Sustainable Recycling of Concrete Fine from Demolition

Ronny Meglin[1], Sabrina Gilg[1], Dominik Wlodarczak[2], Prof. Simone Stürwald[1], Prof. Dr. Susanne Kytzia[1]

[1] HSR University of applied sciences Rapperswil, Switzerland

[2] JURA Management AG, Switzerland

In Switzerland, concrete fines from construction and demolition waste (C&DW) are usually down-cycled for low quality purposes. Therefore, companies have few incentives to improve the demolition process separating the coarse aggregates, sand and the hardened cement matrix. The use of concrete fines from demolition waste, however, could increase value added for companies if properly used in the cement and concrete production. These could be used either to replace part of the raw materials in clinker production or as supplementary cementitious materials (SCM's) reducing the clinker content in cement. Furthermore, they can also be used to replace virgin sand in the concrete production. All these alternative uses of concrete fines will effect CO2-emissions in the Life-Cycle of concrete as well as resource consumption and production costs.

In the ongoing research project "CLOSE", we investigate alternative uses of fines from construction and demolition waste and evaluate their benefits from an environmental and an economic perspective. We also assess possible effects on the quality of concrete produced with these secondary materials, also considering the carbonation of the concrete fines. We work in close collaboration with cement producer JURA Materials, as industry partners, using simulation methods as well as comprehensive material testing according the Swiss standards for cement and concrete.material testing. For the evaluation of environmental and economic impacts, we use Life-Cycle-Assessment focussing on GWP (including the effect of carbon uptake by carbonisation of crushed concrete) as well as cost calculation methods. It is a feasibility study to identify the most promising use of recycled concrete fines and show requirements for appropriate demolition processes and preparation process as well.

In this early-stage paper, we focus on using crushed concrete fine as a raw material substitute in cement production and discuss the chemical composition of construction and demolition waste (C&DW), the carbon uptake and Life-Cycle-Assessment (LCA). First preliminary results are presented and discussed.

Keywords: concrete, cement, recycling, construction and demolition waste, LCA

1 Introduction

In Switzerland, around 15 million tons of construction & demolition waste (C&DW) were produced in 2014 [1], of which approximately 7 million tons are concrete and mixed demolition waste (e.g. masonry). According recent studies [2], [3] the amount of construction waste from building construction will increase significantly due to a higher demolition and renovation ratio. It is assumed, that the amount of C&DW in the building construction will increase to 9 million tons in 2025. In Figure 1 it can be seen, that the biggest increase is to be expected in concrete waste, as the amount of mixed construction waste will remain stable. This is due to the fact, that there is an increasing demolition ration of buildings from 1961 and younger, which are mainly made of concrete. Today, the highest demolition rate is still at buildings aged around 60 to 70 years (build 1947 until 1960), where the share of masonry is higher than concrete [2].

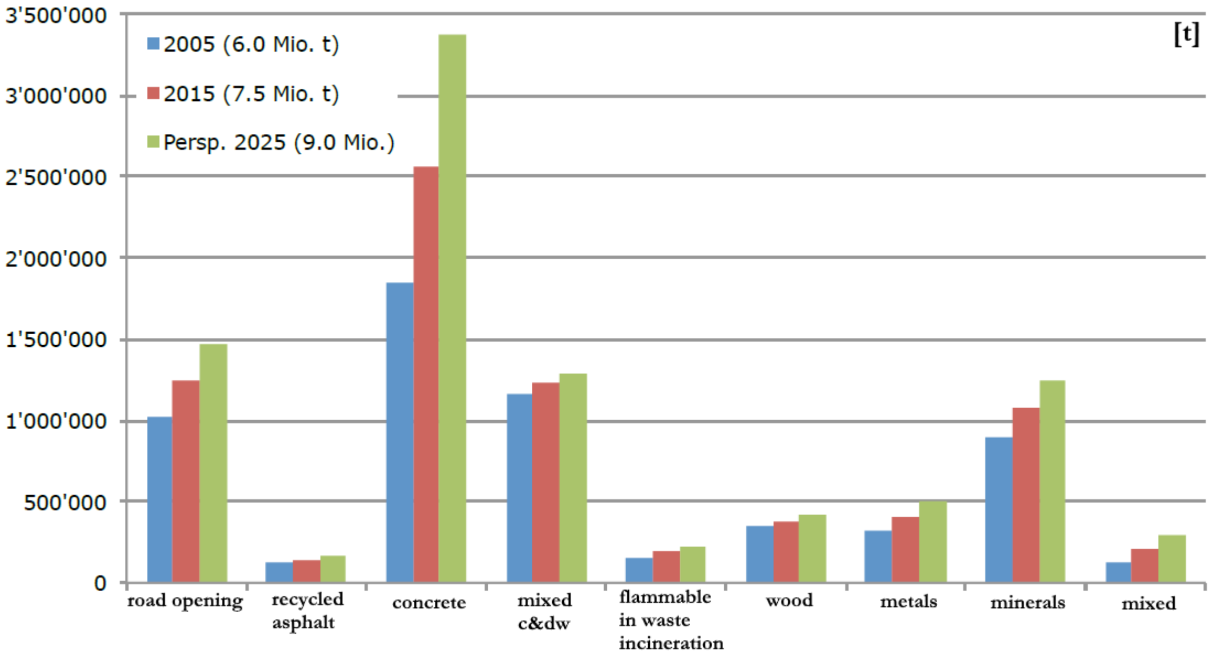

Figure 1: Development 2005-2025 of construction waste by material group in the building construction [2]

As result of the increasing amount of waste, the Federal Office for the Environment of Switzerland(FOEN) declared in 2016, that all waste such as municipal waste or construction and demolition waste "must be recycled or recovered for energy" [4]. The condition is, that the recovery "does less harm to the environment than (a) any other form of disposal; and (b) the manufacture of new products or the acquisition of other heating fuels". In addition, the "Recovery must be carried out according to the state of the art". Around 70-80 % of the overall C&DW, as of today, is recycled for building materials, while the rest is deposited or burned in waste incineration plants [1], [5]. However, most of the processed C&DW is "down-cycled" into materials with subordinate technical requirements such as lean concrete or as road subbase material [6]. One reason for the Downcycling is the crushed concrete sand with grain sizes smaller than 4 mm. The European Cement Research Academy [7] states, that the re-use of crushed concrete is a challenge due to the less favourable properties of the crushed concrete fines.

