TECHNICAL TRANSACTIONS 10/2017
CZASOPISMO TECHNICZNE 10/2017

CIVIL ENGINEERING

DOI: 10.4467/2353737XCT.17.176.7284

Anna Sobotka (sobotka@agh.edu.pl)
Joanna Sagan
Department of Geomechanics, Civil Engineering and Geotechnics, Faculty of Mining and Geoengineering , AGH University of Science and Technology

An environmental life-cycle assessment of selected concrete recycling processes

Ocena środowiskowa wybranych procesów recyklingu betonu

Abstract
Social and economic development trends require that the economy be based on sustainable consumption and sustainable production patterns by means of implementing an effective recirculation policy – this is also important from an environmental perspective. Consequently, the design of economic processes becomes increasingly complex. This paper presents method and results of environmental life-cycle assessment of selected stages of the concrete recycling process. The results will be used in a further, holistic assessment of managing the concrete waste on the construction site.

Keywords: LCA, RCA, sustainable construction

Streszczenie
Społeczno-gospodarcze trendy rozwojowe, wymagają aby gospodarka oparta była na zrównoważonej konsumpcji oraz zrównoważonych wzorcach produkcyjnych, poprzez prowadzenie efektywnej gospodarki recyrkulacyjnej – również w wymiarze środowiskowym. Dlatego też, projektowanie procesów gospodarczych przyjmuje coraz to bardziej złożony charakter. Artykuł prezentuje metodę i wyniki oceny środowiskowej wybranych etapów procesu recyklingu betonu. Rezultaty posłużą do dalszej – holistycznej oceny wariantów gospodarowania odpadami betonowymi na budowie.

Słowa kluczowe: ocena środowiskowa, kruszywo z recyklingu betonu, zrównoważone budownictwo

1. Introduction

The transformation of current production and consumption methods requires adopting a circular economy paradigm which in practice means the implementation of return chains – this is based on the logistics of recycling and the closing of the classical (linear) supply chain [4].

The circular economy concept has already been successfully implemented in many industries, including within the construction industry; the next challenge is to improve the effectiveness of the economic processes [2]. Regarding effectiveness, one should remember the triad of sustainable development – economic, environmental and social aspects. Consequently, the production processes should be designed and optimised based on a multi-criterion analysis which includes an environmental assessment [9]. The goal of the paper is to identify the scale of environmental effects of the concrete recycling process at a construction site and to determine the significant variables and parameters for unit processes – this was achieved by conducting a case study. The description of the assessment methodology forms an extensive part of the paper. In the studied case, the assessment results provided a clear indication as to the organisation of the recycling processes which have the least environmental impact.

2. Research methodology

The research methodology is based on a classical systemic approach using the LCA method [1, 5]. The concrete recycling system was separated and divided into unit processes which are interconnected and connected with surroundings via the input and output values. Thus, the assessment of the environmental impact of recycling is a summary assessment of the impact of individual unit processes. The assessment is consequently a 'gate-to-gate' type. The assessment was made using the *GaBi* software from *Thinkstep* which contains comprehensive *GaBi* databases with worldwide coverage as well as *Ecoinvent* data [7].

2.1. Goal and scope of assessment

The goal of the investigation was to perform a comparative analysis of the environmental effects of concrete recycling processes for various sets of machines. The assessment was simplified (it was based on average values, the main source of data was the literature); nonetheless, by analysing varied parameters, it enabled the identification of key decision variables and parameters which significantly determine the environmental impact of the process. The scope was limited to (and focuses exclusively on) the assessment of the recycling processes carried out directly on site using mobile jaw crushers. There were four unit processes within the system boundaries – preparatory operations, principal operations, accompanying operations, and final operations, these are graphically presented in Fig. 1.

