CARBON DIOXIDE EMISSIONS OF RECYCLED CEMENT PRODUCTION

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ABSTRACT

The cement industry is presently facing the demanding challenge of reducing its large amount of carbon emissions in order to meet the targets set to fight climate changes. One recent, and very promising, approach to reduce the carbon footprint is the production of more eco-efficient recycled cement from cement-based waste materials. This study aims at comparing the difference in terms of energy consumption and carbon dioxide emissions between recycled cement and conventional clinker production. The results demonstrate that overall carbon dioxide emissions, considering both direct and indirect emissions, of the recycled cement are 23% lower than the conventional clinker cement.

KEYWORDS

construction and demolition waste, carbon dioxide emissions, recycled cement, clinker

1 INTRODUCTION

Concrete is the second most consumed material in the world, just falling short to water, with an estimated consumption of over 30 billion tonnes per year (WBCSD 2009; ISO/TC 071 2016). Throughout its lifecycle, it is responsible for two main environmental issues: i) at the early stages, the pollution resulting from the production of the components, in particular cement; and ii) at the end of the life-cycle, the substantial amounts of waste generated.

Carbon emissions, particularly in the form of carbon dioxide (CO_2) during the production of the cement are amongst the most relevant environmental issues related to concrete (BIO 2011). These high carbon emissions arising from the production of its main constituent, clinker, have two major sources: i) carbonate decomposition; and ii) oxidation of fossil fuels. The calcination stage (decomposition of $CaCO_3$ into CaO and CO_2 by the addition of heat) results in the release of large amounts of CO_2 to the atmosphere, since roughly 60% of the clinker raw material is comprised of carbonates (mostly limestone, $CaCO_3$). To attain sintering temperatures (roughly 1450ºC), large amounts of fossil fuels are burned. The reduction of CO_2 emissions in the production of Portland cement has been achieved by (Barcelo et al. 2014, Carriço et al. 2020): i) increasing energy efficiency in the production process; ii) using alternative fuels and/or biomass; iii) replacing clinker by other products; and iv) capturing and storing carbon.

Concrete makes a substantial portion the over 3 billion tonnes of construction and demolition waste generated worldwide per year (Akhtar and Sarmah 2018). New construction is only responsible for a small fraction of this amount, with the majority resulting from renovation and demolition (EPA 1998). To avert concrete waste going into landfills, many countries are effectively using it in other applications. Probably the most “noble” of the uses for concrete waste is its incorporation in new concrete as recycled aggregates. However, the mortar adhering onto their surface affects the concrete performance, namely due to higher water absorption, lower strength and increased chloride penetration (Martín-Morales et al., 2011). As such, in practice concrete waste if mostly used as backfilling material.

Tackling the construction and demolition waste and the cement production challenges simultaneously is possible through cement recycling. This solution is aligned with the circular economy plan devised in the EU (EC 2020; EEA 2020, Wahlström et al. 2020) by creating a closed-loop-recycling (ECRA 2017). At the same time, it will also contribute to meet the goal of re-using, recycling or recovering a minimum of 70% (by weight) of non-hazardous construction and demolition waste, excluding naturally occurring material (article 11.2 of the Waste Framework Directive (EC 2008)). In Europe, the partial or total replacement of Portlant clinker by recycled cement (RC) may play an important role in meeting the green deal targets (CEMBUREAU 2020).

This research effort aims at estimating the CO2 from the industrial implementation of a novel process for recycling cement and compare it with the typical reported emissions from Portland cement production.

2 CASE STUDY AND METHODOLOGY

The process for producing the RC presented herein was developed in the scope of the EcoHydb project funded by the Portuguese National Science Foundation and is based on the thermal reactivation of the cementious fraction of concrete waste. This is not new and a review on cement recycling using this approach can be found in Carriço et al. (2020). The biggest challenge of using this approach is how to separate the hydrated cement from the aggregates prior to the thermal reactivation. In fact, studies have been done mostly using cement pastes produced in the laboratory for research purposes. The novelty of the solution analyzed herein is the use of a patented magnetic separation method developed at IST (Bogas et al. 2020) that enables industrial application to real concrete construction and demolition waste.

Overall, the process developed for producing RC is comprised of three main stages: i) release; ii) separation; and iii) reactivation. The first stage consists in mechanically crushing, milling and grinding the concrete waste to promote the release of the cement paste from the aggregates. The implementation in laboratory conditions was set to produce material with less than 1 mm for the separation, which was then sieved to spilt into four fractions: i) 0.5 to 1 mm; ii) 0.25 to 0.5 mm; iii) 0.15 to 0.25 mm; and iv) less than 0.15 mm. This calibration resulted in a good balance between the amount of cement paste that can be separated and the fraction that is too small or too large to go through the magnetic separator. However, different settings may be more suitable in an industrial setup and depending on the concrete waste characteristics. In laboratory conditions, the material losses, corresponding to particles over 1 mm, were only approximately 2%. Since the efficiency of the magnetic separation process implemented in the laboratory was highly sensible to the presence of ultrafine powder, the material required washing and drying beforehand. The material loss in this stage was less than 1%, in laboratory conditions. The final stage consists in reactivating the cement paste by promoting the de-hydration of the cement compounds. In order to achieve this goal, the material undergoes heat treatment at a temperature of 600-700ºC, with an average value of 650ºC (Bogas et al. 2019, Real et al. 2020). The material loss in this stage was negligible in laboratory conditions. However, there is a reduction of about 20-25% in the waste cement weight due to the release of water from the hydrated cement paste. This reduction depends on the hydration degree of old waste concrete and it may be affected by the size of the cement paste particles and duration of the thermal treatment.