By considering the above-mentioned amount of concrete waste in the building construction sector in Switzerland, it becomes clear, that there is a high potential in the optimisation of the use of the crushed concrete sand. In 2015, approximately 2.5 million tons of concrete waste have accrued. When crushing this concrete waste to aggregate of a typical grading curve (for example Fuller 0/32 mm), we can estimate, that there is a share of around 35 % (0.875 million tons) of crushed concrete fines 0/4 mm. As stated before, this sand is usually used for low-quality purposes, which means, that the special properties of the sand, for example the possible reactivity of the cement paste, remains unused.

The Swiss cement and concrete industry makes a major contribution to the recycling of waste. As shown in Figure 2, secondary materials are used in various processes along the value chain as alternative fuels and raw materials (AFR) in cement kilns, as supplementary cementious materials (SCMs) in the cement mill or concrete production or as aggregates in concrete production. This common practice reduces the burden on the environment in three ways: by saving natural resources (lime, marl, gravel, sand, coal and oil), by reducing waste and by reducing greenhouse gas emissions [6]. The latter effect in particular is decisive, as the contribution of the cement and concrete industry to the greenhouse effect is considerable, accounting for around 8% of total carbon dioxide emissions worldwide [8]. For years, the industry has been using conventional technologies to reduce CO_2 emissions: increasing energy efficiency, clinker substitution and the use of alternative fuels. However, their potential has now largely been exhausted. As a result, little progress is being made in reducing CO_2 emissions [9], [10].

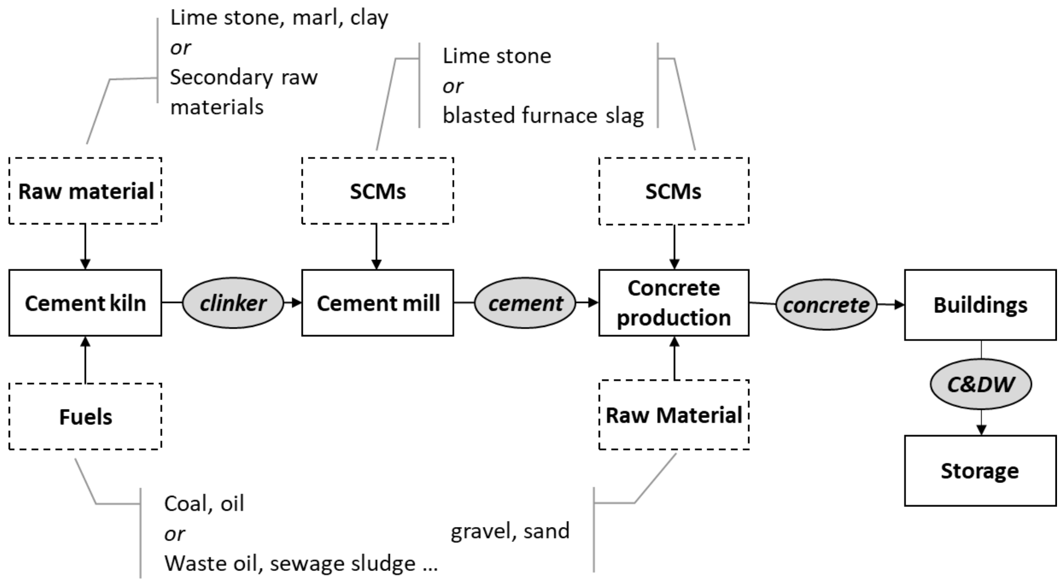

Figure 2: value chain of cement and concrete

[11] suggest that recycling of concrete fine from demolition could further reduce CO_2 emissions in the concrete product system. Yet, quality of crushed sand has a significant influence on the possibilities of returning the crushed sand to cement and concrete production. On the one hand it depends on the methods of concrete demolition treatment [12]–[14] and on the other hand it is also influenced by whether the storage of concrete demolition increases the uptake of CO_2 in the cement paste. This storage is currently being discussed in the cement industry in order to make an additional contribution to climate protection [15]–[17].

This is where the here presented research project CLOSE comes in. Its aim is to optimize the usage of concrete demolition waste, especially the crushed concrete fines as a by-product. The economic efficiency of concrete recycling will be significantly improved if this crushed sand can be used profitably in cement and concrete production. In the CLOSE project, three technically viable applications of this crushed sand are to be evaluated according to sustainability criteria with a focus on climate protection, resource conservation and waste avoidance.

In order to develop concrete specifications for the further development of concrete demolition processing methods, it must be known which crushed sand quality is to be aimed for. This requirement depends on how the crushed sand is returned to the cement and concrete production. Possible applications (see Figure 2) would be: (i) as a raw meal substitute, (ii) as additives in cement mills or concrete production or (iii) as aggregates in concrete production.

Looking at the year 2015, 4.2 million tons of cement where produced in Switzerland [9] which corresponds to a consumption of raw materials of approx. 5 million tons. Considering the above calculated amount of available crushed concrete fines (0.875 million tons), the possible substitution of raw material in the clinker production is calculated to 17 %. In the same period, 39.8 million tons of concrete where produced [18]. Assuming, that around 70 % of the concrete is aggregate and 35 % of that is the fine fraction of sand 0/4 mm, the amount of virgin sand used for the concrete production is approx. 9.75 million tons. That leads to a maximum substitution ratio of concrete fines of 9 %, assuming that all of the available crushed concrete fines are usable.

Based on these interrelationships, an evaluation of the possible application sites of crushed sand represents an essential prerequisite for the development of suitable processing methods.

In the project, the following research questions are to be answered:

(i) To what extent can CO_2 emissions be reduced in cement production (taking carbonation into account)?
(ii) To what extent can the consumption of natural resources (lime, marl, gravel, coal and oil) in cement production be reduced by recycling crushed concrete sand?
(iii) What are the risks for cement and concrete quality?
(iv) What are the requirements for the quality and quantity of the cement paste present in the crushed sand?

