ENVIRONMENTAL BENEFIT OF REUSING CONCRETE AT BUILDING, COMPONENT AND MATERIAL LEVEL

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Abstract

Concrete is the most used man-made material in the world and the production of concrete is responsible for 8% of global CO_2 emissions. In the Netherlands, 15 million tonnes of concrete waste is generated annually of which only 3% is recycled into the production process of concrete. The intended transition into a circular economy requires efficient use and reuse of materials, components, and products, especially in the building industry. This research provides insight into the potential reduction of the environmental impact of concrete by applying and implementing circularity principles to the concrete industry. Three levels of reuse are identified and assessed on the potential environmental benefits using the Global Warming Potential (CO_2 eq.). Results show a potential environmental impact reduction of 70-95%. Considering the current situation, in which concrete is only frequently reused at the level of its structure, through an extensive renovation or transformation, this indicates big improvements are to be made.

Keywords: *Material circularity; Concrete; Reuse; Recycling; Environmental impact;*

Introduction

Climate change requires the building industry to change fundamentally. It is the ambition of the Dutch government to realise a circular economy before 2050. The circular economy is regarded as an essential part of sustainable development and achieving the goals of the 2015 Paris Climate Agreement. The circular economy is a model advocating efficient use and reuse of resources in closed material cycles, keeping materials at the highest possible value at all times. This means moving away from the linear model, ‘cradle to grave’, in which natural resources are depleted and products are eventually disposed of. In other words, the circular model, ‘cradle to cradle', aims to eliminate waste and prevent primary resources to be extracted (Braungart & McDonough, 2002; Ellen MacArthur Foundation, 2013; Ministry of Infrastructure & Environment & Ministry of Economic Affairs, 2016).

This is particularly relevant for concrete. Concrete is the most used material in the world and the concrete industry is responsible for 8% of global CO_2 emissions. In the Netherlands, concrete makes up 26% of total waste, of which only 3% is reused in the construction industry (Intron, 2006; Lehne & Preston, 2018; Ministry of Infrastructure & Environment & Ministry of Economic Affairs, 2016).

Given the intended transition into a circular economy, the high CO_2 emissions and the low reuse rate of concrete, this research aims to provide a comprehensive insight on improving the current situation. Therefore, this research aims to explore high-value reuse options for concrete, following the principles of circularity, and indicate the potential reduction of CO_2 emission related to reusing concrete. To arrive at the objective, the following research question is formulated;

> *“To what extent can the environmental impact of the concrete industry be reduced by reusing concrete at high-value, within architecture, following the principles of the circular economy?”*

Introducing the research question, it is important to identify the various elements it holds and demarcate the scope of this research.

Environmental impact is used in this paper to describe the negative effect of the concrete industry on the environment. The environmental impact of the concrete industry is predominantly caused by the emission of carbon dioxide (CO_2). The emission of CO_2 and other greenhouse gasses is closely related to the issue of global warming and should be reduced according to the United Nations Sustainable Development Goals. Therefore, in this paper, the reduction of environmental impact entails the reduction of CO_2 or related greenhouse gas emissions. Other categories associated with environmental impact, like resource extraction and water/soil contamination, are not included (Cambridge Dictionary, n.d.; Lehne & Preston, 2018; Ministry of Infrastructure & Environment & Ministry of Economic Affairs, 2016).

High-value reuse is defined as, 'reusing materials at the same, or higher, value as they are initially designed for'. This implies there is no loss of value, and the material can be used and reused endlessly in the circular economy (Ellen MacArthur Foundation, 2013).

As concrete has a wide variety of applications across the construction industry, it is important to note that this paper is predominantly focussed on the use and reuse of concrete within architecture, i.e. the construction of buildings. This demarcation can be made easily when discussing direct reuse of concrete in buildings and building elements. However, this distinction is less straightforward for concrete production and waste generation. Therefore, statistics on both the total concrete industry and concrete in architecture are used interchangeably.

The scope of the research is to investigate the potential reduction of environmental impact as a result of high-value reuse when compared to the conventional production method. Efforts of the current, linear, concrete industry to reduce CO_2 emissions during production, like Carbon Capture technologies and lowering the clinker content in cement, with potential CO_2 reductions of 48% and 37% respectively, will not be discussed any further (IEA & CSI, 2018).

Methodology

To answer the research question, the method that appeared to be the most effective was a combination of a literature study and the execution of interviews.

Literature study has been the primary resource of information upon which this research is built. Reports of renowned research institutions provided information on the concrete industry, circular principles and the status quo regarding the reuse of concrete. The environmental impact reduction indicated in this research is also retrieved from literature. This is based on studies in which a Life Cycle Assessment (LCA) is performed. An LCA is used to conduct a comparative analysis of the environmental impact on several impact categories. This paper focusses on the Global Warming Potential (GWP) category to indicate environmental impact reduction. Global Warming Potential measures the impact of greenhouse gasses on the environment in carbon dioxide equivalents (CO_2 eq.). This means the impact of greenhouse gasses like methane (CH_4), carbon oxide (CO), nitrogen oxide (N_2O) are converted to the impact of CO_2 (Lee & Inaba, 2004).

In addition to literature, a series of interviews have been conducted during the preliminary phases of the research. Visits to the annual event of the Dutch concrete sector, a research lab at the TU Delft and a construction company engaged in the recycling of concrete, provided an inventory of ongoing processes and developments. During the visits, experts explained basic principles of concrete production, related chemical reactions and key material properties in the interest of this research.

Structure

This paper is structured in four sections. The first section provides background information on concrete as a construction material, its production process and gives insight into the relevant material properties. The subsequent section presents the principles of circularity and places the circular economy in the context of sustainable development. Section one and two outline the conditions and context in which the research is performed. Section 3 presents the main part of this research, the individual assessment of the three levels of high-value reuse of concrete and indicates the related environmental benefit. This is followed by a discussion in which a strategy is presented incorporating the findings of the research into the architectural context. The paper is concluded with a summary of the findings, the contributions of this research and a suggestion for further research.

1. Background

This section provides background information on concrete as a construction material, outlining the context of this paper. This includes statistics on the use of concrete and principles regarding the production process and material properties.

Status quo

Concrete is the most used man-made material in the world, totalling around 10 billion tonnes every year. Concrete is a composite material comprising aggregates, cement, and water, and is used for a wide variety of applications across the construction industry. Concrete has many beneficial characteristics; it is known for its durability, strength, ease of use, aesthetics, formability, low costs and wide availability of resources. However, there is a downside; the concrete industry is responsible for 8% of global CO_2 emissions (Lehne & Preston, 2018).

Despite the negative impact of concrete on the environment, its use is expected to grow even further (IEA & CSI, 2018). To get an indication of how much concrete is going to be used, Bill Gates provides us with a revealing insight on the scale of concrete use:

> *"The world will add 2 trillion square feet of buildings by 2060 — the equivalent of putting up another New York City every month for the next 40 years." (Gates, 2019)*

In the Netherlands, concrete use has been relatively stable for years, totalling around 14 – 15 million cubic meters annually (33 – 36 million tonnes) (CE Delft, 2013a; Kerkhoven, 2019).

Ingredients & production process

As mentioned, concrete is a composite material, containing aggregates, cement, and water. On average, a cubic meter concrete in the Netherlands is mixed in the following ratio:

Aggregates	75 - 80 %	1900 kg / m³
Cement	12 - 15 %	360 kg / m³
Water	6 – 8 %	180 kg / m³

The exact composition will vary according to its application and strength requirements (CE Delft, 2013a).

Aggregates are inert materials like gravel, rock or sand. A distinction is made between coarse and fine aggregates, respectively gravel and sand. The proper selection of aggregates and the manipulation of their size distribution is very important when aiming to develop high-quality concrete (de Brito & Saikia, 2013). This size distribution is indicated by aggregate packing. Aggregate packing can be explained as the degree in which the shapes of the aggregates complement each other. For this principle the rule applies; the tighter the aggregates are packed together, the more grip and internal force is executed, resulting in increased compressive strength. Furthermore, a higher packing degree means smaller gaps in between the sand and gravel fractions and reduces the amount of cement required to bind the concrete (IPG, 2015).

Cement is a finely milled mineral powder and functions as the binding component in concrete. When mixed with water, cement serves as an adhesive to bind the aggregates and form concrete (Heidelberg, 2019). Portland cement is used in 98% of concrete globally and the production of Portland clinker, the main component of Portland cement, accounts for 95% of the environmental impact of concrete (CE Delft, 2013a; Lehne & Preston, 2018). This Portland clinker is created by heating finely ground limestone, clay, and marl to 1450 degrees Celsius. During this process, several chemical reactions take place, giving clinker its characteristic hydraulic properties. The calcination process of limestone is vital in understanding the high CO_2 emissions.

