Flanders
State of the Art

PUB. N°
5

CO_2 mineralisation for sustainable construction materials

CE CENTER CIRCULAR ECONOMY
POLICY RESEARCH CENTRE

WE MAKE TOMORROW BEAUTIFUL
OVAM

DEPARTMENT OF
ECONOMY
SCIENCE &
INNOVATION

ce-center.be

CE CENTER
CIRCULAR
ECONOMY
POLICY RESEARCH
CENTRE

PUB. N°
5

CO_2 mineralisation for sustainable construction materials

Andrea Di Maria
Sustainable Assessment of Materials, KU Leuven
Kasteelpark Arenberg 44, 3001 Leuven, Belgium

Ruben Snellings
VITO
Boeretang 200, 2400 Mol, Belgium

Luc Alaerts
Sustainable Assessment of Materials, KU Leuven
Kasteelpark Arenberg 44, 3001 Leuven, Belgium

Mieke Quaghebeur
VITO
Boeretang 200, 2400 Mol, Belgium

Karel Van Acker
Sustainable Assessment of Materials, KU Leuven
Kasteelpark Arenberg 44, 3001 Leuven, Belgium

April 2019

CE Center publication N° 5

Contact information:

Luc Alaerts
manager Policy Research Centre
luc@vlaanderen-circulair.be
+32 16 324 969

Karel Van Acker
promoter Policy Research Centre
karel.vanacker@kuleuven.be
+32 16 321 271

CO_2 mineralisation for sustainable construction materials

Summary

The production of Portland cement (PC) is today responsible for 8-10% of the global anthropogenic CO_2 emissions. PC and PC-based blends are by far the most commonly used binder in concrete production, used in more than 99% of concrete applications. In such concrete, PC is accountable for 74-81% of the CO_2 footprint. Therefore, substantial climate impact reductions for concrete will require eco-innovation at the cement level. Today, many new technologies are being developed to lower the CO_2 emissions from cement and concrete industries. One of the most promising technologies is based on the partial substitution of traditional PC with industrial byproducts displaying cementitious properties, such as blast furnace slag form iron production, or coal combustion fly ashes from power generation. As byproducts, however, their availability and properties are rather constrained. For instance the shutdown of coal-fired electricity production already led to shortages in fly ash, or the increasing recycling of steel will lead to lower production of pig iron and less blast furnace slag. Therefore, future sustainable cements must rely on a wider variety of solutions. A diversification of local (secondary) raw materials to extend partial substitution of PC is ongoing, and new so-called “alternative binders” are taking their first steps into the market.

In the future, the construction materials sector will have to be more **diverse** and more **sustainable**, and at the same time **safe** and **performant**, meeting ambitious environmental and technical standards. Moreover, the production of new construction materials should be tailored to local resources, depending on the kind and availability of secondary raw materials from different industrial plants. In this context, the Intergovernamental Panel on Climate Change considers mineral carbonation as an important option to both mitigate atmospheric greenhouse gas concentrations and to produce sustainable concrete. Among others, a suitable class of materials for carbonation are alkaline slags generated as byproducts from steel production industry. For instance, stainless steel slags (SSS) are a byproduct generated during stainless steel production.

This study analyses the environmental performances of three examples of SSS mineralisation-curing, each using a different source of CO_2:

- flue gas from steel industry, in which CO_2 is separated through cryogenic process
- biogas from anaerobic digestion, in which CO_2 is separated through membranes
- waste gas from ammonia production, in which CO_2 is separated through chemical absorption

The CO_2 recovered from the above mentioned sources is used to produce SSS-based construction blocks that are bound by CO_2 as solid, stable carbonates, and that are equivalent in performance to precast non-reinforced concrete products on the market such as bricks or pavers.

Through an environmental evaluation based on life cycle assessment, the study highlights the environmental hotspots of the new proposed technologies. Taking into account only the

production processes, all the three cases present lower total CO_2-equivalent emissions compared to the paver PC-concrete, reducing the total CO_2-equivalent emissions by 71% in the case of cryogenic separation, by 79% in the case of membrane separation, and 77% in the case of chemical absorption. Beside the reduction of the total CO_2-equivalent emissions during the production, the carbonated blocks present also the advantage to serve as CO_2 uptake and storage material, The final CO_2-equivalent balance (difference between the CO_2-equivalent emitted minus the uptake) is negative for all the analysed technologies (-5.4 kg for cryogenic, -6.8 kg for membrane separation and -6.5 kg for chemical absorption).
Therefore, the environmental results show the potential for the carbonation process to reduce the climate change impact of construction blocks production.

The second part of the study identifies the main environmental, economic and social elements playing a role in the development of the SSS-based carbonated blocks. Some of the main conclusions are listed below:

- Development of a CO_2 valorisation network, both concerning the legal framework and infrastructures
- Need to exploit the economic potential of a CO_2 recovery system
- Need to improve the regional CO_2 balances, by taking into consideration also the effects of inter-regional trade
- Need of a successful certification system, to improve the negative perception of waste-derived materials among consumers

The aim is to provide useful elements in preparing the way for future policy advice, towards the reduction of the CO_2 emissions from the cement and concrete industries and towards the high-quality valorisation of industrial residues.

Introduction

The construction sector is one of the biggest resource consumers and waste producers in our society (Yuan et al., 2012). This sector uses up to 40% of the total raw materials extracted globally and generates about 35% of the world's waste (CMRA, 2005; Schrör, 2011). Hence, the construction industry is a priority sector in the implementation of the circular economy. Sustainable construction practices should strive for a better and higher quality recycling, the use of environmentally friendly materials and for more efficient management of resources.

Concrete is the most consumed among all construction materials (Napolano et al., 2016). Concrete is composed of a proportionated mix of cement, acting as a binder, and fine and coarse aggregates. The most common type of cement is Portland Cement (PC), which consists of a 95-97% of a material called PC-clinker. The PC used in concrete production is the most significant contributor to the overall environmental impact of concrete. Its energy-intensive production process contributes to in between 74 and 81% of the total carbon footprint of concrete (Blankendaal et al. 2014; De Schepper et al. 2014; Flower et al. 2007). The cement industry produces a significant amount of GHGs emissions, and it contributes to 8-10% of the global anthropogenic CO_2 emissions (Hossain et al., 2018; Scrivener and Kirkpatrick, 2008).