In this paper, we focus on using crushed concrete fine as a raw material substitute in cement production. By investigating the chemical composition, calculating the carbon uptake and investigating the life cycle of concrete regarding the carbon uptake, we try to answer the first and second above-mentioned questions.

2 State of research

2.1 Concrete fines as raw material for the clinker production

In recent years, several studies have dealt with the quality of construction and demolition waste and their use in the cement and concrete production. On the one hand, the focus was placed on the treatment processes of C&DW, on the other hand several studies investigated the quality of the aggregates for the use as a raw material in the cement industry and came to the conclusion, that the fine aggregate can be used as a raw material [6], [7], [14], [19], [20].

2.1.1 Chemical composition of the crushed concrete fines

Raw materials containing calcium (Ca), silicon (Si), aluminium (Al) and iron (Fe) as main components are used for the production of cement clinker [21]. These are usually limestone, clay and marl. Therefore, the chemical composition of the crushed concrete determines the possibilities for the usage of the concrete fines [22].

One study stated [14], that "if the recycled material consists mainly of concrete, it can serve as a CaO-containing component in cement production, if the proportion of bricks predominates, it can be used as an Al_2O_3 carrier.". Several studies investigated the chemical composition of recycled concrete fines [14], [19], [20], [23]. As recycled crushed concrete sand mainly contains CaO and SiO_2 it is particularly suitable as a clay substitute in clinker production due to its chemical composition [22]. However, depending on the used virgin aggregate (silicate or calcite), the content of CaO and SiO_2 may vary significantly (see Table 1), which makes it essential to determine the chemical compositions of the material which is to be utilized.

Table 1: chemical composition of crushed concrete materials [22]

	[M-%]	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3
Crushed concrete materials n = 65	Ø	64.8	6.1	2.5	12.3	1.2	1.7	0.8	0.6
	Min	16.0	2.1	0.9	5.0	0.4	0.3	0.1	0.3
	Max	77.9	9.2	4.2	37.5	6.5	4.9	1.7	1.3

2.1.2 Burnability

One aim of the project is to investigate the possibility to minimize the environmental impact by using crushed concrete fines. As the burning process of the clinker production represents the highest energy demand in the value chain, it is essential, that the usage of crushed concrete fines as a substitute for raw material does not lead to a higher energy demand or higher CO_2-emmissions. According to [6], a reduction of the firing temperature when using crushed concrete fines as substitution is possible, which would reduce the energy demand of the clinker production. However, it must be noted, that the synthesis of C_3S does not take place completely during the firing process, which leads to a low early strength [20], [23]. The higher the substitution rate, the lower is the C_3S content, which, in the end, leads to a loss of compressive strength.

2.2 Carbon uptake

Concrete is able to capture CO_2 in its service life through carbonation, leading to a significant decrease of the total CO_2 emissions in the value chain of concrete [24], [25]. In this process, the CO_2 from the air is bound by the calcium hydroxide $Ca(OH)_2$ in concrete forming calcium carbonate $CaCO_3$. As this process depends on several boundary conditions like accessible surface, cement composition, concrete quality or exposure conditions [26], there is no consensus in research as to how much CO_2 can be rebound. The values in recent studies vary between 10 and 40 % [16], [25], [27].

2.2.1 Surface area

Even if the values of the possible uptake fluctuate in current research and are subject to uncertainties, all studies clearly show that the CO_2 absorption in the recycling phase is significantly higher than during the lifetime (see Figure 3), as the crushing of the concrete significantly increases its specific surface area and exposes areas that have not yet been carbonated. It is stated that crushed construction and demolition waste (C&DW) can bind more CO_2 than the concrete in the actual construction and, therefore, contributes to further reduce CO_2 emissions if prepared and stored in a favorable way [26], [28].

2.2.2 Water-Cement-Ratio

A higher water/cement ratio (w/c-ratio) causes a higher porosity leading to a higher surface area exposed to CO_2. According a recent study [29], the carbonation rate is highest at a w/c-ratio of 0.6. Another study [30] also concluded that mortar and concrete with a higher w/c-ratio can bind more CO_2 as another study set am optimum w/c-ratio at 0.45 [31].