Chemical reaction of the calcination process:

$$\boldsymbol{CaCO_3 \xrightarrow{1450\,^oC} CaO + CO_2}$$

$$100 \quad : \quad 56 \quad : \quad 44$$

As this reaction demonstrates, an enormous amount of CO_2 is generated during this process. These emissions add up to the emissions generated during the burning of fossil fuel to power the cement kiln, transportation, and electricity (Appendix, figure 2). As a result, the production of 1 ton of Portland cement generates, on average, 0,93 tonnes of CO_2 (Lehne & Preston, 2018).

Next to Portland cement, there are so-called composite cements, in which a portion of the clinker is replaced by alternative raw materials, such as fly ash, furnace slag, or limestone. Cement types are classified according to their composition and early and final strength. Clinker content is the determining factor in distinguishing different cement compositions. The cement types are indicated by the letter combination CEM (cement) followed by a Roman numeral (I – V). Regulations regarding the cement compositions are established in NEN–EN 197-1:2011 (see appendix, figure 2) (Betonhuis, 2019a; CEN, 2011; Heidelberg, 2019).

As the production of Portland clinker generates the majority of CO_2 emission of cement, clinker content determines largely the environmental impact of the cement types (appendix, figure 3 & 4). The Netherlands is the frontrunner in the use of cements with low clinker content. 55% of cement used in the Netherlands is slag cement (CEM III), 35% Portland cement (CEM I) and the remaining 10% is generally CEM II (Betonhuis, 2019b; ENCI, 2017; TNO, 2018). The widespread use of low clinker cements in the Netherlands can be explained by the fact that the steel-producing facility (former Koninklijke Hoogovens; now TATA) and the cement-producing facility (former CEMIJ; now ENCI) in IJmuiden have collaborated since the 1930s, into processing the blast furnace slag into making slag cement (Heerding, 1971). As a result, an average ton of cement used in the Netherlands generates 0,6 tonnes of CO_2.

A diagram showing the complete life cycle of concrete is included in the appendix, figure 1. This diagram shows all key steps in the concrete production process as well as the desired reuse options end-of-life concrete.

Concrete properties

The next section will focus on the hydration process and strength development of concrete. The terms and chemical processes mentioned give concrete its characteristics and are of importance when discussing the recycling of cement.

The totality of changes occurring when cement is mixed with water is called the hydration process. The main result of this reaction is the formation of calcium silicate hydrate, CHS, also referred to as cement paste or hydrated cement. The hydration degree is the fraction of hydrated cement to that of the initial unhydrated cement in the paste. The ratio in which water is added to cement, the so-called w/c-ratio, determines the degree to which anhydrous cement reacts with water (appendix, figure 5) (Betoniek, 1983; Chen, 2006).

Strength development of concrete is closely related to the phases of clinker. The four major phases of clinker are alite (50-70%), belite (15-30%), aluminate (5-10%) and ferrite (5-15%). When mixed with water, two phases, alite and belite, contribute to the strength development in concrete but do so at different rates (appendix, figure 6). Therefore, the alite and belite content determines the strength developing properties of cement (Taylor, 1997).

Alite is the most important constituent of normal Portland clinker. Alite, tricalcium silicate (Ca_3SiO_5 or C3S) reacts relatively quickly with water and is responsible for the early strength of concrete (Taylor, 1997). During construction, early strength determines when formwork or, in case of prefabricated elements, castings can be removed safely. Portland cement does have the highest C2S content resulting in the highest early strength and is therefore preferred in applications when a fast production rate is desired. In the Netherlands Portland cement (CEM I) is predominantly used in the production of prefabricated concrete components (CE Delft, 2013a).

Belite, dicalcium silicate (Ca_2SiO_4 or C2S) reacts very slow with water and contributes only to the final strength of concrete. The alternative components of the composite cements usually have a certain amount of belite, and are therefore considered to have cementitious properties (Taylor, 1997). The differences in clinker content, and thereby alite content, determine largely the strength developing properties of the cement types (appendix, figure 7).

2. Circularity

There are countless definitions of circularity and the circular economy as the economic system built around it. This research adopts the principles as defined by the Ellen MacArthur Foundation, as they provide the most renowned definition (Geissdoerfer et al., 2017).

Circularity refers to ‘the use and reuse of resources in closed material cycles, aiming to keep products, components, and materials in use, at the highest possible value, for as long as possible, through maintenance, reuse, refurbishment and ultimately recycling’ (Ellen MacArthur Foundation, 2013, 2015; Webster, 2015).

The model of circular economy differentiates between two types of material cycles; technical and biological material cycles. Biological materials are designed to re-enter the biosphere safely and built natural capital after use. Technical material cycles are man-made products, designed to circulate at high quality without entering the biosphere. These material cycles are visualised in the ‘Circular Economy System Diagram’ (appendix, figure 8) (Braungart & McDonough, 2002; Ellen MacArthur Foundation, 2013).

Important principles to address, regarding the ‘Circular Economy System Diagram’, are referred to as ‘the power of the inner circle’ and ‘the power of circling longer’:

‘The power of the inner circle’ refers to the level on which the material is reused. The inner-circle represents a more direct form of reuse, implying larger savings in embedded costs in terms of material, labour, energy, capital, and related environmental impact. In general, materials can be reused on three levels, the product, component, and material level.

The other principle, ‘the power of circling longer’, is about the time spent within the circular economy. The longer products, components and materials are kept in use, virgin material inflows are prevented, while simultaneously distributing the initial impact on the environment over al longer period (Ellen MacArthur Foundation, 2013).

Relation sustainability and circularity

Sustainability and circularity are often referred to in the same context, but the relationship between the concepts has not been made explicit in literature, which undermines the efficacy of using the approaches in research and practice. “Circularity contributes to a more sustainable world, but not all sustainability initiatives contribute to circularity. Circularity focuses on resource cycles, while sustainability is more broadly related to people, the planet and the economy.” (Het Groene Brein, n.d.) People, planet, and profit are considered the three pillars of sustainable development, also referred to as the Triple Bottom Line (TBL). “After the World Summit in 2002, the triple bottom line has been referred to as the balanced integration of economic, environmental and social performance” (Geissdoerfer et al., 2017). This paper aims to get insight in the potential reduction of the environmental impact of concrete by incorporating circular principles. Therefore, circularity is the medium contributing to the final goal of realising a more sustainable world.

3. Reuse of concrete

The main part of this research is the assessment of high-value reuse options of concrete. As concrete is a manufactured material, it belongs to the technical material cycle. For concrete used in buildings, the three general levels of reuse in the circular economy can be converted to the following reuse levels; reuse of the concrete structure of a building as a whole,

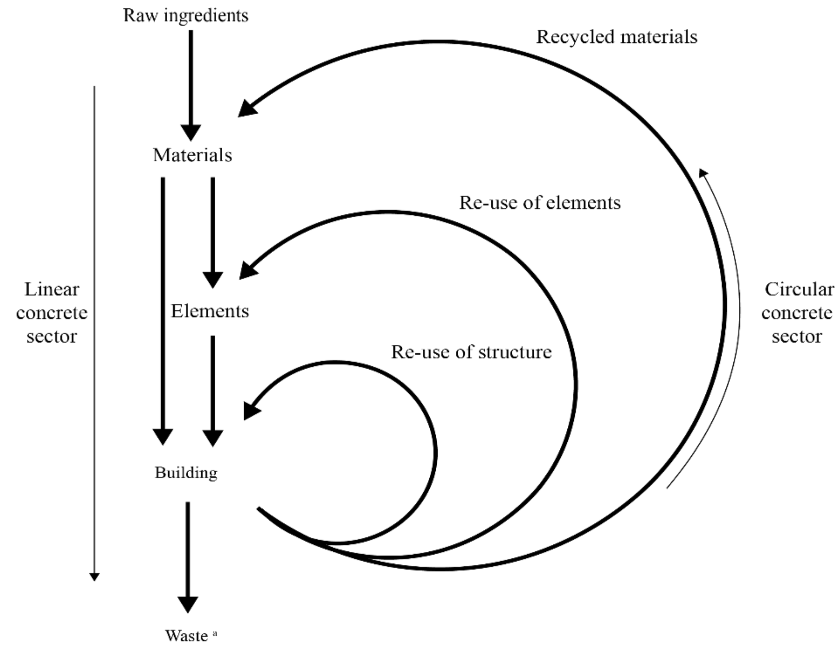

Figure 1. Towards a circular concrete industry. Three levels of concrete reuse relative to the linear concrete sector.

reuse of concrete elements and the use of concrete out of recycled materials. Figure 1 shows these levels in a scheme, derived from the principles of the 'Circular Economy System Diagram' (Addis, 2006; Ellen MacArthur Foundation, 2013).

