Carbon footprint of concrete based on secondary materials

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The use of secondary materials instead of primary raw materials in concrete is a way to decrease its environmental impact. On the one hand it gives a high grade use to the secondary material, thereby avoiding disposal. On the other hand, the production of concrete no longer involves preparation and/or mining of primary raw materials. This way, concrete from secondary materials has the potential to save energy and associated CO_2-emissions compared to more traditional concrete. However, the conversion of secondary material into binders and aggregates with desired properties requires an energy consuming process as well, and an investment. How does it influence the overall impact on the environment?

This paper presents the exploration of the environmental advantages and disadvantages of several secondary raw materials-based concrete formulations compared to traditional lightweight concrete in building applications. Recommendations are provided on how the environmental performance of concretes based on secondary raw materials can be improved over their life cycle.

Keywords: Secondary raw materials, embodied energy, carbon footprint, disposal, life-cycle assessment, SUS-CON

1 Introduction

The use of concrete in construction leads to environmental burdens. Raw materials such as limestone, gravel and sand are mined and processed to produce the constituents of concrete, which leads to emissions of CO_2 and air pollutants. Furthermore, fossil fuels are consumed, contributing to natural resource depletion. In the same way, transport, mixing and curing lead to emissions and depletion of fossil fuel resources and mineral resources. Post service, the construction is demolished, whereby energy is consumed. The same holds for crushing, sorting and disposal of construction waste from demolition. Finally, if the material is applied as e.g. aggregate in new concrete or in (sub)base courses for asphalt roads, an environmental benefit arises from the fact that the use of primary raw materials is avoided.

If the entire life cycle is considered, other studies have pointed out that for concrete the main environmental impact is related to the production processes of the binder and, to a lesser extent, the aggregate. A possible way to reduce the environmental impact of the production of concrete is to use secondary raw materials as source materials for concrete. Provided the material has the required properties and is available in sufficient quantities, it can replace constituents of concrete that are otherwise made of virgin materials such as sand, gravel and Portland cement. The SUS-CON project aims at reducing the embodied energy and the CO_2 footprint of concrete by replacing the current binders by novel binders made from secondary materials. Furthermore, the SUS-CON project targets at producing novel secondary material based aggregates that are lightweight and thermally insulating, to replace current lightweight aggregates. The novel binders and aggregates are combined into environmentally friendly lightweight non-structural concrete.

In the project a number of promising concrete formulations have been developed, for application as precast concrete blocks and façade panels as well as for ready-mix concrete for floor screed underlayment (also known as blinding layer). This paper describes an environmental evaluation on these concrete formulations focused on the greenhouse gas emissions[1]. In other words, a carbon footprint has been established of the promising concrete varieties. To know to what extent this carbon footprint of concrete is affected by the change of source materials, functionally similar benchmark concretes are introduced for each of the three application fields.

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[1] In future work within the project, other environmental impacts are addressed as well, such as the effects of air pollution (e.g. acidification and health effects caused by particulates), toxicity, depletion of abiotic and biotic natural resources and land scarcity.

2 Scenarios

2.1 *General*

To be able to make a comparison of the carbon footprint of innovative concrete products with their traditional counterparts, the environmental impact needs to be expressed relative to the function of the construction they are used in. In other words, products should be compared on a common ground, and expressed in a *calculation unit* that is related to the function of the construction. Table 1 shows the calculation unit for each product type. For instance, the function of a floor is to support the interior, which can be expressed in m^2 area. The floor screed underlay is part of the floor, and its function can be expressed in m^2 as well. One m^2 has been chosen as the calculation unit. The thickness of the floor screed underlay is set to 0.18 m, which means that for each calculation unit of 1 m^2, 0.18 m^3 of concrete is needed. The data in the thickness column in Table 1 have been supplied by manufacturers in the project consortium.

Table 1: Calculation units

Product	Construction	Functional unit	Thickness (m)	Calculation unit	Volume of concrete per calculation unit (m^3)
Block	Block	variable	-	1 m^3 *	1
Floor screed underlay	Floor	supporting 1 m^2 interior	0.18	1 m^2	0.18
Façade panel	Façade	flashing 1 m^2	0.20	1 m^2	0.20

*) because of their versatility, for blocks a unit of volume was chosen as a calculation unit.

2.2 *Benchmark concrete*

Each of the three products has two respective benchmark products, traditional products that are currently on the market. The two benchmarks differ in binder composition: the conservative variety has ordinary Portland cement (OPC) as a binder (CEM I), the second, more environmentally friendly variety has a CEM III/A 32.5 binder with a mix ratio of 50% OPC and 50% ground granulate blast furnace slag (GGBS). The conservative variety is included because in southern Europe OPC is the binder of choice; it can be seen as a worst

case in terms of environmental impact. The second variety is a proxy for the average European binder; it forms the middle ground between OPC and the in some northern countries frequently applied CEM III/B which contains 70% slag.
The aggregates vary among the three products, and were selected in such a way, that the resulting concrete mix density is in the same range as the density of the SUS-CON mixes. For blocks, the benchmark is based on Liapor expanded clay, mixed with natural sand. For floor screeds the aggregate consists of expanded polystyrene (EPS) and natural sand. For the façade panel benchmarks more research needs to be done to find an aggregate with an appropriate density. As a temporary solution, aerated autoclaved concrete (AAC) panels were selected, of which the density is much lower than the corresponding secondary raw material based formulations. The aggregate is natural sand, and gypsum and quicklime as well as aluminum powder are added as active components.

2.3 *SUS-CON concrete*

In Visser *et al*. (2015) an overview is given of the eight mixtures that seemed initially suitable as lightweight concrete for non-structural applications. The materials applied therein are listed in table 2.

Table 2: Secondary binders and aggregates

Category	Material	Specifications
Binder	Pulverized fly ash (PFA)	
	Ground granulated blast furnace slag (GGBS)	
Aggregate	Polyurethane (PU) rigid foam granulate	PU foam scrap
	Tyre rubber scrap	Iron-free tyre rubber granulate
	Remix HD	mixed plastics aggregate
	Remix LD	expanded mixed plastics

2.4 *Mix designs*

Various secondary material based binder-aggregate combinations and formulations were considered for the three applications. The mix designs that have led to promising concrete properties are listed in table 3, 4 and 5 for blocks, floor screeds, and façade panels respectively. The first entries in the tables are the benchmarks, marked with code B. The compositions in kilograms per cubic meter are provided in Annex 1.