According to van Oss and Padovani (2003), the energy consumption during PC production produces an average of 0.48 t CO_2/t clinker, depending on the types and quantities of fuels used. A second essential and inevitable source of CO_2 originates from the calcination of the limestone raw material in the kiln. At temperatures above 900°C, the calcium carbonate $CaCO_3$ contained in the limestone decomposes forming CaO and CO_2, which is released into the atmosphere. van Oss and Padovani (2003) proposed an average calcination emission factor of ≈0.51 t CO_2/t clinker, which is very similar to the one assumed by the Intergovernmental Panel on Climate Change (IPCC). The above-mentioned CO_2 emission factors for energy consumption and calcination represent average values, individual clinker production plants may show significantly different values depending on the operational efficiency, the type of kiln, the locally available raw materials etc. Nevertheless, the average figures highlight the importance of considering the double source of CO_2 emissions during PC clinker production.

A set of actions is therefore undertaken by the cement industry to reduce emissions and other environmental impacts arising during cement production. Improving energy efficiency and switching to alternative fuels, in combination with reducing the clinker content in cement and deploying emerging and innovative technologies like carbon capture and the use of alternative binding materials are the main carbon mitigation methods considered by cement manufacturers.

Today, the use of waste-derived fuels to substitute conventional fossil fuels is common practice in many countries. This practice of coprocessing of waste fuels may reach levels of 85% fuel substitution, thereby proportionally reducing energy CO_2 emissions (Benhelal et al., 2013; Ishak and Hashim, 2015; Pontikes and Snellings, 2014).

The substitution of PC clinker with so-called supplementary cementitious materials (SCM), is considered as the most effective short-term option to lower the carbon footprint of cement production (Habert et al., 2010). SCMs can be simply blended with PC in specific and standardised ratios, reducing the amount of PC required to obtain the desired cementitious properties. Two of the most used SCMs are fly ashes from coal-based electricity production and ground granulated blast furnace slag from pig iron production. However, in view of a continuous reduction of CO_2 emissions from the cement sector, further substitution of PC clinker cannot rely only on an extended use of SCMs, as most of the conventionally accepted SCMs are already entirely used by cement manufacturers. An extension of the range of accepted SCMs to other industrial residues and the development of alternative processes should be further pursued.

Among the alternative processes to produce low carbon cements, the greatest CO_2 reduction potential is offered by cements that actually sequester CO_2 as solid carbonates as part of their solidification process (Biernacki et al., 2017; Gartner and Hirao, 2015). “Carbonate-bonded” construction materials actually mimick their natural limestone counterparts (Benyus, 2002; Lackner et al., 1995). The abundance of limestones in the geological record and their use as traditional building material indicate the potential for long-term durability and preservation of technical quality (Bell, 1993).

The basic concept behind carbonation of Ca(Mg)-silicates is the process of rock weathering. In this natural process calcium and magnesium ions are leached from silicate rocks and react with ambient CO_2 to form solid carbonates.

Direct mineral carbonation is the process in which the extraction of metal ions from Ca/Mg–rich rocks or solid residues and the precipitation of carbonate(s) take place in one process step. It can yield a variety of valuable construction products.

The overall carbonation chemistry in the direct carbonation route using calcium or magnesium silicates is presented in Equation 1:

$$(Ca,Mg)_2SiO_4 + 2CO_2 + H_2O \rightarrow 2(Ca,Mg)CO_3 + SiO_2 + H_2O \qquad (1)$$

The reaction consists of three main subprocesses: (1) the diffusion of CO_2 through the pore network and dissolution of CO_2 in an aqueous solution to form carbonic acid; (2) the dissolution or leaching of calcium and/or magnesium from the silicates in an aqueous solution, and (3) the precipitation of calcium and/or magnesium carbonates (and silica).
In the direct carbonation route steps (1) and (2) occur simultaneously and the rate and extent of carbonation depend on a number of factors such as the precursor composition and moisture saturation degree, but also on the carbonation conditions such as the CO_2 grade and pressure and the relative humidity (RH).

A typical process for direct carbonation of compacts consists of 3 main steps (Figure 1): (1) pre-treatment of the precursors, including mixing and grinding, if required; (2) shaping of the precursor into blocks, e.g. by (hydraulic) compaction; and (3) CO_2 curing in an autoclave (at elevated CO_2 pressure) or in a climate chamber (at low CO_2 pressure). The process requires 4-8 hours to complete.

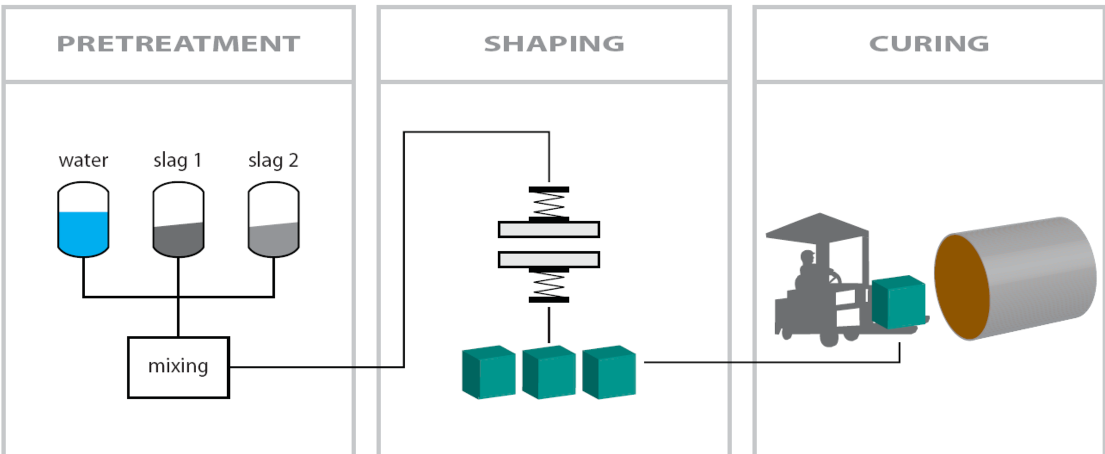

Figure 1:Schematic drawing of the accelerated carbonation process developed for stainless steel slag by Quaghebeur et al. (2015)

Recently, moist carbonation of steel slags was taken to the industrial scale by the DeRuwBouwGroep (DRBG) company for the production of pre-cast building blocks. The products consist of natural sand mixed with fine milled steel slag and are carbonated in a climate chamber at low pressure. The first products were released on the Dutch market early 2017.

