | -46.5        | -72.5        | 15.6  | 16.1   |
| Lead       | -0.105      | -0.165      | -0.334       | -0.231       | -0.315       | 0.004 | 0.004  |
| Zinc       | -0.060      | -0.109      | -0.235       | -0.152       | -0.221       | 0.020 | 0.020  |
| Non renewable resources (kg) |             |             |              |              |              |       |        |
| Basalt     | -0.002      | -0.024      | -0.065       | -0.027       | -0.061       | 0.026 | 0.025  |
| Clay       | 493         | 458         | 537          | 598          | 505          | 405   | 393    |
| Dolomite   | -1.56       | -2.52       | -5.16        | -3.53        | -4.88        | 0.13  | 0.13   |
| Limestone  | 1980        | 1887        | 2172         | 2180         | 2285         | 1602  | 1738   |
| Natural    | 3188        | -737        | -8135        | -1067        | -8021        | 7566  | 7131   |
| Aggregate  |             |             |              |              |              |       |        |
| Pyrite     | 0.0014      | 0.0014      | 0.00180      | 0.00169      | 0.00186      | 0.0010| 0.0011 |
| Quartz sand| 302         | 280         | 329          | 372          | 305          | 249   | 238    |
| Renewable resources (kg) |             |             |              |              |              |       |        |
| Water      | 416163      | 311513      | 221936       | 384683       | 235016       | 440835| 448728 |
| Non renewable energy resources (kg) |             |             |              |              |              |       |        |
| Crude oil  | 91          | 95          | 115          | 126          | 101          |       |        |
| Hard coal  | -46.0       | -95.6       | -165.2       | -139.8       | -142.0       |       |        |
### Non renewable elements (kg)

|               | RAC I | RAC I | RAC I | RAC I | RAC II | RAC II | RAC II | RAC II |
|---------------|------|-------|-------|-------|--------|--------|--------|--------|
| C30_V         |      |       |       |       |        |        |        |        |
| C50_V         |      |       |       |       |        |        |        |        |
| C100_V        |      |       |       |       |        |        |        |        |
| C50_V         |      |       |       |       |        |        |        |        |
| C100_V        |      |       |       |       |        |        |        |        |
| C100_V        |      |       |       |       |        |        |        |        |
| Copper        | -0.0227 | -0.0482 | -0.0838 | -0.0683 | -0.0724 |
| Iron          | -66 | -150 | -245 | -212 | -214 |
| Lead          | -0.350 | -0.571 | -0.907 | -0.797 | -0.795 |
| Zinc          | -0.220 | -0.370 | -0.596 | -0.516 | -0.522 |

### Non renewable resources (kg)

|               | RAC I | RAC I | RAC I | RAC I | RAC II | RAC II | RAC II | RAC II |
|---------------|------|-------|-------|-------|--------|--------|--------|--------|
| Basalt        | -0.0016 | -0.0202 | -0.0436 | -0.0226 | -0.0382 |
| Clay          | 385 | 372 | 420 | 481 | 368 |
| Dolomite      | -5.4 | -8.9 | -14.2 | -12.5 | -12.4 |
| Limestone     | 1607 | 1611 | 1898 | 1862 | 1859 |
| Natural Aggregate | -11793 | -24006 | -41256 | -33503 | -36380 |
| Pyrite        | 0.0014 | 0.0017 | 0.00229 | 0.00213 | 0.00213 |
| Quartz sand   | 234 | 225 | 252 | 295 | 217 |

### Renewable resources (kg)

|               |       |       |       |       |       |       |       |       |
|---------------|------|-------|-------|-------|-------|-------|-------|-------|
| Water         | 330046 | 254944 | 219054 | 312462 | 214074 |       |       |       |

Mostly, the water is consumed for cement production and this effect depends on cement demand. The second process with big water demand is construction waste landfilling. Besides these processes, the production of recycled aggregate is also connected with the production of other types of recycled aggregates, which are not suitable for concrete. By producing these other aggregates, the excavation of primary resources is avoided and so water demand for this excavation is reduced. Therefore, the consumption of water is lower for foundations structure with recycled aggregates. The demand for energy resources reflects the properties of the concrete mixture. Mixtures with higher strength classes are used in smaller volumes and so fewer materials are transported. The V2 mixtures with two-step aggregate have a smaller volume than mixtures with one-step aggregate hence V2 mixtures have a smaller demand for crude oil for transport. Similarly, the recycling process affects hard coal demand. The reduction of hard coal is caused by coal, which is avoided by steel scrap recycling. The more construction and demolition waste is recycled, the more steel scrap is separated and recycled and so more demand for hard coal is avoided. A significant flow is the construction and demolition waste, which is needed to produce enough aggregates to a foundation structure. The production of 1 t of V2 type of aggregate processes more construction and demolition waste than the production of 1 t of V1 type. Table 4. shows the amount of construction and demolition waste for each foundation structure as the main input into the production system.