Table 3: Mix designs considered for lightweight blocks; target density 1000-1400 kg/m³

Mix ID	Binder	Binder additives*	Aggregate
B1	CEM I	-	Liapor, natural sand
B2	CEM III/A	-	Liapor, natural sand
2_1	PFA	waterglass and sodium hydroxide	PU foam 4-8 mm; natural sand 0-2 mm
2_2	PFA	waterglass and sodium hydroxide	PU foam
2_3	PFA	waterglass and sodium hydroxide	Tyre rubber 0-0.6 mm, tyre rubber 2-4 mm; natural sand 0-2 mm
3_3	PFA/GGBS	waterglass and sodium hydroxide	PU foam 0-4 mm, PU foam 4-8 mm
3_4	PFA/GGBS	waterglass and sodium hydroxide	Remix HD 1-4 mm, Remix LD 8-12.5 mm

*) WG + NaOH: waterglass and sodium hydroxide

Table 4: Mix designs considered for lightweight floor screed (underlay); target density <1100 kg/m³

Mix ID	Binder	Binder additives	Aggregate
B3	CEM I	-	EPS and natural sand
B4	CEM III/A	-	EPS and natural sand
3_1	PFA/GGBS	waterglass and sodium hydroxide	PU foam 0-4 mm, PU foam 4-8 mm

Table 5: Mix designs considered for lightweight façade panels; target density <1500 kg/m³

Mix ID	Binder	Binder additives	Aggregate
B5	CEM I	aluminium powder	Gravel, natural sand
B6	CEM III/A	aluminium powder	natural sand
2_4	PFA	waterglass and sodium hydroxide	Remix HD 1-4 mm; natural sand 0-2 mm
3_2	PFA / GGBS	waterglass and sodium hydroxide	PU foam 0-4 mm, PU foam 4-8 mm

3 Approach

3.1 Scope

In environmental evaluations of products, the scope of the evaluation is an important consideration, because one wants all consequences of changing from one to another option to be inside the scope. The complete chain from mining/acquisition of raw materials up to recycling and waste treatment should be included to ensure that a shift of the environmental impact from one phase to the other is taken into account. For concrete from non-traditional materials, it is important to be aware of possible additional impact at the end-of-life treatment of concrete. The present environmental evaluation encompasses a full life-cycle assessment (LCA). A number of guidelines and standards have been published specifically for environmental assessments of building products. The present work has been conducted according to the requirements and the provisions of:

- ILCD Handbook
- EN 15804:2012 Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products
- EN 15978:2010 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method

The environmental assessment in this paper has a 'cradle-to-grave' scope, covering the chain of processes from acquisition of materials up to end-of-service-life recycling of benchmark concrete and SUS-CON innovative concrete. The scope is illustrated in Figure 1 for innovative concrete. Primary raw materials (P) are used, such as waterglass activator. Furthermore, secondary raw materials (S) are needed as an input. In the light of the aim in the project, the secondary waste streams that have little or no economically viable alternative uses at the moment have been shown separately (S0). This holds for e.g. PU foam, tyre rubber and Remix plastics.

Figure 2 shows the scope for the benchmark products. Raw materials include primary raw materials such as Portland cement and sand, as well as secondary raw materials, notably GGBS.

Normally at this point the scope of the analysis would be complete. Yet, if we consider the consequences of using SUS-CON innovative concrete instead of traditional, there is another effect that is not addressed yet: recycling or, more likely, disposal of either PU, tyre rubber or mixed plastics is avoided by using these materials as a constituent of concrete. In other words, in the case of traditional concrete, processing of these 'S0' materials should take place, while in the case of innovative concrete they are utilized. In Figure 2 therefore treatment of 'S0' secondary raw materials is added to the scope.

The other way around this line of reasoning has no consequences: raw materials used in traditional concrete are simply not mined in the case of SUS-CON concrete, or most likely used for a different purpose in the case of PFA or GGBS. One could debate though that the scope discussion has a local demand and supply component as well, which goes beyond the scope of this paper.

The time horizon of the assessment is limited to 100 years. This means that for activities that may generate emissions over a long period of time, such as maintaining a landfill site, the emissions that occur after 100 years are cut off.

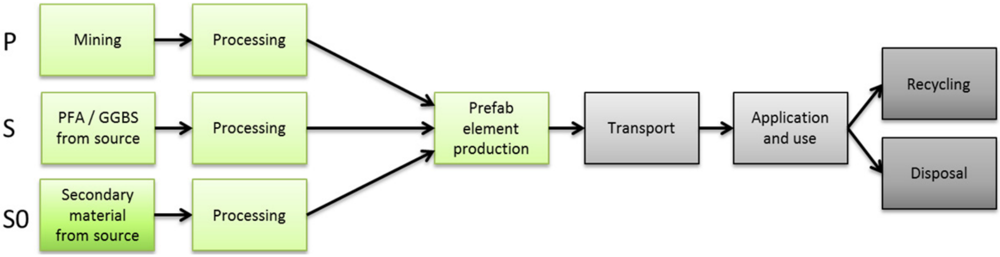

Figure 1: Scope of assessment for innovative concrete. P=primary raw materials, S=secondary materials, S0=secondary raw materials with few alternative destinations

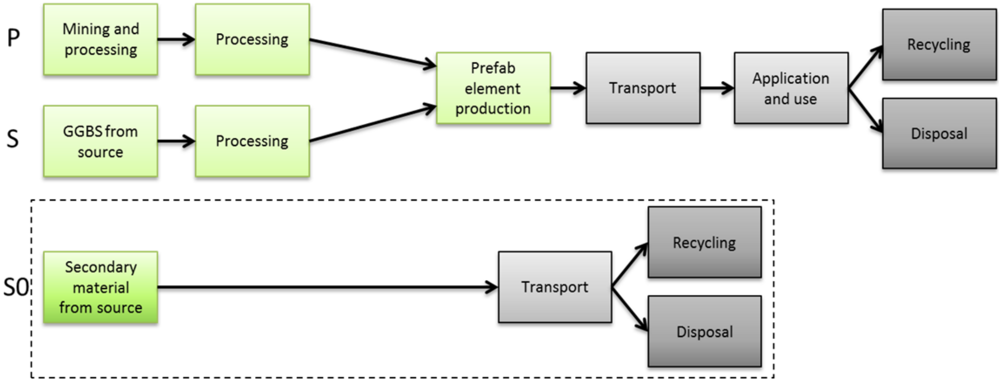

Figure 2: Scope of assessment for traditional concrete. P=primary raw materials, S=secondary materials, S0=secondary raw materials with few alternative destinations

3.2 *Methodology*

Of each process within the scope of the assessment, the direct and indirect emissions of greenhouse gases were collected, weighted and added up for one functional unit as in table 1. Greenhouse gases disturb the energy balance of the earth-atmosphere system, by absorbing and re-emitting thermal infrared radiation that was emitted from the Earth's surface and would have normally disappeared into space. By this process, heat is retained in the atmosphere. Disturbing the natural balance causes climate change. Greenhouse gases include CO_2, methane, dinitrogen monoxide, CFCs and HFCs, SF6 and some other gases. The extent to which radiation into space is prevented by a greenhouse gas is called radiative forcing. As a function of the concentration of a gas in the atmosphere, the radiative forcing is expressed in W/m^2. Apart from the radiative forcing, another factor determining the contribution to climate change is the atmospheric lifetime of a greenhouse gas. The longer the lifetime, the larger the contribution to climate change over time.