It was assumed that the processing of debris would result in obtaining a 0–63 mm ungraded aggregate. The assessment was made for four crusher types with varying parameters (Table 1)

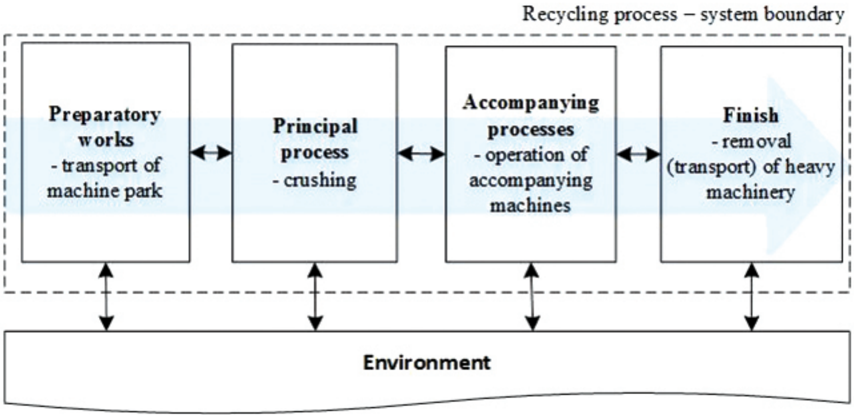

Fig. 1. Concrete recycling system with mobile machinery

for the following boundary conditions: crusher transport distance 200 km; amount of debris to be recycled 100 Mg. The analysis enabled the identification of the most advantageous solution for the studied case.

Table 1. Parameters of assessed crushers

Variant (crusher)	Crusher weight [kg]	Average crushing capacity [Mg/h]	Engine power rating [kW]	Standard
K1	1,400	10	10.8	Stage III A
K2	2,900	17.5	29.6	Stage III A
K3	10,000	40	52.0	Tier IV
K4	27,800	125	168	Stage III A

The recycling process starts with setting up the on-site recycling process line which entails the transport of machines – a crusher and, if not already present on site, an excavator/loader (in the studied case, there was already an excavator on site). The next assessed stage is the principal process – concrete crushing. The remaining components of the process which require assessment are the operation of the excavator which loads the debris and the finishing processes, i.e. removal of machine (crusher only) from the site.

2.2. Life-cycle inventory

The analysis of input and output set was performed on data from literature and was supported by the *GaBi* database. Table 2 presents the sources of input and output data relating to the transport unit processes for various types of crushers to and from the site (preparatory and finishing processes).

In the accepted transport model, the input values for unit processes are diesel and cargo (crusher). The outputs are cargo (crusher) and combustion emissions such as ammonia, benzene, carbon dioxide, carbon monoxide, methane, nitrogen monoxide, nitrogen dioxide, nitrous oxide, NMVOC, particulate PM 2.5, sulphur dioxide etc. Truck production, end-of-life treatment of the truck and the fuel supply chain are not included in the data set.

Table 2. Parameters for assessment of crusher transport

Variant:	Crusher 1	Crusher 2	Crusher 3	Crusher 4
Database	diesel driven, Euro 3, cargo;			
	up to 3.3t p.c.*		up to 11.4t p.c.	up to 27**t p.c.
Common parameters:	Distance: 200 [km]. driving share: 0.5 motorway, 0.33 rural, 0.07 urban. Other: default			
Individual parameter – payload:	1.4 [t]	2.9 [t]	10 [t]	27 [t]

**p.c.-payload capacity; **no data for larger payload.*

The sets of inputs and outputs were determined based on the literature data, including the valid stage and tier emission standards for diesel engines [6] and assuming limit of emissions (s_n). Emissions from the engine (output) and average fuel consumption (input) per megagram of produced concrete aggregate are given in Table 3.

Table 3. Parameters for assessment of crushing process

Variant	Emissions to atmosphere [g/Mg]			CO_2 [kg/l]	Fuel consumption [l/Mg]
	CO	$HC+NO_X$	PM		
Crusher 1	7.13	8.1	0.43	3.2 kg	0.2
Crusher 2	9.3	12.69	1.01		0.29
Crusher 3	6.93	6.52	0.55		0.27
Crusher 4	4.7	5.38	0.27		0.16

Furthermore, the crushing process results also in emissions of PM and PM10 dust from the process of the mechanical grinding of concrete. In the case of crushing dry material with jaw crushers, the average emissions are [8]: PM – 0.32 [g/Mg]; PM10 – 0.15 [g/Mg]. For crushing wet material, the average emissions are: PM – 0.16 [g/Mg]; PM10 – 0.07 [g/Mg].