As mentioned earlier, the potential environmental benefit is indicated using the GWP retrieved from an LCA. To get an accurate indication of potential environmental benefit for each of the reuse levels, a specific LCA is studied, comparing the conventional method of the linear concrete industry with the reuse alternative, corresponding to the relevant reuse cycle. The outermost cycle, the use of concrete out of recycled materials, will be discussed in greater depth relative to the other cycles, as this step is considered crucial into closing the material cycle of concrete, and therefore making concrete a circular material.

Each of the reuse cycles will be assessed according to a set format. comprising respectively *the definition, the status quo, concept (of innovation), potential environmental benefit, limitations, and evaluation.*

3.1 Reuse of concrete structures

The first reuse cycle to be discussed is the reuse of concrete structures. This is represented by the most inner cycle in figure 1 and is, therefore, the most direct type of reuse of concrete discussed in this paper. Consequential, the biggest reduction of environmental impact can be expected.

Definition

Reuse of a concrete structure is defined as 'prolonging the lifespan of a concrete structure, in-situ, by maintenance, reparation or adaptation'. Prolonging the lifespan of a building implies a longer service life, spreading the initial carbon emissions over a longer period of time, decreasing the overall impact of the structure. In practice, prolonging the lifespan of a concrete structure is a result of an extensive renovation, or transformation (Ellen MacArthur Foundation, 2013).

Status quo

In the Netherlands, the amount of square meters of transformed office buildings has been increasing for years, to a total of almost one million square meters in 2016 (appendix, figure 9) (Jensen et al., 2019). Furthermore, the Dutch government estimates 15% of the one million homes required in the Netherlands will be realised as a result of the transformation of a building (RVO, n.d.). Based on these numbers can be concluded that the reuse of concrete structures is already implemented into the field of architecture.

Principle

A standard office building in the Netherlands has an average functional lifespan of 30 years, but the structures are designed to last at least 50 years, and a renovation increases this to around 80 years. Furthermore, the concrete elements comprising the structure have an expected lifespan of at least 200 years (Naber, 2012; TNO, 2018). Prolonging the lifespan of a structure for as long as possible can be interpreted as closing the gap between the functional and the technical lifespan, while simultaneously extending the technical lifespan. In case a building is considered to be demolished, as a result of vacancy or not meeting the required standards, a decision is to be made; prolong the existing structure, or demolition and new construction.

Potential environmental benefits

An LCA performed in a recent study found that the GWP of concrete in a renovation project is reduced by 95% when compared to new construction. This can be explained by the fact that most concrete, the structure, remains untouched and only requires maintenance and reparations. Furthermore, the overall GWP of a renovation project compared to new construction is reduced by 75% (appendix, figure 10 & 11)(Hasik et al., 2019).

Limitations

Criteria in determining whether a building or structure can be transformed or renovated, are of physical, economic, social and functional nature (Langston et al., 2012). Among the most decisive criteria are;

The technical lifespan is determined by the structural integrity, the quality of the existing structure. The condition of the structure is largely dependent on the quality of the initial concrete used, an inferior concrete will have a higher chance of deterioration in early phases and a shorter lifespan as a result. (Naik & Kumar, 2003).

The location of the structure is also of great importance in determining the success probability of a transformation. If the building is at an undesired location and there are no possible users it is very unlikely the building will be transformed and demolition may seem inevitable (Langston et al., 2012).

Evaluation

As the number of transformation projects is growing and the limitations are well indicated, the reuse of concrete structures has good potential. The major reduction of the environmental impact of renovation compared to new construction is a strong argument in favour of prolonging the lifespan of a concrete structure for as long as possible.

3.2 Reuse of concrete elements

The second cycle to be discussed is the direct reuse of concrete elements.

Definition

Reuse of concrete elements is defined as, the direct reuse of an element that has been removed from one building, refurbished or reconditioned, and reused in a different building (Addis, 2006).

Status quo

There is no literature available regarding the direct reuse of concrete elements retrieved form buildings. Therefore, we need to have a look at the statistics about the reuse of building materials in general. In recent years investments have been made in setting up material marketplaces, where used materials and building components are sold. Statistics show that total sales were limited to €200.000,-, in an industry worth around 6 billion euros, indicating that building with retrieved elements or components is just a niche market at the moment (Lukkes, 2018; Slager & Jansen, 2018).

Concept of innovation

A concept promoting the application of used building components is urban mining. The principle of urban mining is to see urban areas as potential material mines, where elements and components can be harvested and reused to make new buildings. In the process of urban mining several phases are distinguished; inventorying, harvesting and distributing (Lukkes, 2018).

During the inventorying phase is the availability and reusability of building components determined. Harvesting comprises the recovering of elements from buildings and processing them to reusable conditions. Instead of demolishing a concrete structure entirely, the reusable elements are removed carefully. The final phase, the distribution of the retrieved elements, is a logistical challenge. Distributing comprises transportation, storage and selling the elements (Lukkes, 2018; Naber, 2012).

Potential environmental benefit

From a material point of view, the direct reuse of concrete elements has almost the same potential environmental benefit as the reuse of a structure as a whole, since the use of new cement is prevented. However, the energy related to retrieving the concrete elements from a building, processing and refurbishing them and transportation decrease the reduction of the environmental impact. The GWP of a retrieved concrete element shows a reduction of 80% when compared to a similar concrete element from primary resources. However, this 80% reduction is based on a transportation distance of only 2km. In addition, an LCA comparing the GWP of a complete building process with used materials to a process using new materials found a reduction of the environmental impact of 35%. Reusing the element in consecutive cycles reduces the impact even further, reusing an element twice increases the reduction to 55% (kg CO_2 / kg) (Appendix, figure 12) (Glias et al., 2014; Naber, 2012; van Nunen, 1999).

Limitations

The process of harvesting concrete elements from a structure is considered to be difficult if it is not designed for deconstruction. Especially reinforced concrete structures are hard to dismantle. Jointing of prefabricated concrete elements is often done using cement, making it hard to reuse (Kanters, 2018). Similar to the reuse of a concrete structure as a whole, the quality of the existing concrete is vital in determining the reusability. This requires specific expertise. And if the concrete elements can be retrieved and reused, there are several big logistical challenges. Planning of deconstruction and new construction should be aligned to a great extent, to ensure the elements arrive at the construction site at the right moment. This could be resolved by separating the moment of harvesting and new construction, requiring large storage sites for the retrieved elements to be stored. Furthermore, if components are stored at a storage facility without a direct reuse destination, extensive information about the object is required. This demands for a classification system, in which the possible applications of the elements are determined. At the moment, there is no clear overview of what elements are available and in what quantities, limiting the retrieved elements to be considered during the design phase. (Lukkes, 2018).

Evaluation

The concept of urban mining and the reuse of concrete elements in construction projects is still in its developing phases. In order to be considered a valid option and gain market share a lot of logistical challenges have to be resolved. At the moment there are too many uncertainties to allow for a widespread reuse sue concrete elements.

3.3 Reuse of concrete materials

The last reuse cycle, discussed in this paper, is recycling end-of-life concrete into its initial ingredients. As this is the outer most cycle of reusing concrete this level is vital in keeping concrete materials inside the circular system.

Definition

Reuse of concrete materials is defined as the use of concrete out of recycled resources. This implies concrete to be fully made from recycled resources. Therefore, these resources are required to have the same, or better functional properties as the initial resources, as discussed in section 1 of this paper (Schepper, 2014).

Status quo

In 2018, the Netherlands generated 15 million tonnes of concrete waste. 95% of this waste is recycled and reused, although this seems impressive, reality shows the majority (>85%) is used as base material in road construction. This means a substantial loss of value. Only 3% of concrete is recycled and reused for construction purposes. The recycled concrete is reused as aggregate, not as a replacement of cement. Therefore, the related environmental impact is negligible (Knoeri et al., 2013). Moreover, the volume of concrete waste is expected to grow to 22 million tonnes by 2025, and demand for base material in road construction is expected to decrease as a result of a limited amount of road construction projects. All these factors contribute to the necessity of finding an alternative, high-value, reuse and recycling method for concrete waste. (Intron, 2006; Ministry of Infrastructure & Environment & Ministry of Economic Affairs, 2016)

Concept of innovation

The challenge of achieving completely recyclable concrete can be divided into two main challenges, namely the challenge of separating concrete waste into its original ingredients after crushing, and once separated, reactivating the hydrated cement paste turning it into anhydrous cement (Schepper, 2014).

