Life Cycle Assessment of Recycling Processes for Demolition Waste

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Abstract. This contribution is aimed to evaluate the environmental impacts of recycling construction and demolition waste with the use of Life Cycle Assessment. In the first step, the LCA was used as an analytical tool for the comparison of recycled aggregates production. Recycled aggregates were produced from brick and concrete waste. Chosen functional unit for the comparison was 1 ton of recycled aggregate (RA). The results show that concrete aggregate production has a higher impact on Climate Change category (1,51 kg CO_2 eq.) than brick aggregate production (1,18 kg CO_2 eq.). Then, in the second step, new concrete mixtures made of recycled aggregates were compared. Functional unit was 1 m^3 of concrete. Environmental impacts of concrete mixtures were compared with reference concrete mixture. These compared concretes are classified as C20/25 according to CSN EN 206 + A1. Mixtures with concrete RA have a higher environmental impact than mixtures which were made of brick RA. GaBi Software ts for data processing was used. Environmental impacts assessment according to the ReCiPe method characterization, version 1.08 was used.

1. Introduction

There are many barriers on the path to a circular economy. One of them is using primary resources in place, where recycled aggregates can be used. Instead of the using of the material potential of secondary raw materials, primary aggregates are used in the construction industry as a subbase. Recycled aggregates (RA) are not used because of two reasons. The first reason is the quality of aggregates. Even though many studies prove the quality of recycled aggregates for some application [1–4]. The second reason is a doubt about the environmental importance of the recycling processes. Therefore, the environmental impacts of recycling processes are assessed [5].

The aim of this study is to evaluate environmental impacts of the use of recycled aggregates in the Czech Republic. Also, the study reveals reducing the environmental impacts of the concrete mixtures with RA in comparison to the referential mixture. Environmental impacts of recycling processes depend on input resources and so the process of recycling brick waste and concrete waste were compared.

Then, in the second step, five mixtures with concrete RA as filler were assumed and compared with the referential mixture without any RA.

1.1. Considered recycled aggregates
The two-phase recycling process was designed. The construction and demolition waste is separated into brick and concrete materials and so two types of RA are considered in this study. The first type is concrete RA made from recycled concrete waste. The second type is brick RA made from bricks and similar waste. Functional unit was 1 t of RA. In the first phase, following fractions are produced: 0–16 mm, 16–63 mm a 63–120 mm. Fraction 63–120 mm enters the second phase. The outputs of this phase are fractions: 0–4 mm, 4–8 mm, 8–16 mm.

1.2. Considered concrete mixtures
RA were used in concrete mixtures. The new mixtures were designed to meet the minimal requirements to be classified as C20/25 according to CSN EN 206 + A1. Also, mixtures were designed with approximately equal energy demand for the processing. Table 1 shows the overview of ingredients for each mixture.

2. Methodology
The scenarios were modeled and compared using the LCA (ISO 14040, 2006; ISO 14044, 2006) [6]. To reach objectives, the following phases were defined:

- Goal and scope describe the main question of the study. In this step, the FU and system boundaries are defined.
- Life cycle inventory (LCI) phase gathers information about the considered system including material and energy flows between system and environment.
- Life cycle impact assessment (LCIA) is based on LCI. Environmental impacts are calculated for every flow.
- Interpretation evaluates results of LCIA. In this phase, the robustness of the results is tested. Also, the influence of parameters is considered.

2.1. Goal and scope
At first, the object of assumption should be described. Also, the aim and purpose of the study are needed to be mentioned. In this phase, the function of the product is specified and system borders are defined. As well considered assumption should be named and presented together with conclusion [7].

In the first step, the considered functional unit was 1 t of aggregates. Recycled aggregates are the product of recycling processes of the construction and demolition waste (CDW). Recycling processes include waste manipulation in the recycling plant, grinding and crushing, separating aggregate fractions and iron scrap. At the same time, the recycled cement powder (RCP) is collected in crushing processes of the concrete waste.

In the second step, the considered functional unit was 1 m^3 of the concrete mixture. Assumed mixtures have a different percentage of recycled aggregates used as filler. Further, cement in mixtures CEM and REC CEM (-) are partly replaced by RCP. Every mixture was tested and can be classified as C20/25 according to CSN EN 206 + A1. These concretes can be used in monolithic constructions, perimeter walls, columns, ceiling structures. Some other properties are described in *3.3. Other properties of considered concretes*. These mixtures have similar energy demand for processing and so energy was not considered. Thus, the environmental impacts of used materials are assumed only. Table 1 shows the overview of ingredients for each mixture. Gravel and sand are primary aggregates.