Among many materials that are today under investigation for carbonation, stainless steel slag (SSS) presents a high potential to be used as a substitute of PC (Salman et al., 2016). SSS is a residue produced during the stainless steel making process. The SSS consists of a mix of calcium-rich minerals that can be activated chemically to achieve a cementitious properties (Shi and Qian, 2000). Today, for various reasons ranging from material handling, techical specifications to environmental quality SSS have only found application as aggregate.

The goal of this study is to provide an analysis of the opportunities and barriers for a full-scale introduction of SSS carbonation technology at the industrial level. This study represents a first exercise in preparation of a more detailed policy strategy, that will aim at (i) a reduction of CO_2 emissions from the construction material industries, (ii) while at the same time achieving a high-quality recycling of industrial residues.

Using a life cycle assessment (LCA) methodology, this study analyses the environmental costs and benefits deriving from the substitution of traditional PC-based concrete with SSS-based carbonated construction blocks (see also Di Maria et al. (2018) for a more detailed environmental analysis on SSS valorisation). Along with the environmental analysis, the report highlights the environmental and economic driving factors in the development of the carbonation technology.

In the first part, the environmental performances of alternative SSS-based carbonated construction materials are analysed. In particular, three different case studies are considered. The environmental analysis can highlight the environmental hotspots of the carbonation process, helping to increase its sustainability. At the same time, the environmental analysis allows comparing the environmental performances of the carbonated construction materials with the ones of PC-concrete construction blocks. The second part of this document provides useful information for policy makers to promote the aspects contributing to sustainability and to limit the ones creating a barrier.

Environmental analysis of SSS carbonated construction blocks

Three case studies

This report analyses the environmental impact of different CO_2 sources for an industrial SSS carbonation process. The output of the process is a carbonated SSS-based monolith that can be used as construction material, replacing conventional PC concrete based products. The CO_2 used in the analysed process is obtained from three different sources: flue gases from steel plants or waste incineration plants (CO_2 concentrations of 10 to 20% (Mikunda et al., 2015)), from fermenters producing biogas (25-55% CO_2 (Zhang et al., 2013)), and from the ammonia production waste gas (the initial concentration of CO_2 is not declared by the CO_2 producers from ammonia waste streams). In the case studies, a 100% pure CO_2 gas stream was assumed. It should be noted that this purity is not required for the carbonation process. Lowering CO_2 concentrations generally prolongue the process.

In all three cases, the gasses undergo a purification process that concentrates the CO_2 and make the gas suitable for carbonation. The study considers three of the most commonly used processes for carbon dioxide separation and storage:

- *<u>Scenario1:</u> cryogenic process* (in the case of steel flue gas)
- *<u>Scenario 2:</u> membrane separation* (in the case of biogas)
- *<u>Scenario 3:</u> chemical absorpion through monoethanolamine (MEA)* (in the case of ammonia production waste gas).

The main characteristics of each proposed technology are further detailed in the next chapter.

The environmental analysis will help to identify the environmental benefits and hotspots of the use of different CO_2 sources for the carbonation processes. Finally, the environmental performances of the carbonated blocks made with different CO_2 sources are compared to the environmental performances of traditional PC-based concrete used for paving applications, which presents similar characteristics compared with the SSS carbonated blocks. The comparison between carbonated blocks and PC concrete helps to understand the potential environmental benefits derived when substituting traditional PC concrete with SSS-based carbonated blocks.

The LCA methodology is used to assess the environmental impacts of the newly developed carbonated materials from SSS, and to compare these to the environmental impact of equivalent traditional concrete. The study was conducted following the International Standard ISO 14040/44 (International Organization for Standardization, 2006), which describes the principles and framework for conducting and reporting LCA studies (figure 2). The LCA methodology has been extensively described in the literature (see for instance (Finnveden et al., 2009; JRC-IEA, 2010; Pennington et al., 2004; Rebitzer et al., 2004)).

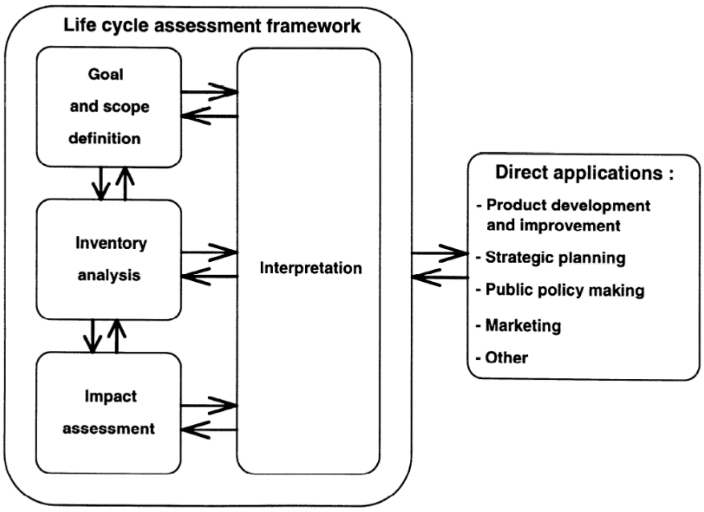

Figure 2: The LCA framework

System boundaries and functional unit of the analysis

The system boundaries of the LCA study are reported in figure 3.

