european cement research academy

European Cement Research Academy

European Cement Research
Academy GmbH

Tannenstrasse 2
40476 Duesseldorf, GERMANY

Phone: +49-211-23 98 38-0
Fax: +49-211-23 98 38-500

info@ecra-online.org
www.ecra-online.org

Chairman of the advisory board:
Daniel Gauthier

Managing director: Martin Schneider

Registration office: Duesseldorf
Court of registration: Duesseldorf
Commercial registration no.: 47580

Technical Report

A-2015/1860

Closing the loop: What type of concrete re-use is the most sustainable option?

Closing the loop: What type of concrete re-use is the most sustainable option?

Client:	CEMBUREAU, The European Cement Association
Ordering date:	10.07.2015
Client's order number:	
Our order number:	A-2015/1860
Project manager:	Christoph Müller
Person in charge:	Jochen Reiners
	Sebastian Palm
Despatch date:	27 November 2015
Content:	41 pages

Index of Contents

Executive Summary

On the basis of several studies, corresponding regulations and practical experience in several European countries, it can be concluded that concrete can be recycled. The rate of recycled aggregates in concrete and the total recycling rate of crushed concrete respectively differ in Europe. The differentiation of “recycling-grades” (Re-cycling, Up-cycling, Down-cycling etc.) is possible, but not mandatory. It depends on how the "benefit" for new materials or energy saving is calculated and how it is included in a sustainability analysis. Generally, concrete production generates higher requirements on the recycled materials than e. g. roadbeds. Screening the recycled material into size fractions and more thorough separating of impurities are required. If the use as an aggregate for roadbeds is possible, this should in many cases be the preferred option from a sustainability perspective, rather than the use as an aggregate in structural concrete. The environmental impacts of producing a concrete with recycled aggregates may exceed those of the production of a concrete with natural aggregates, particularly if natural gravel is replaced. A politically driven specification of “recycling targets” or “recycling quota” linked to a certain application without a case-by-case evaluation (LCA) or LCA-based benchmarks will not lead to the most sustainable solution in all cases.

1 General

The term “recycling” generally describes the re-use or the recovery of products or parts of products in the form of loops. Loops can be defined either within the manufacturing process or at the end of the products’ life cycle.

In literature, the term "recycling" is often altered or modified: Terms such as "down-cycling", "up-cycling", "out-cycling" or "open loop" and "closed-loop-recycling” can be found. These are attempts to say something about a technical or ecological quality of reuse. In addition, an impression of the "form" of the cycle is to be conveyed. None of these terms is clearly defined or even quantitatively occupied today.

A requirement for an "up-cycling", for example, might be the improvement in at least one property of the product containing the reused or recycled material while other properties have not substantially deteriorated. "Recycling" can mean that the properties of the product which contains recycling materials are not changed on average. When the product characteristics have deteriorated significantly through re-using secondary materials, the process might be called “down-cycling”. "Out-cycling" describes the case where a re-used or recovered product is transferred to a substance outside its own loop [1], [2]. For example, by crushing a concrete component a recycled aggregate is created [3]. If these aggregates can be used without affecting the properties of concrete to produce new concrete, the process can be called "recycling". If, for example, more cement would be needed to archive the same concrete properties compared to a concrete with virgin aggregates, the use of recycled aggregates might be seen as a “down-cycling”. The use of the concrete crushed sand provided in the crushing process as a secondary raw material for cement production [4] can be seen as a "recycling". But can it also be assessed as a kind of "up-cycling" if by its use energy and CO_2 in the clinker burning process can be saved? Using crushed limestone as a recycled aggregate for the production of sand-lime bricks, the same applies with regard to “recycling”. If the recycled limestone is used e.g. in road construction or structural concrete, the limestone leaves its own loop. Is that "out-cycling", “open-loop recycling” or “down-cycling”? It depends on how the "benefit" for new materials or energy saving is calculated and how it is included in a sustainability analysis. [5]

The discussion of the terms shows that there are different recycling processes or at least that the definition of different recycling processes is possible. But this differentiation is not mandatory. In many cases the terms are used to give the considered re-use a positive or negative rating.

In the end the question to be answered is, what type of re-use of concrete or other mineral building materials is holistically the most sensible and therefore sustainable option, taking into account parameters like "waste prevention", "conserve natural resources", "technical performance", "availability" and "transport distances", without a significant deterioration of other indicators such as "non-renewable primary energy" or "Global Warming Potential".

Against this background, the following study deals with

- Recycling rates and application rules for recycled (coarse) aggregates in (structural) concrete in Europe
- Alternative use of concrete crushed sand
- Uptake of carbon dioxide from the air over the life cycle of 1t of cement (carbonation)
- Comparative LCA study for different applications of crushed concrete
- Sustainable use of crushed concrete.

The aim is to give indications about what type of concrete re-use is holistically the most sensible and therefore sustainable option and whether a politically driven specification of “recycling targets” or “recycling quota” linked to a certain application would make sense.

2 Recycling rates

2.1 General

With regard to the re-use of concrete in the form of recycled aggregates (crushed concrete and concrete crushed sand) a large series of publications can be found. On the basis of these studies and corresponding regulations in several European countries, it can be concluded that concrete can be recycled.

The basic method of recycling concrete is crushing the debris to produce a granular product of a given particle size. Current technologies for concrete recycling essentially comprise jaw crushers and impact crushers: jaw crushers operate according to the principle of pressure crushing, whereas in impact crushers, the crushed material is picked up by a fast moving rotor, accelerated and smashed against an impact plate. The crushed material is broken repeatedly until it is smaller than a set crushing size. Generally, magnetic separators are incorporated in the crushers to remove remaining ferrous matter, particularly reinforcing steel.

The rate of recycled aggregates in concrete and the total recycling rate of crushed concrete differ greatly in Europe, as can be seen in **Figure 1**.

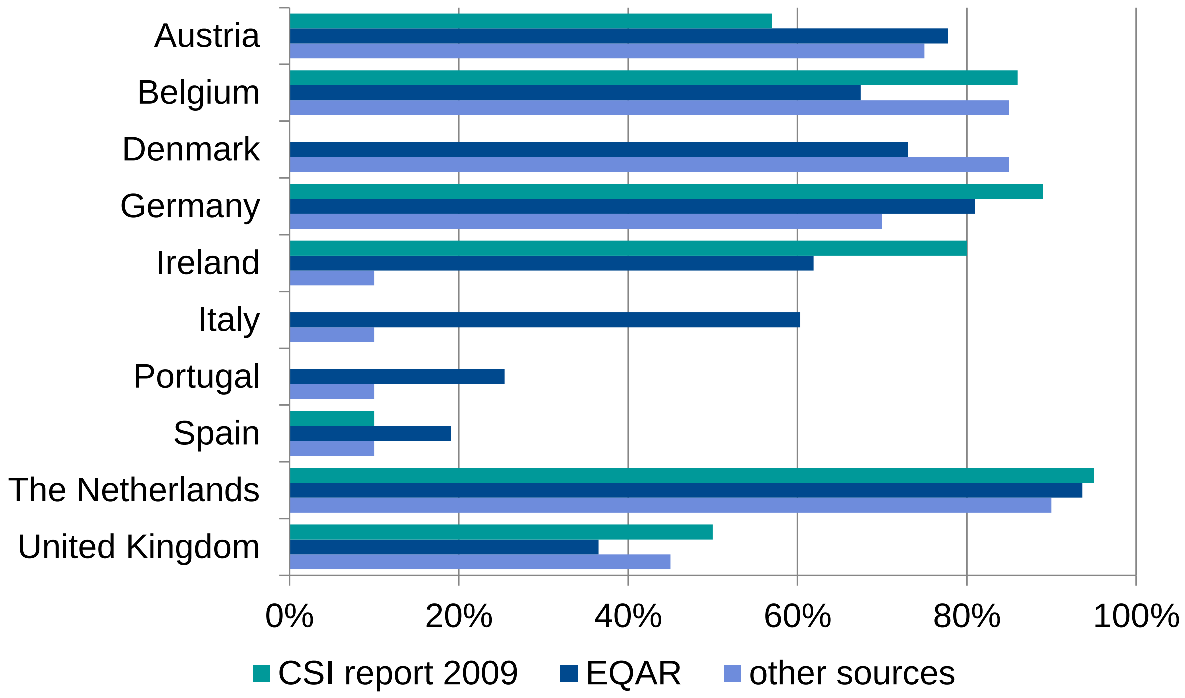


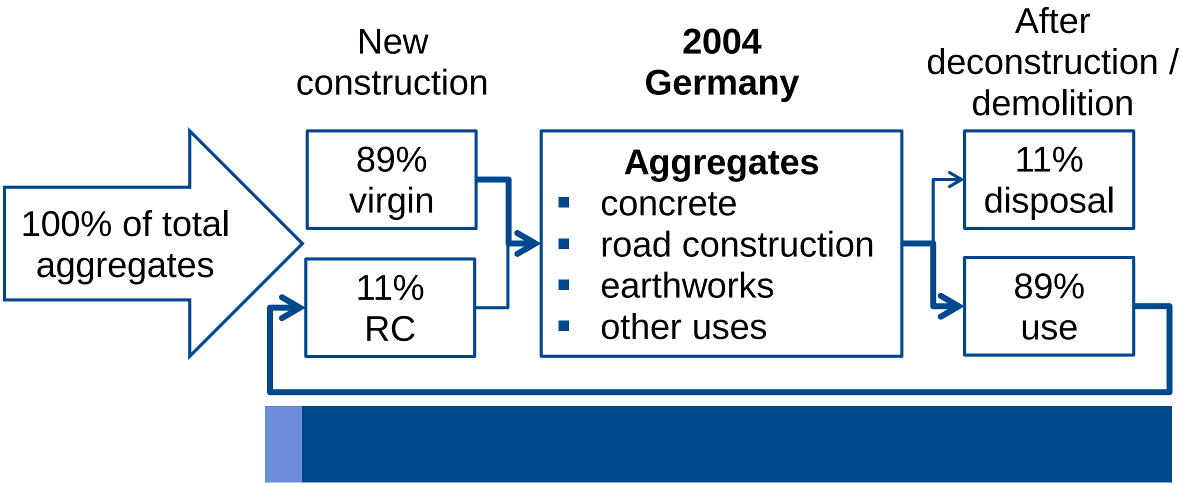
Figure 1 Recycling rates in Europe, data of different sources (1999 - 2009), [6], [7], [8], [9], [10], [11], [12]

There are differences in the different data sources compared in **Figure 1**. These differences may, in parts, result from different definitions of recycling or different system boundaries. One reason for these different numbers between countries is, among others, the availability of natural resources. Especially in the Netherlands, Belgium and the Alpine States Austria and Switzerland, natural gravel sources are limited. Also, the landfill space could be limited in some countries.

In the following paragraphs, a closer look on the situation in some exemplary countries is presented.