The input data for the excavator operation model includes diesel and excavated material. Outputs are combustion emissions due to engine operation and are comprised of regulated emissions (NOx, CO, Hydrocarbons and Particles), fuel-dependent emissions (CO_2, SO_2, benzene, toluene and xylene) and others such as CH_4 and N_2O. Emissions due to machinery production, end of life, and the fuel supply chain was excluded. The parameters of selected excavator operation variants are given in Table 4.

In the case of all unit processes, the environmental load from fuel consumption was calculated using the database, *EU-27 Diesel mix at refinery*.

All the used items of data are highly comparable in terms of time and geography. As far as completeness of *input* and *output* data was assured, only the crushing processes are unverified – these are partially based on assumptions. The major part of the *inputs* and *outputs* set is based on data from literature (68.7%) and on calculations (26.4%).

Table 4. Parameters for the assessment of excavator operation

Variant		Loading 1	Loading 2	Loading 3	Loading 4
Database		Excavator, 100 kW, construction*			
Common parameters:		Material bulk density: 1.8 [t/m³] Fuel consumption (operating): 10 [kg/h] Other: default			
Individual parameters	Bucket capacity [m³] :	0.3	0.5	1.1	2
	Load factor [–]:	0.3	0.4	0.6	0.9
	cycles_min [1/min]:	0.3	0.32	0.4	0.57

* Due to the presence of the excavator on site, the same model was used for different variants

3. Results

The recycling processes were assessed using the ILCD methodology, recommended by the Joint Research Centre (JRC). More information about the selected method can be found in [3]. The set of results only shows selected environmental impact indicators: GWP (Fig. 2),

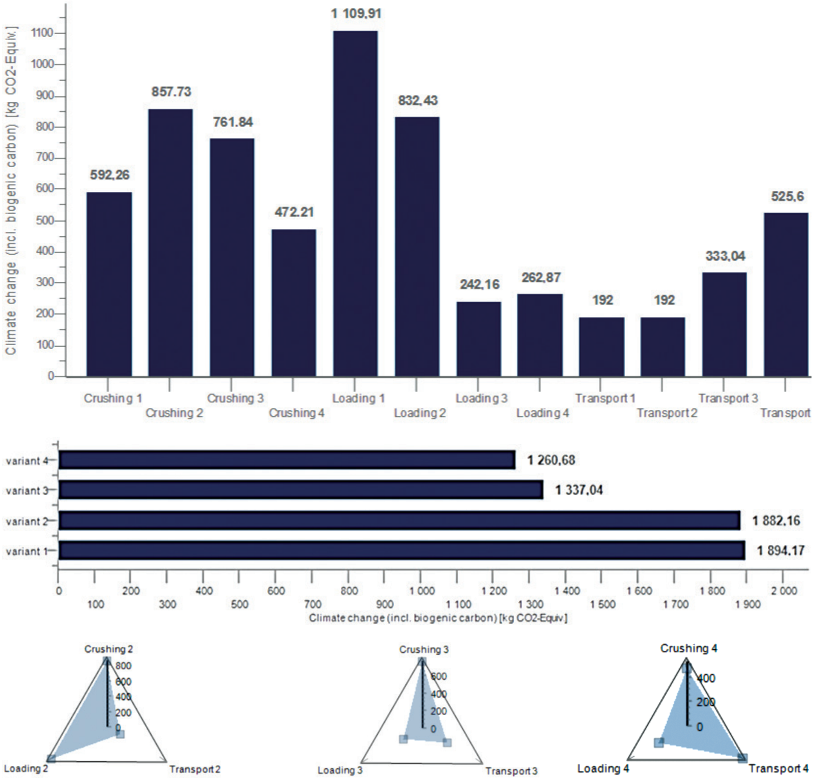

Fig. 2. Global warming potential (GWP): a) for unit processes, b) for individual variants, c) variation of unit processes in selected variants

particulate matter (Fig. 3) and POCP (Fig. 4) – for all unit processes and the impacting factors for individual variants. In the model, the efficiency and power of the excavator is constant – this approach has facilitated inference about the variable capacity of the crusher and has led to interesting conclusions.