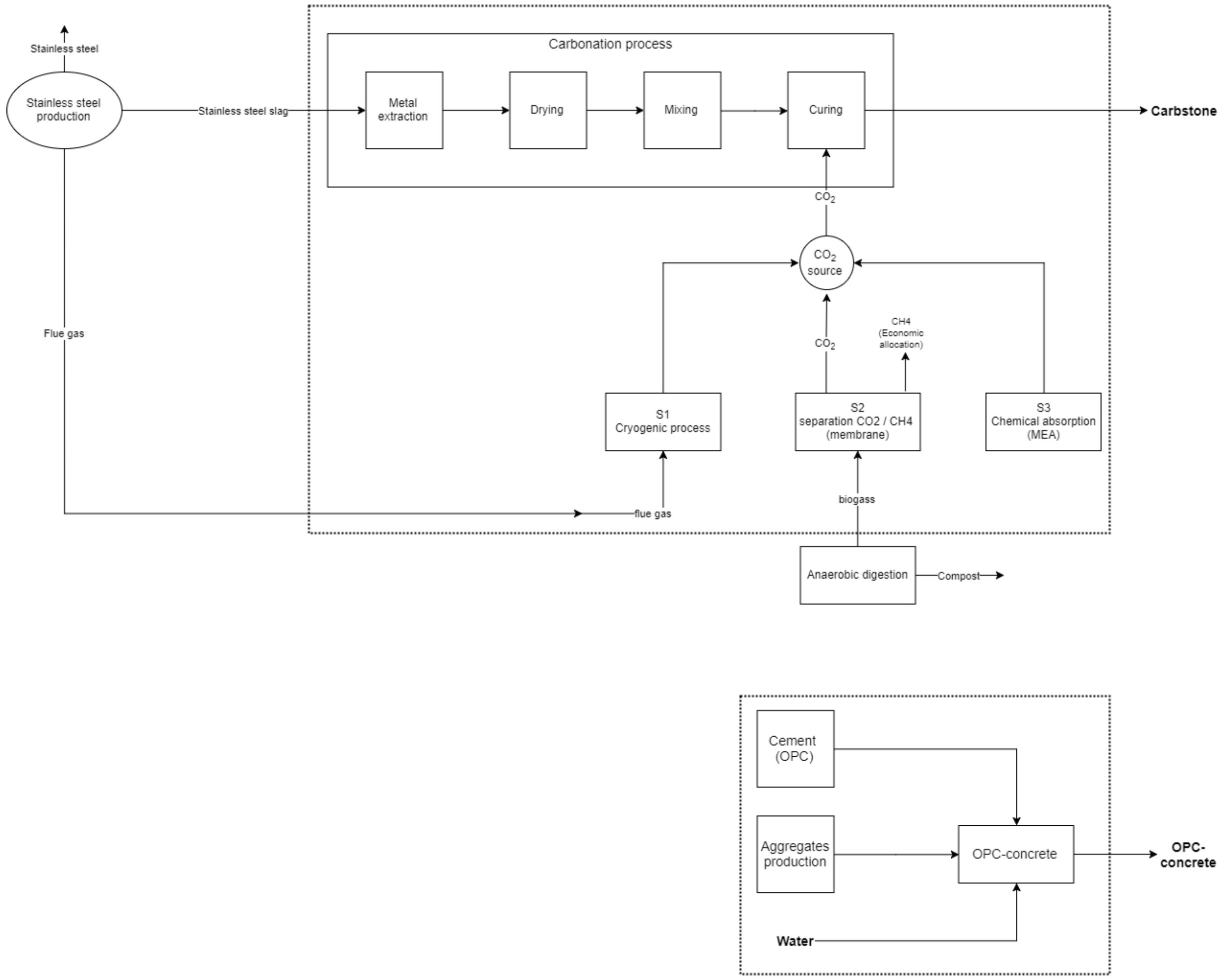

Figure 3: System boundaries considered in the LCA study

The carbonated blocks, also called Carbstone, considered in the study are produced in a carbonation pilot plant operated by DRBG and ORBIX. They present a compressive strength of ca. 40 MPa. For the sake of simplicity, it can be considered that all the carbonated blocks produced in the three cases belong to the same class of application. Therefore they have to provide the same function. The functional unit of the study is represented by the capacity of the construction blocks to provide the same technical performance. As a reference for the functional unit, the LCA will compare the production of 1 m^2 of carbonated blocks with 1 m^2 of paver PC concrete block, presenting a compressive strenght and similar performances. The compared surface is made of 50 blocks, each measuring 20 cm (length), 10 cm (width) and 4 cm (thickness), for a total volume of 800 cm^3 (0.0008 m^3).

Life cycle inventory

Carbonation process

The inventory data for the carbonated blocks production are taken from Garcia-Gonzalez et al., 2016. Before being carbonated, SSS undergoes a metals recovery process. The data on metals recovery is not disclosed, and therefore not included in this analysis. The lack of data on metals recovery can be considered as a limitation of the study. However, the available data on electricity and CO_2 consumption can provide relevant indications on the overall environmental impacts of the carbonation process. The data for the PC paver concrete refer to (Neville, 2012; Ollivier et al., 2012).

In the next paragraphs the three carbon capture technologies considered are described in details. It is assumed that all technologies can produce a 100% pure stream of CO_2, suitable for carbonation (Khoo and Tan, 2006). As reported by Khoo and Tan (2006), the main environmental impact generated by the three technologies is represented by the energy use. Therefore, only the energy use will be considered in the study.

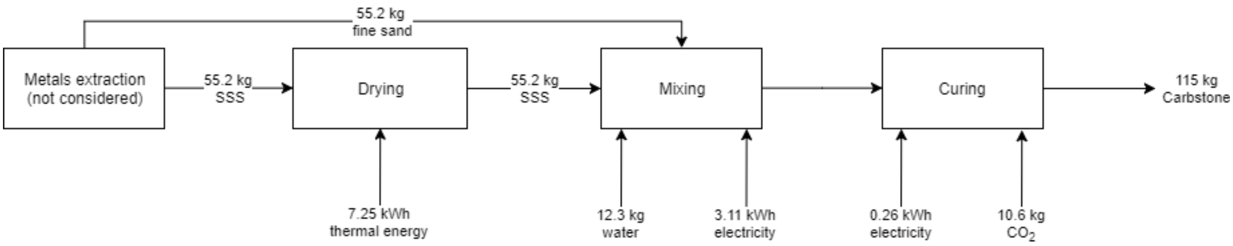

Figure 4: Carbstone production process

S1- Cryogenic separation of CO_2 from flue gas

S1 focuses on the recovery of CO_2 from steel production and waste incineration. Among the different methods currently investigated to reduce the amount of CO_2 released from various industrial plant flue gasses, the S1 focuses on the the cryogenic CO_2 capture. Cryogenic CO_2 capture can remove CO_2 from flue gas in a liquid or solid form that can be readily reused for the carbonation process. In a cryogenic separation system, the CO_2 is separated from other gasses by condensing it at extremely low temperature. The amount of CO_2 recovered ranges between 90-95% of all CO_2 originally contained in the flue gas (Khoo and Tan, 2006). Therefore, the cryogenic CO_2 separation can avoid some shortcomings of other conventional CO_2 separation processes, eliminating water consumption and usage of chemicals. On the other hand, the high energy demand required to keep the process at low temperature, may affect the environmental performance of the cryogenic process. As reported by Khoo and Tan (2006), cryogenic CO_2 separation requires **≈630 kWh** per ton of CO_2 recovered as liquid form.

