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Life cycle assessment of construction and demolition waste management

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ABSTRACT

Life cycle assessment (LCA) modelling of construction and demolition waste (C&DW) management was carried out. The functional unit was management of 1 Mg mineral, source separated C&DW, which is either utilised in road construction as a substitute for natural aggregates, or landfilled. The assessed environmental impacts included both non-toxic and toxic impact categories. The scenarios comprised all stages of the end-of-life management of C&DW, until final disposal of all residues. Leaching of inorganic contaminants was included, as was the production of natural aggregates, which was avoided because of the use of C&DW. Typical uncertainties related to contaminant leaching were addressed. For most impact categories, utilisation of C&DW in road construction was preferable to landfilling; however, for most categories, utilisation resulted in net environmental burdens. Transportation represented the most important contribution for most nontoxic impacts, accounting for 60–95 per cent of these impacts. Capital goods contributed with negligible impacts. Leaching played a critical role for the toxic categories, where landfilling had lower impacts than utilisation because of the lower levels of leachate per ton of C&DW reaching the groundwater over a 100-year perspective. Leaching of oxyanions (As, V and Sb) was critical with respect to leaching. Typical experimental uncertainties in leaching data did not have a pivotal influence on the results; however, accounting for Cr immobilisation in soils as part of the impact assessment was critical for modelling the leaching impacts. Compared with the overall life cycle of building and construction materials, leaching emissions were shown to be potentially significant for toxicity impacts, compared with contributions from production of the same materials, showing that end-of-life impacts and leaching should not be disregarded when assessing environmental impacts from construction products and materials. CO_2 uptake in the C&DW corresponding to 15 per cent carbonation could out-balance global warming impacts from transportation; however, carbonation would also likely result in increased toxicity impacts due to higher leaching of oxyanions.

1. Introduction

Construction and demolition waste (C&DW) is one of the major waste types in modern society. Concrete and masonry debris, constituting the largest fraction of C&DW in Denmark (Danish EPA, 2011), is typically utilised as mineral aggregate. While utilisation as aggregate in new concrete still has some technical limitations related to the shape and properties of crushed concrete, resulting in poor workability of the new concrete and thus increasing the need for cement (e.g. González-Fonteboa and Martínez-Abella, 2008), crushed C&DW is most usually utilised as unbound aggregate in road construction applications (Hendriks and Janssen, 2001). While this practice avoids landfilling and consumption of alternative virgin resources used in construction, leaching from the utilised C&DW may result in waterborne contaminants potentially affecting subsoil and groundwater resources. In the past 25 years extensive research has focused on quantification of contaminant release from C&DW (e.g., Butera et al., 2014, 2015a; Engelsen et al., 2009, 2010; van der Sloot, 2000, 2002) as well as on the methods used for quantification of the release (e.g., Kalbe et al., 2008; Kosson et al., 1996, 2014; van der Sloot et al., 2008).

Life cycle assessment (LCA) is a methodology to assess the potential environmental impacts of a product or a system by

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Abbreviations: ADP_E, abiotic resource depletion potential for elements; ADP_F, abiotic resource depletion potential for fossil; AP, acidification potential; BA, bottom ash; C&DW, construction and demolition waste; CF, characterisation factor; ET_{FW}, ecotoxicity to freshwater; FEP, freshwater eutrophication potential; GWP, global warming potential; HT_C, human toxicity, carcinogenic; HT_{NC}, human toxicity non-carcinogenic; IR, ionising radiation; L/S, liquid to solid ratio; LCA, life cycle assessment; LCIA, life cycle impact assessment; MEP, marine eutrophication potential; MSWI, municipal solid waste incineration; ODP, stratospheric ozone depletion potential; PM, particulate matter; POF, photochemical ozone formation; TEP, terrestrial eutrophication potential; TS, total solid.

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accounting for the environmental exchanges (emissions, consumption of reagents and energy) over the entire life cycle of the product or system (details about LCA concepts and methodology can be found in e.g. Wenzel et al. (1998) and Hauschild and Wenzel (1998)) for a number of so called "impact categories", such as e.g. global warming potential, resource depletion and toxicity. LCA has been widely used over the past years to assess, among others, waste management systems (e.g. Christensen et al., 2010; Manfredi et al., 2011), and within waste management, LCA has been applied to quantify and compare potential environmental impacts related to recovery, utilisation, and final disposal of waste materials. Although several LCA studies have evaluated the environmental aspects of buildings and building materials (e.g., Buyle et al., 2013; Gursel et al., 2014; Lupsea et al., 2012; Stripple, 2001), relatively little effort has been made to systematically assess the environmental impacts associated with management and utilisation of C&DW in construction works: some published studies have not included leaching emissions (e.g., Ibáñez-Forés et al., 2011; Koletnik et al., 2012), and most have disregarded toxicity-related impacts entirely (e.g. Blengini and Garbarino, 2010; Blengini, 2009; Coelho and de Brito, 2012; Kucukvar et al., 2014; Loijos et al., 2013; Mercante et al., 2011). To the extent that leaching has been included in LCA studies, it has typically only been applied to a limited number of contaminants, or based on leaching data that is not necessarily consistent with the actual leaching scenarios (e.g., Chowdhury et al., 2010; Olsson et al., 2006; Toller et al., 2009). Several LCA studies of utilisation and management of mineral residues, such as municipal solid waste incineration (MSWI) air pollution control residues or bottom ash (BA), have shown that leaching may be critical for the outcome of LCA studies (Birgisdóttir et al., 2006, 2007; Carpenter et al., 2007; Eskola et al., 2001; Fruergaard et al., 2010; Mroueh et al., 2001).