Thus, emitting greenhouse gases potentially contributes to climate change, depending on their radiative forcing and their lifetime. The Intergovernmental Panel on Climate Change (IPCC) has published a quantity to be able to compare this effect per kg of gas: Global Warming Potential (GWP). The GWPs have been published in the IPCC Fourth Assessment Report, 2007. The GWPs are expressed relative to the effect of CO_2, for a specific time scale. In this paper, the often-used time horizon of 100 years is maintained (GWP_{100}). The GWP_{100} of methane is 25 kg CO_2-eq., meaning that the potential contribution to climate change of 1 kg of methane emitted is equal to that of the emission of 25 kg of CO_2.

4 Environmental performance: cradle to gate

4.1 *General*

The formulation of each concrete mix considered is available in Annex 1. The production processes of the various concrete components as well as other processes in the chain emit greenhouse gases. The greenhouse gas emission factors for each process are included in Annex 2.

To discuss the results in a logical way, the results in this paper are split in two parts. First, results are shown with a limited scope: 'cradle to gate', which means production of concrete up to the gate of the factory. These results are presented in paragraphs 4.2, 4.3 and 4.4, for the three target products. Secondly, in chapter 5 the full cradle to grave results are shown, i.e. including end-of-life treatment.

4.2 *Precast blocks 1 m^3*

Figure 3 shows the carbon footprint of precast blocks. The benchmarks, CEM I and CEM III/A, both with Liapor expanded clay aggregate, have a CO_2 emission of just over 330 and 200 kg/m^3, respectively. The high content of Portland cement in the CEM I benchmark leads to a high CO_2 emission in production, due to energy consumption and as a direct emission from calcination of calcium carbonate. In the CEM III/A 32.5 mix the binder is a mix of approximately 50% Portland cement with 50% GGBS, which leads to a lower footprint for the binder than pure Portland cement as GGBS has a low CO_2-emission. This low CO_2-emission results from the fact that it is a secondary product from the steel industry, and size reduction and dewatering are the only activities to prepare it for use in concrete.

As transport of raw materials contributes little and curing is done at room temperature, the production of expanded clay aggregate is the only other significant source of CO_2-emissions for benchmark mixes. The energy consumption for clay expansion is largely responsible for this.

All innovative concrete formulations have either pulverized fly ash (PFA) or a mix of PFA and ground granulate blast furnace slag (GGBS) as a geopolymer binder. The carbon footprint of preparing these binders is small compared to Portland cement containing binders (roughly twenty times lower per kg; see table 6). Nevertheless, geopolymer binders require significant amounts of waterglass and/or sodium hydroxide as activators. The production of these two compounds causes the high CO_2-eq. emissions. For PFA binders, curing demands elevated temperatures, here 70 °C. This gives rise to CO_2 emissions as well.

The production of the secondary aggregates is discussed in detail in Attanasio *et al*., 2015. Generally speaking, several crushing, sieving and/or sorting steps are required to convert PU scrap, old tyres and plastics waste into aggregate. Moreover PU needs a heated pelletization process, and LD Remix needs a thermal expansion process. All of these activities require energy, leading to CO_2 emissions. Considering the mixes in figure 3, of the three aggregates it is PU that leads to the least CO_2 emissions. For a decrease of the CO_2 emission, research should be targeted at, respectively, an energy efficient pelletization for PU, the possible application of tyre rubber scrap that has been cleaned less thoroughly, or a reduction of the heat requirement for the expansion of LD Remix. Also, the acceptance of a larger average grain size can contribute to energy savings.

Although having a small contribution for all cases, transport emissions are higher for innovative concrete cases than for the benchmarks. The reason is that fly ash, blast furnace slag and polyurethane waste have a limited number of sources in Europe. Transport distances are therefore higher than e.g. for natural sand, while concrete plants are built near mineral sources for practical and financial reasons. What further increases the differences, is that sand is assumed to be transported by ship, while other aggregates are assumed to be transported by truck. The CO_2 emission of a ship is generally lower than for a truck, per unit of transport performance (see also Annex 2, table A6).

All of the PU based formulations lead to a lower carbon footprint than the CEM III/A-expanded clay benchmark. The mix of PFA/GGBS with PU aggregate and the mix of PFA with PU and sand aggregate have the lowest CO_2 footprint of the formulations studied: around 130 kg CO_2-equivalents. The Remix based and tyre rubber based formulations result in a CO_2-equivalents emission of around the value for the best benchmark, the CEM III/A-expanded clay formulation.

Concluding, all PU based formulations have a lower carbon footprint than the two benchmarks, while the other formulations are comparable to the best benchmark. For the SUS-CON concrete, the binder contributes most, caused mainly by the use of activators. Of the aggregates, PU has the lowest impact. The best option for blocks is a combination of PU

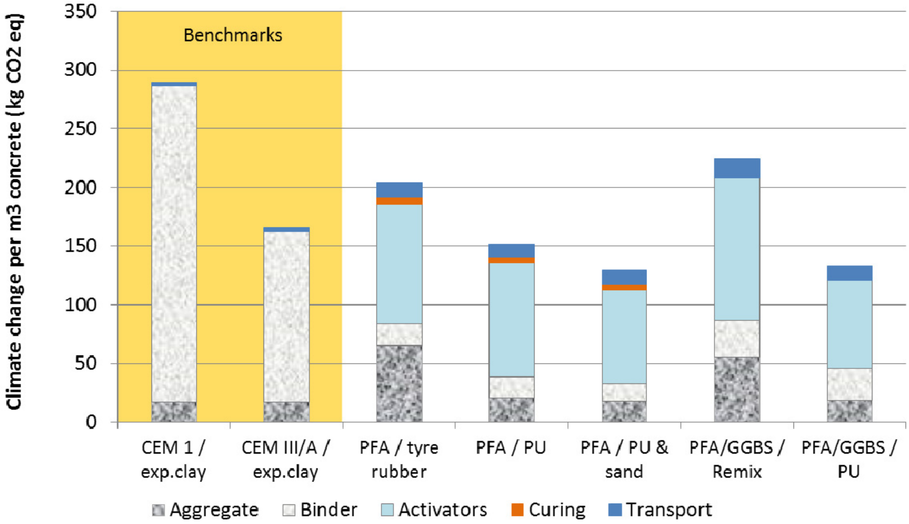

Figure 3: Carbon footprint of 1 m^3 of concrete blocks: traditional and innovative formulations

and a binder with low activator consumption.

*4.3 **Floor screed (underlay) 1 m^2***

In figure 4 two traditional concrete floor screed underlays (CEM I based and CEM III/A based) are compared to a screed underlay from geopolymer concrete with PU aggregate.

The carbon footprint of the traditional mix concrete is approximately 60 kg of CO_2-equivalents per m^2 for the formulation with CEM I (Portland cement) binder, and 35 kg for CEM III/A binder based formulation. The binder contributes 65 to 80% to the total CO_2 emission. The aggregates are 410 kg of natural sand and 20 kg of EPS (expanded polystyrene) per m^3. The impact of the latter is much higher, despite the limited weight. The production of EPS from crude oil is an energy intensive process, while the excavation and transportation of sand is not.