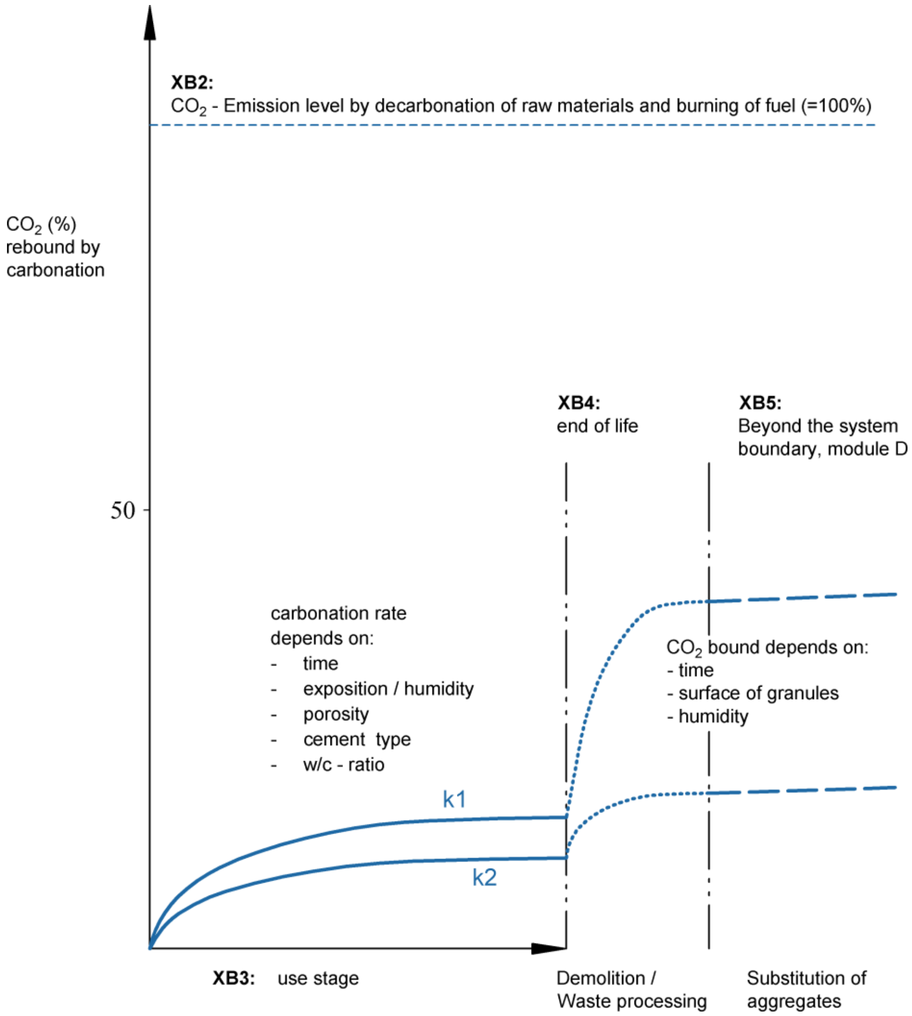

Figure 3: Rebinding of C02 by carbonation of concrete [32]

2.2.3 Humidity

According to [33], the maximum speed of carbonation can be achieved at a relative humidity of 60 to 80%. Humidity plays an important role for two reasons. Firstly, the presence of water is a prerequisite for starting the chemical reaction. On the other hand, too much moisture inhibits the reaction, as the CO_2 can penetrate less quickly. Therefore, a relative humidity of 50 to 70% is assumed to be optimal for carbonation [26].

2.2.4 Targeted carbonation

Due to the carbonation process the density of the cement paste increases, while the porosity decreases. This is due to the fact that the end product of the chemical reaction, $CaCO_3$ has a higher density than the starting product $Ca(OH)_2$. For this reason, there are already several studies dealing with targeted carbonation. The aim is not only to reclaim CO_2, but also to improve the properties of the crushed sand. According to [15], [31], [33], the treatment of aggregates with CO_2 leads to an increase in bulk density and thus to a reduction in porosity. In particular, capillary porosity is reduced, which has a positive effect on compressive strength compared to a reference concrete with the same aggregate.

In the case of using the crushed concrete fines as substitute of raw material in the clinker production, as described in this paper, a low carbonation ratio is desired, as otherwise the bound CO_2 must be released again in the combustion process in the clinker production.

2.3 Life-Cycle-Assessment of concrete

Life cycle assessment (LCA) is a methodological framework used to assess environmental impacts of a product or service from a life cycle perspective, including resource extraction, production, use and end-of-life activities (e.g. waste treatment). Its development started in the 1960s focusing on the comparison of environmental impact of consumer goods and first studies in the construction sector appear in the1980s [34]. A common methodological framework wasn't developed until the late 1990s when the International Organization for Standardization (ISO) published its 14040 series [35], [36]

Since then, the interest in LCA rapidly increased. It encouraged the development of a specific methodological framework for LCA of building materials and products with a set of environmental data defined by pre-set categories of parameters based on the ISO14040 series. It results in Environmental Product Declarations (EPDs) and was standardized on a general level by ISO (ISO Technical committee (TC) 59 'Building Construction') [37] as well as by the European Committee for Standardization (CEN) in its Technical Committee (TC) 350 'Sustainability of construction works'. This led to the emergence of EPD programs (mostly in Europe, Canada and the US) that started developing and publishing specific methodological frameworks for product categories, called PCRs (Product Category Rules). In 2015, [38] state that more than 28 EPD programs exist worldwide referring to ISO 14025" (…), providing more than 2256 PCR documents and more than 3600 EPDs. Yet, the growing number of LCA studies for construction materials also revealed the need to further develop the method [34], [39]–[42].

Looking at different LCA studies for concrete there is a surprisingly wide rage in the results for different environmental impacts such as Global Warming Potential (GWP) or Cumulative Energy Demand (CED). Some of this variation can be explained by the use of different data sources or methodological choices [38], [43], [44]. Yet, even within an identical methodological framework using the same data sources, results can vary up to 100% for the same type of concrete [45]. For LCA experts, this reveals the need to further develop the method [34], [39]–[42].

Along the value chain of cement and concrete production several strategies have been identified to reduce environmental impacts [11], [46]–[48]. The most significant strategies are:

- improving the energy efficiency of cement plants and substituting fossil fuels in the cement kiln
- reducing the clinker content in cement (clinker to cement ratio)
- reducing the cement content in concrete
- optimizing the use of concrete in construction

By implementing all strategies in parallel by different stakeholders, it is claimed, that CO_2-emissions of concrete production worldwide could be reduced by about 80 % until 2050 [47].

Considering carbonation, it is assumed, that recycling demolished concrete could further reduce CO_2 emissions from the cement and concrete industry. At the same time, the consumption of mineral raw materials can be reduced [19]. Two effects are decisive for this:

(i) Through the targeted processing and storage of concrete demolition, the rebinding of CO_2 in the cement paste can be significantly increased. Individual studies estimate that 10-15% of the amount of carbon dioxide produced in the cement kiln during clinker production can be bound during a few years [26], [49]. Carbonation causes limestone to form and compact in the cement stone. This limestone can be used as a secondary raw material in cement production.

(ii) The production of concrete granulate also results in a fine fraction (crushed sand) consisting of sand, hard cement stone and fine foreign particles (such as wood and plastic particles). Due to insufficient quality, crushed sand is not yet used in a targeted manner. The CO_2-intensive cement stone is lost unused. However, this material could be reused in cement and concrete production and thus contribute to reducing environmental pollution.

The described project will evaluate to what extent the environmental impacts of the cement and concrete industry can be reduced by further developing processes for recycling concrete demolition. The focus is on the use of crushed sand - a residue from the recycling process - in various processes along the value chain (Figure 2).