In 2015, an Interdisciplinary Project Group (IPG) at the TU Delft and Leiden University researched the efforts of closing the material cycle for concrete. As a result, two technologies are identified as most promising in achieving a circular concrete industry. These technologies, C2CA and Smart Crusher technology, differ in approach and both will be briefly discussed (IPG, 2015).

C2CA – technology

C2CA (Concrete to Cement & Aggregates) is a technology developed by 14 different partners across the concrete industry and the University of Technology Delft. C2CA is focused on producing high quality aggregates to be reused in concrete as coarse or filler fraction. C2CA uses advanced sensor technologies to separate concrete rubble into different size fractions. After separation, the fraction of ultra fines (< 0,2mm) is heated to around 500 degrees Celsius. This process gives the ultra fines *cementitious* properties, allowing it to be mixed into the cement composition to up to 10%. The process is concluded by a quality check, a Laser Induced Breakdown Spectroscopy, LIBS, detects contaminants and monitors the quality output streams. The setup in which advanced technologies work together is promising. However, C2CA is not focused on the complete recycling of cement and therefore the reduction of the environmental impact is limited (Gebremariam,2019; IPG, 2015; Lotfi, 2016).

Conventionally concrete is crushed with a jaw crusher, operating at a compressive force of 400 MPa, exceeding the compressive strength of the individual concrete components. As a result, not only the composite bonds of the hydrated cement are crushed, but also the aggregates and cement itself. This results in high levels of silica (SiO_2) in the fraction of ultra fines, liming the recyclability of cement. (Florea et al., 2012).

Smart Crusher technology

The Smart Crusher technology is focused on recovering and separating all the initial ingredients of concrete, including cement. The Smart Crusher crushes concrete in an innovative way, based on the difference in compressive strength of the bonds created by the hydrated cement (15 MPa) and the individual components of concrete (>200 MPa.). The Smart Crusher crushes concrete using two counter-rotating elements, applying a force of around 40 MPa, only breaking the bonds of the hydrated cement. Separating the different size fractions is executed by a series of sieves and as a result, the initial gravel, sand and cement fraction are retrieved. Tests have shown the aggregate fraction, gravel as well as sand, to be of a higher quality than aggregates from primary resources. Due to little scratches on the surface of the particles, aggregate packing and internal force is increased (Schenk & Schippers, 2018; Schenk, 2019; Hiskemuller van der Zijden, 2019).

The maximum hydration degree indicates that in all concrete there is a share of unreacted cement. Tests show this share to be 30 – 40 %, which means that from one tonne of end-of-life concrete 60 kg of unhydrated cement can be extracted. It is this unhydrated cement that is of great interest, as this has not reacted with water, it can directly be reused once isolated. (IPG, 2015; Schenk, 2019). Separating the hydrated cement from the unhydrated cement can be done using a wind sifter, based on the difference in volumetric mass.

The share of hydrated cement can be recycled in serval ways. Firstly, the hydrated cement can directly be used as filler in the concrete mixture, reducing the amount of cement needed by a relatively small amount. Secondly, after a dehydration process, heating the hydrated cement to 500ºC, the formation of high levels of belite is demonstrated. This means cementitious properties have formed, and the dehydrated cement can be used as a (partial) replacement of fly-ash or furnace slag, creating so-called CHS-cement, referring to the hydrated cement this cement originates from (CE Delft, 2013b; De Schepper et al., 2014; Schenk & Schippers, 2018).

And finally, the hydrated cement can be used as a CO_2-free resource to produce Portland cement. The latter option is the most interesting because this implies creating conventional Portland cement without harmful CO_2 emissions. So far tests have proved pure hydrated Portland cement can be fully reactivated by heating it to 1450 degrees Celsius, as is done in the initial production process of cement. Ongoing tests are investigating to which extent alternative cement composites and contaminants, as a result of crushing, are influencing recovered cement to be reactivated. These tests are currently performed at the Catholic University of Leuven, using an innovative microwave technology, requiring only 30% of the energy compared to the fossil fuel powered cement kiln (Dilissen et al., 2019; IPG, 2015; Schenk & Schippers, 2018).

Potential environmental benefits

The Life Cycle Assessment used to determine the environmental benefit of using concrete out of recycled resources show a reduction in GWP of 70% when compared to conventional concrete production. In another LCA performed by the IPG comparing concrete recycled with the Smart Crusher this reduction even increases to 75% (IPG, 2015; Schepper, 2014).

Limitations

It is very unlikely that 100% of the unhydrated cement can be extracted from end-of-life concrete, further development regarding the separation technologies is required. Improving the efficiency of extracting the cement fraction could mean a substantial share of unhydrated cement can be directly reused (IPG, 2015).

At the moment, the Smart Crusher lacks strong backup from parties in the concrete industry. C2CA does have this industry backing, as it originated from a collaboration between industry partners and universities. As a result, the Smart Crusher technology has very high interest but substantially lower power than C2CA (IPG, 2015).

Furthermore, there is only one full-scale Smart Crusher installation in operation, which has a recycling capacity of 150,000 tonnes annually. In order to have a substantial impact, this should be drastically increased. This requires upscaling, both in recycling capacity and recycling locations. Recycling locations are of importance as this decreases the transportation distance, and related environmental impact, and increases the overall reach of the technology. (Hiskemuller van der Zijden, 2019)

Evaluation

The potential of the Smart Crusher technology is promising. At the moment, concrete made with CEM I, thus with a high Portland cement content can be 100% recycled into new concrete. This is done by combining the unhydrated share of cement, 30-40%, with the dehydrated cement with cementitious properties. This creates a new cement type, CHS cement. This cement can then be mixed with the recycled aggregates and water to form completely recycled concrete.

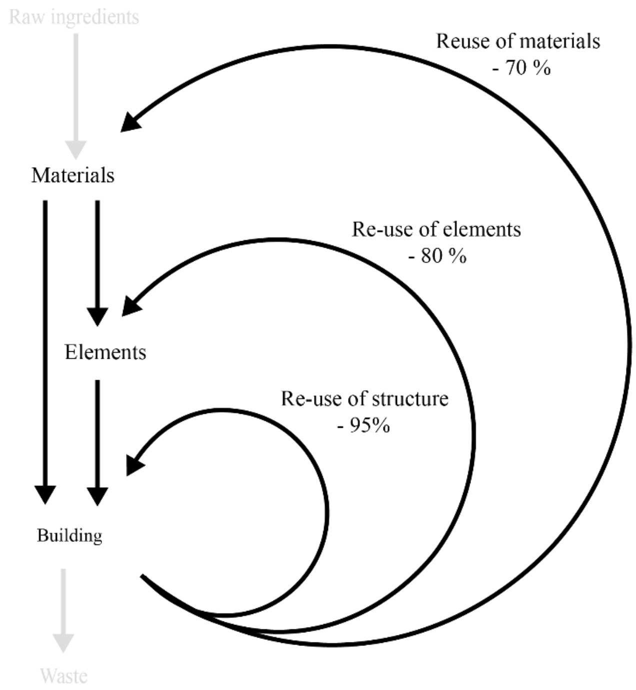

Figure 2. Environmental benefit of reusing concrete at three value levels (GWP)

Conclusion reuse of concrete

Figure 2 shows the results of this research section. The results support the key principle of 'the power of the inner cycle', by showing a substantial difference in environmental impact reduction from the inner cycle going outwards. The reuse levels already show a significant difference in the potential reduction of environmental impact, however, these differences will be even bigger in practice. The reductions indicated in this research are the result of the GWP comparison of the conventional linear method of versus the reuse alternative, up to the level discussed. This means the environmental impact related to the further processing of concrete up to the functional building level, is not taken into account yet. Additional impact related to processing and transporting the reused elements and materials will predominantly cause the differences in environmental benefit to be amplified (Ellen MacArthur Foundation, 2013; Naber, 2012).

4. Discussion; Circular concrete

This section provides a strategy regarding the use and reuse of concrete in accordance with the findings presented above. As the previous section proved the principle of 'the power of the inner cycle', this strategy is focussed on the other principle 'the power of cycling longer' and keeping concrete inside the circular economy as long as possible.

1. Reduce the amount of concrete used

As mentioned, concrete is currently the most used man-made material in the world. The high CO_2 emissions are predominantly a result of the enormous scale on which concrete is used today. Concrete demand can be reduced, sometimes by more than 50 per cent, by taking a new approach to design, using higher quality concretes, substituting concrete for other materials, improving the efficiency with which it is used on construction sites, and increasing the share of concrete that is reused and recycled (Lehne & Preston, 2018).

2. Prolong the life span of buildings (& its components)

Premature demolition is often the imminent consequence of vacancy, and thus the loss of functionality (Lukkes, 2018). To prevent demolition and maximise the lifespan of buildings, this means functionality loss has to be prevented. Functional flexibility, technical adaptability, and human appreciation are three determining factors in regard to maximising functional lifespan of buildings (Schilperoort, 2017).