The footprint of the SUS-CON innovative floor screed underlay is over 40% lower than the footprint of the lowest EPS concrete underlay. Both binder and aggregate contribute to that result. For the polyurethane aggregate holds that the material is obtained 'for free', in other words: no burden for the original production is taken into account, because this is attributed to the previous product. Consequently, only the processing (and transport) is accounted for: pulverisation and compression moulding.
As can be seen in figure 4, the PFA/GGBS binder has an advantage over CEM I and CEM III/A as well. The footprint of the PFA/GGBS binder is mainly related to the production of waterglass and sodium hydroxide activators, and not to the preparation of fly ash or blast furnace slag.

Concluding, the carbon footprint of innovative floor screed underlay is over 40% lower than those of the two benchmarks. The production of activators, used in a significant amount, is the main cause of the emission of CO_2. Transport related emissions are higher than for the benchmarks, but contribute just a few percent.

*4.4 **Façade panels***

In figure 5 a Remix/PFA based façade panel is compared to two benchmarks. Both benchmarks are aerated autoclaved concrete. The binder consists of Portland cement and a 50%/50% Portland cement/GGBS mixture, respectively, supplemented with gypsum and quicklime. The aggregate is sand. Aluminium powder is added and reacts with quicklime

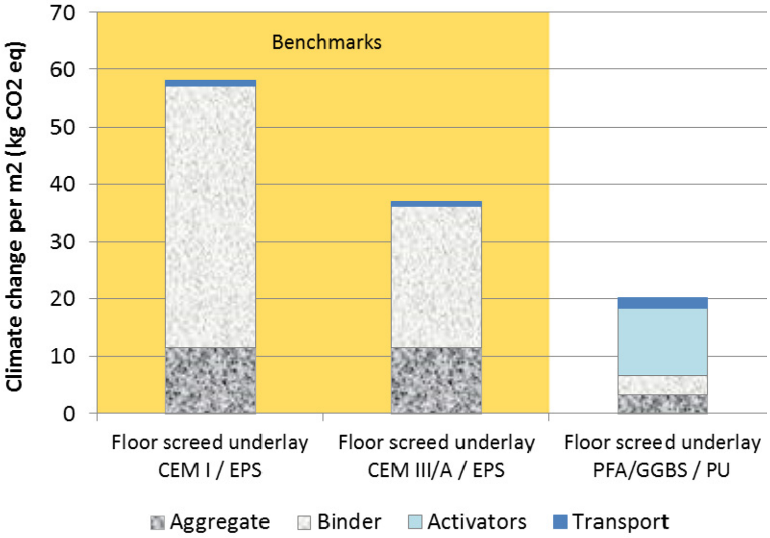

Figure 4: Carbon footprint of 1 m² of floor screed underlay: traditional and innovative formulations

to form hydrogen gas, resulting in bubbles in the concrete, which give it its low density. The SUS-CON concrete panels have PFA as a binder, which performs better in terms of CO_2 emission than the binders containing Portland cement. Nevertheless, the production of alkaline activators required for geopolymeric binders such as PFA makes the benefit of PFA more than reversed in terms of CO_2 emissions.
As can be seen in figure 5, the impact of sand as an aggregate is negligible. The contribution of Remix aggregate is small as well, also compared to the Remix based block in figure 3. The reason for the low impact is that for panels only high density Remix is used, thereby avoiding the energy intensive expansion process for the low density Remix.

The benchmarks are hardened in an autoclave. The CO_2-emissions resulting from the production of steam for the autoclave are visible under the item 'curing'. Curing energy is also required for the PFA/Remix formulation.

Transport emissions are higher for the innovative concrete formulations, due to larger delivery distances for secondary materials based aggregates, compared to the delivery distance of sand for the benchmarks. Moreover trucks are used instead of the barges used for sand.

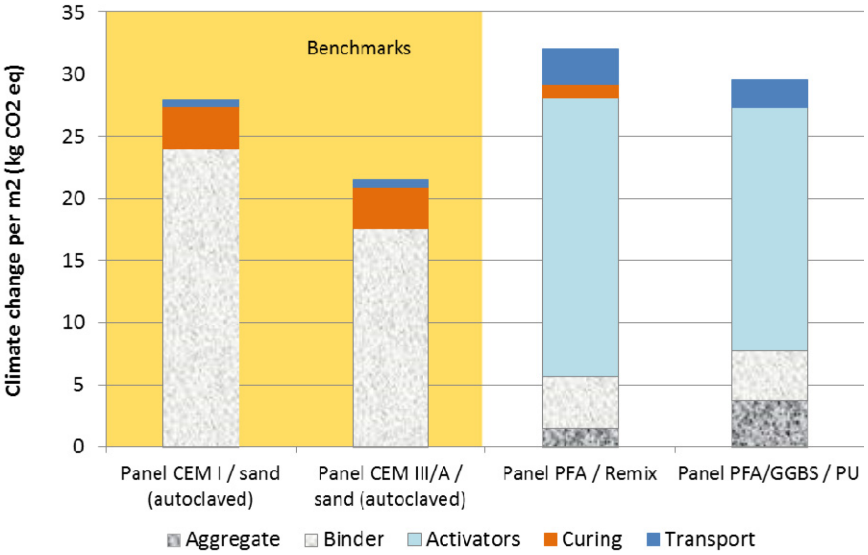

Figure 5: Carbon footprint of 1 m² of façade panels: traditional and innovative formulations

Concluding, SUS-CON façade panels have a carbon footprint that is around or slightly higher than that of the CEM I based benchmark. The activator for the binder largely determines the footprint. Transport related emissions are higher than for the benchmarks, but contribute just a few percent.

5 Environmental performance: cradle to grave

5.1 *General*

So far in this paper the destination of materials at the end of life has not been taken into consideration. This holds for both the (avoided) end-of-life treatment of the secondary materials used as constituents of SUS-CON concrete, as well as end-of life processing of the SUS-CON concrete products. To avoid repetition, the results in this chapter are illustrated for concrete blocks only.

5.2 *Avoided waste treatment*

As explained in chapter 2, in innovative concrete either PU, tyre rubber or Remix is used which would otherwise have no or little useful purpose. For traditional concrete where neither of these materials is used, PU, tyre rubber or Remix would have to be incinerated or landfilled. Therefore, the scope of the assessment needs to be enlarged. Because the

innovative concrete puts 'waste' to use, the greenhouse gas emissions associated with the waste treatment should be added to the greenhouse gas emissions of traditional concrete. This line of reasoning is only valid in direct comparisons; if one compares traditional concrete with PU based innovative concrete, waste treatment of the corresponding amount of PU should be added to the CO_2 balance of the traditional concrete. Comparing with a tyre rubber based innovative concrete, this should be the respective amount of tyre rubber, and so on.
In Europe, incineration is mandatory for combustible waste. Given the high calorific value of PU foam, tyre rubber and Remix, these materials shall be incinerated. To account for incineration, the direct emissions related to combusting these materials are included. Furthermore, because incineration plants are commonly fitted with equipment to produce electric power and heat , an environmental credit is awarded for the avoided production of electricity in a power station and heat in a boiler.