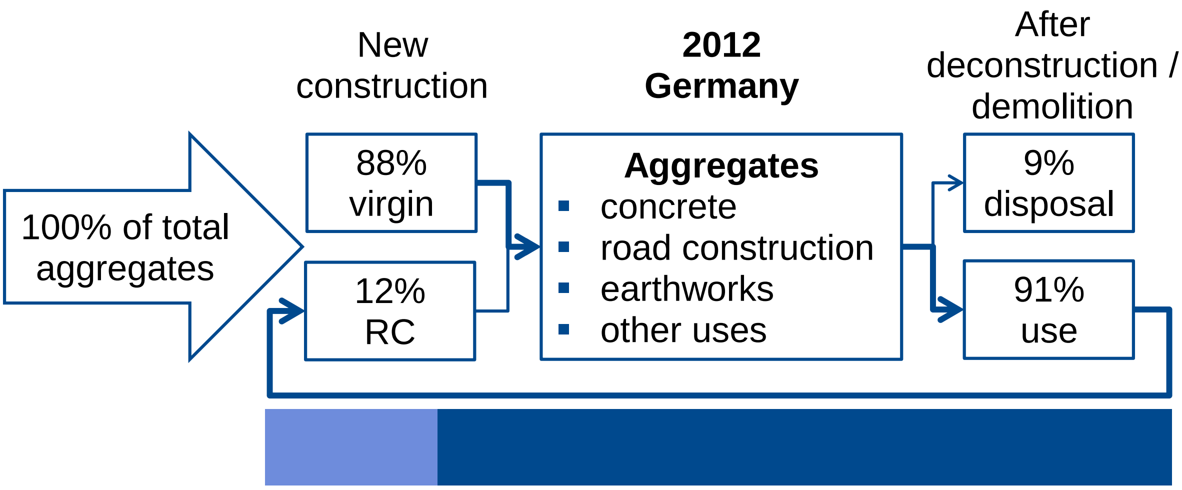
2.2 Germany

According to the data available for example on the homepage of the “Federal office for statistics” or in [13], [14], Germany had a recycling rate of 89% in 2004 and of 91% in 2012 for mineral building wastes. The following diagrams (**Figure 2**, **Figure 3**) show the amount of aggregates which were replaced by recycled material in 2004 and 2012. Additionally, the share of using recycled aggregates in concrete compared to other uses (road construction for example) is given.



	use of recycled aggregates
concrete, asphalt	4%
road construction, earthworks, other uses	96%

Figure 2 Recycling situation in Germany 2004 [13]

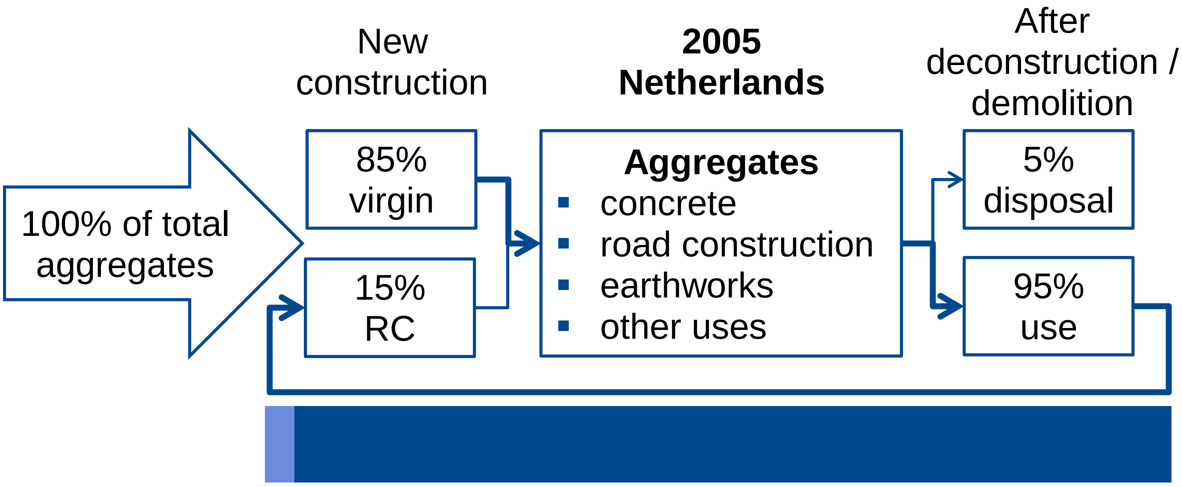


	use of recycled aggregates
concrete, asphalt	19%
road construction, earthworks, other uses	81%

Figure 3 Recycling situation in Germany 2012 [14]

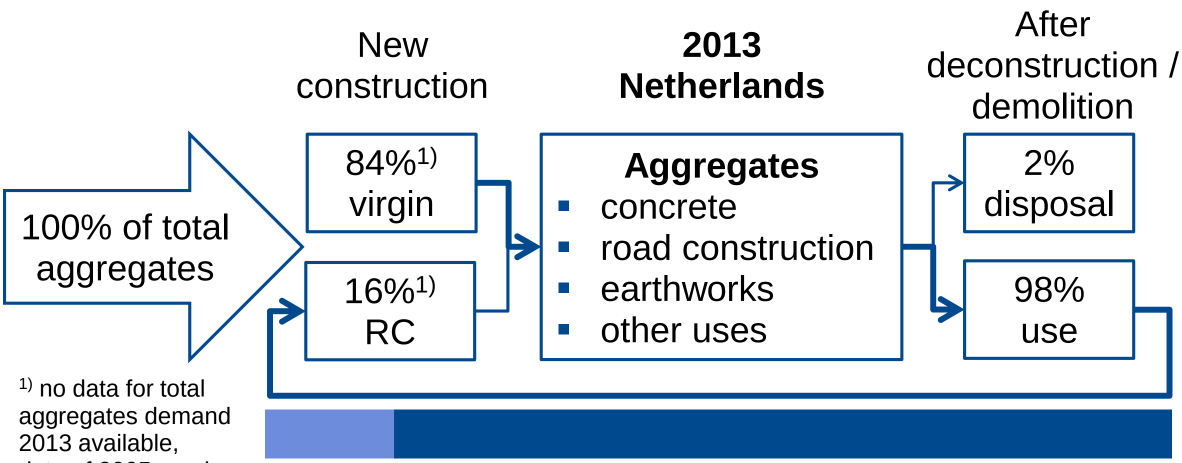
2.3 The Netherlands

The recycling situation in the Netherlands is represented in the same way in **Figure 4** and **Figure 5**. Although the Netherlands and Germany have very high rates of recycling, the amount of recycled building materials is not nearly enough to meet the demand for aggregates - its percentage amounts only to approx. 10 - 15%. In both countries, the share of recycled material used in concrete has risen in the past years.



	use of recycled aggregates
concrete, asphalt	3%
road construction, earthworks, other uses	97%

Figure 4 Recycling situation in the Netherlands 2005 [12], [15], [16]



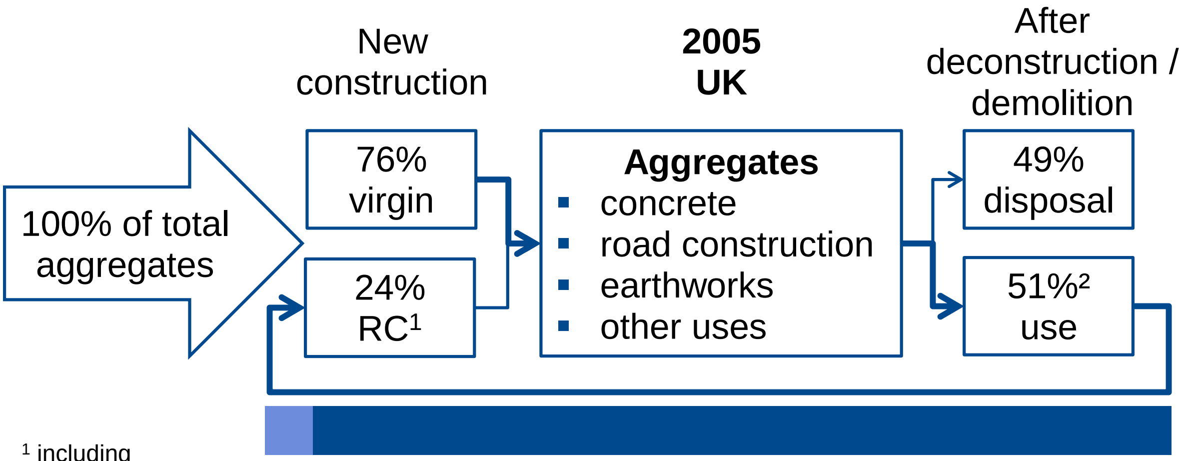
1) no data for total aggregates demand 2013 available, data of 2005 used

	use of recycled aggregates, Data 2010: Ramon Janssen (AVG): Recycling in the Netherlands
concrete, asphalt	14%
road construction, earthworks, other uses	86%

Figure 5 Recycling situation in the Netherlands 2013 [17]

2.4 United Kingdom

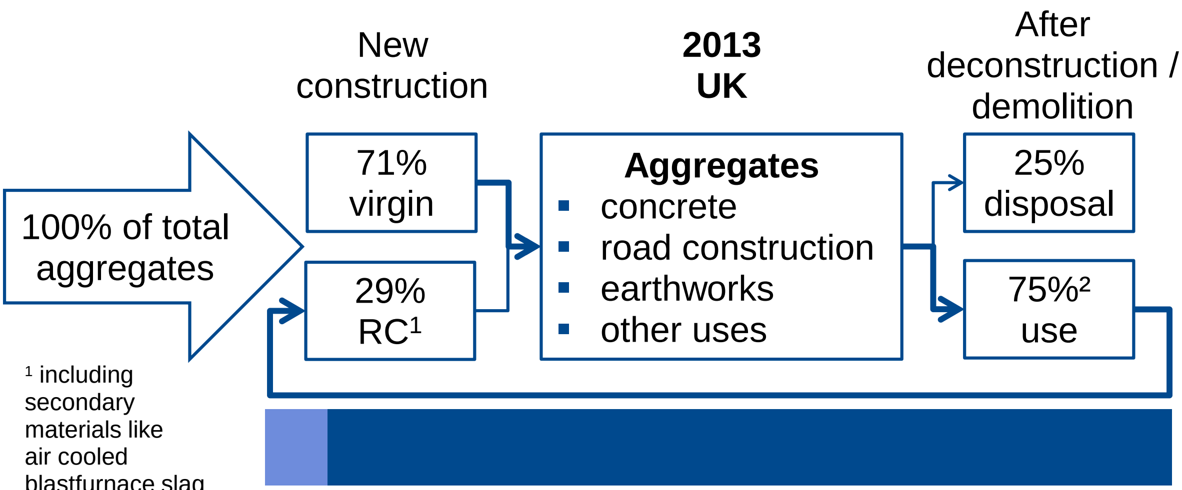
The recycling situation in the United Kingdom is represented in the same way in **Figure 6** and **Figure 7**. Compared to Germany and the Netherlands, the United Kingdom has relatively high rates of recycled aggregates replacing virgin material. This may be caused by the fact that this value includes additionally secondary materials like air cooled blast furnace slag which comes from outside the construction loop [18].



1 including secondary materials like air cooled blastfurnace slag
2CSI report 2009

	use of recycled aggregates (2008, earliest available value)
concrete, asphalt	5%
road construction, earthworks, other uses	95%

Figure 6 Recycling situation in the United Kingdom 2005 [12], [19], [18]



1 including secondary materials like air cooled blastfurnace slag
2EISC LTD: Construction sector: Overview in the UK, 2012

	use of recycled aggregates
concrete, asphalt	7%
road construction, earthworks, other uses	93%

Figure 7 Recycling situation in the United Kingdom 2013 [19], [20], [18]

3 Application rules

3.1 General

The European concrete standard EN 206:2013, annex E and EN 13369:2012 for precast concrete elements contain informative recommendations on the use of coarse recycled aggregates in concrete. Following EN 206:2013 – table E.2 (**Table 2**), two types of recycled aggregates are defined with reference to EN 12620. Recommendations for the maximum replacement rates are given depending on the exposure class. Additionally, recommendations are given for physical and chemical aspects. EN 206 is a non-harmonised standard. Therefore, paragraph 5.1.3 of EN 206 states: "(2) *Recycled and manufactured aggregates, other than air-cooled blast furnace slag, listed in EN 12620 with identified history of use, may be used as aggregate for concrete if the suitability is established by provisions valid in the place of use*." This means that application rules for the use of recycled aggregates are different in the European countries (CEN member states). In the following chapters, application rules for some countries are given as examples.

The reference point of "aggregates replacement rate" is not the same in each of the countries mentioned in the following chapters. In Germany for example, the replacement rate refers to total aggregates. In the UK, on the other hand, the reference point is "aggregates > 4 mm". To make the following numbers clear, all replacement rates will be calculated with reference to "% of total aggregates" using 3 exemplary aggregates grading curves given in **Table 1**.