**Table 4.** Demolition waste consumption for building concrete foundation structure (kg).

| RAC I | RAC I | RAC I | RAC I | RAC I | RAC I | RAC I | RAC I |
|-------|-------|-------|-------|-------|-------|-------|-------|
| C30_V | C30_V | C50_V | C50_V | C100_V | C100_V | C30_V | C30_V |
| 1     | 2     | 1     | 2     | 1     | 2     | 1     | 1     |
| 5602  | 18139 | 8679  | 29509 | 17368 | 46816 | 12100 | 41140 |
| 16436 | 41028 | 124074 |       |       |       |       |       |
3.2. Life cycle impact assessment

The results of the impact category indicators are shown in Table 5. Considering Climate Change, the reference foundations have a smaller impact than foundation structures with V1 RAC, but foundation structures with V2 RAC have an even smaller impact in this category. The difference between V1 and V2 is caused mainly due to the difference between the impacts of 1 t of V1 and V2 aggregate. The best result in this category was reached with the RAC I C50_V2 mixture (865 kg CO$_2$ eq.) and the RAC II C100_V2 mixture (865 kg CO$_2$ eq.). The very similar results are caused by balancing two factors: the amount of cement and the amount of V2 aggregate. While RAC I C50_V2 has a smaller amount of cement, RAC II C100_V2 has a bigger amount of V2 aggregate. For this category, these factors were combined with the most appropriate way, which was considered in this study.

In our comparison, the reference foundation (NAC I and NAC II) reached the best result only in the category of Agricultural land occupation (26.0 m$^2$a). It is mainly the consequence of a smaller volume of the concrete mixture. In the comparison with recycled concrete, reference concretes are not influenced by the impact of the recycling process, where specifically in this category is the significant negative impact of recycling of iron steel scrap and additional transport. Interestingly, these reference foundations have the biggest impact in the Urban land occupation category, where the main contributor is gravel production. And because the CDW recycling process leads to avoiding gravel consumption, the foundation with recycled concrete reach a better result. Similarly, the bigger impact of reference concretes in the categories Ozone depletion, Freshwater eutrophication and Metal is caused due to the same reasons: no gravel avoided and no credits for steel recycling.

Table 5 shows, that foundation with mixture RAC I C100_V1 reached the best results in various impact categories such as Freshwater ecotoxicity, Ozone depletion, Urban land occupation. In these categories, the main influence is caused by credits for avoided gravel. In this foundation structure, the biggest mixture volume is used and also the biggest amount of V1 aggregate. The production of recycled aggregate is connected with the production of other fractions of recycled aggregates. These other aggregates can be used also to avoid primary gravel production. Therefore, more V1 aggregate is produced, more primary gravel is avoided. Different approach to design a mixture was used in the foundation structure with RAC II C100_V2. This foundation structure with a higher percentage of V2 aggregate in comparison with RAC I C50_V2 and smaller volume comparing to RAC I C100_V2 reached also some pretty good results in the various indicators as is shown in Table 5.

To summarize, the two mixtures are more suitable for considered function than others: RAC I C100_V1 and RAC II C100_V2. The first of them has the biggest volume of foundation among all considered options. The results are mainly influenced by the big amount of avoided gravel. The second mixture contains V2 aggregates. The better properties of the mixture with these V2 aggregates leads to better characteristics of foundation structure and its smaller volume. Likewise, the V2 aggregates are more beneficial in categories, in which the impact is affected by the recycling of CDW and specifically by the iron scrap recycling.

### Table 5. Results of selected impact category indicators for foundation structures

| Impact category indicator                        | RAC I C30_V1 | RAC I C50_V1 | RAC I C100_V1 | RAC II C100_V1 | NA C1 | I |
|-----------------------------------------------|--------------|--------------|---------------|----------------|-------|---|
| Agricultural land occupation [m2a]            | 32.7         | 31.2         | 37.6          | 39.4           | 36.4  | 26.0 |
| Climate change, incl. biogenic carbon [kg CO2 eq.] | 1379         | 1268         | 1369          | 1491           | 1395  | 1177 |
| Fossil depletion [kg oil eq.]                 | 197          | 176          | 179           | 214            | 170   | 175 |
| Freshwater ecotoxicity [kg 1,4 DB eq.]        | 0.058        | -0.030       | -0.178        | -0.025         | -0.167 | 0.153 |
### Impact Indicators