Functional flexibility makes a building less dependent on the type of use. Flexible buildings can accommodate several functions, without the requirement of an extensive transformation. The principles of 'open building' and the separation of 'support and infill', are principles allowing for an efficient interchange of functions. The potential of a building to be transformed according to these principles are mostly depending on its location, spatial organisation, and circulation, and structural grid size and structural principle (Bijdendijk, 2015; Habraken, 1961; Schilperoort, 2017).

Technical adaptability allows for changes of parts of the building if required. This may include updating building installations, façade and spatial arrangement. Separation between building components with different functions and expected lifespan allows for an easy exchange and replacement if necessary. This means component and building installations should not be embedded into, for example, the structure (Brand, 1994; Schilperoort, 2017)

Transforming concrete structures according to these principles extends the structure's lifespan not just for one, but several functional lifecycles. This ensures a longer period of use and thereby follows the principle of cycling longer.

3. Optimise the reuse of concrete elements

For the optimal reuse of concrete elements retrieved from a building, refurbished, reconditioned and used in another building, the logistical hurdles surrounding this principle should be resolved. Two strategies reducing the logistical obstacles are distribution by manufacturer and online availability of data regarding the retrieved concrete elements. As the manufacturer of concrete elements already has a distribution network, distributing the retrieved elements could be integrated into their business model. A collaboration between a demolition company and product manufacturer is even more promising, as the combined expertise resolves the complete issue surrounding the inventorying, harvesting and distribution. If there is not an immediate destination for the retrieved element to be reused, an online available databank containing essential information about the retrieved elements would allow for the implementation of such elements into the design from an early phase (Jensen et al., 2019; Lukkes, 2018).

Moreover, it is of great importance these improvements are made as soon as possible, especially for concrete. Reusing concrete elements has a much larger potential of reducing the environmental impact of the building industry, when compared to other building component categories as windows or facades (appendix, figure 11) (Hasik et al., 2019).

4. Concrete out of recycled resources

As long as concrete can not be recycled for the full 100% and the demand for concrete exceeds the supply of recycled materials, a pure circular concrete industry cannot be achieved. At the moment, the volume of generated concrete waste encompasses around half of the demand for new concrete. The amount of concrete waste is expected to increase to around 22 million tonnes by 2025, but it is uncertain how the demand for new concrete will develop. But for now, it is paramount the technologies continue developments, and ensure integration into the concrete producing industry. It could be promising if the advanced detection technologies of C2CA are combined with the separation technique of the Smart Crusher already producing a low contaminated fraction of fines. This could allow pure Portland Cement to be retrieved from the powdered fraction after crushing. This hydrated cement fraction can then be activated by the low energy microwave technology, maximising the reduction of environmental impact.

The discussion of how and when to use the concrete out of recycled materials most efficiently is up for discussion and it is closely related to the reduction of concrete use, discussed in nr. 1 in this section. Thereby this discussion is back at the beginning, closing the cycle in this section.

Conclusion

The answer to the research question: *"To what extent can the environmental impact of the concrete industry be reduced by reusing concrete at high-value, within architecture, following the principles of the circular economy?"*, is that reusing concrete at building, component and material level shows a potential environmental impact reduction of 95%, 80%, and 70% respectively when compared to the conventional, linear industry alternative. However, considering the current situation, in which concrete is only frequently reused at the level of its structure, this implies big improvements are to be made on component and material level.

This paper provides a comprehensive overview of high-value reuse options and gives insight into the environmental benefits of reusing concrete. The knowledge presented in this paper can be considered crucial for everyone involved in sustainable development within architecture. However, reusing concrete shows a substantial benefit over its conventional alternative, it should be realised still a lot of energy is required during the reuse process, causing greenhouse gas emissions. Therefore, if concrete is going to be used, it should be designed to maximise its potential lifespan.

Consecutive research could be conducted on several aspects of the use of concrete in the circular economy. For example, it could be interesting to investigate the consequences of an optimised use and reuse of concrete to the demand for new concrete and the volume of generated concrete waste.

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Appendix

Figure 1. Life cycle of concrete, showing the production process in the lower half of the diagram and the desired recycle options in green on the upper part. (De Schepper et al., 2014)

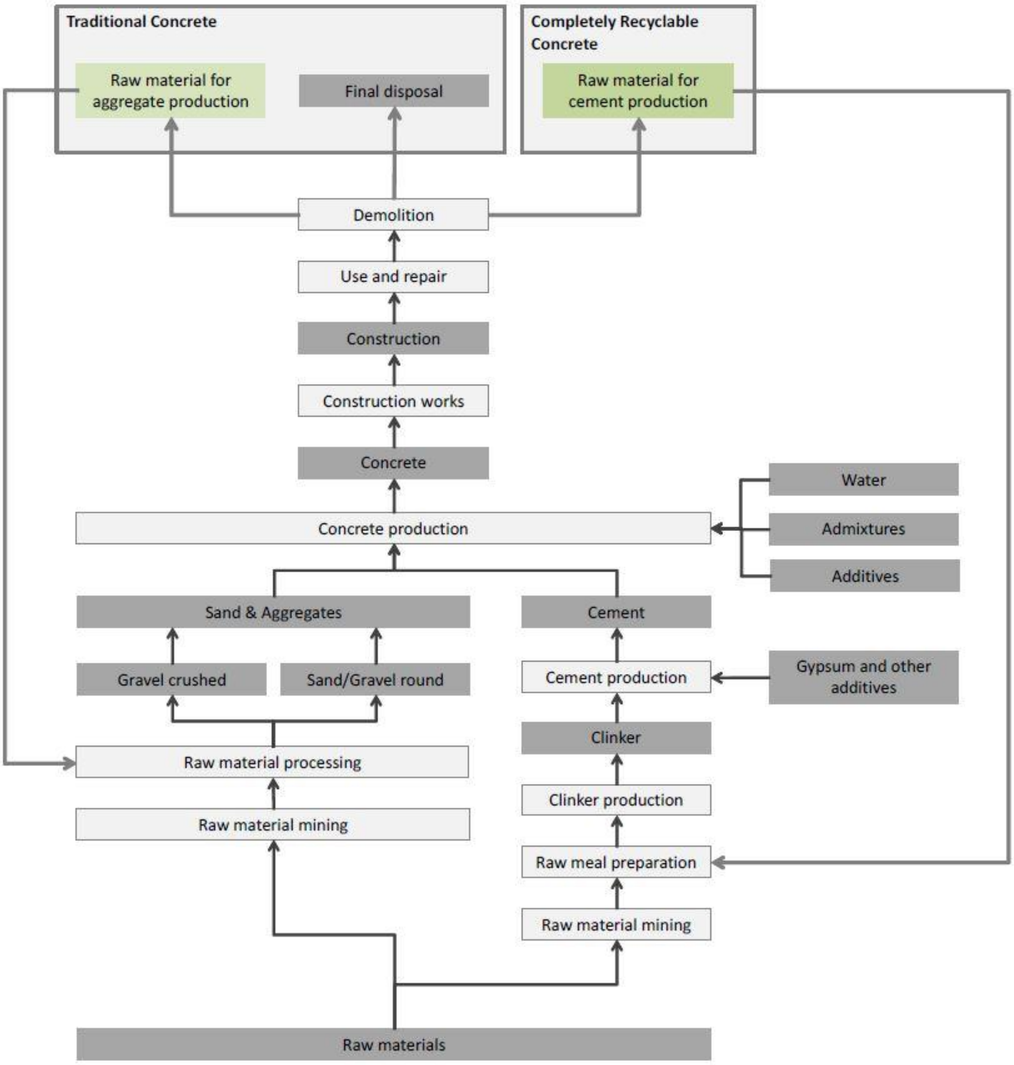


Figure 2. CO$_2$ emissions in the cement production process at ENCI, in kg CO$_2$ / tonne cement. (ENCI, 2019)