Table 1 Aggregates grading curves

Grading curve	Passing mesh size in mm							
	0.25	0.5	1	2	4	8	16	32
	in mass-%							
MAS 8	8.0	20.0	31.5	46.5	67.5	100.0	100.0	100.0
MAS 16	5.5	14.0	22.0	31.5	46.0	68.0	100.0	100.0
MAS 32	8.0	11.5	18.0	25.5	35.0	50.0	71.0	100.0

MAS: Maximum aggregate size

Table 2 Recommendation for the use of coarse (d ≥ 4 mm) recycled aggregates according to EN 206:2013

Recycled aggregate type	Reference point	Exposure class			
		X0	XC1, XC2	XC3, XC4, XF1, XA1, XD1	all other exposure classes [a]
Type A: (Rc_{90}, Rcu_{95}, Rb_{10-}, Ra_{1-}, FL_{2-}, XRg_{1-})	**≥ 4 mm**	**50%**	**30%**	**30%**	**0%**
	total aggregates, MAS 8	16%	10%	10%	0%
	total aggregates, MAS 16	27%	16%	16%	0%
	total aggregates, MAS 32	33%	20%	20%	0%
Type B [b]: (Rc_{50}, Rcu_{70}, Rb_{30-}, Ra_{5-}, FL_{2-}, XR_{g2-})	**≥ 4 mm**	**50%**	**20%**	**0%**	**0%**
	total aggregates, MAS 8	16%	7%	0%	0%
	total aggregates, MAS 16	27%	11%	0%	0%
	total aggregates, MAS 32	33%	13%	0%	0%

[a] Type A recycled aggregates from a known source may be used in exposure classes to which the original concrete was designed with a maximum percentage of replacement of 30 %.

[b] Type B recycled aggregates should not be used in concrete with compressive strength classes > C30/37.

Bold: normative value

3.2 Germany

The German code of practice (DAfStb Guideline) "Concrete with recycled aggregate" permits the use of a maximum of 45% of the total aggregates as recycled aggregates larger than 2 mm for concretes with a maximum strength class C30/37, depending on the exposure classes and the moisture classes according to the code of practice for alkali-silica-reaction (**Table 3**). Those concretes can be dimensioned according to EN 1992-1-1 as concretes with normal aggregates. The use of recycled aggregates for pre-stressed concrete or light-weight concrete is not allowed in Germany.

Table 3 Maximum use of coarse (d ≥ 2 mm) recycled aggregates in Germany in mass %

Recycled aggregate type	**Reference point**	**Exposure class**		
		WO, XC1 WF, XC1-XC4	**WF, XF1, XF3**	**WF, XA1**
Type 1: (Rcu_{90}, Rb_{10-}, Ra_{1-}, FL_{2-}, XRg_{1-})	**total aggregates (all grading curves)**	**45%**	**35%**	**25%**
	≥ 2 mm, MAS 8	84%	65%	47%
	≥ 2 mm, MAS 16	66%	51%	36%
	≥ 2 mm, MAS 32	60%	47%	34%
Type 2: (Rcu_{70}, Rb_{30-}, Ra_{1-}, FL_{2-}, XRg_{2-})	**total aggregates (all grading curves)**	**35%**	**25%**	**25%**
	≥ 2 mm, MAS 8	65%	47%	47%
	≥ 2 mm, MAS 16	51%	36%	36%
	≥ 2 mm, MAS 32	47%	34%	34%
Bold: normative value				

Additionally, different requirements on physical (for example density, particle shape), chemical (for example Chloride and Sulphate content) and other properties (for example freeze-thaw resistance, alkali-reactivity-class) are defined.

3.3 United Kingdom

In the UK, the use of 100% of the coarse crushed concrete aggregate (> 4 mm) is allowed for concretes with a strength class no greater than C16/20. For particular concretes in strength classes from C20/25 to C 40/50, up to 20% coarse crushed concrete aggregate can be used. For particular concretes in strength classes up to C40/50, 100% of crushed concrete aggregate can be used if the concrete is for exposure classes X0, XC1 to XC4 inclusive, XF1 and the UK chemical resistance class DC-1 (similar to XA1).

Table 4 Maximum use of coarse (d ≥ 4 mm) recycled aggregates in UK in mass %

Recycled aggregate type	**Reference point**	**Strength class**	
		≤ C16/20	**≤ C40/50**
no types defined	**≥ 4 mm**	**100%**	**20%**
	total aggregates, MAS 8	33%	7%
	total aggregates, MAS 16	54%	11%
	total aggregates, MAS 32	65%	13%
Bold: normative value			

3.4 Switzerland

In Switzerland, concrete is defined as “recycling concrete” if at least 25% of total aggregates are recycled aggregates. Two types of recycling concretes are defined:

- RC-C (C for concrete) with at least 25% of recycled aggregates from concrete products (R_c) and with a maximum of 5% of recycled aggregates from masonry products (R_b).
- RC-M (M for mixed rubble) with at least 25% of recycled aggregates (R_c+R_b) and with at least 5% of recycled aggregates from masonry products (R_b).

In Switzerland, all fractions, including the fine fraction 0/4 can be used to produce recycling concrete [21]. Normally, concrete is crushed, sieved into fractions and directly used. Mixed rubble is crushed twice: The fractions 0/8 or 0/16 of the first crushing are not normally used for the production of concrete. The coarser fraction is crushed a second time and is then used like crushed concrete [22], [23]. Recycled concrete in practice is used with rates of re-placing aggregates with recycled material between 40 – 60% of total aggregates. [23]

These concretes are allowed to be used under the concrete exposure conditions given in **Table 5**.

Table 5 Requirements for use of recycling concrete in Switzerland [21]

<table>
<tr><th rowspan="2">Recycling concretes</th><th colspan="5">Exposure class</th></tr>
<tr><th>X0</th><th>XC1 (dry)</th><th>XC1 (wet), XC2, XC3</th><th>XC4</th><th>XD, XF, XA</th></tr>
<tr><td>RC-C</td><td colspan="4">allowed</td><td>further testing required</td></tr>
<tr><td>RC-M with R_b 5 -25 % and R_c+R_b > 25 %</td><td colspan="3">allowed</td><td>further testing required</td><td rowspan="2">not allowed</td></tr>
<tr><td>RC-M with R_b > 25 %</td><td colspan="2">allowed</td><td colspan="2">further testing required</td></tr>
</table>

Annex Q of EN 13369:2012 provide specific information for reclaimed crushed aggregates obtained from precast concrete products manufactures in the same factory.

4 Concrete crushed sand

For the re-use of crushed concrete in structural concrete, concrete crushed sand is a chal-lenge. The reason is – in comparison to larger particles – the less favourable properties of concrete crushed sand, primarily due to the former cement matrix, adhered to the aggregate. Therefore, a complete re-use of crushed concrete as aggregates for new concrete is usually not achieved. The crushed concrete sand is usually used in road constructions or earth-works, or it has to be deposited.

Studies on cement works have shown that concrete crushed sand usually meets the tech-nical requirements for use as secondary raw material in the clinker burning process [4]. In a work trial, a high quality clinker was produced using concrete crushed sand. The results and its follow-up LCA show that under certain conditions, the use of concrete crushed sand for cement clinker production can be environmentally beneficial. Regarding this recycling path, further development potential is given. Different processing techniques that may lead to different properties of concrete crushed sands offer the chance to increase the potential of concrete sand use in the production of cement clinker.

A solution to the above-described problem could be a new processing technique described in [24]. Concrete is separated in the cement matrix and aggregates by electro dynamic fragmentation. In contrast to crusher techniques, no or much fewer parts of the matrix remain adhered to the aggregates. That leads to the possibility of using all fractions, including the fraction < 2mm, as recycled aggregates in concrete. Regarding this recycling technique, further development potential is given and further investigations are necessary.

5 Carbonation

During and after the lifetime of concrete structures or other cement-based products, hydrated cement contained within the product reacts with CO_2 in the air. Part of the CO_2 emitted during cement production is reabsorbed by the mortar or concrete through carbonation. The quantity of CO_2 taken up will depend on the type of application and also its treatment after its lifetime. This reaction takes place mainly on the surface of cement-based products. Structural concrete applications are designed according to strict codes and standards which ensure that carbonation at the concrete surface does not lead to corrosion of reinforcement. Carbonation can nevertheless be particularly relevant after demolition when the surface area in contact with air increases very significantly. [25]

There are different sources [26], [27], [28], [29], [30], [31], [32], [33], [34], [35] in which the amounts of carbon dioxide absorbed over the life cycle of 1t of cement are calculated. Depending on conditions and assumptions, approximately 10% to 30% of the CO_2 from the cement production can be taken up during the life cycle of cement.

Remark: In the LCA study in paragraph 6 of this report, the uptake of CO_2 through carbonation has not been taken into account.

6 Comparative LCA study according to EN 15804

6.1 General

To assess the environmental impacts of

- the use of recycled concrete as a constituent of the roadbed in road construction (or below foundations) versus
- the use of recycled concrete as an aggregate in concrete acc. to EN 206 and national regulations or EN 1992-1-1 respectively,

an LCA study according to EN 15804 [36] has been carried out in the scope of this project. The study is based on process data which was obtained in the context of a research project carried out at the Technical University of Cottbus in 2009/2010 [37]. For the research project, the energy demand of all processes involved with concrete recycling was monitored at a typical stationary recycling plant in Germany. Emissions (noise, vibrations, dust) were not measured.

The information on environmental impacts related to the recycling processes will be presented in the modular structure defined in EN 15804. **Table 6** gives an overview of the relevant information modules.

Table 6 Relevant information modules considered in the LCA study

Module (EN 15804)	**Content**	**LCA in which Module is included**
Module C	end of life stage	LCA of the demolished construction works
Module D	benefits and loads beyond the system boundary	LCA of the demolished construction works
Module A1	raw material supply	LCA of the new construction works

A selection of the environmental indicators specified in EN 15804 is used to quantify the environmental impacts. These were calculated using the characterisation factors from CML-IA version 4.1, dated October 2012 (Institute of Environmental Sciences Faculty of Science University of Leiden, Netherlands).

The demolition of the construction works during the period observed was carried out in a way that the amount of extraneous (i.e. non-concrete) materials was minimised.

Figure 8 gives a schematic overview of the waste processing at the examined recycling plant. For both

- the intended use of crushed concrete in road construction and
- the intended use of crushed concrete as a recycled aggregate,

initially the same recycling processes are carried out (see “waste processing” below). It is assumed that after these conventional recycling processes the “end of waste” state is reached (blue dotted line). While according to **Scenario A**, the crushed concrete is used without further processing as a constituent of roadbeds in road construction, **Scenario B** examines the additional processes required to use the recycled concrete as an aggregate in fresh concrete.