2.2. LCI
Life Cycle inventory is a phase when all elementary flows are summarized. Gabi software ts was used to create a model of recycling processes. Site-specific data were used for the description of key processes like crushing and manipulation. Also, generic data from Gabi database were used for the description of sidewalk processes like producing of emission by a combustion engine. The referential primary aggregate production was based on Gabi database only and includes these processes: extraction and washing of the stone, sorting in sieves and heating after wet processing.

Table 1. The overview of concrete mixtures

Ingredients	Mixtures					
	REF	OPT	REC	CEM	REC CEM (-)	REC CEM (+)
Water [kg]	160	234	215	160	207	231
CEM I 42,5 R [kg]	320	320	320	288	304	352
Sand [kg]	681	374	668	681	603	668
Gravel 4/8 [kg]	550	0	0	550	0	0
Gravel 8/16 [kg]	633	0	0	633	0	0
RA 0/4 [kg]	0	438	0	0	216	0
RA 4/8 [kg]	0	279	416	0	310	416
RA 8/16 [kg]	0	733	722	0	714	722
RCP [kg]	0	0	0	32	16	0

2.3. LCIA
ReCiPe method, version 1.08, was used for characterization in Impact Assessment phase. The ReCiPe obtains three datasets of indicators to impacts assessment (Individualist, Egalitarian, Hierarchist). These datasets are different and each of them evaluates impacts based on cultural perspective. In this study, the Egalitarian indicators were used. It is "the safest" scenario, which calculates impacts in the longest time horizon and assumes incompletely developed impact category.

2.4. Interpretation
Study results can be influenced by different contributions. Interpretation phase shows the importance of each variant and assumes how the contribution can change the results. Thus, the validity and robustness of study should be tested by changing parameters. Accepted assumptions can be tested as well.

3. Results and discussion

3.1. Recycled aggregates
Table 2. shows the midpoint indicators results of concrete aggregates fractions 63–120 mm and 4–8 mm. Also, there are brick fractions 63–120 mm and 4–8 mm mentioned. Primary aggregate in the table represents fraction of coarse nature aggregate (gravel).

The producing of concrete fraction 8–16 mm is tied to impact on Climate Change category and can be quantified as 1,51 kg CO_2 eq. (for midpoint indicator of Climate Change category). Compared to this, the same fraction of the brick aggregate has the impact 1,18 kg CO_2 eq. But, the fraction 63–120 mm has a lower impact in this category for both types of aggregates. By producing of the brick aggregate 63–120 mm can be prevented impact quantified as 7,60 kg CO_2 eq and by producing concrete aggregate even more (21,53 kg CO_2 eq). The biggest influence is caused by the process of iron scrap recycling. Construction waste obtains an iron scrap in a big amount. Therefore, the benefits of iron recycling become evident in the recycling processes of construction and demolition waste. In comparison, the raw aggregate has the biggest impact (17,96 kg CO_2 eq).

The compared process of raw materials producing has a more negative impact on most of the categories. The only exception is its impact in Ozone depletion midpoint category, which can be expressed as $5{,}55\times10^{-12}$ kg CFC-11eq.

Some indicators have negative value in Table 2. It means, that production system has a positive impact in that category. For example, that kind of result can represent resource, which has not been consumed or emission, which has not been exhausted. In similar way, negative value of Metal depletion indicator describes how many kg Fe eq. did not have to be extracted.

Table 2. Midpoint indicators results of chosen fractions and primary aggregate for FU