2.4 Standards

In Europe, the chemical composition of cement is defined in EN 197-1:2011 [50]. This standard limits the main and secondary constituents as well as their respective contents. The development of low CO_2-cement with high substitution rates of the constituents would not be possible within the framework of this standard. As the Swiss cement industry aims to reduce the CO_2 emissions caused by the cement production, the guideline 2049 [51] was published to expand the possible usage of inorganic components and to support the usage of sustainable cement. In this guideline, new technical requirements and limits of the main and secondary constituents are set which make it possible to develop new cement compositions. This guideline also regulates the requirements and tests for the durability of concrete produced with the new cement.

However, these standards would only be relevant in the case of the use of crushed sand as a supplementary cementitious material in the cement mill. When using the crushed concrete sand as a substitute of raw material in the clinker production, the requirements for the clinker in accordance with the standards is given by calculating the setting parameters to produce the respective reference clinker (see 3.2).

3 Methodology and Data

To determine the properties of the crushed concrete fines and estimate the potential for their use as alternative raw material, several testing methods and calculations are used. These are described in the following subsections.

3.1 Polarized light microscopy

As a first indicator to validate the possible usage of the crushed concrete fines, the ratio of aggregate to hardened cement paste is assessed. For this purpose, a sample of the crushed concrete fine 0/4 mm is poured into a fluorescent plastic compound and processed into a thin section. This thin section is then examined under the petrographic microscope and the ratio of aggregate to hardened cement paste estimated.

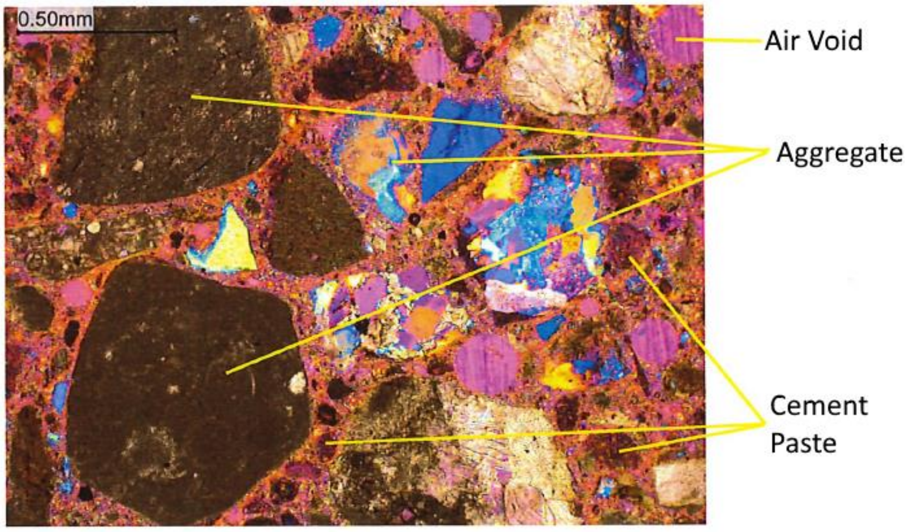

Figure 4: microscopic image in polarized light

In Figure 4 a picture of crushed concrete fines collected within this project can be seen. First preliminary result of this first sample have shown that the content of hardened cement paste is approximately around 15 %. Further microscopic investigation will lead to results that are more robust.

3.2 XRF

To determine the chemical composition of the crushed concrete fines, an X-ray fluorescence spectroscopy (XRF) with wavelength dispersive spectrometers is carried out. The specific elements of the sample are identified by measuring the energy of the emitted radiation, while the amount of the elements are measured by the intensity of the emitted radiation. With the elements Calcium oxide (CaO), Silicon dioxide (SiO_2), Aluminium oxide (Al_2O_3) and ferric oxide (Fe_2O_3) the setting parameters lime saturation factor (LSF). silicate modulus (SM) and alumina modulus (AM) can be calculated as follows:

$$\text{lime saturation factor (LSF)} = \frac{100\ CaO}{2.8\ SiO_2 + 1.18\ Al_2O_3 + 0.7\ Fe_2O_3} \quad (1)$$

$$\text{silicate modulus } (SM) = \frac{SiO_2}{Al_2O_3 + Fe_2O_3} \quad (2)$$

$$\text{alumina modulus (AM)} = \frac{Al_2O_3}{Fe_2O_3} \quad (3)$$

These parameters are then used to calculate the needed amounts of raw materials to produce a pre-defined reference clinker with corresponding properties. With the results, we can estimate how much raw material can be replaced by the crushed concrete fines.

First preliminary results of XRD-analysis in this study can be seen in Table 2. These samples of processed C&DW were collected in two different recycling centres in Switzerland. It can be seen, that the contents of the relevant elements (CaO, SiO_2, Al_2O_3 and Fe_2O_3) can differ significantly. Especially the difference of around 13 % in the content of CaO must be noted, as it has a crucial impact on the usage of the crushed concrete fines. This difference results in different lime saturation factors (LSF), which are used to determine the maximum substitution rate in cement production. [21] states, that the LSF for ordinary portland cement should be between 92 and 102. Since the LSF of the investigated samples is between 21 and 28 (see Table 2), the assumption can be expressed that these samples are only partly suitable to be used as substitution in the cement production. Therefore, further investigations are needed before a definitive statement can be provided.

Table 2: preliminary XRF results of two samples of crushed concrete fines

		sample 1	sample 2
particle size	mm	0-4	0-4
ignition loss	%	23.50	20.88
SiO2	%	47.66	41.12
Al2O3	%	5.22	4.87
Fe2O3	%	2.31	2.20
CaO	%	39.16	25.96
MgO	%	2.32	2.09
SO3	%	0.57	0.40
K2O	%	0.98	0.85
Na2O	%	0.80	0.63
TiO2	%	0.24	0.22
P2O5	%	0.09	0.09
Mn2O3	%	0.08	0.07
SrO	%	0.07	0.06
Cr2O3	%	0.01	0.01
ZnO	%	0.01	0.01
Na2O-Eq	%	1.10	1.18
LSF		**27.78**	**21.23**
SM		**6.37**	**5.82**
AM		**2.25**	**2.22**

3.3 LCAs of concrete

In previous own studies [52] we used an LCA to evaluate how environmental impacts of concrete product systems are affected by

(i) variations of technical parameters, such as cement content, clinker cement ratio, origin of aggregate or fuel mix, and
(ii) alternative methodological choices in LCA, such as allocation regarding carbon uptake.