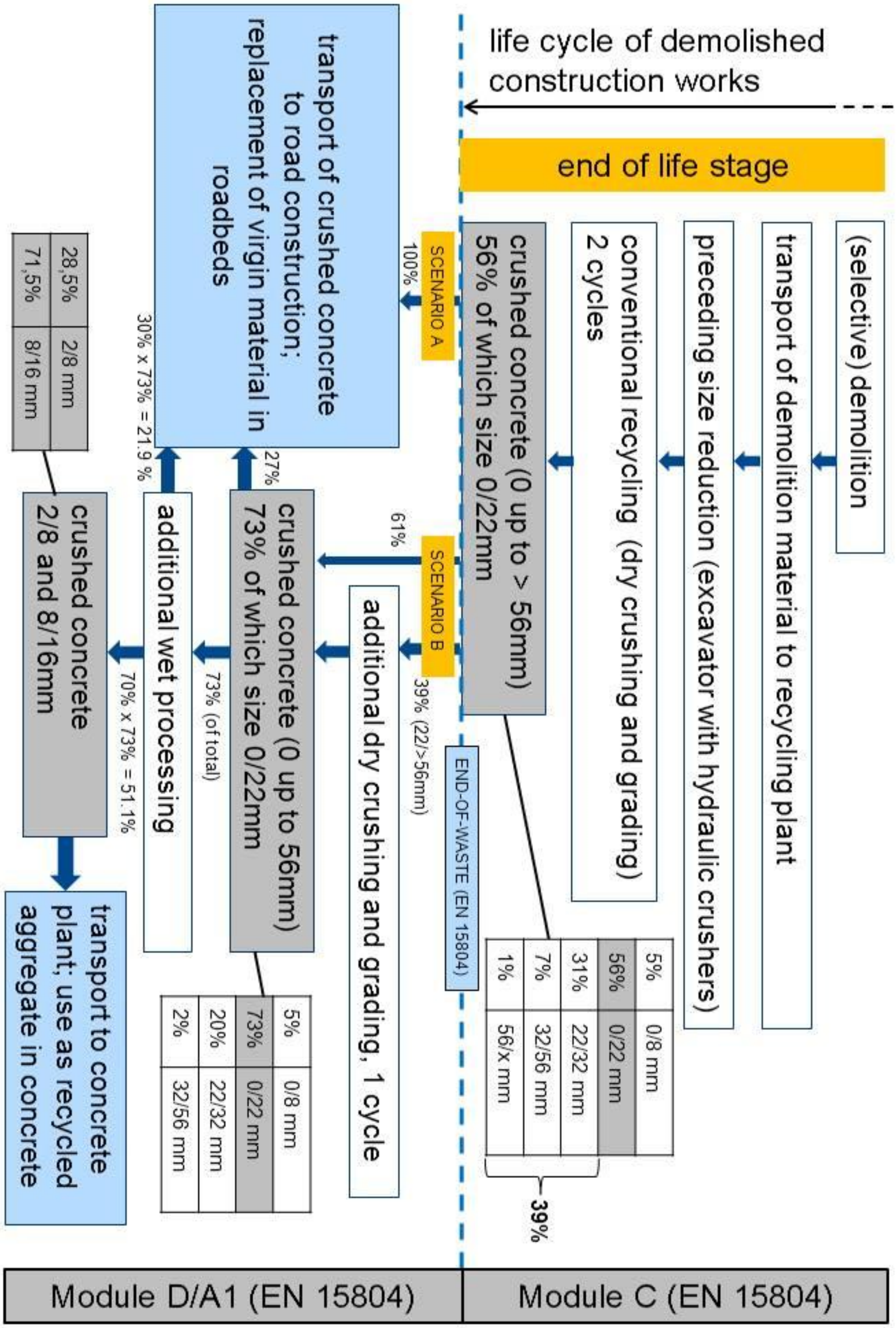


Figure 8 Flowchart showing the processes of concrete recycling (based on the material flows at the observed recycling plant [37])

Transport processes influence the net impact that has to be declared in Modules C, D and A1. **Figure 9** shows that for recycled material typically one additional transport process is required.

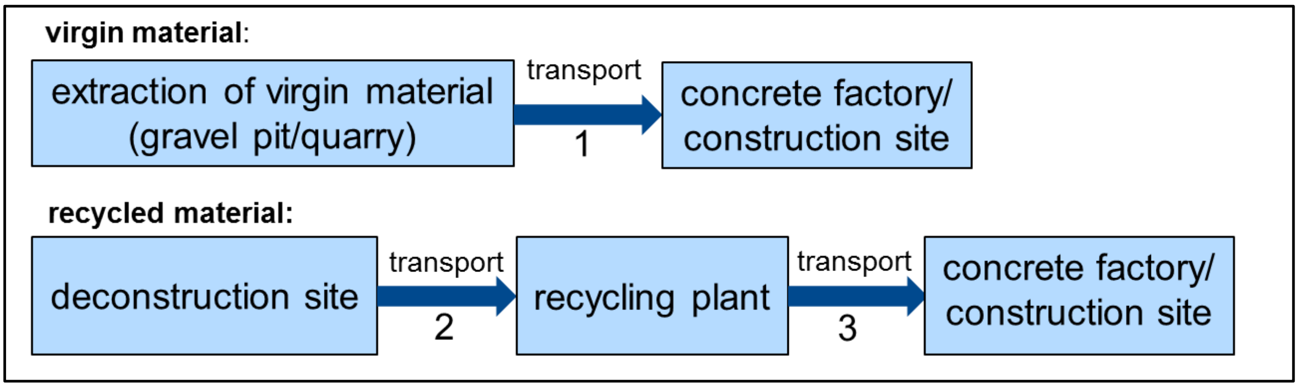


Figure 9 Transport processes for virgin material and recycled material

6.2 Waste processing (Module C according to EN 15804)

According to the "polluter-pays-principle" in EN 15804, processes of waste processing should be assigned to the product system that generates the waste until the end-of-waste state is reached. The related environmental impacts are therefore part of the system of the demolished construction works. For the processes monitored in the research project, they should be declared in Module C (waste processing) as follows:

Module C1: (selective) demolition

Module C2: transport of demolition material to the recycling plant ("transport 2" in **Figure 9**)

Module C3: preceding size reduction using an excavator with hydraulic crushers

Module C3: "conventional" dry crushing and grading

In the observed recycling plant, the "conventional" recycling is accomplished in two cycles, the first of which is carried out with a jaw crusher, the second with an impact crusher. Moreover, the material passes through a number of screens and a magnetic belt to size it into different fractions and separate extraneous material. In the context of this comparative study, the environmental impacts associated with these processes are not relevant as they arise for both Scenario A and Scenario B.

After these conventional recycling processes, the recycled concrete can be sold, e.g. for the use in roadbeds. According to EN 15804 [36], Annex B.1, it is therefore assumed that the "end-of-waste" state (EN 15804) is reached at this point.

Remark: It should be pointed out that if the demolished concrete was not processed/recycled, it would generally be transported to a landfill for disposal. Most related environmental impacts (as verified with the GaBi-process "Glass/inert waste landfill with surface and basic sealing, 100 years deposit, EU 27, 2013"), which would then be reported in Module C4, would however significantly exceed those of the recycling processes (after the selective demolition) monitored in the observed recycling plant (Examples: Global Warming Potential (GWP) for the landfill of glass/inert waste: 13,5 kg CO_2–eq/t, GWP "conventional recycling +

preceding size reduction": 2,1 kg CO_2–eq/t; use of non-renewable primary energy (PE_{nren}) for the landfill of glass/inert waste: 186 MJ/t, PE_{nren} "conventional recycling + preceding size reduction": 32,8 MJ/t). The GaBi dataset contains (among others) the impacts of sealing materials (clay, mineral coating, PE film) and considers environmental impacts of the landfill process occurring within 100 years. A detailed comparison of the environmental impacts of concrete and masonry debris either landfilled or used as unbound aggregate in road construction is presented in [38].

6.3 Benefits and loads beyond the system boundary (Module D according to EN 15804)

6.3.1 General

After having reached the "end-of-waste" state, further processing may be necessary in order to replace primary material or fuel in another product system. According to EN 15804, such processes are considered to be beyond the system boundary and are assigned to Module D. The net impacts (potential benefits or avoided loads) to be declared in Module D are calculated by adding the impacts connected to the recycling or recovery processes from beyond the system boundary (after the end-of-waste state) up to the point of functional equivalence where the secondary material or energy substitutes primary production and subtracting the impacts resulting from the substituted production of the product or substituted generation of energy from primary sources.

As the processes considered in Module D will take place in the future, assumptions have to be made to estimate their environmental impacts. According to EN 15804, the scenarios for waste processing should be based on current average technology/practice.

6.3.2 Scenario A

For Scenario A, the total environmental impacts of the processes in **Table 7** can be declared in Module D:

Table 7 Processes declared in Module D (Scenario A)

Module and content	Processes	Sign
Module D: benefits and loads of crushed concrete beyond the system boundary	avoided impacts of transports of virgin material to a concrete factory or road construction site ("transport 1" in **Figure 9**)	negative sign (benefit)
	avoided impacts of transports of extracting/producing virgin material	negative sign (benefit)

Table 8 shows the environmental impacts of the transport of one ton of material per lorry (calculated with GaBi 6).

Table 8 Environmental impacts related to the transport of one ton of material per lorry (emission standard Euro 3, distance 100km, payload 22 tons, utilisation 85%, return journey not considered)

Parameter	**Unit (expressed per 1 ton material conveyed)**	**Transport 100 km**
Global warming potential, GWP	kg CO_2 equiv	5.1
Depletion potential of the stratospheric ozone layer, ODP	kg CFC 11	3.72E-11
Acidification potential of soil and water, AP	kg SO_2 equiv	0.0324
Eutrophication potential, EP	kg $(PO_4)^{3-}$	0.0077
Formation potential of tropospheric ozone, POCP	kg Ethene	-0.0128
Abiotic depletion potential (ADP-elements) for non-fossil resources	kg Sb equiv	2.21E-07
Abiotic depletion potential (ADP-fossil fuels) for fossil re-sources	MJ, net calorific value	70.7
Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materi-als)	MJ, net calorific value	2.83
Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, net calorific value	71.1

Table 9 shows the environmental impacts of the extraction/production of crushed natural stone and natural gravel according to the GaBi 6 database.

Table 9 Environmental impacts related to the extraction/production of natural aggregates

Parameter	**Unit (ex-pressed per 1 ton ag-gegate)**	**1 t crushed natural stone DE**	**1 t natural gravel (from pit) EU 27**
Global warming potential, GWP	kg CO_2 equiv	19.3	2.20
Depletion potential of the stratospheric ozone layer, ODP	kg CFC 11	9.73E-10	6.21E-10
Acidification potential of soil and water, AP	kg SO_2 equiv	0.0513	0.0141
Eutrophication potential, EP	kg $(PO_4)^{3-}$	0.00973	0.0023
Formation potential of tropospheric ozone, POCP	kg Ethene	-0.0507	0.00148
Abiotic depletion potential (ADP-elements) for non-fossil resources	kg Sb equiv	2.61E-6	3.90E-7
Abiotic depletion potential (ADP-fossil fuels) for fossil resources	MJ, net calorific value	217	27.7
Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, net calorific value	41.8	4.3
Total use of non-renewable primary energy resources (primary ener-gy and primary energy resources used as raw materials)	MJ, net calorific value	268	33.9

The values in **Table 8** in relation to those in **Table 9** show that transport processes are rele-vant for this study and should not be neglected.

In a region where typically gravel from pits is used for roadbeds and the concentration of gravel pits would result in an average transport distance (gravel pit to road construction site) of 100 km, Module D could be declared as shown in **Table 10**.

Table 10 Environmental benefits of crushed concrete replacing natural gravel in road-beds (Module D, absolute values = sum of the right columns in **Table 8** and **Table 9**)

Parameter	**Unit (expressed per 1 ton aggregate)**	**1 t crushed concrete Module D**
Global warming potential, GWP	kg CO_2 equiv	-7.34
Depletion potential of the stratospheric ozone layer, ODP	kg CFC 11	-6.58E-10
Acidification potential of soil and water, AP	kg SO_2 equiv	-0.0465
Eutrophication potential, EP	kg $(PO_4)^{3-}$	-0.01
Formation potential of tropospheric ozone, POCP	kg Ethene	0.0113
Abiotic depletion potential (ADP-elements) for non-fossil resources	kg Sb equiv	-6.11E-07
Abiotic depletion potential (ADP-fossil fuels) for fossil resources	MJ, net calorific value	-98.4
Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, net calorific value	-7.1
Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, net calorific value	-105.0

6.3.3 Scenario B

For Scenario B, the total environmental impacts of the processes in **Table 11** can be declared in Module D.

Table 11 Processes in Module D (Scenario B)

Module and content	**Processes**	**Sign**
Module D: benefits and loads of crushed concrete beyond the system boundary	impacts of additional processing to obtain crushed concrete suitable for use as recycled aggregate in structural concrete	positive sign (load)
	avoided impacts of transports of virgin material to a concrete factory or road construction site (“transport 1” in **Figure 9**)	negative sign (benefit)
	avoided impacts of transports of extracting/producing virgin material	negative sign (benefit)

Compared to Scenario A, the impacts of additional recycling reduce the benefit beyond the system boundary that can be declared in Module D: in Scenario B an environmental load has to be taken into account while no additional benefit can be declared (since for both Scenario A and Scenario B, the recycled material replaces virgin material).

At the recycling plant evaluated in the considered research project, an average of 39% (by weight) of the crushed concrete has sizes greater than 22mm after the conventional recycling (Figure 8). To maximise the share of the size fractions 2/8 and 8/16mm which will later be used as recycled aggregate, these 39% are conveyed to a third dry crushing cycle which involves an impact crusher and subsequent screening processes. All units are electrically operated. Table **12** gives the typical electricity consumption of the units involved.