Midpoint impact category	Con. f63-120	Con. f8-16	Brick f63-120	Brick f8-16	Primary aggregate
Agricultural land occupation [m^2a]	0.884	0.156	0.496	0.101	0.856
Climate change, incl. biogenic carbon [kg CO_2 eq.]	-27.98	1.51	-7.87	1.18	17.96
Fossil depletion [kg oil eq.]	-6.05	0.55	-1.43	0.40	5.64
Human toxicity [kg 1,4-DB eq.]	8.26	2.22	5.58	1.46	31.75
Ionising radiation [U_{235} eq.]	0.526	0.015	0.201	0.007	0.487
Metal depletion [kg Fe eq.]	-39.37	-0.49	-14.26	-0.12	0.86
Natural land transformation [m^2]	0.00338	0.00005	0.00124	0.00002	0.00038
Ozone depletion [kg CFC-11 eq.]	2.1E-07	2.6E-09	7.5E-08	6.2E-10	5.6E-12
Particulate matter formation [kg PM_{10} eq.]	-0.00923	0.00304	0.00050	0.00211	0.05403
Photochemical oxidant formation [kg NMVOC eq.]	-0.0161	0.0127	0.0099	0.0087	0.0998
Terrestrial acidification [kg SO_2 eq.]	-0.0350	0.0089	-0.0013	0.0062	0.1068
Urban land occupation [m^2a]	-0.0116	-0.0001	-0.0042	0.0000	0.0093
Water depletion [m^3]	9.76	0.26	3.71	0.13	15.13

Negative value of indicator represents positive environmental impact. It is impact, which were prevented or caused positive change.

Concrete fractions from the same phase have the same environmental impacts according to allocation rules. Also, it is true for the brick fractions from the same phase. Allocation rules are based on physical relations. In this case, the relation is the weight of the compared functional unit. Therefore, environmental impacts are equally divided among every ton of recycled aggregate from the same phase. Results can be expressed on endpoint level of indicators, too. Results of endpoint indicators were normalized with dataset ReCiPe 1.08 (E), End-point Normalization, Europe, incl. biogenic carbon (person equivalents). These normalized indicators can be summarized for each aggregate.

Figure 1 shows endpoint indicators results after normalization and their sum. Concrete fraction 63–120 mm has three times bigger positive total environmental impact than compared brick fraction after endpoint normalization. On the other hand, the production of 1 t of concrete aggregate fraction 8–16 mm caused bigger environmental impact by 22 % than the production of the same brick fraction. This disproportion is influenced by allocation rules. It means that the positive impact of iron scrap recycling is allocated to the first phase of recycling processes and so this influence did not show in such an extent in case of fraction from the second phase.

The total environmental impact is significantly affected by results of indicators in these categories: Metal depletion, Fossil depletion, Climate Change Ecosystems. The impact of iron scrap recycling processes has a dominant effect in these categories.

In the comparison, production of primary aggregate is tied to the biggest negative total environmental impact.

3.2. Concrete mixtures

Between 13 and 20 % of emissions CO_2, which are exhausted by the concrete production, is tied to aggregates. But these aggregates represent about 70 % of the weight of the concrete [8].

Table 3 shows the results of midpoint indicators for designed concrete mixtures per cubic meter. Results confirm the significant influence of cement on the environmental impacts of the mixtures.

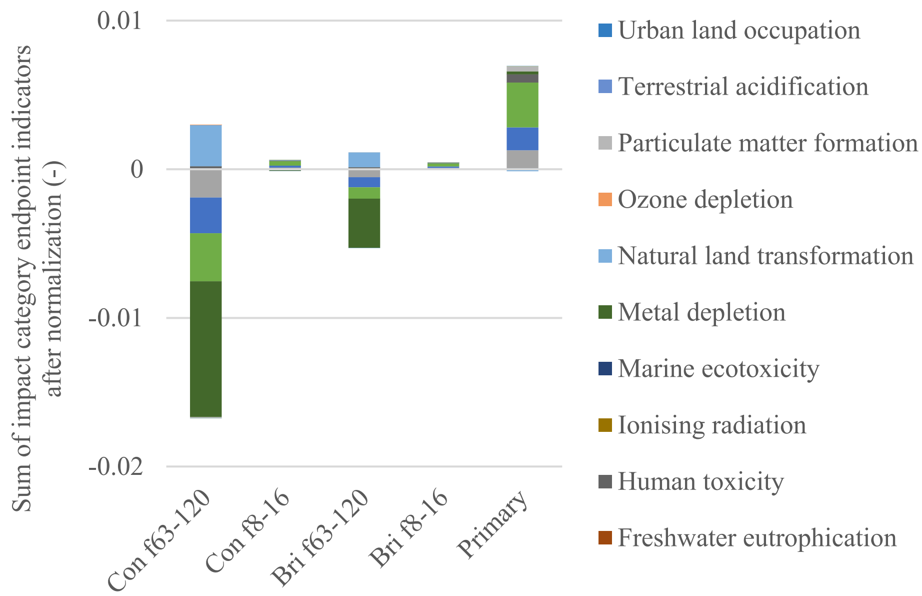

Figure 1. Endpoint indicators results of chosen fractions and primary aggregate after normalization (E)

The CEM Mixture causes the smallest impacts on most of the categories. For example, in Climate change category CEM concrete make an impact 254 kg CO_2 eq. Likewise, The CEM mixture is tied to the smallest impact in Human toxicity category (57.9 kg 1,4-DB eq.). The impact of REC CEM (+) mixture caused in Climate change category is 304 kg CO $_2$eq. In comparison to this mixture, each mixture causes the smallest impact and except REC CEM (+) each mixture has a smaller impact than the REF mixture.