| Indicator category | Indicator | RAC I | RAC II | RAC I | RAC II | RAC I | RAC II |
|--------------------|-----------|-------|--------|-------|--------|-------|--------|
|                    | C30_V2    | C50_V2| C100_V2| C30_V2| C50_V2| C100_V2| C100_V2|
| Agricultural land occupation [m2a] | 26.9 | 27.5 | 32.8 | 34.8 | 29.6 | 26.0 |
| Climate change, incl. biogenic carbon [kg CO2 eq.] | 983 | 865 | 888 | 969 | 865 | 1224 |
| Fossil depletion [kg oil eq.] | 131 | 104 | 94 | 118 | 84 | 172 |
| Freshwater ecotoxicity [kg 1,4 DB eq.] | 0.041 | -0.035 | -0.123 | -0.035 | -0.106 | 0.150 |
| Freshwater eutrophication [kg P eq.] | 0.00123 | -0.00083 | 18 | -0.00075 | 6 | 17 |
| Human toxicity [kg 1,4-DB eq.] | 51.3 | 48.7 | 54.2 | 62.4 | 48.6 | 54.3 |
| Ionising radiation [U235 eq.] | 16.19 | 10.74 | 6.82 | 13.34 | 7.04 | 24.5 |
| Metal depletion [kg Fe eq.] | -155 | -264 | -426 | -370 | -372 | 19.7 |
| Natural land transformation [m2] | 0.195 | 0.126 | 0.072 | 0.162 | 0.059 | 0.290 |
| Ozone depletion [kg CFC-11 eq.] | -7.6E-08 | -9.3E-07 | 06 | -1.0E-06 | 06 | 06 |
| Particulate matter formation [kg PM10 eq.] | 0.553 | 0.293 | 0.064 | 0.241 | 0.109 | 0.99 |
| Photochemical oxidant formation [kg NMVOC eq.] | 1.95 | 1.81 | 1.97 | 2.20 | 1.83 | 2.19 |
| Terrestrial acidification [kg SO2 eq.] | 1.68 | 1.49 | 1.54 | 1.77 | 1.45 | 2.01 |
| Urban land occupation [m2a] | -0.16 | -1.74 | -3.73 | -2.06 | -3.27 | 2.13 |
| Water depletion [m3] | 319 | 238 | 192 | 289 | 190 | 448 |

3.3. Normalization and weighting

**Figure 1.** shows the results of impact indicators after normalization and their summarization for each foundation structure. These summarizations are presented in columns, which have positive and negative parts. The positive part represents the damages to the environment, which were caused by the foundation structures in some categories. The negative part of the columns shows the impact, which was avoided during the compared life cycles.

In LCIA, the two mixtures reached the best result: RAC I C100_V1 and RAC II C100_V2. The second has more beneficial results in the Metal depletion category and it has a less damaging impact in
the Human toxicity category. After summarization of normalized and weighted results in one result of the overall impact, RAC I C100_V2 can be proposed as the most suitable option in this study.

![Figure 1. Results of impact indicators after normalization and weighting.](image)

4. Conclusions
We have successfully demonstrated that RAC can be used for foundation structure and they have a smaller overall environmental impact than foundation structure containing NAC. Such utilization of RAC for the foundation structure will enable us to reduce primary resource consumption and construction and demolition waste production. For example, the RAC II C30_V2 foundation structure consumes almost 41 t of demolition waste. Furthermore, we identified the four key factors which affect the environmental impact of foundation structure: the amount of recycled aggregate, type of aggregate, amount of cement and volume of concrete. The RAC I C100_V1 foundation structure reached the best results in the Urban land occupation impact category (-4.39 m²a) and other categories, which are influenced by the amount of avoided natural gravel. However, the RAC I C100_V2 foundation structure has the biggest amount of avoided natural aggregate (41 t). Similarly, the RAC II C100_V2 foundation structure has the most beneficial impact in the Fossil depletion category (84 kg oil eq.) because of the smallest volume of the mixture. Among the considered mixtures, the best combination of the above-mentioned factors is represented by RAC I C100_V2. The sum of normalized results for this foundation structure is -0.31. Foundation with this mixture reached the best environmental result after normalization due to impact in category Metal depletion (-426 kg Fe eq.), which is affected by the amount of two-step recycled aggregate.

Although our results do not represent all possible utilization of recycled aggregate, we suggest concrete containing two-step recycled aggregate as a more environmentally beneficial alteration of natural aggregates.

To support the use of two-step recycled aggregate, future work is planned to designed reusable elements containing RAC. These elements will enable us to reach an even more circular building industry.

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