As stated before, the project CLOSE aims to reduce the environmental impacts in the cement- and concrete production. In context with the use of the crushed concrete sand as a raw material substitute, the consideration of CO_2 uptake is particularly important (see 2.2). Therefore, the results of LCAs without allocation (see 3.3.2) will be extended with a calculated carbon uptake according [32] (see 3.3.3).

3.3.1 System under investigation

The investigated concrete product system also corresponds to the here described value chain shown in Figure 2: We analysed the system with two alternative system boundaries.

System boundary A "cradle to gate" includes

- Cement production with kiln and mill with all corresponding up-stream processes needed to supply raw materials (lime stone, clay etc.), fuels (coal, oil etc.) and electricity. The supply of alternative fuels is also included, but the allocation of the associated environmental impacts
- Concrete production with all corresponding upstream processes needed to supply raw materials (gravel, limestone etc.) and electricity.
- Transport processes between cement and concrete production are explicitly included. All other transport processes are modelled as part of the upstream processes of supplied materials and energy.

System boundary B "Cradle to grave" includes the system defined as "cradle to gate" as well as the use of concrete during the service life of a structure and storage of crushed concrete at a recycling plant or landfill. We model these processes to analyse carbon uptake (see following section). No environmental impacts are analysed for these processes.

We compared environmental impacts of one cubic meter of concrete (functional unit) of an ordinary construction concrete in Switzerland focussing on the Global warming potential (GWP) according IPCC 2011 (100 years in kg CO2eq).

The life cycle inventory was set up in SimaPro 8.5. The data basis for the LCI is ecoinvent Version 3.4 from November 2017. As basis, the process "Concrete, sole plate and foundation {CH}| concrete production, for civil engineering, with cement CEM II/A | Cut-off, U" in its version 3.0.2.0 was used and modified in order to enable varying the concrete mix design. The electricity represents the Swiss electricity production mix in 2014. The mix designs of the respective concrete can be seen in Table 3:

Table 3: mix design of the concretes for LCA [52]

		280 CEM I round	300 CEM I round	320 CEM I round	350 CEM I round	280 CEM I crushed	280 CEM II / A round	280 CEM II / B round	280 CEM III / A round	280 CEM III / B round	280 CEM III / C round
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
cement-content	kg/m³	280	300	320	350	280	280	280	280	280	280
clinker-ratio	%	95	95	95	95	95	80	65	35	20	5
blast furnace slag	%						15	30	60	75	90
gypsum	%	5	5	5	5	5	5	5	5	5	5
sand	kg/m³	668	678	678	657	668	668	668	668	668	668
gravel	kg/m³	1221	1241	1212	1201	1221	1221	1221	1221	1221	1221
water	kg/m³	190	190	190	190	190	190	190	190	190	190
Fuel mix						Swiss mix 2014					

3.3.2 *Results without allocation*

Different scenarios were defined to analyse how environmental impacts are affected by variations of technical parameters in LCA. We focus on the technical parameters with a significant influence on environmental impacts of the product system [47]: cement content level, clinker-cement-ratio and geometric shape of the aggregates (round vs. crushed). Carbon uptake is not considered as technical parameter because no technologies have been implemented up to now to increase CO_2 binding during service life and recycling. An ordinary construction concrete with 280 kg/m³ and round aggregates was chosen as reference.

Table 4: results of LCAs without allocation

	1	2	3	4	5	6	7	8	9	10
IPCC 2011 GWP 100a [kg CO2 eq]	231.25	246.94	262.34	285.48	234.13	208.79	186.33	141.42	118.96	96.50

The results of the LCAs are shown in Table 4. It can be seen, that the environmental impact, calculated as GWP, increases as the cement content increases in the mix designs 1 – 4. The increasing usage of ground granulated blast furnace slag in the mixes 6 – 10 results in decreasing CO_2-emmissions. The usage of crushed aggregate (mix 5) instead of round aggregates leads to a slight increase of the GWP of 3 kg CO_2 eq.

3.3.3 *Results considering carbon uptake*

In DIN EN 16757 [32] an allocation method for the carbon uptake is presented. There, several calculations are made to estimate the carbon uptake in total, during service life of concrete structures and through its usage stage and in its end-of-life phase. The formula for calculating the maximum carbon uptake is as follows:

$$CO_2 - uptake = \left(\frac{\%\ reactive\ CaO}{100}\right) \times binder\ content\ \times \frac{molar\ weight\ of\ CO_2}{molar\ weight\ of\ CaO} \qquad (4)$$

Where the amount of reactive CaO is about 65 %, the molar weight of CO_2 is 44 g/mol and for CaO 56 g/mol, respectively [32]. If we apply the calculation to the mix designs investigated in [52] (see Table 3), the following maximum carbon uptake are as follows:

Table 5: results considering CO2 uptake according [32], [52]

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
max. carbon uptake [kg CO2]	136	146	155	170	136	114	93	50	29	7
75 % carbon uptake [kg CO2]	102	109	116	127	102	86	70	38	21	5

In Table 5 it can be seen, that a maximum carbonation would lead to a significant uptake of carbon dioxide from the air, which in turn would lead to a significant lower environmental impact regarding CO_2. However, it must be noted that the carbonation of concrete depends on several conditions (see 2.2).Assuming, that around 75 % of the carbonation can be reached during service life and end-of-life phase [32], up to 127 kg CO_2 can be bound back in the mix 4 with 350 kg cement. Due to its chemical composition, blast furnace slag is not able to capture CO_2 like ordinary Portland cement, which can also be seen in Table 5 (mix 6 – 10).

3.3.4 Carbon uptake of crushed concrete in the cement production

This carbon uptake is highly relevant for the usage of the crushed concrete sand as substitute for raw material, as a high carbonation would lead to a high amount of CO_2, which must be expelled again during the burning process. However, exactly this amount of bound CO_2 would be used as a credit for environmental product declarations (EPD) as it is not counted as geogenic CO_2. In that case, double counting has to be considered and avoided.