Figure 1 resumes the mass fluxes of the process implemented in laboratory. In each field, the values presented on top, middle and bottom represent the best, average and worst results in terms of RC obtained, respectively. The performance of the thermal treatment stage is constant since the degree of purity of the cement paste separated and the mass loss from the de-hydration of the cement compounds showed very little variability in the laboratory implementation.

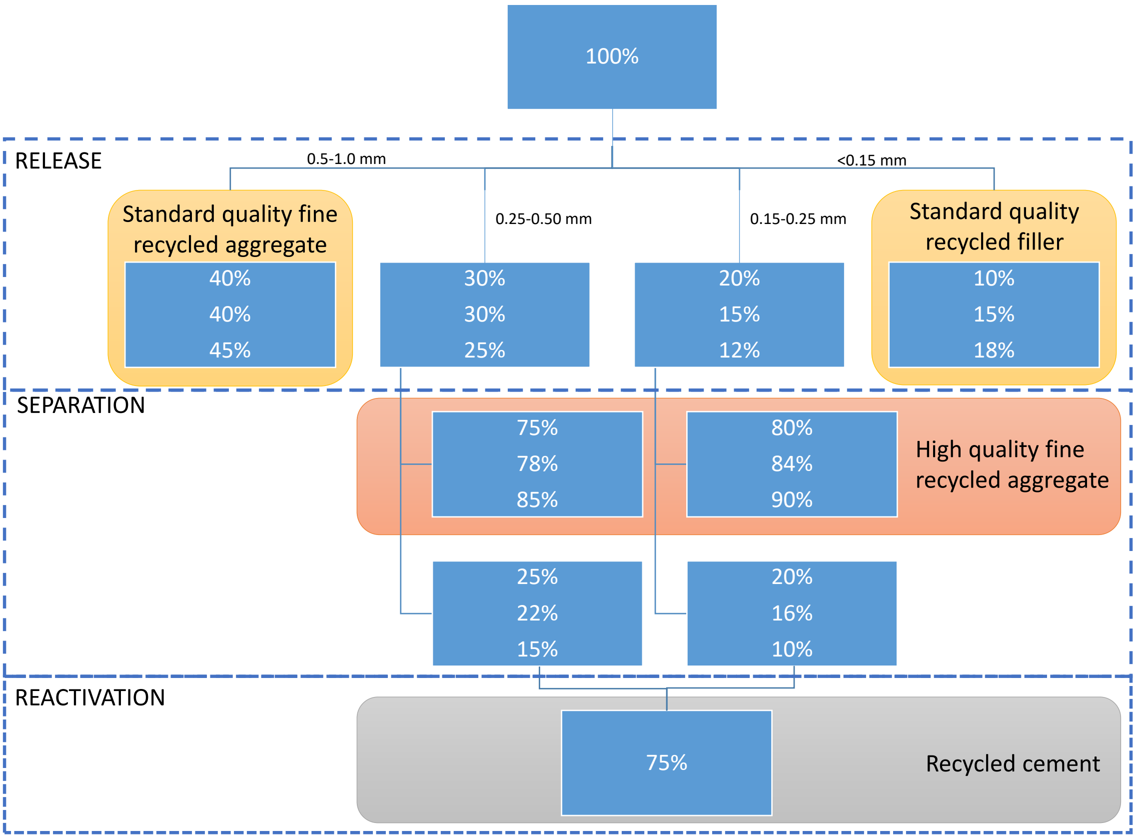

Figure 1 – Mass fluxes of the recycled cement production process (Sousa and Bogas 2021)

Two main approaches are available for extrapolating the laboratory results to an industrial setup: i) by simulation; and ii) by analogy. The first consists in mimicking the experimental setup at a larger scale by selecting and assembling a hypothetical production line. This requires considering that: i) the productivity advertised for the industrial equipment, which may have not been specifically tested for this application, is a good estimate of the real performance; and ii) the efficiency measured on the various stages at the laboratory scale do not change at the industrial scale. The underlying idea of the analogy approach is to extrapolate from a similar industrial process, in this case the production of the conventional Portland cement and the production of recycled and/or artificial fine aggregates, to the RC production. This alternative is restricted by the fact that some stages simply do not exist in any of the processes used for establishing the analogy, while others are distinct. There is, however, a third option of mixing simulation and analogy in a hybrid approach, by complementing the stages for which an analogy is not possible with simulation.