However LCA modelling of leaching from mineral residues utilisation scenarios presents a range of methodological challenges. The leaching emissions may be accounted for in different ways: the leachate may be assumed to be released directly into a soil compartment (Chowdhury et al., 2010) or directly into a water compartment (Olsson et al., 2006; Toller et al., 2009). Due to the way in which leaching has been modelled thus far in LCA, the potential immobilisation processes in the subsoil immediately below the mineral residue layer – for example, a road construction scenario – have not been taken into account, apart from two recent studies for MSWI BA and different granular secondary materials (Allegrini et al., 2015; Schwab et al., 2014). In the context of C&DW, this might be particularly critical for Cr, which has been identified as one of the elements of main concern in leachates from C&DW in relation to utilisation in construction works (Butera et al., 2014, 2015a; van der Sloot, 2000; Wahlström et al., 2000), and which has been shown to be retained by subsoils (Butera et al., 2015b). Furthermore, ageing and carbonation of cementitious C&DW during storage may affect leaching of the materials (e.g., Mulugeta et al., 2011), but may also lead to significant CO_2 uptake after the initial crushing process owing to the smaller particle size, and therefore larger surface area (e.g., Engelsen et al., 2005). These effects have not yet been addressed within LCA modelling of C&DW management.

In addition to the abovementioned material- and leaching-specific aspects, other more general limitations of LCA studies have not been evaluated in relation to LCA of C&DW: in particular, exclusion of impacts from capital goods (i.e. the construction of treatment facilities), and lack of uncertainty assessment. Both aspects have been demonstrated as critical in relation to LCAs of solid waste management (Brogaard, 2013; Laurent et al., 2014) but have yet to be evaluated with respect to C&DW. Overall, while C&DW can be considered technically appropriate for utilisation in construction works, and is de facto used for such purposes, the environmental consequences related to this utilisation have not yet been assessed in a comprehensive manner.

The overall aim of this paper is to quantify, based on LCA, the potential environmental impacts associated with C&DW utilisation in road construction. The results are compared with landfilling of C&DW, which is the only alternative disposal option, and evaluated with respect to critical methodological aspects including: (i) the variability of experimental leaching data, (ii) the importance of emission pathways and potential immobilisation processes occurring in subsoil, with specific focus on Cr, (iii) the importance of C&DW carbonation, and (iv) the choice of marginal technology for production of virgin aggregates. Finally, the results for the end-of-life phase are discussed with respect to potential transportation distances and the full life cycle of construction products.

2. Methodology

2.1. Goal, scope and time horizon

The goal of the LCA was to evaluate the environmental impacts related to the end-of-life phase of the mineral fraction of construction and demolition waste (that is, concrete and masonry debris, hereafter referred to as C&DW) in the two hypotheses of either utilisation as unbound aggregate in road construction or landfill disposal. The functional unit was the management of 1 Mg of C&DW (1 Mg C&DW) as obtained after source–segregation at the demolition/construction site; the material includes concrete, possibly mixed with soil, tiles, bricks and mortar. Other material fractions potentially present in C&DW (e.g. plastic, paper, gypsum, wood and metal) were not included, as a consequence of the source–segregation step carried out during the demolition process in accordance to Danish legislation.

The LCA was conducted according to a consequential approach (EU JRC, 2010), meaning that it studied the consequences caused by a change in the modelled system. The modelled change was the treatment of 1 additional Mg of C&DW. Following common practice within LCA, a time horizon of 100 years was selected. Even though roads typically have life-times of 20–40 years (Birgisdóttir, 2005; Stripple, 2001), they are rarely dismantled after the end of their lifetime. Road sub-base layers are therefore likely to remain, suggesting that a time horizon of 100 years may be appropriate and represent the "foreseeable future". Any impacts after the 100 years were not included.

While the geographical scope of the assessment was limited to Danish conditions (for instance, the precipitation rates, marginal technologies, and type of subsoil in the subgrade affecting the fate of emitted pollutants), evaluation of the importance of key assumptions and methodological choices (such as variability of leaching, carbonation levels, and transportation) may allow the result to be applicable to other contexts as well. The temporal scope of the assessment was 2015–2030.

2.2. Scenarios

The system boundaries extended from the construction, demolition or renovation site (however excluding the demolition phase itself) until final disposal of all residues. Two parallel end-of-life scenarios were analysed:

(a) Utilisation of 1 Mg C&DW in road construction, as a filler material in road sub-bases.
(b) Disposal of 1 Mg C&DW in a mineral landfill.

Included within the system boundary was the following: transport and treatment processes, followed by either utilisation in road