For PFA and GGBS used in innovative concrete, no waste treatment has to be 'charged' onto the traditional concrete in the comparison, because these materials would otherwise be used as cement replacements, or otherwise usefully applied, e.g. as a filler for asphalt; see Attanasio *et al.*, 2015 and Pascale *et al.*, 2015. Thus, no benefits are accounted to innovative concrete for PFA nor GGBS.

Figure 6 shows a comparison of the carbon footprint of concrete blocks: one Portland cement based benchmark concrete, and one PFA based concrete with tyre rubber aggregate (see also figure 3, the first and third column). The greenhouse gas emissions of incineration of tyre rubber have been added for the benchmark case. As can be seen, this increases its carbon footprint by more than a factor of 3.

Similarly, results were generated for all other benchmark-innovative concrete block combinations. In order to avoid having to show a large number of graphs[2], an attempt has been made to simplify the presentation. In the next graphs the waste treatment related greenhouse gas emissions are not added to the benchmark, but rather subtracted from the

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[2] For each innovative concrete a different waste treatment-related CO_2 emission is to be added to the benchmark, since it is related to the material (and amount) used in the innovative concrete: PU, tyre rubber or Remix. This leads to a large number of graphs.

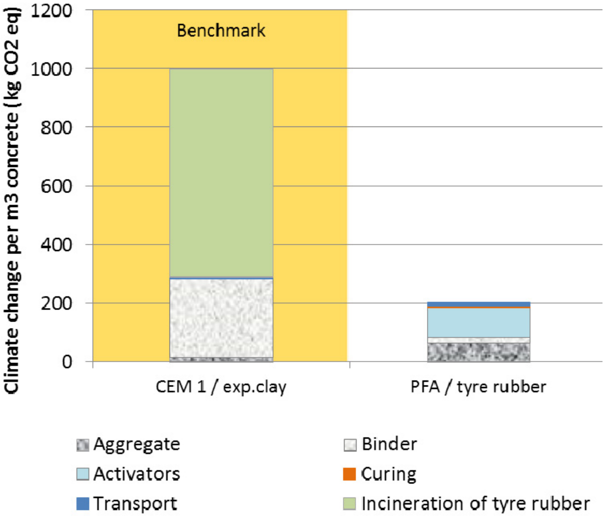

Figure 6: Carbon footprint of 1 m^3 of concrete blocks: influence of avoided end-of-life treatment (burden of waste treatment added to greenhouse gas emissions of benchmark concrete)

results for innovative concrete. In the comparison this leads to the same absolute differences between traditional and innovative concrete footprints.

In figure 7, the influence of the avoided end-of-life treatment of secondary materials on the carbon footprint is shown for concrete blocks. It can be seen that for each of the secondary aggregates used in innovative concrete, there is an significant additional benefit for the environment. After all, the alternative route for the secondary materials was less environmentally friendly. The benefit is even larger than the environmental burden to manufacture the concrete (the bars below zero are larger than the bars above zero), leading to a net saving of CO_2-eq. emissions. The net values, which are written in the graph, are negative in that case. Obviously the balance is only complete when end-of-life treatment of SUS-CON concrete is incorporated as well.

The bonus for not incinerating PU, Remix and tyre rubber is the main effect in figure 7. The contribution of avoided recycling as aggregate of PFA and GGBS to the results is very small.

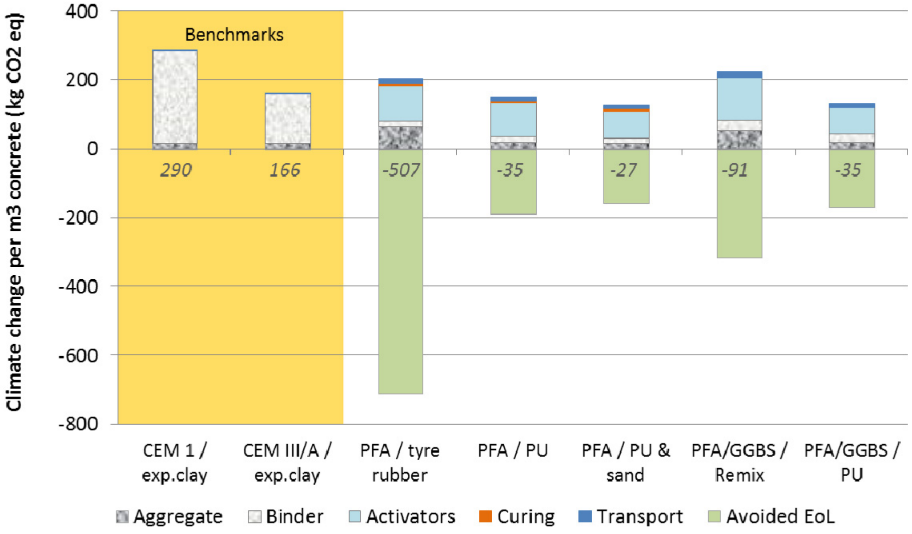

Figure 7: Carbon footprint of 1 m³ of concrete blocks: influence of avoided end-of-life treatment of secondary material

5.3 *End-of-life treatment of traditional and innovative concrete*

To make the balance complete, the foreseen end-of-life treatment of the building products (SUS-CON innovative concrete and benchmark concrete products) should be included as well. Several scenarios are possible. Given the life span of concrete products end-of-life treatment will take place in the far future, which makes it difficult to predict which options are realistic.

If it will be possible to separate polymer/rubber aggregates from binders, the polymers can be incinerated while the binders can be reused as aggregate material for other purposes. This would undo the environmental benefits shown in figure 7; effectively the end-of-life treatment of the secondary materials is delayed by the life span of the concrete. Obviously there is an additional burden due to energy consumption and possibly chemicals consumption for the separation process. While it is a theoretical route, it can serve as a worst case scenario.

If binders and aggregates of SUS-CON concrete formulations cannot be separated, it is more likely that the concrete is either recycled into fresh concrete (if the properties are acceptable), thereby replacing sand or gravel, or landfilled. Replacing sand and gravel has a (small) benefit because it avoids mining of these materials. With respect to landfill, controlled conditions are needed to prevent leaching of metals from the blast furnace slag content, and emission of these metals to soil. The controlled conditions also prevent full biological decomposition of plastics or rubber.

For the benchmarks the most likely scenario would be recycling into fresh concrete as aggregate material. No market effects of oversupply are assumed.

Figure 8 and 9 indicate the environmental consequences of recycling of concrete and landfill of concrete on the life cycle of concrete blocks. The modelling is based on Ecoinvent database version 2.2, 2010.

As can be observed, the benefits of recycling of concrete are hardly visible in the graph; the effect is negligible on the total carbon footprint of concrete blocks. The effect of landfill on the other hand is clearly visible, mainly in the case of SUS-CON concrete, and is caused by CO_2 and methane emissions from landfill. These emissions are a result of the use of machines to construct and maintain the landfill site, as well as of partial biodegradation of plastics and rubber. The total greenhouse gas emissions over 100 years (see paragraph 3.1) are approximately 80 g CO_2-eq. per kilogram of landfilled plastics or rubber. The order of preference of the concrete mixtures is not different if landfill is assumed.