Table 12 Electricity use for the additional dry crushing and screening processes [37]

Unit	**Number of units**	**Max. capacity**	**Electricity use at maximum capacity**	**Number of units used for additional dry crushing**	**Percentage of units used**	**Average utilised capacity**	**Total electricity use**
		[t/h]	**[MJ/h]**		**[%]**	**[%]**	**[MJ/t]**
Jaw crusher	1	133	324	0	0	75	0
Impact crusher	1	133	324	1	100	75	1.83
Conveyor belts	16	133	302.4	11	69	75	1.17
Screens	4	133	212.4	2	50	75	0.60
Pushcart	1	133	108	0	0	75	0.00
Vibrating unit below crusher	4	133	21.6	2	50	75	0.06
Vibrating unit below feed hopper	2	133	14.4	1	50	75	0.04
Magnetic belt	3	133	39.6	2	67	100	0.20
Heating	4	133	21.6	0	0	0	0
Illumination	1	133	5.4	0	0	0	0
Total							**3.90**

After the additional dry crushing and grading, 73% of the total concrete (by weight) belongs to the desired size fraction 0/22mm. While the remaining 27% are used in roadbeds, these 73% undergo a subsequent wet crushing and screening process. All units are electrically operated. **Table 13** gives the typical electricity consumption of the units involved in the wet process. Moreover, two wheel loaders (diesel consumption 0.2 l/ton of crushed concrete) are employed.

Table 13 Electricity use for the wet crushing and screening processes [37]

Unit	Max capacity	Electricity use at maximum capacity	Average utilised capacity	Total electricity use
	[t/h]	[MJ/h]	[%]	[MJ/t]
Pumps	80	10.37	75	7.8
Conveyor belts	80	2.39	75	1.8
Compressor	80	0.52	75	0.4
Screens	80	3.23	75	2.4
Aquamators	80	0.86	75	0.6
Magnetic belt	80	0.27	100	0.3
Feed hopper	80	0.52	75	0.4
Illumination	80	0.14	25	0.0
Heating	80	0.45	25	0.1
Others	80	0.52	50	0.3
Total				**14.1**

70% of the output of the wet processing (51.1% of the total weight after the conventional recycling) has the desired size fractions 2/8 and 8/16mm and can be used as a recycled aggregate whereas the remaining 30% is used in roadbeds.

The impacts of additional processing to obtain crushed concrete suitable for use as a recycled aggregate in structural concrete to be declared in Module D can be calculated as follows:

impacts of additional processing (per ton of crushed concrete) =
39% x impacts of additional dry processing + 73% x impacts of wet processing

To determine the impacts of the use of electrical energy, an electricity mix of the six EU countries with the highest concrete production volume [39] was used.

Table 14 Electricity mix used in the LCA model

National electricity mix	Share in LCA mix
Germany	25.8%
France	20.8%
Italy	17.9%
Poland	12.3%
Spain	12.3%
United Kingdom	10.8%

Table 15 shows the environmental impacts of the additional processing. For many indicators, the values are in the same order of magnitude as those related to the extraction/production

of natural gravel, while they are significantly lower than those related to the extraction/production of natural crushed stone (see **Table 9**).

Table 15 Environmental impacts related to the additional processing to obtain crushed concrete suitable for use as recycled aggregate in fresh concrete (Module D)

Parameter	Unit (expressed per 1 ton crushed concrete)	1 t crushed concrete Module D
Global warming potential, GWP	kg CO_2 equiv	2.1
Depletion potential of the stratospheric ozone layer, ODP	kg CFC 11	1.20E-9
Acidification potential of soil and water, AP	kg SO_2 equiv	0.00772
Eutrophication potential, EP	kg $(PO_4)^{3-}$	0.000815
Formation potential of tropospheric ozone, POCP	kg Ethene	0.000596
Abiotic depletion potential (ADP-elements) for non-fossil resources	kg Sb equiv	2.44E-7
Abiotic depletion potential (ADP-fossil fuels) for fossil resources	MJ, net calorific value	24.7
Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, net calorific value	5.1
Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, net calorific value	34.5

In a region where typically gravel from pits is used for roadbeds and structural concrete and the concentration of gravel pits would result in an average transport distance (gravel pit to road construction site or concrete plant) of 100 km, Module D could be declared as shown in **Table 16**. Compared to the values in **Table 10**, the additional processing reduces the environmental benefits of the recycled material that can be declared.

Table 16 Environmental benefits of crushed concrete replacing natural gravel in road beds (48.9%) and aggregate in structural concrete (51.1%) (Module D, values = sums of the right columns in **Table 10** and **Table 15**)

Parameter	Unit (expressed per 1 ton aggregate)	1 t crushed concrete Module D
Global warming potential, GWP	kg CO_2 equiv	-5.24
Depletion potential of the stratospheric ozone layer, ODP	kg CFC 11	5.42E-10
Acidification potential of soil and water, AP	kg SO_2 equiv	-0.039
Eutrophication potential, EP	kg $(PO_4)^{3-}$	-0.0092
Formation potential of tropospheric ozone, POCP	kg Ethene	0.0119
Abiotic depletion potential (ADP-elements) for non-fossil resources	kg Sb equiv	-3.67E-07
Abiotic depletion potential (ADP-fossil fuels) for fossil resources	MJ, net calorific value	-73.7
Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, net calorific value	-2.01
Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, net calorific value	-70.5

6.4 Raw material supply (Module A1 according to EN 15804)

6.4.1 Scenario A

Following the “polluter pays principle”, the environmental loads of conventional recycling are assigned to the product system that generates the waste. Therefore, for the use of crushed concrete as roadbed material in Scenario A, only the impacts resulting from the transport of the material from the recycling plant to the road construction site have to be declared in Module A1 (**Table 17**).

Table 17 Processes in Module A1 (Scenario A)

Module and content	Process
Module A1 (raw material supply): supply of crushed concrete	impacts of the transport of crushed concrete from the recycling plant to the road construction site (“transport 3” in **Figure 9**)

Consequently, in this scenario, as long as the environmental impacts of “transport 3” are not greater than the sum of the impacts of the extraction/production of virgin material (**Table 9**) and “transport 1”, using recycled material will reduce the environmental impact of new construction works determined according to EN 15804. In the example evaluated in this study, for example, the indicators GWP and PE_{nren} will have lower values if crushed concrete replaces gravel from pits and the transport distance of “transport 3” is not more than approx. 45 km longer than the transport distance of “transport 1”. If crushed concrete replaces crushed natural stone, the indicators GWP and PE_{nren} will be lower if the transport distance of “transport 3” is not more than approx. 375 km longer than the transport distance of “transport 1”.

6.4.2 Scenario B

According to EN 15804, the environmental impacts of the processes in **Table 18** have to be declared in Module A1:

Table 18 Processes in Module A1 (Scenario B)

Module and content	Process
Module A1 (raw material supply): supply of recycled concrete for the use as aggregate in structural concrete	impacts of additional crushing (i.e. after the “end of waste” state is reached)
	impacts of the transport of crushed concrete from the recycling plant to the concrete factory (“transport 3” in **Figure 9**)

The processes related to the additional crushing are described under Scenario B, Module D. As, however, only approximately half of the crushed concrete can be used as a recycled aggregate in structural concrete whereas the remaining half is used in roadbeds, more than one output flow is generated (joint production). In these cases it is necessary in the LCA to divide the environmental impacts from such processes between the co-products according to an appropriate method. This is referred to as “co-product allocation”.

In Module A1 an allocation of the total environmental impacts between the two co-products

- crushed concrete used as an aggregate (51.1%) and
- crushed concrete used in roadbeds (48.9%)

has to be carried out. According to EN 15804, co-product allocation should respect the main purpose of the processes studied. As the only purpose of the additional crushing in the production of a recycled aggregate to be used in structural concrete, all environmental impacts of the corresponding processes are allocated to these 51.1% of the total input flow.

The impacts of additional processing to obtain crushed concrete suitable for use as a recycled aggregate in structural concrete to be declared in Module A1 are calculated as follows:

impacts of additional processing (per ton of recycled aggregate) =
(39% x impacts of additional dry processing + 73% x impacts of wet processing)/0.511

Table 19 Environmental impacts related to the additional processing to obtain crushed concrete suitable for use as recycled aggregate in structural concrete (Module A1)

Parameter	Unit (expressed per 1 ton recycled aggregate)	1 t recycled aggregate, Module A1
Global warming potential, GWP	kg CO_2 equiv	4.1
Depletion potential of the stratospheric ozone layer, ODP	kg CFC 11	2.36E-09
Acidification potential of soil and water, AP	kg SO_2 equiv	0.0150
Eutrophication potential, EP	kg $(PO_4)^{3-}$	0.00158
Formation potential of tropospheric ozone, POCP	kg Ethene	0.00116
Abiotic depletion potential (ADP-elements) for non-fossil resources	kg Sb equiv	4.76E-07
Abiotic depletion potential (ADP-fossil fuels) for fossil resources	MJ, net calorific value	48.2
Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, net calorific value	10.0
Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, net calorific value	67.2

The environmental impacts corresponding to the provision of recycled aggregates for the use in structural concrete (in Module A1) thus significantly exceed the impacts of the extraction/production of gravel (Table 9, right column). For most environmental indicators, they are in the order of 18% to 30% of the impacts of the production of crushed natural stone.

6.5 Impacts of the use of recycled aggregates on the LCA of concrete production

To demonstrate the impacts of the use of recycled aggregates on the LCA of concrete production a typical concrete composition was modelled. According to ERMCO statistics [39] the average cement content of ready-mix concretes across Europe was 290 kg/m³ in 2013 while the average fly ash content was 60 kg/m³. These quantities, in combination with a water content of 176 l/m³, correspond to the typical composition of a C25/30 concrete [40].

Table 20 shows the composition considered for the LCA model. The maximum grain size is assumed to be 16 mm, with a share of 31.5% in the grain size group 0/2mm (sand) and a share of 68.5% in the grain size group 2/16mm (natural gravel or crushed natural stone). For the cement, an average European CEM II cement was chosen (EPD [41] published by CEMBUREAU). For fly ash, the low environmental impacts resulting from an economic allocation of the electricity production in coal fired power plants have been neglected. For all concrete constituents a transport distance of 100 km to the concrete factory is assumed. This assumption is based on the authors' estimations regarding the geographical distribution of the relevant infrastructure in Europe (cement plants, concrete plants, etc.).

Table 20 Typical composition of a concrete in Europe for the LCA model

Constituent	Quantity
Cement	290 kg/m³
Fly ash	60 kg/m³
Water	176 kg/m³ (w/c_{eq}=0.56)
Aggregates	1815 kg/m³ (572 kg/m³ sand 0/2mm, 1243 kg natural gravel or crushed natural stone 2/16mm)
Superplasticiser	1.2 kg/m³

Table 21 shows the corresponding environmental impacts.