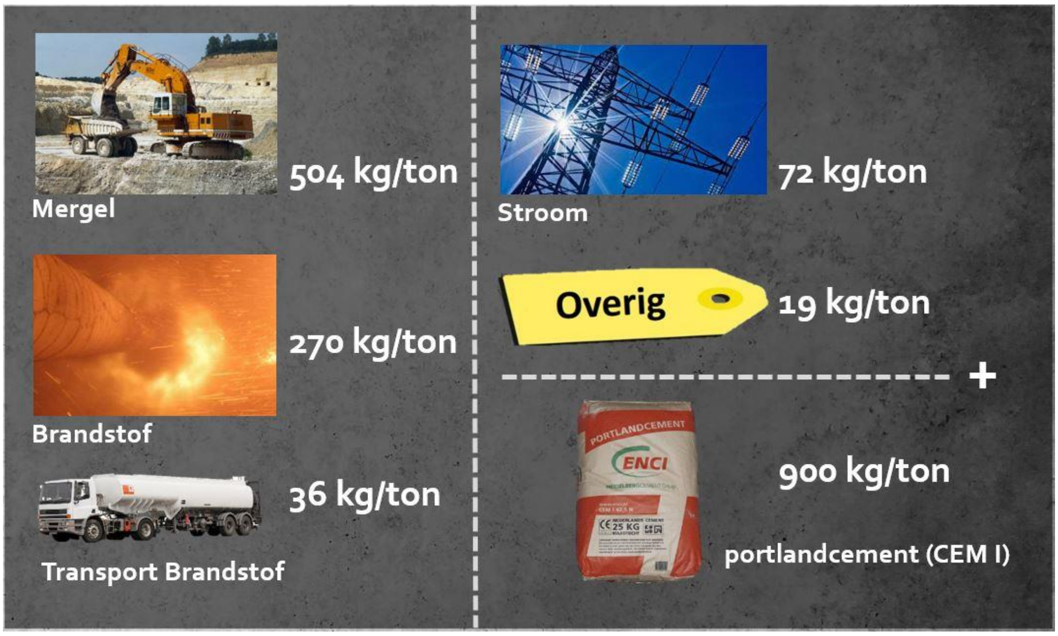
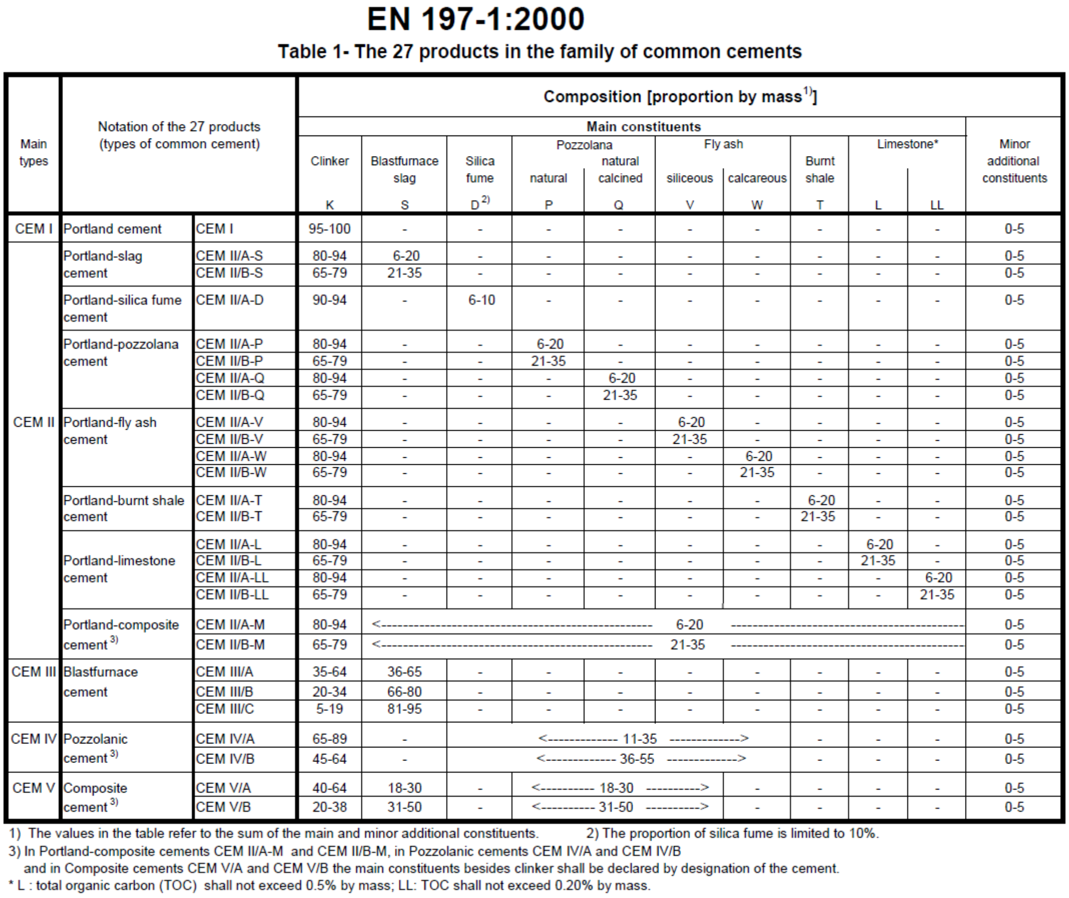


Figure 3. Cement types as defined in NEN-EN 197-1:2000 (CEN, 2011)



EN 197-1:2000

Table 1- The 27 products in the family of common cements

Main types	Notation of the 27 products (types of common cement)		Composition [proportion by mass 1)]										
			Main constituents										Minor additional constituents
			Clinker	Blastfurnace slag	Silica fume	Pozzolana		Fly ash		Burnt shale	Limestone*		
						natural	natural calcined	siliceous	calcareous				
			K	S	D 2)	P	Q	V	W	T	L	LL	
CEM I	Portland cement	CEM I	95-100	-	-	-	-	-	-	-	-	-	0-5
CEM II	Portland-slag cement	CEM II/A-S	80-94	6-20	-	-	-	-	-	-	-	-	0-5
		CEM II/B-S	65-79	21-35	-	-	-	-	-	-	-	-	0-5
	Portland-silica fume cement	CEM II/A-D	90-94	-	6-10	-	-	-	-	-	-	-	0-5
	Portland-pozzolana cement	CEM II/A-P	80-94	-	-	6-20	-	-	-	-	-	-	0-5
		CEM II/B-P	65-79	-	-	21-35	-	-	-	-	-	-	0-5
		CEM II/A-Q	80-94	-	-	-	6-20	-	-	-	-	-	0-5
		CEM II/B-Q	65-79	-	-	-	21-35	-	-	-	-	-	0-5
	Portland-fly ash cement	CEM II/A-V	80-94	-	-	-	-	6-20	-	-	-	-	0-5
		CEM II/B-V	65-79	-	-	-	-	21-35	-	-	-	-	0-5
		CEM II/A-W	80-94	-	-	-	-	-	6-20	-	-	-	0-5
		CEM II/B-W	65-79	-	-	-	-	-	21-35	-	-	-	0-5
	Portland-burnt shale cement	CEM II/A-T	80-94	-	-	-	-	-	-	6-20	-	-	0-5
		CEM II/B-T	65-79	-	-	-	-	-	-	21-35	-	-	0-5
	Portland-limestone cement	CEM II/A-L	80-94	-	-	-	-	-	-	-	6-20	-	0-5
		CEM II/B-L	65-79	-	-	-	-	-	-	-	21-35	-	0-5
		CEM II/A-LL	80-94	-	-	-	-	-	-	-	-	6-20	0-5
		CEM II/B-LL	65-79	-	-	-	-	-	-	-	-	21-35	0-5
	Portland-composite cement 3)	CEM II/A-M	80-94	<--------------------- 6-20 ---------------------									0-5
		CEM II/B-M	65-79	<--------------------- 21-35 ---------------------									0-5
CEM III	Blastfurnace cement	CEM III/A	35-64	36-65	-	-	-	-	-	-	-	-	0-5
		CEM III/B	20-34	66-80	-	-	-	-	-	-	-	-	0-5
		CEM III/C	5-19	81-95	-	-	-	-	-	-	-	-	0-5
CEM IV	Pozzolanic cement 3)	CEM IV/A	65-89	-	<------------- 11-35 ------------->					-	-	-	0-5
		CEM IV/B	45-64	-	<------------- 36-55 ------------->					-	-	-	0-5
CEM V	Composite cement 3)	CEM V/A	40-64	18-30	-	<---------- 18-30 ---------->			-	-	-	-	0-5
		CEM V/B	20-38	31-50	-	<---------- 31-50 ---------->			-	-	-	-	0-5

1) The values in the table refer to the sum of the main and minor additional constituents. 2) The proportion of silica fume is limited to 10%.

3) In Portland-composite cements CEM II/A-M and CEM II/B-M, in Pozzolanic cements CEM IV/A and CEM IV/B and in Composite cements CEM V/A and CEM V/B the main constituents besides clinker shall be declared by designation of the cement.

* L : total organic carbon (TOC) shall not exceed 0.5% by mass; LL: TOC shall not exceed 0.20% by mass.