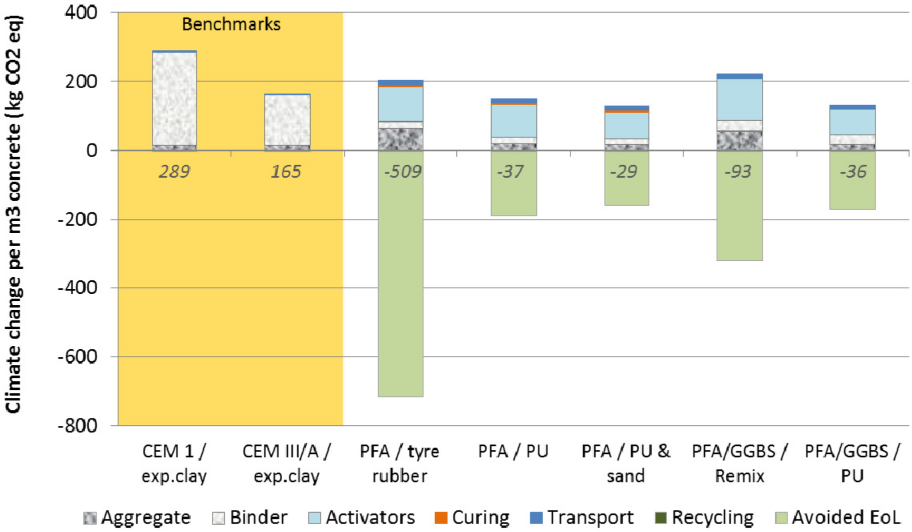

Figure 8: Carbon footprint of 1 m³ of concrete blocks: influence of recycling of end-of-life concrete

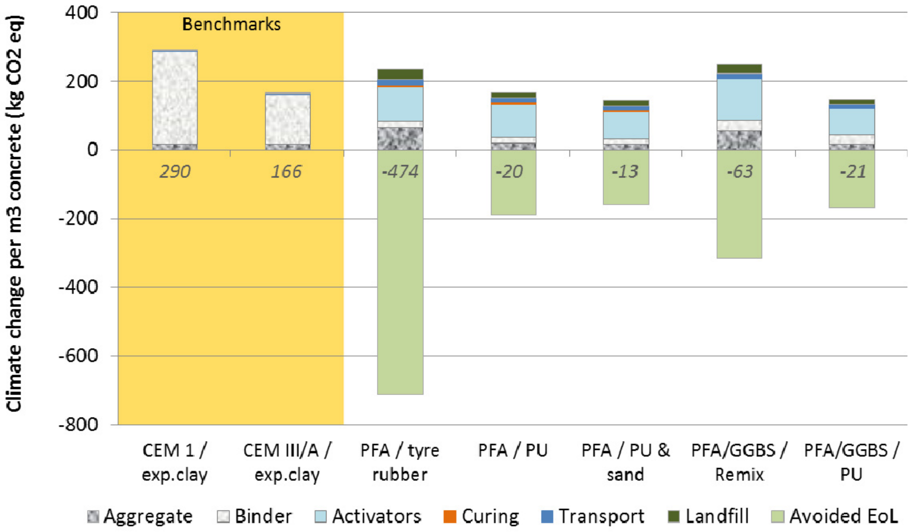

Figure 9: Carbon footprint of 1 m^3 of concrete blocks: influence of landfill of end-of-life concrete

Concluding, the avoided end-of-life treatment of the secondary materials used in SUS-CON innovative concrete may have a significant influence on the results. If the aggregate materials would have been incinerated, innovative products get a large credit for avoiding that to happen. If the aggregate materials would have been recycled, SUS-CON products should get an additional burden. The avoided end-of-life treatment of PFA and GGBS has no significant influence on the carbon footprint of concrete products.
The destination of SUS-CON concrete and benchmark concrete at the end of their service life has a limited influence on the results presented in this paper.

6 Environmental performance: sensitivity analysis

Since the information that the carbon footprint was built upon is somewhat uncertain, and assumptions were made on some occasions, it is important to have an indication of the robustness of the conclusions with regard to these uncertainties. This can be done by testing the sensitivity of the results to a variation in input data or assumptions, within reasonable boundaries.

The production of activators has a large share in the carbon footprint of the innovative concrete cases. The CO_2 emission of the production of sodium hydroxide and waterglass was taken from the ecoinvent database version 2.2. For sodium hydroxide (50% in water) this is a production mix of three production routes: diaphragm cell, membrane cell and mercury cell. The carbon emissions vary approximately 15% among these routes. This is mainly a result of differences in electricity consumption - the main driver for CO_2 emission in the production of sodium hydroxide, see figure 10.

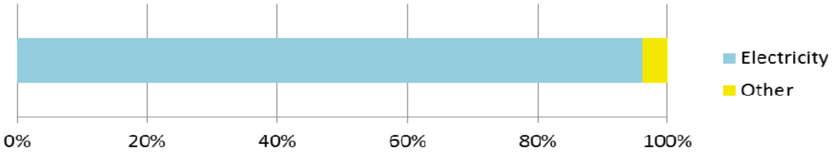

Figure 10: Contribution of electricity consumption in carbon footprint of sodium hydroxide (50%) production

For waterglass activator (37% waterglass in water), greenhouse gas emission data was taken for the furnace process, which has an approximately 10% lower carbon footprint than the alternative, a hydrothermal process. The choice for the furnace process is an arbitrary one, no details have been requested from waterglass manufacturers. Figure 11 shows the breakdown of the carbon footprint of waterglass solution. Besides heat and electricity, significant emissions emerge from the process itself, as well as in the production of soda, one of the two main raw materials (the other one being silica).

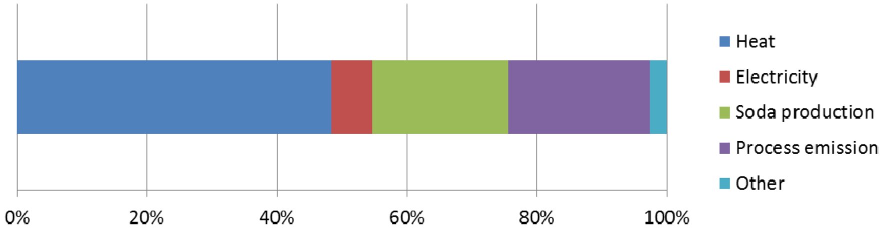

Figure 11: Breakdown of carbon footprint of waterglass (37%) production via the furnace route

Apart from the variations in the production route, the data source is also of influence. If the GaBi database is used (PE International, 2014) instead of the Ecoinvent database (ecoinvent, 2010), the resulting carbon emissions are different. The reasons are that data from different factories were used, and that different methodological choices were made while interpreting the data. For instance, a German electricity mix is considered in the sodium hydroxide production process in the GaBi database, as opposed to a European average mix in the data set in the Ecoinvent database.