The results confirm, that the amount of cement in the mixture have a dominant influence on the total environmental impact of concrete. This influence is affected by the environmental impact of cement production. Hendricks estimates, that the cement industry produces about 5 % emissions worldwide [9].

Table 3. Midpoint indicators results of 1 m^3 of concrete production(E)

Midpoint impact category	REF	CEM	OPT	REC CEM (-)	REC CEM (+)	REC
Agricultural land occup. [m^2a]	3.38	3.08	3.28	3.14	3.59	3.29
Climate change, incl biogenic carbon [kg CO_2 eq.]	280.1	254.2	271.1	263.9	304.4	278.5
Fossil depletion [kg oil eq.]	22.7	21.3	19.3	21.0	23.8	22.3
Human toxicity [kg 1,4-DB eq.]	63.8	57.9	62.5	59.9	68.6	62.8
Ionising radiation [U_{235} eq.]	3.87	3.54	3.55	3.49	4.02	3.68
Metal depletion [kg Fe eq.]	3.38	3.05	2.59	2.56	3.11	2.78
Natural land transformation [m^2]	0.00159	0.00144	0.00160	0.00152	0.00175	0.00160
Ozone depletion [kg CFC-11 eq.]	4.3E-11	3.9E-11	3.8E-09	3.2E-09	3.0E-09	3.0E-09
Particulate matter formation [kg PM_{10} eq.]	0.212	0.195	0.184	0.181	0.208	0.191
Photochemical oxidant formation [kg NMVOC eq.]	0.356	0.323	0.359	0.346	0.397	0.363
Terrestrial acidification [kg SO_2 eq.]	0.377	0.342	0.376	0.362	0.416	0.381
Urban land occupation [m^2a]	0.0222	0.0210	0.0123	0.0118	0.0137	0.0124
Water depletion [m^3]	75.9	69.1	70.4	68.2	78.7	72.0

Figure 1 shows endpoint indicators results after normalization and their sum. Table 5 shows this sum and relative percentage of total endpoint impact for each compared concrete mixture. The mixture CEM with no recycled aggregate and with the smallest amount of cement causes the lowest total environmental impact. The amount of the cement is the main factor which affects the environmental impact of the concrete [10]. In comparison with referential concrete, total environmental impacts of other mixtures with the same amount of cement is relatively lower. For example, the total environmental impact of the OPT mixture reaches only 94 % of the REF mixture. Nevertheless, the use of recycled aggregates in concretes can cause decreasing of total environmental impact on 88 % [11].

The OPT concrete has a more positive impact than the REC concrete. Both of them have the same amount of cement, but the amount of primary sand is different. Thus, the use of RA is more suitable than the use of primary sand.

