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Identifying hotspots of environmental impact in the development of novel inorganic polymer paving blocks from bauxite residue

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ABSTRACT

High bauxite residue content inorganic polymer paving blocks have the potential not only to provide a solution to the ongoing waste management issues faced by the alumina sector, but to simultaneously provide low environmental impact building materials to the construction sector. In order to realise the potential of this emerging technology, it is important to understand where the hotspots of environmental impact are likely to occur, and identify routes to reduce this impact, at an early stage of development. In this study we use anticipatory Life Cycle Assessment (LCA) to identify hotspots of environmental impact in the production of paving blocks made from inorganic polymers derived from bauxite residue. This technology has only been demonstrated at laboratory scale; however, production was modelled at industrial scale. The bauxite residue is fired in a rotary kiln in the presence of a carbon and silica source, in order to create a reactive precursor. When mixed with an alkali the precursor forms a solid block. Our results identify the firing process as the major hotspot of environmental impact, primarily due to the combustion of fossil fuels in the rotary kiln. Steps to reduce the impact of the firing step or to reduce the amount of fired precursor used in the final paving block are suggested as routes for future impact reduction. Optimisation of the environmental aspects of these building materials at an early stage in their development could lead to a promising future for high-volume bauxite residue valorisation at low environmental cost.

1. Introduction

The production of building materials from bauxite residue (BR) has a number of potential benefits. BR is an unavoidable residue resulting from the first stage of aluminium production, and as such its management has long been a concern of the alumina industry (Evans, 2016). Diverting BR from current landfill practices and utilising it as a secondary resource is seen as an important aspiration for the future of BR management (ibid.). Recycling of BR into building materials offers a high-volume valorisation pathway for this waste. At the same time, there is increasing demand from the construction industry for building materials which demonstrate high environmental performance. Both BREEAM[1] and LEED[2], the two leading sustainable construction accreditation schemes, contain requirements to consider and minimise the life cycle environmental impact of the materials chosen and encourage the use of materials with a high level of recycled material content (BRE Global, 2016; USGBC, 2017). Use of industrial residues, such as BR, in place of virgin materials in the production of building materials is

Abbreviations: AC, terrestrial acidification; FE, freshwater eutrophication; FT, freshwater toxicity; GW, global warming; HT-C, human toxicity - carcinogenic effects; HT-NC, human toxicity - non-carcinogenic effects; IR-A, ionising radiation - artificial radionuclides; IR-N, ionising radiation - NORM (releases to environment); NORM, naturally occurring radioactive materials; ME, marine eutrophication; OZD, ozone layer depletion; PM, particulate matter formation; POC, photochemical ozone formation; RD, resource depletion; BR, bauxite residue; IP, inorganic polymer; LCA, life cycle assessment; LCI, life cycle inventory; LCIA, life cycle impact assessment; LCPD, life cycle process design; BREEAM, building research establishment environmental assessment method; LEED, leadership in energy and environmental design

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potentially consistent with both of these requirements. At a higher level, the European Commission has set out an EU wide action plan for the Circular Economy (European Commission, 2015), which stresses the importance of secondary raw materials being fed back into the economy, and commits to promote innovative industrial processes in which the wastes of one industry become the inputs to another.

The presence of supply-side, demand-side and policy-level drivers for the utilisation of BR in building products indicates that the stage is set for the development of innovative technologies for high volume utilisation of this abundant secondary resource. However it is of vital importance that these technologies offer a more sustainable approach than the situation today. It is unwise to naively assume that 'waste valorisation' or 'circular economy' approaches are more sustainable than conventional approaches. Indeed questions have been raised as to the validity of the fundamental assumptions which underpin the circular economy concept (De Man and Friege, 2016), and life cycle assessment studies of some closed loop systems have shown that in practice they can lead to a higher overall environmental impact than their conventional counterparts (Bjørn and Strandesen, 2011).

It is therefore important to understand the life cycle environmental performance of new technologies for BR utilisation at an early stage in their development in order to minimise the impact caused and maximise the benefit achieved. The identification of potential hotspots of environmental impact is an important first step in this process. In this study we investigate the environmental performance of one emerging technology for high volume valorisation of BR as a building product – the production of inorganic polymer paving blocks.

Recent research has confirmed that BR can be transformed into inorganic polymers (Hertel et al., 2017, 2016). Inorganic polymer products have the potential to be utilised as high performance building materials (Duxson et al., 2007b). A novel solution for creating high BR content inorganic polymers suitable for use in paving applications has been proposed by Hertel et al. (2016), based on lab-scale results. From a technical perspective, this approach has a great deal of potential, however the sustainability issues associated with this solution are yet to be assessed.