A low carbonation, and therefore a low CO_2 amount in the substitute would lead to a lower energy demand in the burning process as the burning temperatures or burning time can be optimized. This would lower on the one side the overall environmental impacts of the clinker production, but also the economic impacts as the production process can be optimized.

4 Discussion and conclusions

Efforts to optimise the recycling of mineral construction waste today focus on mixed demolition, as there are currently too few recycling possibilities for this secondary building material. The demolition of concrete is not yet considered a problem and the potential of its recycling is not yet sufficiently recognised.

This will change in the coming years or decades, because:

(i) The amount of concrete demolition will increase once the concrete structures from the second half of the last century have reached the end of their useful life. Since 1960, the proportion of concrete structures/components in the building stock has increased continuously. Therefore, the proportion of mixed demolition in mineral construction waste will decrease in the future and the proportion of concrete demolition will increase accordingly.

(ii) The possible uses of RC concretes in structural engineering will increase and with it the demands on the building material. Today, qualitative deficiencies in the concrete granulate are compensated by adjustments in the concrete mix design (more cement, more admixtures). This leads to higher costs and environmental pollution. In the future, attempts will be made to improve the quality of concrete demolition.

(iii) The pressure on the cement industry to make its contribution to climate protection is increasing (e.g. through higher CO_2 fees and measures taken by public clients). Many representatives of this industry see a promising approach to solving this problem by rebinding CO_2 in concrete. For this, the greatest potential lies in the rebinding capacity in the crushed sand of the concrete demolition.

For these reasons, efforts to develop new processes for the separation and processing of C&DW will increase significantly in the coming years and further investigations for the usage of C&DW will be necessary. The here described research project improves the decision-making basis for the development of new technologies and possibilities to use a material which, until now, is down-cycled.

As this project is still in an early stage, further investigations has to be carried out in order to present robust results and discuss these results regarding the alternative uses of fines from construction and demolition waste and their benefits from an environmental and an economic perspective

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5 Bibliography

[1] D. Hiltbrunner, “Das Bauwerk als Rohstofflager,” vol. 22, pp. 65–69, 2017.

[2] F. Guerra and B. Kast, “Bauabfälle in der Schweiz - Hochbau Studie 2015 [Construction waste in Switzerland - Building Construction Study 2015],” Bern, 2015.

[3] S. Schubert and C. Hoffmann, “Grundlagen für die Verwendung von Recyclingbeton mit Mischgranulat,” EMPA, Abteilung Ingenieur-Strukturen, 2011.

[4] Swiss Waste Ordinance, *Ordinance on the Avoidance and the Disposal of Waste*. 2015, pp. 1–46.

[5] J. Almeida and C. Wälti, “Ent-Sorgen? Abfall in der Schweiz illustriert,” Bern, Nr. 1615, 2016.

[6] C.-T. Galbenis and S. Tsimas, “Use of construction and demolition wastes as raw materials in cement clinker production,” *China Particuology*, vol. 4, no. 2, pp. 83–85, 2007.

[7] C. Müller, J. Reiners, and S. Palm, “Closing the loop: What type of concrete re-use is the most sustainable option?,” 2015.

[8] F. Preston and J. Lehne, “Making Concrete Change,” Chatham House, the Royal Institute of International Affairs, 2018.

[9] CemSuisse, “Annual Report 2018 key figures,” Association of the Swiss Cement Industry, Bern, 2018.

[10] WBCSD, “Global Cement Database on CO_2 and Energy Information, Getting the Numbers Right,” 2013. [Online]. Available: http://www.wbcsdcement.org/index.php/key-issues/climate-protection/gnr-database.

[11] CEMBUREAU, “The Role of Cement in the 2050 Low Carbon Economy,” Brussels, 2013.

[12] K. Weimann and C. Adam, “RECDEMO - Vollständige Verwertung der Sandfraktion aus dem Bauschuttrecycling,” pp. 1–4, 2017.

[13] C. Müller and B. Dora, *Verwertung von Brechsand aus Bauschutt*, vol. 506. Berlin: Beuth, 2000.

[14] A. Muller, K. Rubner, and A. Schnell, “Potential of Construction and Demolition Waste as Raw Material,” *Chemie Ing. Tech.*, vol. 82, no. 11, pp. 1861–1870, 2010.

[15] M. Seidemann and H.-M. Ludwig, "Einfluss von carbonatisierten sekundäten Gesteinskörnungen auf die Eigenschaften von Recyclingbeton," in *Mineralische Nebenprodukte und Abfälle.Aschen, Schlacken, Stäube und Baurestmassen*, K. J. Thomé-Kozmiensky, Ed. TK-Vlg, 2015, pp. 639–651.

[16] A. Leemann and F. Hunkeler, "Carbonation of concrete: assessing the CO2 uptake," 2016.

[17] A. Leemann and F. Moro, "Carbonation of concrete: the role of CO2 concentration, relative humidity and CO2 buffer capacity," *Mater. Struct. Constr.*, vol. 50, no. 1, pp. 1–14, 2017.

[18] M. Gauch, C. Matasci, I. Hincapié, R. Hörler, and H. Böni, "Material- und Energieressourcen sowie Umweltauswirkungen der baulichen Infrastruktur der Schweiz," BAFU Bundesamt für Umwelt, 2016.

[19] J. Schoon, K. De Buysser, I. Van Driessche, and N. De Belie, "Fines extracted from recycled concrete as alternative raw material for Portland cement clinker production," *Cem. Concr. Compos.*, vol. 58, pp. 70–80, Apr. 2015.

[20] E. Kwon, J. Ahn, B. Cho, and D. Park, "A study on development of recycled cement made from waste cementitious powder," *Constr. Build. Mater.*, vol. 83, pp. 174–180, 2015.

[21] J. Stark and B. Wicht, *Zement und Kalk*. Basel: Birkhäuser Basel, 2011.

[22] A. Müller, *Baustoffrecycling*, vol. 63, no. 11–12. Wiesbaden: Springer Fachmedien Wiesbaden, 2011.