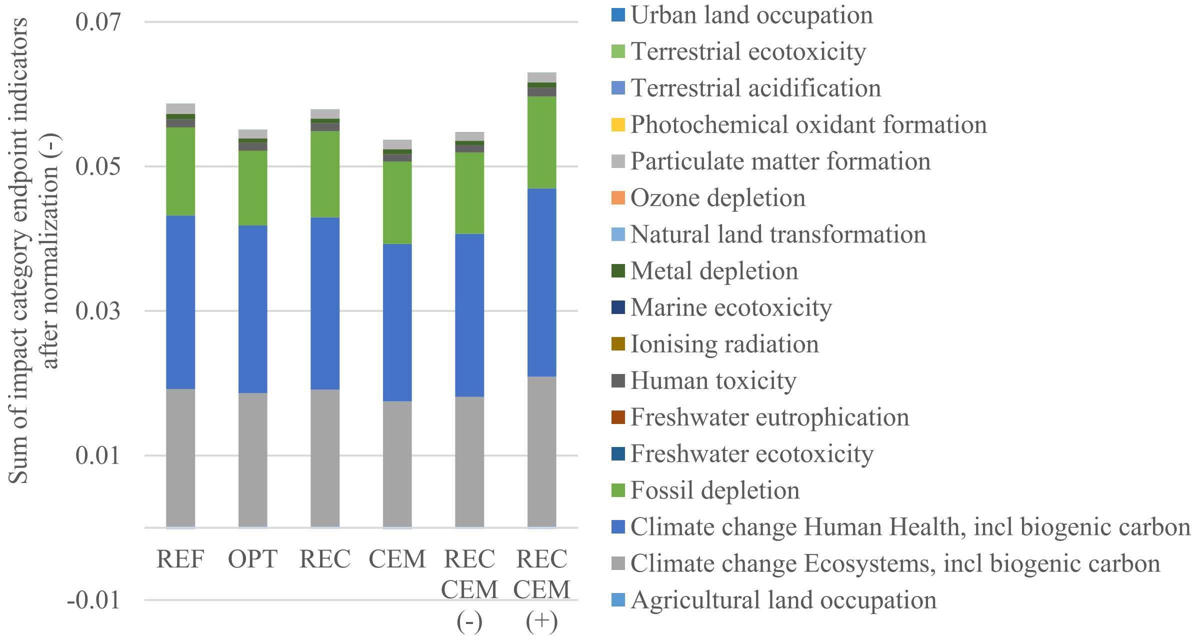

Figure 2. Endpoint indicators results of chosen fractions and primary aggregate after normalization

Similarly, the comparison of REF and REC mixtures shows, that primary gravel can be replaced with recycled aggregate. This replacement causes to decreasing environmental impact, too.

Table 4. Sum of endpoint indicator results after normalization

Mixture	REF	CEM	OPT	REC CEM (-)	REC CEM (+)	REC
Sum of impacts	0.0585	0.0535	0.0549	0.0546	0.0628	0.0577
Percentage of impacts	100.0	91.5	94.0	93.4	107.4	98.7

The recycled cement powder (RCP) was used as the partial cement replacement in two mixtures (CEM and REC CEM (-)). The RCP is a side product from the second phase of the CDW recycling process. In comparison with the production of each fraction, the production of RCP is minimal and so it did not take into account. Therefore, no environmental impacts were allocated on this material flow. Also, the amount of RCP in mixtures is about 1–2 % of weight and so it is insignificant.

3.3. Other properties of the assessed concretes

Mechanical and physical properties of concretes with RA were investigated in many studies. Table shows properties of the new concrete mixtures and the referential mixture.

Table 5. The overview of properties of the assessed concretes

Properties	REF	OPT	REC	CEM	REC CEM (-)	REC CEM (+)
Dry density [kg.m^{-3}]	2280	2140	2190	2260	2150	2250
Compressive strength [MPa]	36.6	25.4	29.3	37.8	35	32.2
Flexural strength [MPa]	4.6	4.7	5.6	5.1	4.1	6.2
Static modulus of elasticity [GPa]	28.3	31.4	29.4	28.4	25.2	32.3
Water absorption [%]	2.9	4.1	4.8	3.0	8.2	4.3

Mixtures with natural and recycled aggregates have been tested by Chen et al. Compressive strength of concretes with 100 % mixed coarse aggregate reached 75–85%, modulus of elasticity reached 70–80 % and bending strength was 78–91 % [1]. The capability of RA concrete to absorb water was influenced by water absorption of aggregates and so it was higher in comparison with conventional concrete. Zaharieva et al. have mentioned that water absorption could be 75 % higher for concrete with concrete RA [12]. The replacement of cement did not cause any negative impact on mechanical properties. Therefore, the possible use of RCP could be an opportunity for further research [13].

Considered RA were used for C20/C25 mixtures. However, RA can be used also for higher grade concrete. That utilization means higher cement demand to reach minimal mechanical properties. In this study, we suggest to replace a cement partly by RCP. This could be the solution for decrease of properties.

3.4. Influence of transportation

Transportation of CDW was not included into the considered system borders. For recycling processes is used the mobile crushing unit. This unit weighs about 50 t and it can be easily transported between building sites. Thus, only the manipulation on the recycling plant was considered. However, one of the most frequent question among producers of recycled aggregates is: How far can be recycled aggregate transported to be environmentally acceptable in comparison with nature aggregate?