By combining the variations in greenhouse gas emissions among production routes and among literature sources, a min-max graph was made, see Figure 12. Sodium hydroxide and waterglass are shown separately, accounting for the amounts used per m^3 of concrete blocks. As can be seen, the influence of the variation of sodium hydroxide (NaOH) is much more significant than the differences between the highest and lowest greenhouse gas emission values found for waterglass.

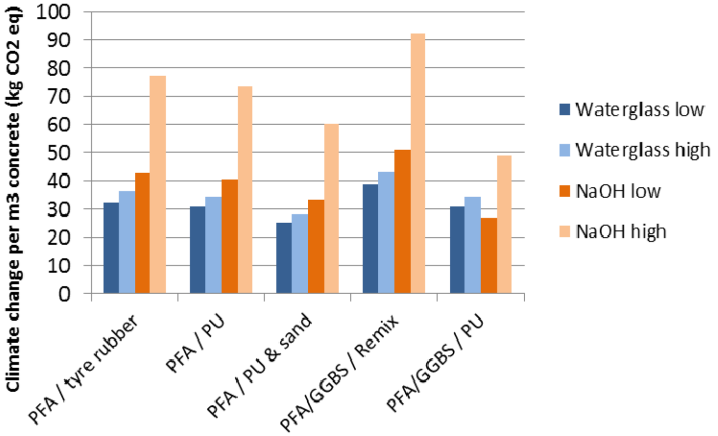

Figure 12: Carbon footprint of activators per m^3 of concrete blocks; highest and lowest values

The effect on the total carbon footprint of the production of concrete blocks can be seen in Figure 13. It can be concluded that the sensitivity of the results to the data used for the production of activators is so large, that it can determine whether the three PU based innovative concretes perform better or worse than the CEM III/A based benchmark.

Which dataset is most representative for real world geopolymeric concrete manufacturing, is dependent on the specific supplier of waterglass and sodium hydroxide, and its location. Also, not enough information is available to judge the general data quality of the used data sets. It is recommended to make a specific assessment for activators whenever production of innovative concrete based products is planned.

In general, it is recommended to attempt optimization of the consumption of sodium hydroxide and waterglass, and to do further research into utilizing secondary alkaline materials for geopolymeric concrete.

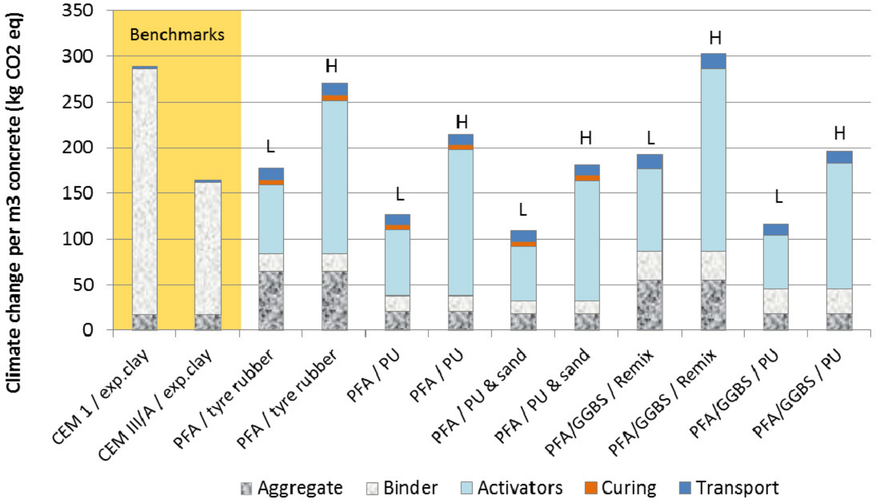

Figure 13: Carbon footprint of the production of concrete blocks; highest and lowest emission values for activators; L=lowest emission data, H=highest emission data

7 Conclusions

Secondary raw material based concrete products have the potential to decrease the carbon footprint of state of the art concrete products. The potential is influenced by: 1) the footprint of the production of activators for geopolymer binders, which are currently not based on secondary materials, 2) the amount of energy needed for processing the secondary materials into binders or aggregates, 3) the CO_2 footprints of the traditional constituents that are replaced by the secondary materials, such as Portland cement, and 4) the avoided end-of-life treatment of the secondary materials utilized.

For the innovative products considered – blocks, floor screed underlays and façade panels, activators contribute most to the carbon footprint. For blocks, in terms of production the best option is a combination of PU and a binder with low activator consumption. The carbon footprint of its production is 20% lower than the best benchmark. For the floor screed underlay, the mix design considered is performing 40% better than the best benchmark (CEM III/A based) in terms of carbon footprint. Transport related emissions are higher than for the benchmarks due to longer distances, but contribute just a few percent. The mix designs considered for façade panels perform marginally worse than either of the two benchmarks. Also for panels transport related emissions are higher than for the benchmarks, but contribute just a few percent.

In this article particular attention is paid to end-of-life treatment. Using secondary materials with few alternative uses, such as PU foam waste, tyre rubber and Remix plastics, avoids incineration of these materials. If the CO_2 emissions from avoided incineration are credited to the innovative concrete, the results change considerably. The benefits of keeping PU, tyre rubber or Remix from being incinerated are larger than the burdens from producing the concrete, expressed in terms of greenhouse gas emissions. The true effect depends on the destination of innovative concrete after use. If aggregate and binder can be separated in any way, and the aggregates are incinerated after all, the sole effect is that incineration of PU, tyre rubber or Remix is delayed.
It is more likely that traditional and innovative concrete are reused as aggregate material after the use phase. In that case, the end-of-life processing of concrete products has a limited influence on the results presented in this paper.

The production of alkaline activators contributes over 50% to the greenhouse gas emissions of the production of any of the innovative concrete mixes proposed. A sensitivity analysis has been carried out of the main results for concrete blocks to variations in manufacturing data of waterglass and sodium hydroxide. The results show that the total CO_2-eq. emissions of the production of concrete can vary up to 40% as a result of variations in activator production data. The sensitivity of the results to the data used for the production of activators is large enough to determine whether PU based innovative concrete blocks perform better or worse than the CEM III/A based benchmark.
Efforts to improve the carbon footprint of the innovative concretes proposed, should first be directed towards optimizing activator use or replacing the alkaline activator by a secondary flow. Nevertheless, in SUS-CON the latter option was rejected after research, due to a lack of availability of suitable flows. Other improvement directions are to reduce energy consumption in pelletization of PU and the expansion of LD Remix, and using larger average grain sizes for aggregates if possible.

Literature

Attanasio, A. *et al.*, Waste materials as innovative aggregates for sustainable concrete, 2015 (unpublished).

Corti, A. and L. Lombardi, End life tyres: alternative final disposal processes compared by LCA, *Energy* 29 (2004) 2089-2108, 2004.

Ecoinvent, Ecoinvent database 2.2, www.ecoinvent.ch, 2010.

EN 15804:2012 Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products, 2012.

EN 15978:2010 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method, 2012.