[23] C. Diliberto, A. Lecomte, J. M. Mechling, L. Izoret, and A. Smith, "Valorisation of recycled concrete sands in cement raw meal for cement production," *Mater. Struct. Constr.*, vol. 50, no. 2, p. 333, 2017.

[24] S. Butera, T. H. Christensen, and T. F. Astrup, "Life cycle assessment of construction and demolition waste management," *Waste Manag.*, vol. 44, pp. 196–205, Oct. 2015.

[25] A. L. Empa, A. Beton, and H. Widmer, "Berechnung der CO 2 - Aufnahme während der Nutzungsdauer zementgebundener Baustoffe," 2018.

[26] S. Baetzner and R. Pierked, "Release and uptake of carbon dioxide in the life cycle of cement," 2007.

[27] F. Collins, "Inclusion of carbonation during the life cycle of built and recycled concrete: Influence on their carbon footprint," *Int. J. Life Cycle Assess.*, vol. 15, no. 6, pp. 549–556, Jul. 2010.

[28] E. Possan, E. F. Felix, and W. A. Thomaz, "CO2 uptake by carbonation of concrete during life cycle of building structures," *J. Build. Pathol. Rehabil.*, vol. 1, no. 1, p. 43, 2016.

[29] A. B. Bauchemie, "Kohlendioxidaufnahme von Stahlbetonbauten durch Karbonatisierung," 2012.

[30] T. Kikuchi and Y. Kuroda, "Carbon Dioxide Uptake in Demolished and Crushed Concrete," *J. Adv. Concr. Technol.*, vol. 9, no. 1, pp. 115–124, 2011.

[31] M. Thiery, P. Dangla, P. Belin, G. Habert, and N. Roussel, "Carbonation kinetics of a bed of recycled concrete aggregates: A laboratory study on model materials," *Cem. Concr. Res.*, vol. 46, pp. 50–65, Apr. 2013.

[32] EN 16757, *Sustainability of construction works - Environmental product declarations - Product Category Rules for concrete and concrete elements*. Berlin: Beuth Verlag GmbH, 2017.

[33] B. Lagerblad, *Carbon dioxide uptake during concrete life cycle – State of the art*, vol. CBI 2005:2, no. February. Stockholm: Cement- och betonginstitutet TS - Sweden National Library Libris T4 - State of the art M4 - Citavi, 2005.

[34] M. Buyle, J. Braet, and A. Audenaert, "Life cycle assessment in the construction sector: A review," *Renew. Sustain. Energy Rev.*, vol. 26, pp. 379–388, Oct. 2013.

[35] *SN EN ISO 14040:2006 Umweltmanagement - Ökobilanz - Grundsätze und Rahmenbedingungen*. SNV

Schweizerische Normen-Vereinigung, 2006.

[36] D. G. I. for S. DIN Deutsches Institut für Normung e. V., *DIN EN ISO 14044:2006 Umweltmanagement- Ökobilanz- Anforderungen und Anleitungen*. SNV Schweizerische Normen-Vereinigung, 2006.

[37] ISO/DIS 21930, "Sustainability in buildings and civil engineering works - Environmental declaration of building products (Draft version)." 2016.

[38] A. Passer *et al.*, "Environmental product declarations entering the building sector: critical reflections based on 5 to 10 years experience in different European countries," *Int. J. Life Cycle Assess.*, vol. 20, no. 9, pp. 1199–1212, Sep. 2015.

[39] A. F. Abd Rashid and S. Yusoff, "A review of life cycle assessment method for building industry," *Renew. Sustain. Energy Rev.*, vol. 45, pp. 244–248, May 2015.

[40] V. Augiseau and S. Barles, "Studying construction materials flows and stock: A review," *Resour. Conserv. Recycl.*, vol. 123, pp. 153–164, 2017.

[41] A. Petek Gursel, E. Masanet, A. Horvath, and A. Stadel, "Life-cycle inventory analysis of concrete production: A critical review," *Cem. Concr. Compos.*, vol. 51, pp. 38–48, Aug. 2014.

[42] P. Van Den Heede and N. De Belie, "Environmental impact and life cycle assessment (LCA) of traditional and 'green' concretes: Literature review and theoretical calculations," *Cem. Concr. Compos.*, vol. 34, no. 4, pp. 431–442, Apr. 2012.

[43] C. Dossche, V. Boel, and W. De Corte, "Use of Life Cycle Assessments in the Construction Sector: Critical Review," *Procedia Eng.*, vol. 171, pp. 302–311, 2017.

[44] A. Ehrenberg, "Methoden zur Bewertung des ökologischen Einflusses von Eisenhüttenschlacken," *Strasse und Autobahn*, no. 10, pp. 836–843, 2018.

[45] NSF, "NRMCA Member Industry-Wide EPD for Ready Mixed Concrete," 2016.

[46] "TECHNOLOGY ROADMAP," in *Encyclopedia of Production and Manufacturing Management*, Springer US, 2006, pp. 781–782.

[47] A. D. et al. Favier, "a Sustainable Future for the European Cement and Concrete Industry," 2018.

[48] A. J. Boero, A. D. Ramirez, D. A. Salas, J. Duque-Rivera, D. M. Petroche, and C. R. Rodríguez, "Environmental impacts, life cycle assessment and potential improvement measures for cement production: a literature review," *J. Clean. Prod.*, vol. 113, pp. 114–122, 2015.

[49] F. Xi *et al.*, "Substantial global carbon uptake by cement carbonation," *Nat. Geosci.*, vol. 9, no. 12, pp. 880–883, Dec. 2016.

[50] BS-EN197-1:, *Cement Part 1: Composition, Specifications and Conformity Criteria for Common Cements*, no. November. SIA swiss society of engineers and architects, Zurich, 2011, p. 50.

[51] SIA MB 2049, *Data Sheet 2049 Requirements for new cements*. SIA swiss society of engineers and architects, Zurich, 2014.

[52] R. Meglin and S. Kytzia, "Environmental Assessment in the Building Materials Industry: How Are the Results of Life-cycle-assessment (LCA) for Concrete Influenced by Technology and Regulations? (unpublished)," in *Fifth International Conference on Sustainable Construction Materials and Technologies (SCMT5)*, 2019.