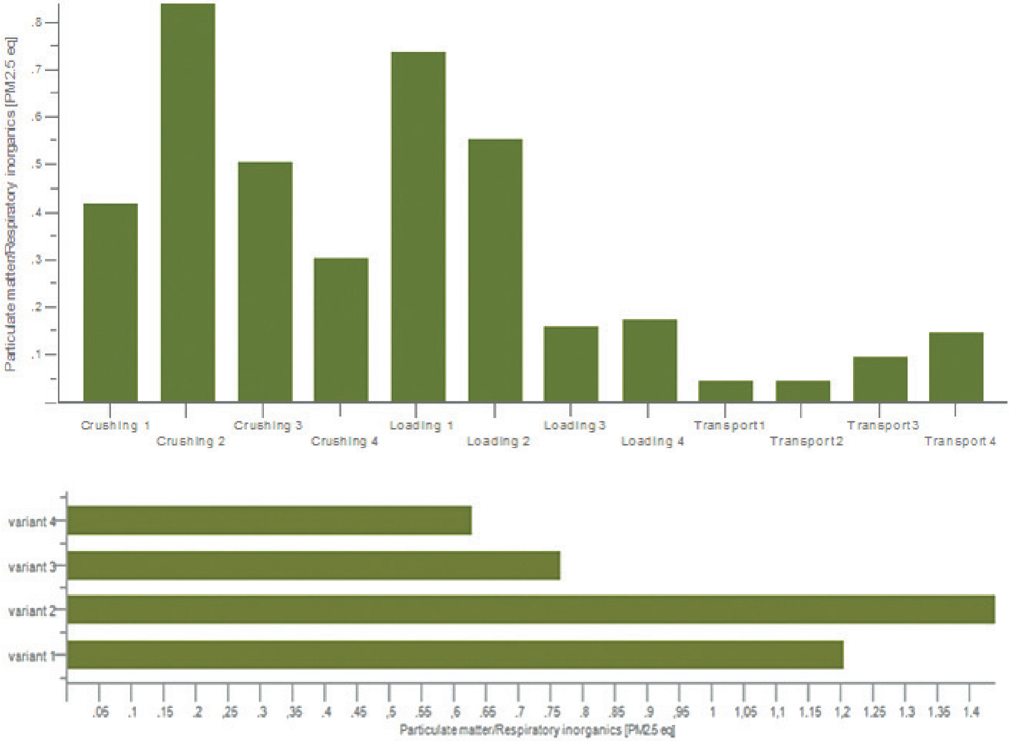

Fig. 3. Particulate matter: a) for unit processes, b) for individual variants

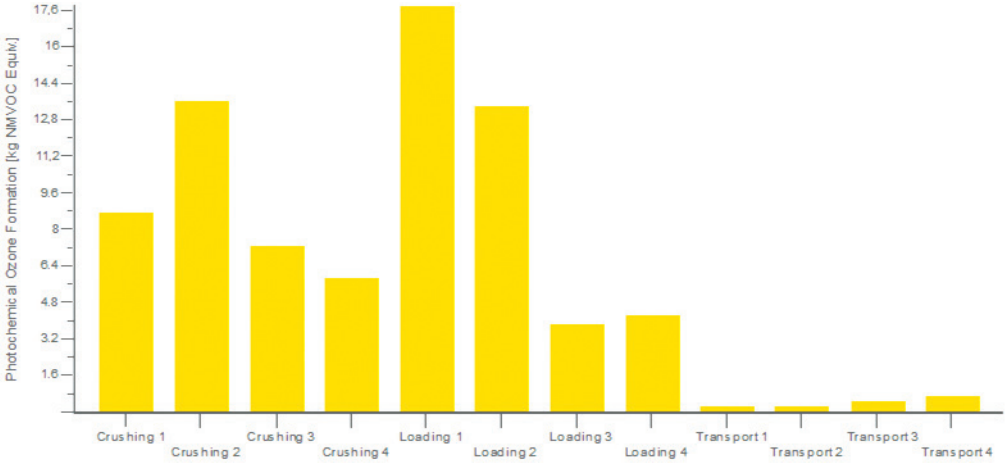

Fig. 4. Photochemical ozone creation potentials (POCP) for unit processes

Adopting a powerful excavator model and equipping it with low-capacity crushers (variants 1 & 2) causes the entire system to become environmentally inefficient – attention is drawn to the intensification of the companion process *loading 1* and *loading 2* (GWP: 1109.91 and 832.43 kg CO2-eq.), which cannot be compensated even by the transport process (for a given distance, GWP: 192 kg CO2-eq).

The most advantageous solution for the given conditions is option 4, the use of machines of relatively high efficiency and large dimensions, even with the intensification of the transport process for this variant (GWP: 525.6 kg CO2-eq). This is due not only to the high efficiency of the operation of the crusher (the lowest GWP, PM, POCP) but also effective cooperation with the excavator. Due to the individual parameters of the model, the results are not comparable with data from the literature.

4. Summary and conclusions

The recycling of concrete using the described technology has an impact on the environment, particularly contributing to global warming, emissions of particulate matter, and the creation of photochemical smog. The burning of fuel to power the construction machines and transport vehicles constitutes a significant share of the carbon dioxide emissions. It is not possible to explicitly indicate the process in the entire recycling process which has the largest environmental impact – this is evidenced by the varied load level of the unit processes in the different variants (Fig. 2c). Furthermore, the environmental loads of the unit processes and their share in individual variants were indeed dependent upon numerous parameters – distance to transport equipment, amount of debris, relationship between fuel consumption and the effectiveness of the crushing process, engine class, road quality, etc. – these relationships will be studied in further analyses.