Figure 4. Environmental impact of cement types produced by ENCI in the Netherlands (ENCI, 2019)

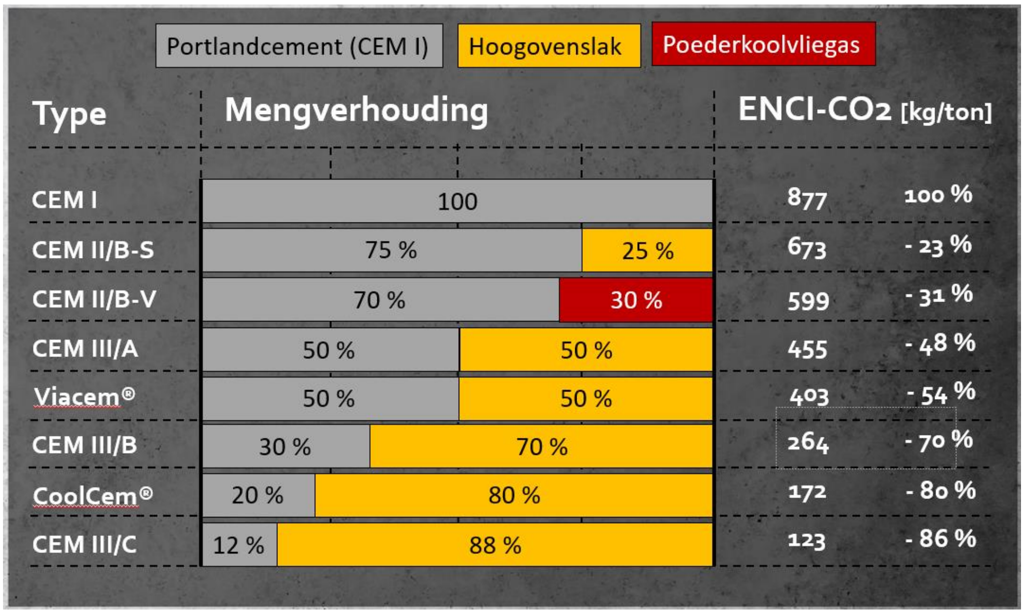
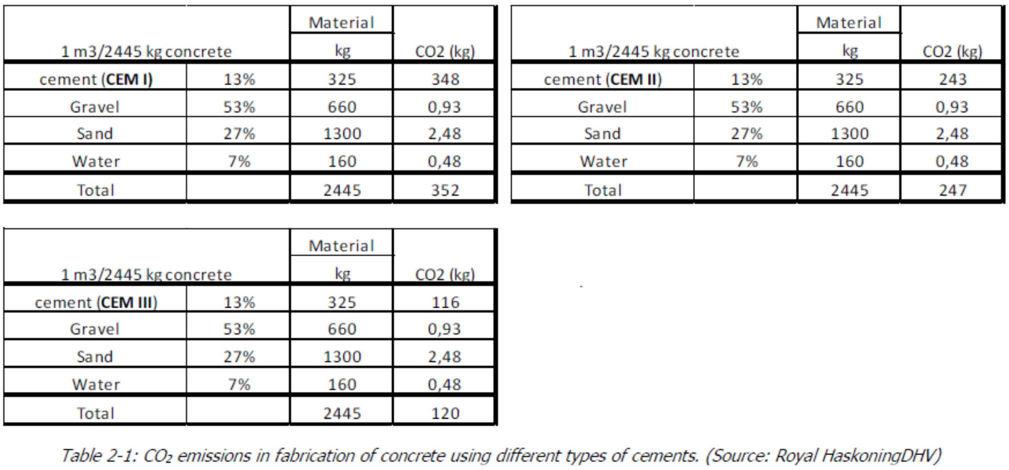


Figure 5. Environmental impact and composition of concrete with the most used cements in the Netherlands (Naber, 2012)



1 m3/2445 kg concrete		Material kg	CO2 (kg)
cement (**CEM I**)	13%	325	348
Gravel	53%	660	0,93
Sand	27%	1300	2,48
Water	7%	160	0,48
Total		2445	352

1 m3/2445 kg concrete		Material kg	CO2 (kg)
cement (**CEM II**)	13%	325	243
Gravel	53%	660	0,93
Sand	27%	1300	2,48
Water	7%	160	0,48
Total		2445	247

1 m3/2445 kg concrete		Material kg	CO2 (kg)
cement (**CEM III**)	13%	325	116
Gravel	53%	660	0,93
Sand	27%	1300	2,48
Water	7%	160	0,48
Total		2445	120

Table 2-1: CO_2 emissions in fabrication of concrete using different types of cements. (Source: Royal HaskoningDHV)

Figure 6. Hydration degree as result of water / cement ratio (Betoniek, 1983)

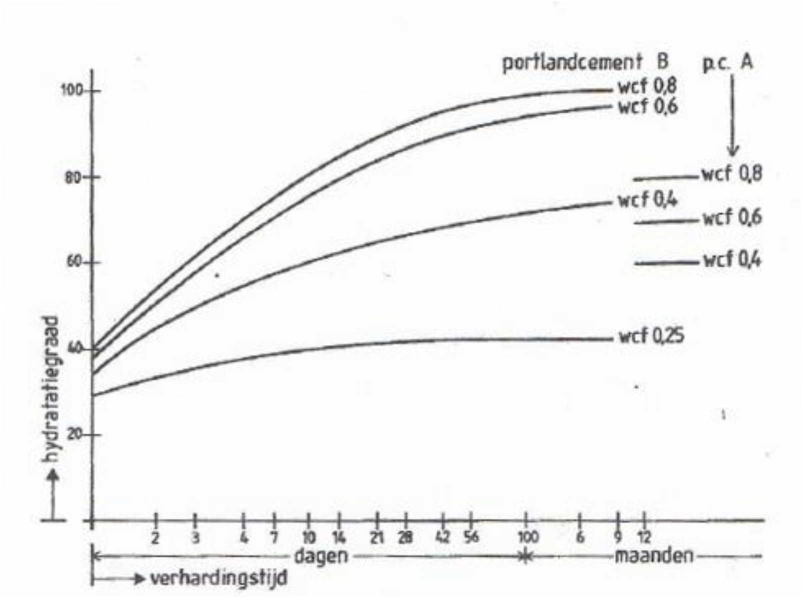


Figure 7. Strength development as a result of the reaction rates of Alite (C3S) and Belite (C2S) (Abd elaty, 2014)

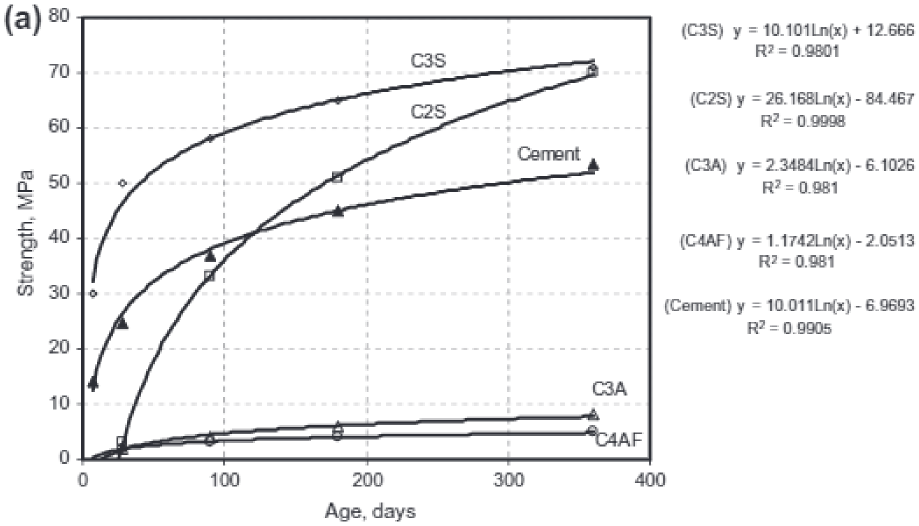
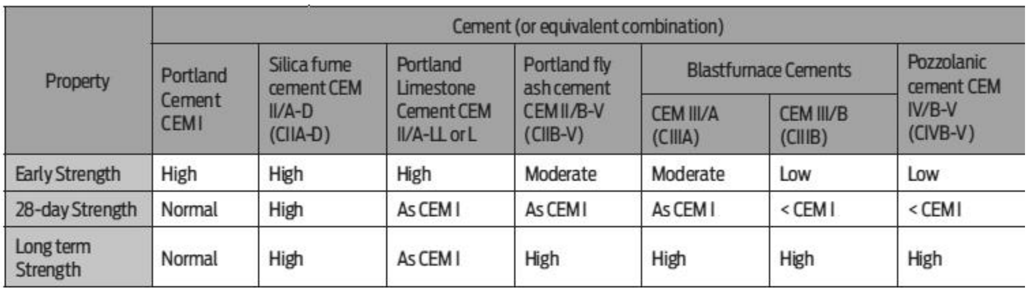