The EU Waste Framework directive (Council Directive 2008/98/EC art. 4, (European Commission, 2008)) makes clear that while the Waste Hierarchy[3] should be applied in priority order, measures should aim to deliver the *'best overall environmental outcome'* based on *'life-cycle thinking on the overall impacts of the generation and management'* of the waste. Focusing any study on the goal of landfill diversion alone would necessarily be mute on broader sustainability issues, and may not deliver the best overall environmental outcome. Similarly, for users of products derived from secondary materials, a life cycle approach to the assessment of the environmental performance of the materials is desirable. Indeed, both BREEAM and LEED specifically refer to life cycle approaches in the assessment of sustainable materials (BRE Global, 2016; USGBC, 2017).

Thus, for both producers of waste and users of waste derived products, Life Cycle Assessment (LCA) is an important tool for understanding the potential environmental impact of products and processes from a holistic perspective. Applied properly it can be used to highlight major sources of impact and suggest alternative, more environmentally sustainable approaches to both product and process design (Hellweg and Milà i Canals, 2014).

Regardless of whether the study is product or process focussed, the timing of the study falls prey to the 'design paradox' (Ullman, 1997). In short, at the earlier stages in the design or development process, there is more scope for change in the design but knowledge of the specifics of the design is uncertain. In the latter stages of the process the reverse is true; knowledge of the design is very good, but the ability to make changes to it is much more limited. From the perspective of life cycle assessment, this poses a particular problem, as 'product knowledge' is analogous to the availability of reliable life cycle inventory (LCI) foreground data. Early in the design process, where the conclusions and recommendations of an LCA are potentially most useful, the data they are based on is of relatively poor quality. Conversely, as the data quality improves as knowledge of the design increases, the ability to make changes based on the LCA results decreases.

One possible solution to the design paradox which is particularly suited to research and development, advocated by Wender et al. (2014), is to incorporate *anticipatory LCA* at multiple stages in the research process. Rather than a major 'one shot' study this approach allows iterative changes to be made throughout the course of the research and development process. Another possible solution is to base the LCA not on primary data collected from experiments that have been conducted at bench scale, but on mathematical models of the process, grounded in the experimental data but designed to represent full plant scale. This approach has been productively applied to identify hotspots at early stages in process design in many cases, including biofuels (Brentner et al., 2011; Gerber et al., 2011; Guo et al., 2014), biorefinery processes (Fazeni et al., 2014), and gasification technology (Gasafi et al., 2003). In this study we combine both approaches.

The aim of this study is to identify potential hotspots of environmental impact in the production of paving blocks from novel high BR content inorganic polymers, with a view to identifying opportunities to reduce this impact prior to the final development of the technology. In order to achieve this, we apply the anticipatory LCA methodology to the early stages of the development of the technology. The results of this study will be of benefit to the engineers and scientists developing the technology. The LCA is based on laboratory scale experiments modelled to represent full scale production. This study represents the beginning of an ongoing process of assessment throughout the development of this technology.

2. Background

2.1. Inorganic polymers as building materials

Inorganic polymers, and the closely related geopolymers, are binders: substances which as a result of a chemical reaction form a solid matrix in which aggregates can be entrained. The term geopolymer was introduced by the French scientist Joseph Davidovits in the 1970s (Davidovits, 1991) for an amorphous alkalialuminosilicate binder formed by the reaction of an aluminosilicate precursor, such as metakaolin, with an alkali(-silicate) solution. The mixing of the solid precursor with the alkali activating solution, to start the polymerisation reactions, is referred to as 'activation'. The dissolved aluminate and silicate species form gels when oversaturation is reached and further condensation and rearrangement leads to the formation of a 3D network where tetrahedral Al and Si are connected via oxygen bridges (Duxson et al., 2007a). A simplified representation of this process is shown in Fig. 1.

Inorganic polymer is a more general term than geopolymer, and can be considered a *supergroup* with a deviation from the original aluminosilicate chemistry. Inorganic polymers (or IP) therefore also encompass other precursor materials, for instance, metallurgical slags, rich in Fe (Komnitsas et al., 2007; Onisei et al., 2012) among various other residues or wastes (Provis et al., 2015). As binders, inorganic- and geopolymers draw attention because of their satisfying properties, often surpassing those of conventional binders, such as high fire resistance, high compressive and flexural strength, and chemical resistance (Duxson et al., 2007b; Lloyd et al., 2012).

In addition to their excellent material properties and the potential of using various waste streams as raw material, Van Deventer et al. (2010) highlights the potential for alkali activated materials (a further, higher classification of binders of which inorganic polymers form a part) as a

[3] The Waste Hierarchy: 1. Prevention, 2. Preparing for reuse, 3. Recycling, 4. Other recovery 5. Disposal