The result of the environmental assessment of the excavator and loader operation is interesting. Effectiveness does not depend on the productivity of individual machines but on their effective cooperation. The oversized excavator in variants 1 and 2 made the whole system environmentally ineffective. This example confirms the importance of the correct selection of accompanying machines to the principal process not only because of the economic effectiveness – this relationship is generally known – but also in relation to the environmental issues.

References

[1] Adamczyk W., *Ekologia Wyrobu – jakość, cykl życia, projektowanie,* PWE, Warszawa 2006.

[2] European Commission, *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and Committee the Regions. "Resource efficiency opportunities in the building sector"*, EC, Brussels 2014.

[3] European Commission Joint Research Center, Institute for Environment and Sustainability, *International Reference Life Cycle Data System (ILCD) Handbook – General guide for LCA*, Publications Office of EU, Luxembourg 2010.
[4] Hosseini M., Chileshe N., Rameezdeen R., Lehmann S., *The Crucial Role of Design for Reverse Logistics (DfRL) and Harvesting of Information (HoI) in Reverse Logistics Systems*, The 4th International Conference on Engineering, Project, and Production Management (EPPM 2013), Bangkok 2013.
[5] Kowalski Z., Kulczycka J., Góralczyk M., *Ekologiczna ocena cyklu życia procesów wytwórczych (LCA)*, PWN, Warszawa 2007.
[6] Kruczyński W., Chrupek B., Wojs M.K., *Metody ograniczania poziomu emisji stosowane w silnikach maszyn budowlanych w świetle wymagań norm emisji spalin: Stage IIB/Stage IV*, Zeszyty Naukowe Instytutu Pojazdów, vol. 1(97), 2014, 109–118.
[7] PE INTERNATIONAL, *GaBi Paper Clip Tutorial*, Leinfelden-Echterdingen 2013.
[8] Texas Commission on Environmental Quality, *Emissions Calculation Spreadsheet* (APDG 6253v2, Revised 10/14).
[9] United Nations – General Assembly, *Transforming our World: The 2030 Agenda for Sustainable Development*, NYC 2015.