S2- Membrane separation of CO_2 from Biogas

Membrane separation is a physical process that allows CO_2 to pass through a membrane, while excluding all other gasses. Polymeric gas separation membranes are the most commonly membranes used for this process, with energy demand around **≈75 kWh** per ton of CO_2 recovered, and a removal rate around 82-88% of CO_2 from the biogas. Additionally, as shown in figure 2 for the case of biogas, the membrane separation process produces the double effect of CO_2 removal on one side, and purified biogas (CH_4 concentrated) on the other side. Therefore, when accounting for the environmental impact of CO_2 production through membrane separation, the whole impact of the membrane separation process must be allocated between the two products (CO_2 and purified biogas). According to the ISO 14044 (2006) , allocation in LCA is defined as the partitioning of the inputs/outputs of a multifunctional process between the product system under study and one or more other product systems. The use of market price as allocation criteria is often found in practice. The allocation based on prices is commonly used due to its simplicity and its ability to summarize complex attributes of the different products produced during a multifuncional process. For the current study, the environmental impacts arising from the membrane separation process are allocated between CO_2 and purified biogas according to their market prices. According to Mikunda et al. (2015), the price of purified biogas in 2015 is ≈168 USD/t, while the market price of liquid CO_2 is ≈115 USD/t. Therefore, 41% of the impacts from the membrane separation process are assigned to the CO_2 production, while the 59% are assigned to the purified biogas production.

S3- Chemical absorption of CO_2 (MEA)

Chemical absorption by solvents is the most widely used process for CO_2 removal, while monoethanolamine (MEA) is the most commonly used solvent in this process (Cuéllar-Franca and Azapagic, 2015). The MEA is completely regenerated during the process, but high heat consumption is required to allow the solvent regeneration. Data for the CO_2 chemical absorption considered in this study refers to the dataset described by Althaus et al. (2007) , which represents also the reference process for CO_2 chemical absorbtion in the Ecoinvent 3.3 database. This dataset represents the extraction and purification of CO_2 from an ammonia production waste gas stream. The energy demand is estimated to be **400 kWh** per ton of CO_2 recovered.

Table 1 lists all the inputs and outputs used in the study. All the background processes, referring to the inputs of materials and energy, are modelled using the Ecoinvent database V.3.

Table 1: Inputs of the processes (reference per functional unit)

Carbstone	
Technical properties	
Density (kg/m³)	2300
Weight of functional unit (kg)	115
Carbonation process	
SSS (kg)	55.2
Fine sand (kg)	55.2
CO_2 input (kg)	10.5
Electricity[1] (kWh)	3.37
Thermal energy (kWh)	7.34
Water (kg)	12.3
CO_2 production processes	
S1- Cryogenic separation	
Electricity (kWh)	6.3
S2- Membrane separation	
Electricity (kWh)	0.7
Purified biogas	*59%*
CO_2	*41%*
S3- Chemical absorption	
Electricity (kWh)	4.2

PC-concrete	
Technical properties	
Density (kg/m³)	2600
Weight of functional unit (kg)	130
Production process	
Aggregates (kg)	108
PC (kg)	20
Water	7

[1] *without CO_2 production*

For the electricity, the Belgian mix of 2017 is used, as reported in table 2 (Elia (Belgium's electricity transmission system operator, 2017).

Table 2: Belgian electricity mix 2017 (Elia (Belgium's electricity transmission system operator, 2017)

Source	*%*
Coal	6.1%
Oil	0.3%
Gas	26.5%
Biofuels	4.9%
waste	2.9%
nuclear	46.4%
solar	2.1%
wind	4.0%
other	6.3%

Life cycle impact assessment

The results of the life cycle impact assessment (LCIA) for IPCC_AR5 are reported in figure 5. Since the membrane separation process uses the lowest amount of electricity to produce the CO_2 required for the carbonation process, the S2-membrane separation represents the scenario with the lowest CO_2-equivalent emissions (3.7 kg), followed by the S3-chemical absorption (4 kg) and S1-cryogenic separation (5.1 kg). However, in all three cases, the carbstone presents lower CO_2-equivalent emissions compared to the PC concrete, showing the potential for the carbonation process to reduce the climate change impact of construction blocks production (-71% in the case of cryogenic separation, -79% in the case of membrane separation, and -77% in the case of chemical absorption). It is also important to notice that the amount of CO_2 taken up to produce the carbstone is 10.5 kg (see table 1). The results in figure 5 show that the final CO_2-equivalent balance (difference between the CO_2-equivalent emitted minus the uptake) is negative for all technologies, being -5.4 kg for cryogenic, -6.8 kg for membrane separation and -6.5 kg for chemical absorption. Therefore, the production of Carbstone has the potential to take up a higher amount of CO_2-equivalent than the CO_2-equivalent produced and emitted during the production process.

Looking at the contribution of each single processes, the highest amount of CO_2-equivalent is emitted by the use of fossil fuel (to produce thermal energy). The electricity consumed during CO_2 production has a significant impact only in the case of cryogenic separation (30% of total CO_2-equivalent emitted), while it become less significant for chemical absorption (10%) and membrane separation (only 5%).