Table 21 Environmental impacts related to the production of 1 m³ of concrete with natural aggregates (Modules A1-A3)

Parameter	Unit (expressed per 1m³ concrete)	1 m³ concrete, Modules A1-A3 gravel	1 m³ concrete, Modules A1-A3 crushed natural stone
Global warming potential, GWP	kg CO_2 equiv	235	256
Depletion potential of the stratospheric ozone layer, ODP	kg CFC 11 equiv	1.36E-7	1.36E-7
Acidification potential of soil and water, AP	kg SO_2 equiv	0.486	0.532
Eutrophication potential, EP	kg $(PO_4)^{3-}$ equiv	0.0784	0.0876
Formation potential of tropospheric ozone, POCP	kg Ethene equiv	0.00118	-0.00698
Abiotic depletion potential (ADP-elements) for non-fossil re-	kg Sb equiv	0.000318	0.000321
Abiotic depletion potential (ADP-fossil fuels) for fossil resources	MJ, net calorific value	1110	1340
Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, net calorific value	73	120
Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, net calorific value	1190	1480

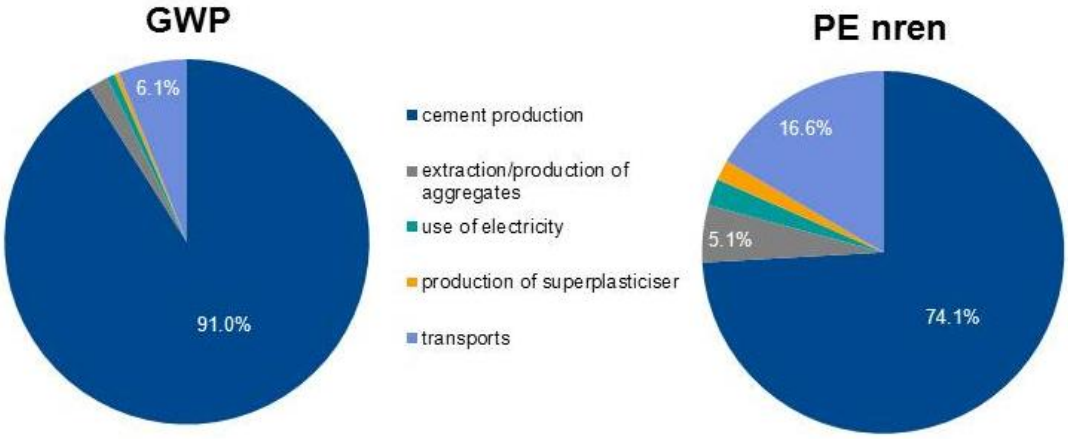


Figure 10 Influence of sub-processes in the production of concrete containing natural gravel on the global warming potential (left) and the use of non-renewable primary energy (right)

As **Figure 10** shows, the environmental impacts of concrete production are clearly dominated by the impacts of cement production.

Several scientific publications [1], [34], [33] state that concrete with aggregates from recycled concrete can have a reduced compressive strength compared to concrete with natural aggregates and the same water/cement ratio, which is mainly due to a reduced compressive strength of the recycled aggregates compared to natural aggregates.

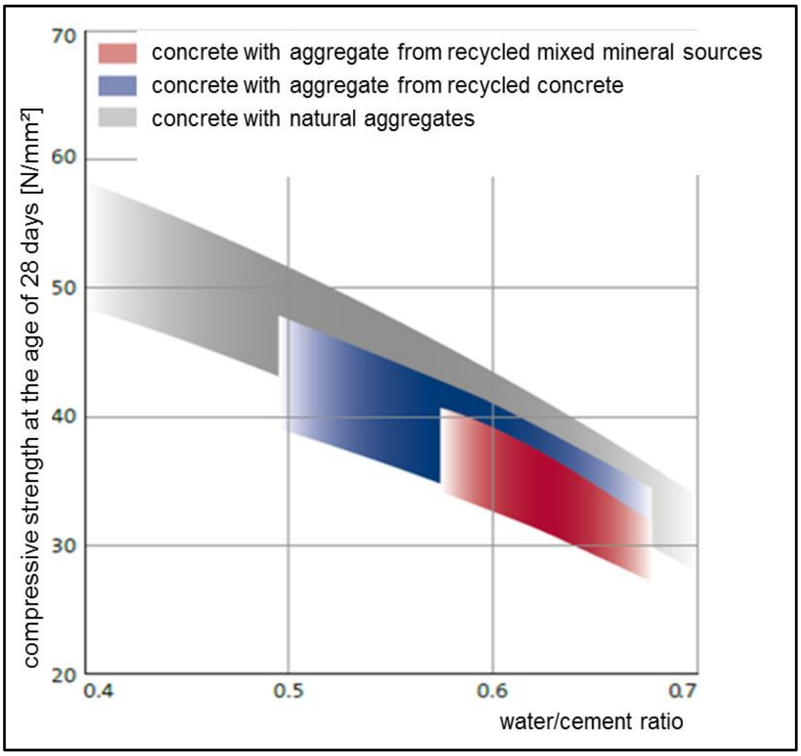


Figure 11 Compressive strength versus the water/cement ratio of concrete with natural aggregates and concrete with recycled aggregates [42]

According to **Figure 11** it can be assumed that the reduction in compressive strength is in the order of magnitude of approximately 4 N/mm². This loss in strength may be compensated by reducing the water/cement ratio by about 0.05. In our example, this would mean increasing the cement content from 290 kg/m³ to approximately 320 kg/m³. **Table 22** shows the modified concrete composition. As in the previous example, the transport distance to the concrete factory is assumed to be 100 km for all constituents.

Table 22 Assumed composition of a concrete with recycled aggregates

Constituent	Quantity
cement	320 kg/m³
fly ash	60 kg/m³
water	176 kg/m³ (w/c_{eq}=0.51)
aggregates	1790 kg/m³ (564 kg/m³ sand 0/2mm, 1226 kg recycled aggregate 2/16mm)
superplasticiser	1.2 kg/m³

Table 23 shows the corresponding environmental impacts.

Table 23 Environmental impacts related to the production of 1 m³ of concrete with recycled aggregates (Modules A1-A3)

Parameter	**Unit (ex-pressed per 1m³ concrete)**	**1 m³ concrete, Modules A1-A3 recycled aggregate**
Global warming potential, GWP	kg CO_2 equiv	260
Depletion potential of the stratospheric ozone layer, ODP	kg CFC 11	1.41E-7
Acidification potential of soil and water, AP	kg SO_2 equiv	0.523
Eutrophication potential, EP	kg $(PO_4)^{3-}$	0.0827
Formation potential of tropospheric ozone, POCP	kg Ethene	0.00418
Abiotic depletion potential (ADP-elements) for non-fossil resources	kg Sb equiv	0.000351
Abiotic depletion potential (ADP-fossil fuels) for fossil resources	MJ, net calorific value	1220
Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, net calorific value	85.3
Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, net calorific value	1320

As expected after the findings in 6.4.2, the environmental impacts of producing a concrete with recycled aggregates exceed those of the production of a concrete with natural gravel (**Table 21**). The environmental “advantage” of recycled aggregate as opposed to crushed natural stone [43] is compensated by the additional cement demand required to obtain the same compressive strength. In this example, from an environmental point of view, the use of recycled concrete as an aggregate in structural concrete is therefore not reasonable.

Remark: As mentioned previously, a transport distance of 100 km was assumed for the LCA calculations in this paragraph. Due to the large share (by weight) of aggregates in concrete and the corresponding “leverage”, the LCA results are influenced to a comparatively large extent by changes in the transport distance of the aggregates (absolute influence: approximately 1,8 x values in ***Table*** **8***). Thus, in an area where natural aggregates are not available at close range while the transport distance of recycled aggregates is short, the use of recycled aggregates could, from an LCA point of view, become the preferred option in concrete production.*

6.6 Conclusions of the comparative LCA study according to EN 15804

The LCA study shows that from an environmental point of view, Scenario A (where the crushed concrete is used as a constituent of roadbeds in road construction) should be the preferred scenario at the end of life of concrete.

Scenario B (where additional processes required to use the recycled concrete as an aggregate in structural concrete are carried out) should only be chosen if a demand for roadbed/foundation material does not exist. Where recycled concrete is used as an aggregate, it is likely that the environmental impacts of concrete production will exceed those of the production of concrete with natural aggregates.

In an LCA study which compares

- concrete production with natural aggregates on the one hand to
- concrete production with recycled aggregates on the other hand,

the transport distances of the natural and recycled aggregates should be carefully considered as they may influence the result of the study.

7 Comparative studies according to other standards/methods

7.1 General

The purpose of this paragraph is to assess briefly whether the conclusions of the comparative LCA study described in paragraph 6 to assess the environmental impacts of

- the use of recycled concrete as a constituent of the roadbed in road construction (or below foundations) versus
- the use of recycled concrete as an aggregate in concrete acc. to EN 206 and national regulations or EN 1992-1-1 respectively,

would be similar if the comparison was not based on the rules of EN 15804 but on other standards/methods. For this assessment, two relevant ISO standards and the PEF methodology are chosen.

7.2 Comparison of environmental impacts using ISO standards

Relevant ISO standards for life cycle assessment are

- ISO 14044 [44] and
- ISO 21930 [45].

ISO 14044 can be applied for Life Cycle Assessment in all product categories and is not limited to the construction sector. As such, most information provided is of a general nature and mainly describes the steps to be carried out and aspects to be considered in LCA without giving detailed rules for the issues that are identified. This is also the case for the “allocation procedures for re-use and recycling” described in paragraph 4.3.4.3 of the standard (e.g. “Several allocation procedures are applicable for re-use and recycling.[…] Re-use and recycling may change the inherent properties of materials in subsequent use”). A comparison of different uses of recycled concrete with the rules of ISO 14044 alone is therefore unfeasible.

As opposed to ISO 14044, ISO 21930 provides rules that are specific for construction works and construction products. It contains an initial approach for a distinction of “information modules” according to which the LCA information should be declared separately for each life cycle stage of construction works. These rules however are still less concrete than in EN 15804. With respect to recycling, reference is made to ISO 14044 (“Reuse and recycling shall be treated in accordance with provisions of ISO 14044:2006”).

At the time of this report, ISO 21930 is being revised. The available draft version (2nd CD stage) indicates that many paragraphs are being closely aligned with EN 15804. In particular, the rule

> “*In principle waste processing is part of the product system under study. In the case of materials leaving the system as secondary materials or fuels, such processes […] are, as a rule, part of the waste processing of the system under study. However, after having reached the “end-of-waste” state further processing may also be necessary in*

> *order to replace primary material or fuel input in another product system. Such processes are considered to be beyond the system boundary and are assigned to stage D.*"

was adopted in the draft standard. It can therefore be expected that a comparison applying the revised ISO 21930 standard will arrive at the same results as the study carried out in paragraph 6.

7.3 Comparison of environmental impacts using the PEF (Product Environmental Footprint) methodology

DG Environment has worked together with the European Commission's Joint Research Centre (JRC IES) and other European Commission services towards the development of a harmonised methodology for the calculation of the environmental footprint of products. At the time of this report, "Product Environmental Footprint Category Rules (PEFCR)" are being developed in a pilot phase with the participation of different products and sectors.

According to the current PEF rules [43], a "Resource Use and Emissions Profile" (RUaEP) per unit of analysis can be estimated using the formula provided in **Figure 12**, which allocates the impacts and benefits due to recycling equally between the producer using recycled material and the producer producing a recycled product ("50/50 allocation split"). It assumed that high RUaEP values are less favourable than low values.

$$\left(1-\frac{R_1}{2}\right)\times E_V+\frac{R_1}{2}\times E_{recycled}+\frac{R_2}{2}\times\left(E_{recyclingEoL}-E^*_V\times\frac{Q_S}{Q_P}\right)+R_3\times\left(E_{ER}-LHV\times X_{ER,heat}\times E_{SE,heat}-LHV\times X_{ER,elec}\times E_{SE,elec}\right)+\left(1-\frac{R_2}{2}-R_3\right)E_D-\frac{R_1}{2}\times E^*_D$$

Figure 12 "Resource Use and Emissions Profile formula" according to [43]

In the formula, R_1, R_2 and R_3 represent dimensionless fractions of material.

R_1 = "recycled (or re-used) content of material", is the proportion of material in the input to the production that has been recycled in a previous system.

R_2 = "recycling (or reuse) fraction of material", is the proportion of the material in the product that will be recycled (or re-used) in a subsequent system.

R_3 = the proportion of material in the product that is used for energy recovery (e.g. incineration with energy recovery) at EoL.