Institut Bauen und Umwelt e.V., Environmental Product Declaration of Ytong Autoclaved Aerated Concrete, Declaration number EPD-XEL-2009112-E, 2009.

Internal information FP7 SUS-CON

JRC-IES, International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Provisions and Action Steps, 2010.

Pascale, S. *et al.*, Useable secondary materials for concrete products around Europe and the barriers for general use, 2015 (unpublished).

PE International, GaBi LCA databases, 2014

Quadrini, F., D. Bellisario and L. Santo, Recycling of thermoset polyurethane foams, 2013.

Roorda, A.A.H., E. Langerak and B.L. van der Ven, Milieu-analyse verwerkingsmethoden van kunststofonderdelen van afgedankte auto's, TNO, 1996.

SBR CUR net, Ontwerptool Groen Beton (Designtool Green Concrete), 2013.

United Nations Intergovernmental Panel on Climate Change, Climate Change 2007, Fourth Assessment Report, 2007.

Visser, J.H.M. *et al.*, Sustainable concrete: design and testing, *HERON* Vol. 60 (2015) No. 1/2, pp. 59–91.

Wittstock *et al.* 2012, EeBGuide Guidance Document - Part A: Products – Operational guidance for Life Cycle Assessment studies of the Energy Efficient Buildings Initiative, 2012.

Annex 1 Mix formulations

Numbers are per m^3 of concrete.
In the benchmark products, CEM I has a slag content of 0% and CEM III/A has a slag content of 50%. Slag in this context is ground granulated blast furnace slag.

Table A1: Mix designs considered for lightweight blocks

Mix ID	Binder	Binder additives*	Aggregate	Other	Density fresh state (kg/m³)
B1	CEM I 330 kg	-	Liapor 54 kg natural sand 83 kg	Water 165 kg	632
B2	CEM III/A 330 kg	-	Liapor 54 kg, natural sand 83 kg	Water 165 kg	632
2_1	PFA 459 kg	WG 92 kg and NaOH 53 kg	PU foam 4-8 mm 139 kg; natural sand 0-2 mm 477 kg	Water 116 kg	1336
2_2	PFA 558 kg	WG 112 kg and NaOH 65 kg	PU foam 165 kg	Water 70 kg	970
2_3	PFA 589 kg	WG 118 kg and NaOH 68 kg	Tyre rubber 0-0.6 mm 49 kg, tyre rubber 2-4 mm 315 kg; natural sand 0-2 mm 331 kg	Water 135 kg	1605
3_3	PFA 76 kg and GGBS 433 kg	WG 112 kg and NaOH 43 kg	PU foam 0-4 mm 52 kg, PU foam 4-8 mm 97 kg	Water 149 kg	962
3_4	PFA 350 kg and GGBS 350 kg	WG 140 kg and NaOH 81 kg	Remix HD 1-4 mm 259 kg, Remix LD 8-12.5 mm 53 kg	Water 171 kg	1404

*) WG: waterglass; NaOH: sodium hydroxide (50%).

Table A2: Mix designs considered for lightweight floor screed (underlay)

Mix ID	Binder	Binder additives*	Aggregate	Other	Density fresh state (kg/m^3)
B3	CEM I 310 kg	-	EPS 19 kg, natural sand 410 kg	Water 170 kg	909
B4	CEM III/A 310 kg	-	EPS 19 kg, natural sand 410 kg	Water 170 kg	909
3_1	PFA 367 kg and GGBS 122 kg	WG 98 kg and NaOH 38 kg	PU foam 0-4 mm 52 kg, PU foam 4-8 mm 97 kg	Water 148 kg	922

Table A3: Mix designs considered for lightweight façade panels

Mix ID	Binder	Binder additives*	Aggregate	Other	Density fresh state (kg/m^3)
B5	CEM I 86 kg, gypsum 13 kg, quick-lime 45 kg	Aluminium powder 0.5 kg	Natural sand 227 kg	Water 167 kg	599
B6	CEM III/A 86 kg, gypsum 13 kg, quick-lime 45 kg	Aluminium powder 0.5 kg	Natural sand 227 kg	Water 167 kg	599
2_4	PFA 648 kg	WG 130 kg and NaOH 75 kg	Remix HD 1-4 mm 255 kg, natural sand 0-2 mm 358 kg	Water 130 kg	1596
3_2	PFA 481 kg and GGBS 85 kg	WG 113 kg and NaOH 66 kg	PU foam 0-4 mm 74 kg, PU foam 4-8 mm 74 kg	Water 166 kg	1059

Annex 2 Inventory of greenhouse gas emission data

In Table A4 greenhouse gas emissions are listed per process for manufacturing of concrete components. The information has been derived from the Ecoinvent database version 2.2,

Table A4: CO_2-equivalent emission factors of manufacturing concrete components

Material	CO_2-eq. emission factor (g of CO_2-eq. per kg)	Based upon
CEM I	816	Ecoinvent
CEM III/A (50% slag)	440	Ecoinvent
Pulverized fly ash (PFA)	32	Ecoinvent
Ground granulated blast furnace slag (GGBS)	57	Ecoinvent
Natural sand	2	Ecoinvent
Gravel	2	Ecoinvent, assumed equal to sand
EPS	3376	Ecoinvent
Liapor	320	Ontwerptool Groen Beton 2013
PU rigid foam granulate	126	Ecoinvent + Quadrini 2013, Roorda 1996
Tyre rubber scrap	178	Ecoinvent + Corti 2004
Remix HD	28	Ecoinvent + Internal information from Centro Riciclo
Remix LD	922	Ecoinvent + Internal information from Centro Riciclo
Waterglass activator, 37%	277	Ecoinvent (sensitivity analysis: PE International 2014)
Sodium hydroxide solution, 50%	1013	Ecoinvent (sensitivity analysis: PE International 2014)
Aluminium powder	11740	Ecoinvent
Tap water	0	Ecoinvent

For tyre rubber scrap, the process results in recyclable steel threads. The environmental benefits of recycling this steel have not been attributed to the rubber scrap aggregate.

Table A5 shows CO_2 emission factors for waste disposal processes. All information in the table has been derived from the Ecoinvent database version 2.2.

Table A5: CO_2-equivalent emission factors of waste disposal processes

Process	CO_2-eq. emission factor (gram of CO_2-eq. per kg)
Landfill of inert material	2.4
Landfill of PFA	2.9
Landfill of GGBS (with immobilization)	312
Landfill of PU foam	85
Landfill of Remix	82
Landfill of rubber from tyres	82
Incineration of PU foam*	1140
Incineration of Remix*	1020
Incineration of rubber from tyres*	1960

*) with energy recovery

Table A6 shows CO_2 emission factors for some key processes in the concrete life cycle. All information in the table has been derived from the Ecoinvent database version 2.2.

Table A6: CO_2-equivalent emission factors of other processes

Process	CO_2-eq. emission factor (gram of CO_2-eq. per unit)
Transport by truck (1 ton.km)	106
Transport by inland vessel (1 ton.km)	35
Transport by seagoing vessel (1 ton.km)	9
Electricity (1 kWh)	583
Heat from natural gas (1 MJ)	70