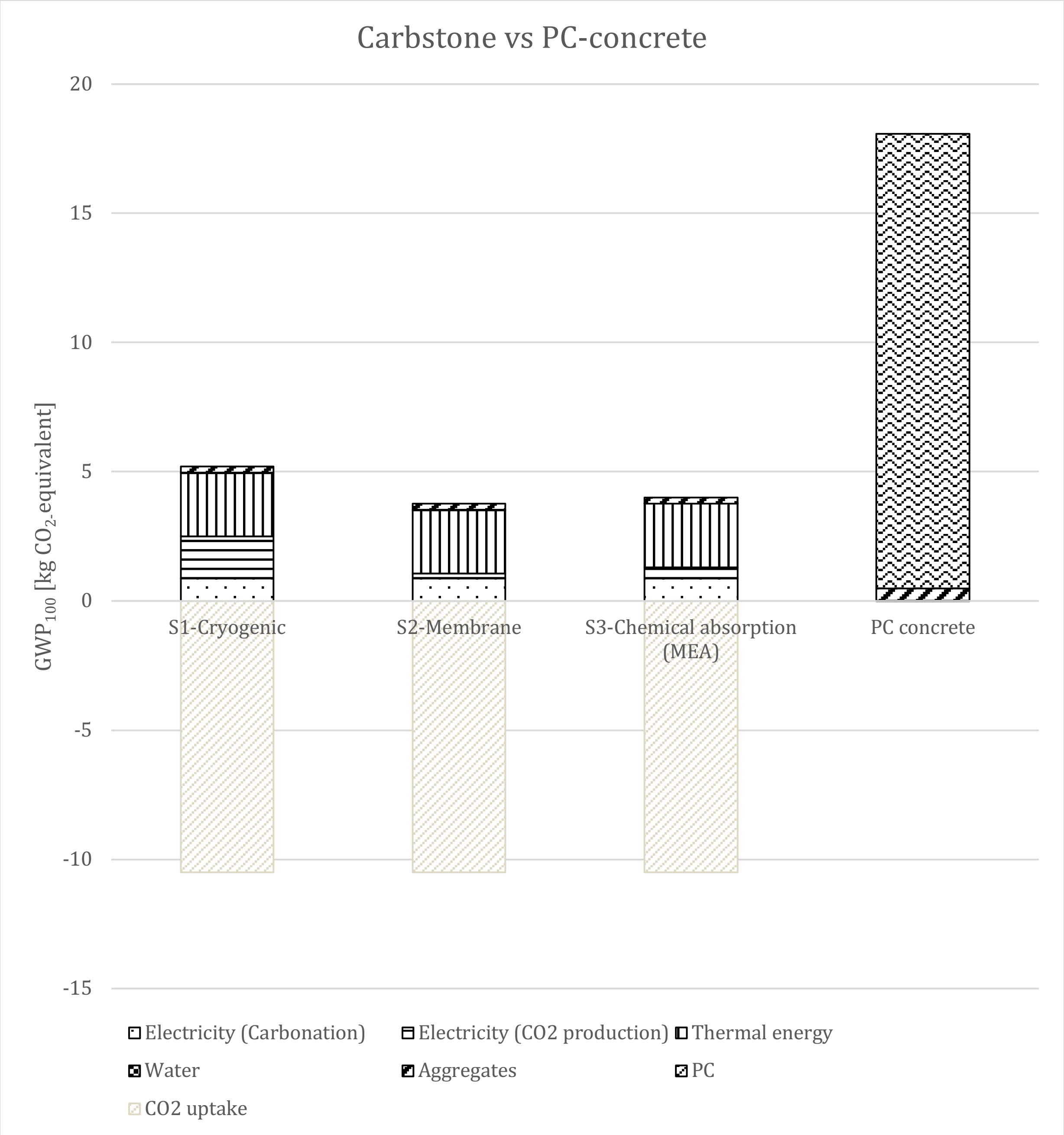

Figure 5: LCA results in terms of CO_2-equivalent

Finally, it is also worth to highlight the limitations of the presented LCA results. A first limitation is represented by the assumptions made to solve the allocation issue. First, an allocation problem arises when deciding what share of the environmental burdens of the the stainless steel production generating the SSS should be allocated to the Carbstones. Following the Waste Framework Directive 2008/98/EC and the recommendations put forth in the ISO 14041, an allocation coefficient should be indeed applied only if the waste can be considered as a byproduct, while no allocation is advised if the waste is considered as an unintended residue. (Iacobescu et al., 2016) reported that SSS does not have the status of a byproduct, because of the uncertainty on its further use as secondary resources. Consequently, SSS is today legally considered as waste material. Therefore, for the LCA presented in this paper, the allocation procedure has been avoided, and no impacts are attributed to the SSS. However, in the future, the carbonation technology is expected to develop, and further applications of an allocation coefficient for SSS may be needed. A second allocation issue arises when considering the membrane separation process to separate CO_2 and purified biogas. In the study, an allocation coefficient based on the market price is applied. As stated by Ardente and Cellura (2012), however, it must be always kept in mind that economic allocation does have limitations, arising for instance from the volatility of prices and from the low correlation between prices and physical flows.

A second limitation arises from the assumption that no CO_2 transport occurs between the CO_2 production source and the carbonation plant. However, transport CO_2 for long distances may affect the final environmental footprint and the economic viability of the carbonation process, as the transport cost for long-distances can reach the 25€-40€ per ton of CO_2 delivered.

A final limitation of the LCA study is represented by the intrinsic limitation of attributional LCA when it comes to industrial decision making and evaluation of industrial symbiosis applications. As clarified by (Marvuglia et al., 2013; Vázquez-Rowe et al., 2013), an attributional approach provides a sound environmental analysis and understanding of the main environmental impacts within the concerned production system. On the other hand, it omits the analysis of potential indirect effects engendered in the markets. Therefore, attributional LCA results provide a good environmental analysis at a product level, which enables a reliable comparison between alternative products. However, an expansion of the analysed system may be required to draw significant conclusions on the environmental consequences of product substitution.

Policy suggestions

The environmental analysis in part 1 of this document has shown the potential environmental benefits of the carbonation process regarding climate change effect reduction. This analysis in itself has already presented some challenges, opportunities and limitations for future development of policy advice. However, this is only a limited part of preparing the way towards the implementation of effective policy actions. A broader outlook on the elements that can play a role in the implementation of the carbonation process is listed below:

- A **CO_2 valorisation network** would need to be developed in order to further support the development of these technologies. Legislative framework and infrastructure should be supported by the public sector, to enable CO_2 stream sharing between neighbour industries. In this sense, the symbiosis network/platform for material streams exchange, already exsisting in Flanders, can serve as a base to the further development of a CO_2 valoriasation network. Finally, to ensure environmental and economic viability of the CO_2 valorisation, long transport distances of the recovered CO_2 should be avoided.