In the case of crushed concrete used in road construction or as a recycled aggregate, neither energy recovery nor disposal are relevant (R_2=1, R_3=0). Therefore, the formula above can be presented in the simplified form shown in **Figure 13**.

$$\underbrace{\left(1-\frac{R_1}{2}\right)\times E_V + \frac{R_1}{2}\times E_{recycled}}_{\text{production (virgin + recycled content)}} + \underbrace{\frac{R_2}{2}\times\left(E_{recyclingEoL} - E^{*}_{V} \times \frac{Q_S}{Q_P}\right)}_{\text{recyclability}}$$

Figure 13 Simplified “Resource Use and Emissions Profile” formula

In this formula, the variables have the following meaning:

> E_V = specific emissions and resources consumed (per unit of analysis) arising from virgin material (i.e. virgin material acquisition and pre-processing)
>
> $E_{recycled}$ = specific emissions and resources consumed (per unit of analysis) arising from the recycling (or re-use) process of the recycled (or re-used) material, including collection, sorting and transportation processes
>
> $E_{recyclingEoL}$ = specific emissions and resources consumed (per unit of analysis) arising from the recycling process at the End-of-Life stage, including collection, sorting and transportation processes
>
> E_{*V} = specific emissions and resources consumed (per unit of analysis) arising from virgin material (acquisition and pre-processing) assumed to be substituted by recyclable materials
>
> Q_s/Q_p is a dimensionless ratio taken as an approximation for any differences in quality between the secondary material and the primary material (“downcycling”). The possibility of identifying a relevant, underlying physical relationship as a basis for the quality correction ratio will be assessed (the limiting factor shall be determining). If this is not possible, some other relationship shall be used, for example, economic value. In this case, the prices of primary versus secondary materials are assumed to serve as a proxy for quality. In such a situation, Q_s/Q_p would correspond to the ratio between the market price of the secondary material (Q_s) and the market price of the primary material (Q_p).

For the recycling processes at the end of life of concrete, the second addend in the simplified formula (**Figure 13**) is relevant. If recycled concrete is used as an aggregate in structural concrete, the “Resource Use and Emissions Profile” will be greater (i.e. less favourable) than if it is used in roadbeds:

- $E_{recyclingEoL}$ will be greater for recycled concrete used as aggregate
- E_{*V} will have the same value (as natural aggregates are replaced in both cases)
- Q_s/Q_p will be approximately 1 for the use of recycled aggregates in roadbeds whereas it will have a value smaller than 1 for recycled concrete used as an aggregate (to account for modifications the concrete composition required to achieve the same compressive strength, see **Figure 11**).

Qualitatively, the use of the PEF formula will therefore lead to the same conclusion as the LCA study described in paragraph 6).

8 Sustainable use of crushed concrete

From an environmental point of view, concrete recycling is recommended primarily for two reasons:

- As natural aggregates (gravel or crushed stone) can be replaced by recycled concrete, concrete recycling contributes to the reduction of the use of non-renewable resources
- Concrete recycling keeps concrete debris out of landfill, thus saves landfill space and avoids environmental burdens associated with landfill.

Presently, recycled concrete is primarily used in road construction where it replaces natural aggregates. Comparatively small amounts of recycled concrete are also used as a substitute of aggregates in concrete production. From an environmental point of view it appears questionable whether the use of recycled concrete in the production of new concrete is advisable and should be aimed for in all cases. Generally, concrete production generates higher demands on the recycled materials than road construction: to qualify recycled materials for the use in concrete, additional processes (screening the recycled material into size fractions, more thorough separating of impurities) are required. While these processes generate additional environmental burdens, an additional benefit is arguable because in road construction as well as in concrete production, recycled concrete replaces natural aggregates.

If the use as an aggregate for the roadbed is possible, this should currently be preferred to the use as an aggregate in structural concrete.

9 Conclusions

- The differentiation of “recycling-grades” (Recycling, Up-cycling, Down-cycling etc.) is possible, but not mandatory. It depends on how the "benefit" for new materials or energy saving is calculated and how it is included in a sustainability analysis.
- On the basis of several studies and corresponding regulations in several European countries, it can be concluded that concrete can be recycled.
- The rate of recycled aggregates in concrete and the total recycling rate of crushed concrete respectively differ in Europe.
- The use of concrete crushed sand for cement clinker production can be environmentally beneficial. Regarding this recycling path, further development potential is given.
- There are different studies in which the amounts of carbon dioxide taken up due to carbonation over the life cycle of 1t of cement are calculated. Depending on conditions and assumptions, 10% to 30% of the CO_2 from the cement production can be taken up during the life cycle of cement.
- Generally, concrete production generates higher requirements on the recycled materials than e. g. roadbeds. Screening the recycled material into size fractions and more thorough separating of impurities are required.

- The environmental impacts corresponding to the provision of recycled aggregates for the use in structural concrete significantly exceed the impacts of the extraction/production of gravel. For most environmental indicators, they are in the order of 18% to 30% of the impacts of the production of crushed natural stone. Concrete with aggregates from recycled concrete can have a reduced compressive strength compared to concrete with natural aggregates, which can be compensated, e.g. by using more cement. As a consequence, the environmental impacts of producing a concrete with recycled aggregates may exceed those of the production of a concrete with natural aggregates, particularly if natural gravel is replaced.
- Due to the large share (by weight) of aggregates in concrete and the corresponding "leverage", the LCA results are influenced to a comparatively large extent by changes in the transport distance of the aggregates. This conclusion is in agreement with findings presented in [38].
- If the use as an aggregate for roadbed is possible, this should in many cases be the preferred option from a sustainability perspective, rather than the use as an aggregate in structural concrete.
- A politically driven specification of "recycling targets" or "recycling quota" linked to a certain application without a case-by-case evaluation (LCA) or LCA-based benchmarks will not lead to the most sustainable solution "in all cases".

European Cement Research Academy GmbH

Dr Christoph Müller Dr Sebastian Palm Jochen Reiners

10 Literature / References

[1] C. Müller, Concrete as a recycable building material - Beton als kreislaufgerechter Baustoff, Berlin: Beuth – DAfStb: Schriftenreihe; Heft 513, 2001.

[2] P. Schießl und C. Müller, „Werkstoffliche Anforderungen an mineralische Baustoffe für kreislaufgerechtes Bauen," Institut für Bauforschung - Forschungsbericht Nr. F555, Aachen, 1999.

[3] Deutscher Ausschuß für Stahlbeton (DAfStb), „Beton nach DIN EN 206-1 und DIN 1045-2 mit rezyklierten Gesteinskörnungen nach DIN 4226-100," 2007.

[4] B. e. a. Hauer, Potenziale des Sekundärstoffeinsatzes im Betonbau - Teilprojekt B1., Bde. %1 von %2Schlussberichte zur zweiten Phase des DAfStb/BMBF-Verbundforschungsvorhabens „Nachhaltig Bauen mit Beton", Berlin: Beuth, DAfStb: Schriftenreihe Heft 584, 2011.

[5] C. Müller, S. Palm, A. Caballero González, E. Schmincke und G. Spanka, „Final report „Effects of the enhanced European basic requirements for construction works on the regulations of harmonised technical specifications (harmonised European Standards) and European Assessment Documents," Research Institute of the Cement Industry, 2011.

[6] K. Weimann, Untersuchungen zur Nassaufbereitung von Betonbrechsand unter Verwendung der Setzmaschinentechnik, Bd. Band 51, Berlin: BAM-Dissertationsreihe, 2009.

[7] Arbeitsgemeinschaft Kreislaufwirtschaftsträger, „4. Monitoring-Bericht Bauabfälle (Erhebung 2002)," Berlin, Dusseldorf, Duisburg, 2005.

[8] Vazquez, E., et al., „Draft of spanisch regulations for the use of recycled aggregate in the production of structural concrete," in *Use of recycled materials in buildings and structures*, Barcelona, 2004.

[9] S. G. Ltd, „Construction and demolition waste management practices and their economic impacts," London, European Commission, 1999.

[10] E. Commission, „Management of construction and demolition waste," 2000.

[11] EQAR - European Quality Association for Recycling , „Recycling of building materials for environmental resources protection".

[12] The Cement Sustainability Initiativ, „Recycling Concrete - full report and executive summary," WBCSD, 2009.

[13] Arbeitsgemeinschaft Kreislaufwirtschaftsträger Bau, „5. Monitoring-Bericht Bauabfälle (Erhebung 2004)," Berlin, 2007.

[14] Kreislaufwirtschaft Bau, „Mineralische Bauabfälle Monitoring 2012," 2015.

[15] M. v. d. Meulen, S. v. Gessel und J. Veldkamp, „Aggregate resources in the Netherlands,“ Netheralnds Journal of Geosciences, 2005.

[16] RILEM, „Use of Recycled Materials, Final report of RILEM Technical Committee 198-URM,“ RILEM Publications S.A.R.L., 2005.

[17] Ramon Janssen (AVG), „Recycling in den Niederlanden,“ in *EQAR Conference: Construction Materials Recycling in Europe*, Brussels, 2013.

[18] Mineral Products Association, „The Mineral Products Industry at a Glance,“ London, 2015.

[19] MPA: The Concrete Centre, „Concrete Industry Sustainability Performance Report, 7th report: 2013 performance data,“ 2014.

[20] EISC LTD, „Construction sector: Overview in the UK,“ 2012.

[21] K. M. C. Hoffmann, *Aktualisiertes SIA-Merkblatt «Recyclingbeton»,* EMPA, 2010.

[22] A. L. C. Hoffmann, „Recycled concrete and mixed rubble as aggregates: Influence of variations in composition on the concrete properties and their use as structural material,“ in *Sustainable construction materials and technologies*, Coventry, June 2007.

[23] A. Leemann, *personal information,* 2015.

[24] V. T. C. K. S. Seifert, Elektrodynamische Fragmentierung, 2014.

[25] prEN 16908:2015 Cement and building lime - Environmental product declarations - Product category rules complementary to EN 15804.

[26] C. Clear und T. De Saulles, „BCA Recarbonation Scoping Study,“ British Cement Association, 2007.

[27] Danish Technological Institute (DTI), „Guidelines – Uptake of carbon dioxide in the life cycle inventory of concrete,“ Report of Nordic Innovation Centre project 03018 “CO2 uptake during the concrete life cycle”, 2005.

[28] C. Engelsen, J. Mehus, C. Pade, D. Saether und N. B. R. I. (BYGGFORSK), „Carbon dioxide uptake in demolished and crushed concrete,“ Report of Nordic Innovation Centre project 03018 “CO2 up take during the concrete life cycle", 2005.

[29] J. Gajda und F. Miller, „Concrete as a sink for atmospheric carbon dioxide: A Literature Review and Estimation of CO2 Absorption by Portland Cement Concrete,“ Portland Cement Association, R&D Serial No. 2255, Skokie / Illinois, 2000.

[30] J. Gajda, „Absorption of atmospheric carbon dioxide by portland cement concrete,“ Portland Cement Association, R&D Serial No. 2255a, Skokie / Illinois, 2001.

[31] M. Glavind, „CO2 uptake during the concrete lifecycle,“ Danish Technological Institute, Nordic Innovation Centre project number: 030185, 2006.

[32] Iceland Building Research Institute (IBRI), „Information on the use of concrete in Denmark Sweden, Norway and Iceland,“ Report of Nordic Innovation Centre project 03018 “CO2 uptake during the concrete life cycle”, 2005.

[33] S. Jacobsen und P. Jahren, „Binding of CO2 by carbonation of Norwegian OPC concrete,“ in *CANMET/ACI Int. Conf. on Sustainability and Concrete Technology*, Lyon, 2002.

[34] K. Kjellsen, M. Guimaraes und A. Nilsson, „The CO2 balance of concrete in a life cycle perspective,“ Report of Nordic Innovation Centre project 03018 “CO2 uptake during the concrete life cycle”, 2005.

[35] B. Lagerblad und Swedish Cement and Concrete Research Instit (CBI), „Carbon dioxide uptake during concrete life cycle – State of the art,“ Report of Nordic Innovation Centre project 03018 “CO2 uptake during the concrete life cycle”, 2005.

[36] „EN 15804:2012+A1 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products“.

[37] BTU Cottbus, Lehrstuhl Altlasten, Fachgruppe Bauliches Recycling, „Ökologische Prozessbetrachtungen - RC-Beton (Stofffluss, Energieaufwand, Emissionen),“ Cottbus, 2010.

[38] S. Butera, T. H. Christensen and T. F. Astrup, “Life cycle assessment of construction and demolition waste management,” *Waste Management ,* vol. 44, pp. 196-205, 2015.

[39] ERMCO, „Ready mixed concrete industry statistics,“ 2013.

[40] VDZ, „Hintergrundbericht zu den EPDs für Beton in Deutschland (vertraulich, unveröffentlicht),“ 2013.