Herein, a hybrid approach was adopted the CO_2 emissions from an industrial implementation of the cement recycling process presented. The emissions from thermal processing were already estimated in another research effort (Sousa and Bogas, 2021), so the emissions from electricity consumption were obtained by analogy with clinker and aggregates production and simulation was used to estimate the emissions from transportation.

It is assumed that the release and separation stages will be done at the existing construction and demolition waste processing plants and the reactivation will be carried out in the existing cement plants. It is also assumed that the concrete waste used is already processed for use as backfill of concrete aggregates at the waste processing plants. So, the functional unit considered includes: i) the additional gridding and sieving of the concrete waste; ii) the separation of the cement paste from the aggregates; iii) the transportation of the cement paste to a concrete plant; and iv) the thermal processing.

3 RESULTS AND DISCUSSION

The average CO_2 emissions from thermal energy consumption the RC were estimated by Sousa and Bogas (2021) to be between 612 kg/t of RC and 646 kg/t of RC, depending on the estimation method. In the EU-28, this compares with emissions between 797 kg/t of clinker and 1011 kg/t of clinker from the thermal processing of clinker (carbonation plus fuels burning emissions), depending on the production technology. A weighted average of 815 kg of CO_2/t of clinker was estimated for the EU-28 in 2018 by GCCA (2018), but the emissions from fuel consumption is significant depending not only on the technology but also on the fuel mix used.

In 2018, an average of 116 kWh of electricity were consumed per tonne of cement produced in the EU-28 (GCCA 2018). In the same year, the average proportion of clinker in the cement produced was 75% (GCCA 2018), resulting in an electricity consumption of 154 kWh per tonne of clinker. The distribution of electrical energy consumption per stage of clinker production can be found in Medlool et al. (2011). Making the analogy between the stages that are common between the clinker and the recycled cement, it was assumed the following:

1) The energy for the additional crushing and sieving of the concrete waste was assumed, conservatively, to be half of the energy required to prepare the clinker raw material. Not only the raw material of the clinker has to be grinder more, but the mechanical properties are higher.
2) The energy consumed in the oven and kiln was estimated making a proportion with the temperature required (400ºc in the drying oven, 700 in the thermal processing kiln). This are conservative estimates, since neither the drying oven nor the thermal processing kiln require average temperatures this high.
3) The energy for gridding the RC was assumed, conservatively, to be half of the energy required for the clinker. This is the stage in the clinker production consuming the highest amount of

electricity due to the toughness of the clinker and the size of the particles required for the final material.

The magnetic separation stage does not exist in the clinker production process, but a magnetic roll separator consumes only 1 kWh/t of material processed. The electricity consumption estimates for the production of the RC are presented in Table 1.

Table 1 – Electricity consumption for clinker and RC production

Clinker production	**Proportion [%]**	**Consumption [kWh/t clinker]**	**RC production**	**Proportion [%]**	**Consumption [kWh/t RC]**
Raw material preparation			*Release*		
Extraction	2	3			
Preparation	24	37	Crushing and sieving	57	145
			Separation		
			Washing and drying	18	45
			Magnetic separation	1	4
Thermal processing			*Reactivation*		
Kiln	29	45	Kiln	12	30
Coal mill	7	11	Coal mill	3	7
Cement processing					
Gridding	31	48	Gridding	9	24
Packaging	7	11			
Total	**100**	**154**		**100**	**254**

Considering that, in 2017, the average CO_2 emissions for producing electricity in the EU-28 was 294 g/kWh (EEA, 2017) and the emissions from land transportation was 140 g/t.km (EEA 2017). Considering an average distance of 200 km between the construction and demolition waste treatment facilities and the cement plants, the total emissions for clinker and RC are presented in Table 2. The RC allows for an average CO_2 emissions reduction of over 23% comparing to the clinker.

Table 2 – Total CO_2 emissions from clinker and RC production

Stage	**CO2 emissions [kg/t]**	
	Clinker	**Recycled Cement**
Thermal energy	815	629
Electrical energy	45	75
Transport		28
Total	**861**	**732**

4 CONCLUSIONS

Cement is simultaneously a largely consumed material worldwide with high CO_2 emissions in its production, resulting in significant contribution to the global CO_2 emissions. Additionally, concrete make up a large portion of the construction and demolition waste generated. Therefore, attempting to recycle cement using a green technology may contribute to solve these two problems.

The present research effort demonstrates that the RC production process developed under the scope of the EcoHydb project funded by the Portuguese National Science Foundation allows for reducing the CO_2 emissions by 15% in comparison with the clinker production. These saving are highly conservative and there is the potential for a significant increase if a dry production process can be implemented. Avoiding the washing and drying of the material prior to the magnetic separation would reduce the CO_2 emissions from thermal energy consumption in the RC production from 629 kg/t to roughly 115 kg/t.

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