- The construction sector is considered as a key sector for **sustainability**, which can be an opportunity in this context. For instance, the implementation of green certificates based on LCA reports can be an essential asset to increase green public procurements. The **green public procurement** is a powerful tool to drive the whole sector towards sustainable production, as the public sector plays a vital and pioneering role in the market.
- The document "*Guidelines for National Greenhouse Gas Inventories*" (IPCC, 2006) provides methodologies to estimate the anthropogenic CO_2 emissions by source and the removals by sinks at a regional level. However, it accounts only for the emissions produced within a region, ignoring the (beneficial or negative) effects that the implementation of new technologies may also have for other regions. For instance, Flanders produces most of the SSS in Belgium, while Wallonia has most of the PC production. The valorisation of SSS (as well as of other metallurgical slags) may increase the regional CO_2 accounting for Flanders slightly, while potentially decreasing the one for Wallonia significantly. As global warming is a global environmental issue, regional CO_2 balances should take into consideration also the effects of inter-regional trade . An approach to do this is to use the concept of the carbon footprint of the Flemish consumption.
- The production of new construction blocks through carbonation of SSS is a **constrained technology**. In a constrained technology, the production capacity (or supply) is inelastic, as it cannot be adjusted to meet an increase in demand for the product. SSS occurs as a secondary material of stainless steel production. Due to the difference between the price of the stainless steel and the price of the SSS, the production will be driven by the demand for stainless steel rather than the demand for SSS. Consequently, the metallurgic process will be focused on the properties of stainless steel, rather than on the quality and volumes of the SSS. Therefore different compositions of the SSS may affect the efficiency and stability of the production of the carbonated blocks. For an economically attractive waste-to-product scheme, an SSS quality control system must be put in place. Additionally, to make such quality control system also cost efficient, it should also include other metallurgic slags that can be used to produce carbonated blocks. On top of that, the maximum production of carbonated blocks in Flanders will depend on the available quantity of SSS, which is not likely to change due to the development of the carbonation technology. According to data available for 2011, the total production of SSS in Belgium has been 300 kton, while recent data estimates a cement PC production in Belgium of 6500 kton in 2016. PC production can be used as an indirect measure of the use of PC-concrete. It is clear that the carbonated blocks from SSS represent only a small share of the total construction blocks market in Belgium. Therefore, ongoing research is currently undertaken to use other residues, such as concrete demolition waste, incineration ashes, biomass ashes etc. This can strongly expand the volumes of secondary-raw materials available for the carbonation process.
- **Economic potential:** The production of conventional PC concrete requires the extraction of primary raw materials, and it produces a significant amount of CO_2 emissions. However, the price for raw materials extraction is continuously increasing, and available quarries are becoming scarce. Also, the carbon tax for GHGs emissions is increasing, including carbon emissions as a part of the economic competition. On the other hand, the CO_2 production is the most expensive component of the carbonation process. Therefore, creating a CO_2 sharing system can lower the final price of CO_2 and,

consequently, the final price of the carbonated products will strongly stimulate market uptake.

- Many products produced from secondary raw materials struggle with the **perception as waste**. In the general idea of consumers, a product from waste may be thought to have inferior quality, or to contain hazardous compounds. The presence of chromium and other heavy metals in the SSS, for instance, may represent a barrier to the success of the carbonation technology. To overcome the barrier represented by the waste image, a combination of positive communication and scientific research is fundamental, to increase the awareness of customers on the potential use of waste as secondary raw materials. In this regard, a quality certification system for waste material used by the construction sector is already in place in Flanders. A quality certification system can set clear quality requirements both for the final product and for its constituents. The successful implementation of such a system represents a key tool to remove the obstacles to the use of SSS and industrial residues in general, in building products.

Owing to climate change, resource scarcity and the needs to valorise waste streams and secondary resources, carbonation of SSS to produce new construction materials represents a valuable opportunity. This document can help industrial and public policy makers in identifying the main technical, environmental and economic bottlenecks for the further implementation of the carbonation technology.

References

Althaus, H.J., Hischier, R., Osses, M., Primas, A., Jungbluth, N., Chudacoff, M., 2007. Life Cycle Inventories of Chemicals. Final report ecoinvent data v.2.0 No. 8, Ecoinvent report n.8. EMPA, Swiss Centre for Life Cycle Inventories, Dübendorf.

Ardente, F., Cellura, M., 2012. Economic Allocation in Life Cycle Assessment. J. Ind. Ecol. 16, 387–398. https://doi.org/10.1111/j.1530-9290.2011.00434.x

Bell, F.G., 1993. Durability of carbonate rock as building stone with comments on its preservation. Environ. Geol. 21, 187–200. https://doi.org/10.1007/BF00775905

Benhelal, E., Zahedi, G., Shamsaei, E., Bahadori, A., 2013. Global strategies and potentials to curb CO2 emissions in cement industry. J. Clean. Prod. 51, 142–161. https://doi.org/10.1016/j.jclepro.2012.10.049

Benyus, M., 2002. Biomimicry: Innovation Inspired by Nature. William Morrow & Company.

Biernacki, J.J., Bullard, J.W., Sant, G., Brown, K., Glasser, F.P., Jones, S., Ley, T., Livingston, R., Nicoleau, L., Olek, J., Sanchez, F., Shahsavari, R., Stutzman, P.E., Sobolev, K., Prater, T., 2017. Cements in the 21st century: Challenges, perspectives, and opportunities. J. Am. Ceram. Soc. 100, 2746–2773. https://doi.org/10.1111/jace.14948

Blankendaal, T., Schuur, P., Voordijk, H., 2014. Reducing the environmental impact of concrete and asphalt: a scenario approach. J. Clean. Prod. 66, 27–36. http://dx.doi.org/10.1016/j.jclepro.2013.10.012

CMRA, 2005. Construction Materials Recycling Association. Chicago, Illinois.

Cuéllar-Franca, R.M., Azapagic, A., 2015. Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. J. CO2 Util. 9, 82–102. https://doi.org/10.1016/j.jcou.2014.12.001

De Schepper, M., Van den Heede, P., Van Driessche, I., De Belie, N., 2014. Life Cycle Assessment of Completely Recyclable Concrete. Materials 7, 6010–6027. https://doi.org/10.3390/ma7086010

Elia (Belgium's electricity transmission system operator, 2017. Belgium's generating facilities [WWW Document]. URL http://www.elia.be/en/grid-data/power-generation/generating-facilities (accessed 7.17.17).