[41] CEMBUREAU, „Environmental Product Declaration (EPD) according to EN 15804 and ISO 14025, Portland-composite cement (CEM II) produced in Europe,“ http://www.cembureau.be/topics/sustainable-construction/sustainability-standards-epds, 2015.

[42] C. Hoffmann, „Stand von Forschung und Entwicklung,“ ETH Zurich, Presentation 9. Schweizer Betonforum "Recyclingbeton – die sinnvolle Alternative?", 1. Juli 2015.

[43] COMMISSION RECOMMENDATION of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations.

[44] ISO 14044 - Environmental management - Life cycle assessment - Requirements and guidelines (ISO 14044:2006).

[45] ISO 21930:2007 - Sustainability in building construction — Environmental declaration of building products.

[46] C. Hoffmann und F. Jacobs, „Überblick über Regelungen zu Beton mit rezyklierter Gesteinskörnung," *Beton- und Stahlbetonbau 105,* pp. 805-812, 12 2010.

[47] DIN, *DIN 4226-100, 2002: Gesteinskörnungen für Beton und Mörtel, Teil 100: Rezyklierte Gesteinskörnungen,* Berlin.

[48] DAfStB, *Baustoffkreislauf-Richtlinie des DAfStB: Beton nach DIN EN 206-1 und DIN 1045-2 mit rezyklierten Gesteinskörnungen nach DIN 4226-100, Teil 1: Anforderungen an den Beton für die Bemessung nach DIN 1045-1,* Berlin: Deutscher Ausschuss für Stahlbeton, 2004.

[49] BS, *BS 8500-2: Concrete – Complementary British Standard to BS EN 206-1: Specification for constituent materials and concrete,* London: British standard organisation, 2006.

[50] NEN, *NEN 8005 CUR-VB: Beton - Teil I: Festlegung, Eigenschaften, Herstellung und Konformität,* NEN, 2004.

[51] BV, *Richtlinie für Recycling-Baustoffe,* Österreichischer Baustoff Recycling Verband, 7. Auflage 2007.

[52] SIA, *Merkblatt 2030 Recyclingbeton,* Zürich: SIA, 2010.

[53] NB, *Recycling of concrete and masonry for production of concrete,* Oslo: Norsk Betongforening (Norwegische Betonvereinigung), 2003.

[54] F. Roos, Ein Beitrag zur Bemessung von Beton mit Gesteinskörnung aus rezyklierter Gesteinskörnung nach DIN 1045-1, TU München: Dissertation Lehrstuhl Massivbau, 2002.

[55] RILEM, „Specifications for concrete with recycled aggregates - Recommendations," *Materials & Structures, Vol. 27,* pp. 557- 559, 1994.

[56] B. Statistisches Bundesamt und D. BRB.

[57] V. Thome, „Blitz, schlag ein!," *Der Bausachverständige, Heft 6,* p. 5, 2012.

[58] Bundesverband Baustoffe – Steine und Erden e.V., „Mineralische Bauabfälle Monitoring 2012," Druckwerkstatt Lunow, Berlin, 2015.

[59] R.-R. Schulz, „Untersuchung des Kriechverhaltens von Betonsplittbeton (Beton aus gebrochenem Altbeton)," Institut für Bauforschung, Aachen, 1982.

Annex A:

Example of the influence of the use of recycled concrete in lieu of virgin material on the total Global Warming Potential (GWP)

Assumption: 2400 kg of crushed concrete that have undergone conventional recycling processes („end-of-waste“ reached) are available to replace natural gravel.

Scenario A: the total mass (2400 kg) is used to replace natural gravel in roadbeds.

Scenario B: 1226 kg (51.1% according to **Figure 8**) of the crushed concrete are used as an aggregate for the production of 1 m³ concrete (cf. **Table 22**) whereas the remaining 1174 kg are used to replace natural gravel in roadbeds.

> *Remark: The values given for Module A1 in the figures below indicate the* <u>*difference*</u> *in GWP resulting from the use of recycled aggregates instead of natural gravel. This is why in this example avoided impacts are specified in Module A1.*

Case 1: “transport 1” = “transport 3” = 100 km (equal distance from concrete factory/road construction site to recycling plant and gravel pit)

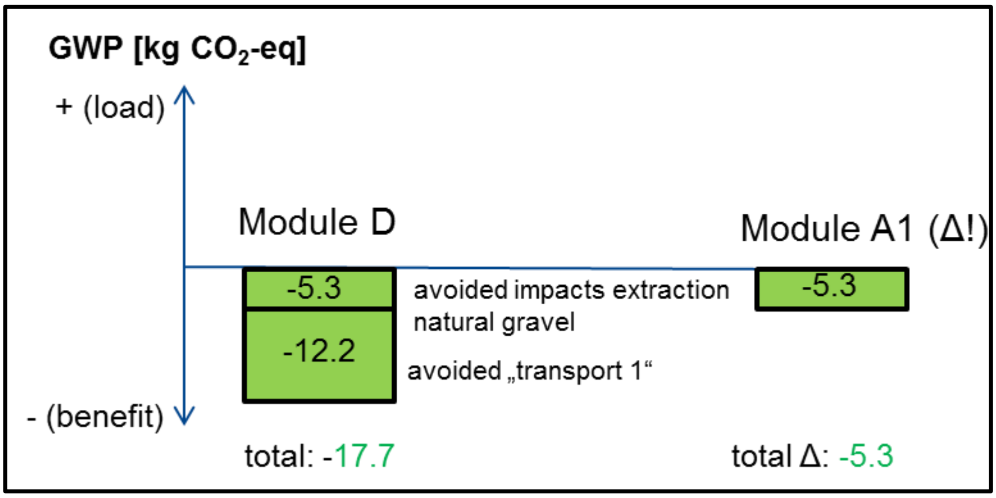


Figure A1 Influence of the use of recycled concrete in lieu of natural gravel on the GWP (Scenario A, case 1)

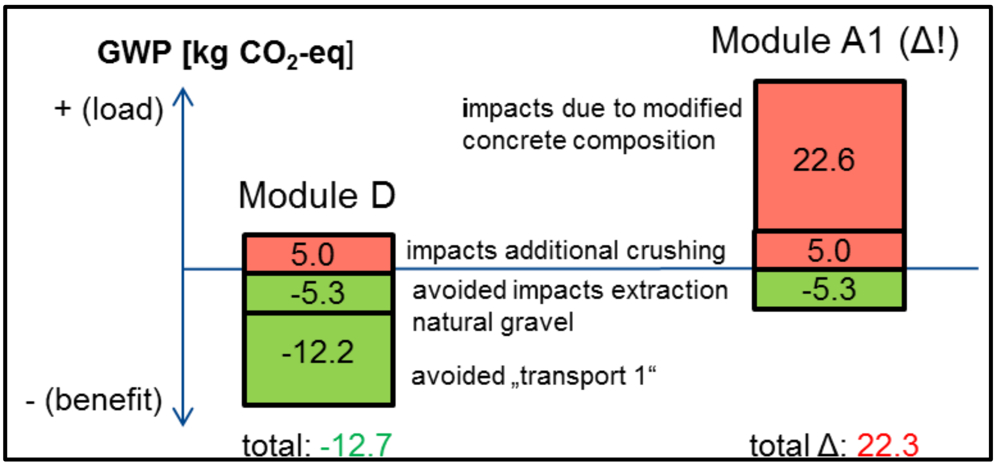


Figure A2 Influence of the use of recycled concrete in lieu of natural gravel on the GWP (Scenario B, case 1)

The comparison of the values in Figure A1 and Figure A2 leads to the conclusion that when only the GWP is considered,

- Scenario A should be preferred to Scenario B (lower values in **Figure A1** for both Module D and Module A1)
- the use of recycled aggregate instead of natural gravel will increase the total GWP in Module A1 (positive total Δ in **Figure A2**).

Case 2: "transport 1" = 300 km, "transport 3" = 0 km (i.e. longer distance from gravel pit to concrete factory/road construction site than from recycling plant to concrete factory/road construction site)

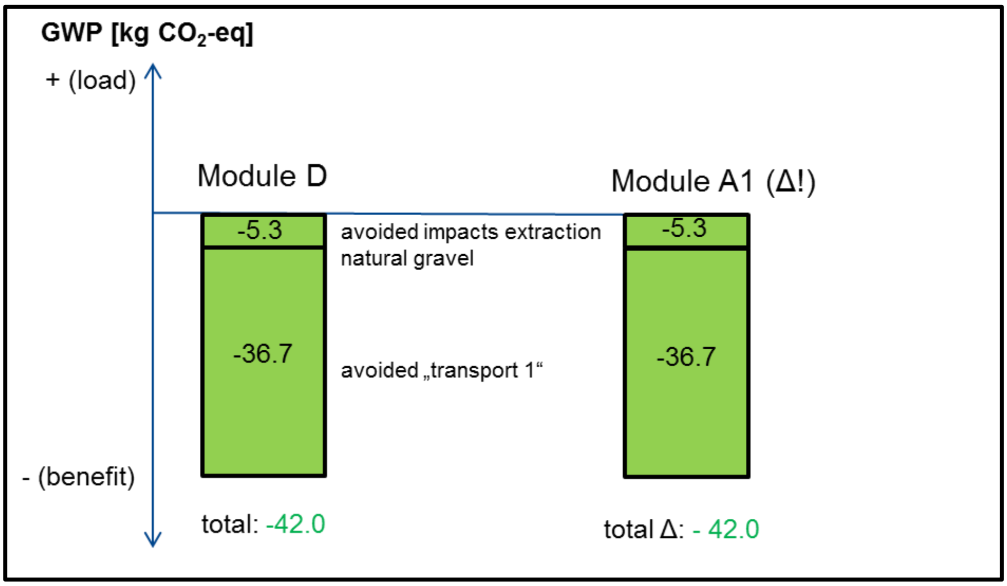


Figure A3 Influence of the use of recycled concrete in lieu of natural gravel on the GWP (Scenario A, case 2)

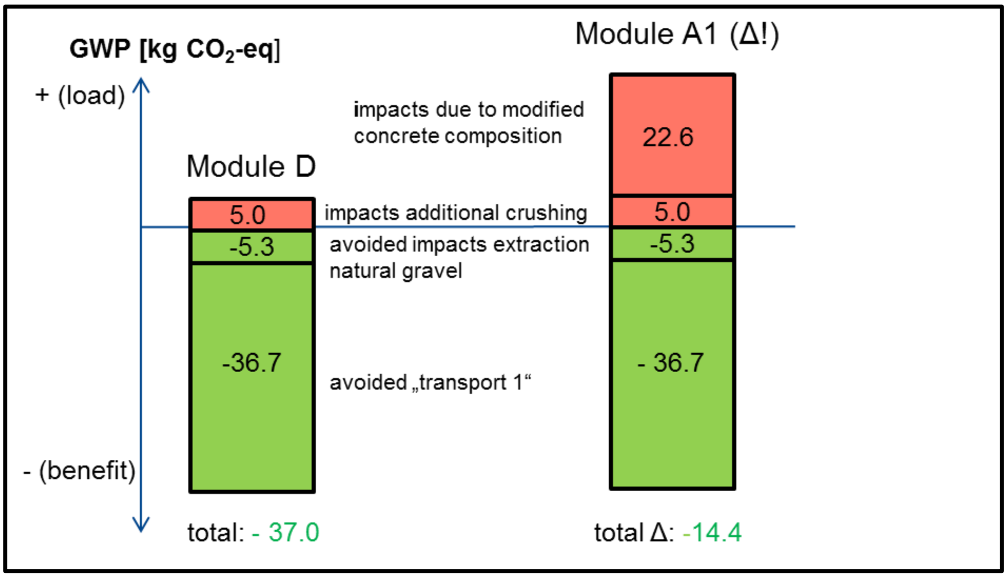


Figure A4 Influence of the use of recycled concrete in lieu of natural gravel on the GWP (Scenario B, case 2)

The comparison of the values in Figure A3 and Figure A4 leads to the conclusion that when only the GWP in considered,

- Scenario A should be preferred to Scenario B (lower values in **Figure A3** for both Module D and Module A1)
- the use of recycled aggregates instead of natural gravel will decrease the total GWP in Module A1 (negative total Δ in **Figure A4**).