Typical functional unit for transportation is 1 tkm. This unit expresses transport capacity and it can be calculated as the product of weight and distance.

Environmental impacts of transportation were estimated with a generic process. This process was described as a transport with a lorry (EURO 3, 20 t load capacity). The chosen midpoint indicator results for this process are: 0,058 kg CO_2 eq. (Climate change category), 0,066 kg 1,4-DB eq. (Human toxicity), 0,02 kg oil eq. (Fossil depletion), $8{,}6\cdot10^{-5}$ kg SO_2 eq. (Terrestrial acidification). This process is suitable also for transportation of primary aggregates.

The difference between total environmental impacts of the production of primary aggregate and recycled aggregate can be dived with the total environmental impact of the transport. For calculation were used endpoint indicator results after normalization. The output of this numerical operation is the maximal environmental acceptable distance for one ton of RA. Brick fraction 8–16 mm has a maximal distance 279 km and concrete fraction 8–16 mm has a maximal distance 299 km.

4. Conclusion

The aim of this study was to compare the utilization of primary resources with recycled materials and their overall environmental impact. In the first step, producing of recycled fractions and raw material was assessed. The recycling CDW and so production of recycled aggregates causes lower environmental impact. The significant influence is caused by the recycling of iron scrap from concrete waste.

In the second step, concrete mixtures with different amount of RA were assessed. The use of RA can reduce the overall environmental impact of concrete production. But this impact is affected by the amount of used cement mainly. However, the use of RA reduces environmental impacts by approximately 6 % (for OPT mixture) and still, the mixture can be classified as C20/25 strength class.

Also, the influence of transportation was considered separately. The maximal environmental acceptable distance for one ton of RA has estimated 279 km for brick fraction 8–16 and 299 km for concrete fraction 8–16. Hence, the transportation factor should not be a barrier for use of RA for the Czech industry.

The study confirms that replacing primary resources (gravel, sand, cement) by recycled aggregates causes reducing of environmental impacts even in case of mixtures which can be classified as C20/25 strength class.

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References

[1] Chen H J, Yen T and Chen K H 2003 Use of building rubbles as recycled aggregates *Cem. Concr. Res.* **33** 125-32

[2] Rao A, Jha K N and Misra S 2007 Use of aggregates from recycled construction and demolition waste in concrete *Resour. Conserv. Recy.* **50** 71–81

[3] Silva R V, de Brito J and Dhir R K 2014 Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production *Constr. Build. Mater.* **65** 201–17

[4] Knoeri C, Sanye-Mengual E and Althaus H J 2013 Comparative LCA of recycled and conventional concrete for structural applications *Int. J. Life Cycle Assess*. **18** 909–18

[5] Lockrey S, Verghese K, Crossin E and Nguyen H 2018 Concrete recycling life cycle flows and performance from construction and demolition waste in Hanoi *J. Clean. Prod.* **179** 593–604

[6] Finkbeiner M, Inaba A, Tan R B H, Christiansen K and Kluppel H J 2006 The new international standards for life cycle assessment: ISO 14040 and ISO 14044 *Int. J. Life Cycle Assess*. **11** 80–5

[7] Kočí V 2012 LCA a EPD stavebních výrobků: posuzování životního cyklu a environmentální prohlášení o produktu jako cesta k udržitelnému stavebnictví (Česká rada pro šetrné budovy)

[8] Flower D J M and Sanjayan J G 2007 Green house gas emissions due to concrete manufacture *Int. J. Life Cycle Assess*. **12** 282–8

[9] Hendriks C A 2000 Emission Reduction of Greenhouse Gases from the Cement Industry *Greenhouse Gas Control Technologies Conf.*

[10] Vieira D R, Calmon J L and Coelho F Z 2016 Life cycle assessment (LCA) applied to the manufacturing of common and ecological concrete: A review *Constr. Build. Mater.* **124** 656–66

[11] Turk J, Cotic Z, Mladenovic A and Sajna A 2015 Environmental evaluation of green concretes versus conventional concrete by means of LCA *Waste Manage.* **45** 194–205

[12] Zaharieva R, Buyle-Bodin F and Wirquin E 2004 Frost resistance of recycled aggregate concrete *Cem. Concr. Res.* **34** 1927–32

[13] Pavlu T and Sefflova M 2014 *Proc. Special Concrete and Composites 2014,* ed P Reiterman (Stafa-Zurich: Trans Tech Publications Ltd) pp 221–6