Figure 8. Strength development of cement types (Clear, 2011)



Property	Cement (or equivalent combination)						
	Portland Cement CEM I	Silica fume cement CEM II/A-D (CIIA-D)	Portland Limestone Cement CEM II/A-LL or L	Portland fly ash cement CEM II/B-V (CIIB-V)	Blastfurnace Cements		Pozzolanic cement CEM IV/B-V (CIVB-V)
					CEM III/A (CIIIA)	CEM III/B (CIIIB)	
Early Strength	High	High	High	Moderate	Moderate	Low	Low
28-day Strength	Normal	High	As CEM I	As CEM I	As CEM I	< CEM I	< CEM I
Long term Strength	Normal	High	As CEM I	High	High	High	High

Figure 9. Circular Economy System Diagram; (Braungart & McDonough, 2002; Ellen MacArthur Foundation, 2013)

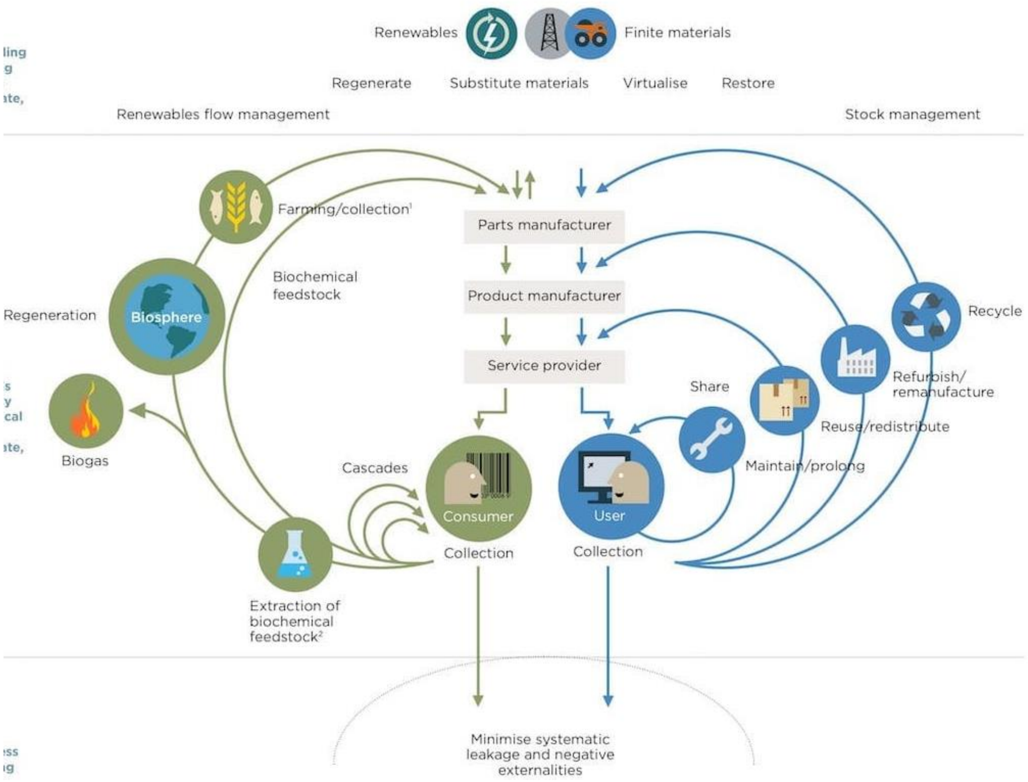


Figure 10. Total square meters of office buildings transformed & demolished in the Netherlands (Jensen et al., 2019)

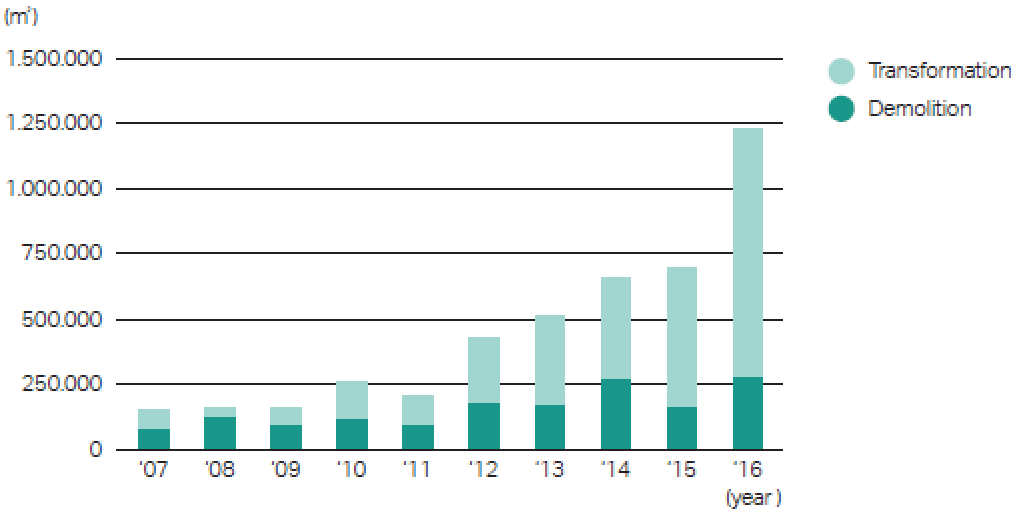


Figure 11. Comparison of the total life cycle impacts of new construction and renovation (Hasik et al., 2019)

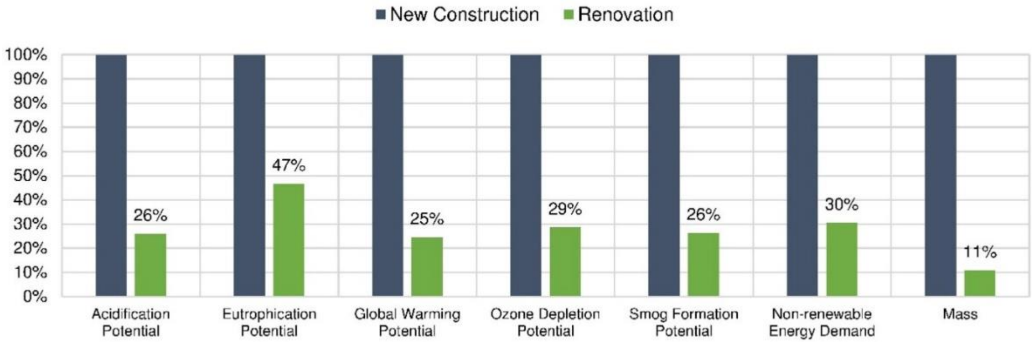


Figure 12. Global Warming Potential by material / component group (Hasik et al., 2019)

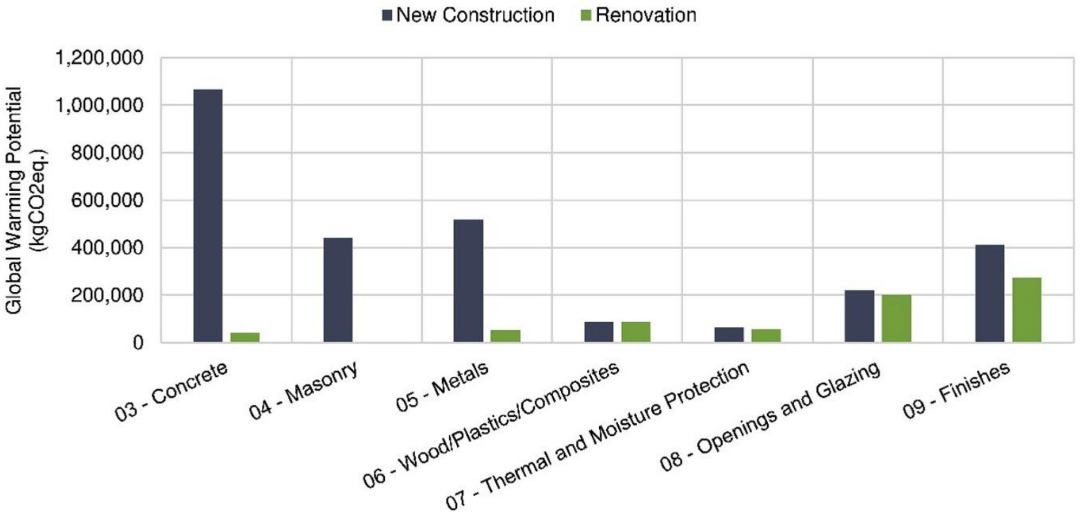


Figure 13. Global Warming Potential of reused concrete element vs new element (Glias et al., 2014)