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in Life Cycle Assessment. J. Environ. Manage. 91, 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018

Flower, D.J.M., Sanjayan, J.G., 2007. Green house gas emissions due to concrete manufacture. Int. J. Life Cycle Assess. 12, 282–288. https://doi.org/10.1065/lca2007.05.327

Gartner, E., Hirao, H., 2015. A review of alternative approaches to the reduction of CO2 emissions associated with the manufacture of the binder phase in concrete. Cem. Concr. Res., Keynote papers from 14th International Congress on the Chemistry of Cement (ICCC 2015) 78, 126–142. https://doi.org/10.1016/j.cemconres.2015.04.012

Habert, G., Billard, C., Rossi, P., Chen, C., Roussel, N., 2010. Cement production technology improvement compared to factor 4 objectives. Cem. Concr. Res. 40, 820–826. https://doi.org/10.1016/j.cemconres.2009.09.031

Hossain, M.U., Poon, C.S., Dong, Y.H., Xuan, D., 2018. Evaluation of environmental impact distribution methods for supplementary cementitious materials. Renew. Sustain. Energy Rev. 82, 597–608. https://doi.org/10.1016/j.rser.2017.09.048

Iacobescu, R.I., Angelopoulos, G.N., Jones, P.T., Bart Blanpain, Pontikes, Y., 2016. Ladle metallurgy stainless steel slag as a raw material in Ordinary Portland Cement production: a possibility for industrial symbiosis. J. Clean. Prod. 112, Part 1, 872–881. https://doi.org/10.1016/j.jclepro.2015.06.006

International Organization for Standardization, 2006. ISO 14040-Environmental management - Life Cycle Assessment - Principles and Framework, International Organization for Standardization. https://doi.org/10.1016/j.ecolind.2011.01.007

Ishak, S.A., Hashim, H., 2015. Low carbon measures for cement plant – a review. J. Clean. Prod., Carbon Emissions Reduction: Policies, Technologies, Monitoring, Assessment and Modeling 103, 260–274. https://doi.org/10.1016/j.jclepro.2014.11.003

JRC-IEA, 2010. International Reference Life Cycle Data System (ILCD) Handbook—General guide for Life Cycle Assessment—Detailed guidance. Publications Office of the European Union, Luxembourg.

Khoo, H.H., Tan, R.B.H., 2006. Life Cycle Investigation of CO2 Recovery and Sequestration. Environ. Sci. Technol. 40, 4016–4024. https://doi.org/10.1021/es051882a

Lackner, K.S., Wendt, C.H., Butt, D.P., Joyce, E.L., Sharp, D.H., 1995. Carbon dioxide disposal in carbonate minerals. Energy 20, 1153–1170. https://doi.org/10.1016/0360-5442(95)00071-N

Marvuglia, A., Benetto, E., Rege, S., Jury, C., 2013. Modelling approaches for consequential life-cycle assessment (C-LCA) of bioenergy: Critical review and proposed framework for biogas production. Renew. Sustain. Energy Rev. 25, 768–781. https://doi.org/10.1016/j.rser.2013.04.031

Mikunda, T., Neele, F., Wilschut, F., Hanegraaf, M., 2015. A secure and affordable CO 2 supply for the Dutch greenhouse sector.

Napolano, L., Menna, C., Graziano, S.F., Asprone, D., D'Amore, M., de Gennaro, R., Dondi, M., 2016. Environmental life cycle assessment of lightweight concrete to support recycled materials selection for sustainable design. Constr. Build. Mater. 119, 370–384. https://doi.org/10.1016/j.conbuildmat.2016.05.042

Neville, A.M., 2012. Properties of concrete, 5th ed. Trans-Atlantic Publications, Inc.

Ollivier, J.P., Torrenti, J.M., Carcasses, M., 2012. Physical Properties of Concrete and Concrete ConstituentsProperties of concrete. Wiley-ISTE.

Pennington, D.W., Potting, J., Finnveden, G., Lindeijer, E., Jolliet, O., Rydberg, T., Rebitzer, G., 2004. Life cycle assessment Part 2: Current impact assessment practice. Environ. Int. 30, 721–739. https://doi.org/10.1016/j.envint.2003.12.009

Pontikes, Y., Snellings, R., 2014. Chapter 16 - Cementitious Binders Incorporating Residues, in: Handbook of Recycling. Elsevier, Boston, pp. 219–229. https://doi.org/10.1016/B978-0-12-396459-5.00016-7

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B.P., Pennington, D.W., 2004. Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. Environ. Int. 30, 701–720. https://doi.org/10.1016/j.envint.2003.11.005

Salman, M., Dubois, M., Maria, A.D., Van Acker, K., Van Balen, K., 2016. Construction Materials from Stainless Steel Slags: Technical Aspects, Environmental Benefits, and Economic Opportunities. J. Ind. Ecol. 20, 854–866. https://doi.org/10.1111/jiec.12314

Schrör, H., 2011. Generation and Treatment of Waste in Europe. Eurostat, European Union, Luxembourg.

Scrivener, K.L., Kirkpatrick, R.J., 2008. Innovation in use and research on cementitious material. Cem. Concr. Res., Special Issue — The 12th International Congress on the Chemistry of Cement. Montreal, Canada, July 8-13 2007 38, 128–136. https://doi.org/10.1016/j.cemconres.2007.09.025

Shi, C., Qian, J., 2000. High performance cementing materials from industrial slags — a review. Resour. Conserv. Recycl. 29, 195–207. https://doi.org/10.1016/S0921-3449(99)00060-9

van Oss, H.G., Padovani, A.C., 2003. Cement Manufacture and the Environment Part II: Environmental Challenges and Opportunities. J. Ind. Ecol. 7, 93–126. https://doi.org/10.1162/108819803766729212

Vázquez-Rowe, I., Rege, S., Marvuglia, A., Thénie, J., Haurie, A., Benetto, E., 2013. Application of three independent consequential LCA approaches to the agricultural sector in Luxembourg. Int. J. Life Cycle Assess. 18, 1593–1604. https://doi.org/10.1007/s11367-013-0604-2

Yuan, H., Chini, A.R., Lu, Y., Shen, L., 2012. A dynamic model for assessing the effects of management strategies on the reduction of construction and demolition waste. Waste Manag. 32, 521–531. http://dx.doi.org/10.1016/j.wasman.2011.11.006

Zhang, Y., Sunarso, J., Liu, S., Wang, R., 2013. Current status and development of membranes for CO2/CH4 separation: A review. Int. J. Greenh. Gas Control 12, 84–107. https://doi.org/10.1016/j.ijggc.2012.10.009

CE CENTER
CIRCULAR
ECONOMY
POLICY RESEARCH
CENTRE

WE MAKE TOMORROW BEAUTIFUL
OVAM

DEPARTMENT OF
ECONOMY
SCIENCE &
INNOVATION

ce-center.be