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Integrated policies to promote sustainable use of steel slag for construction—A consequential life cycle embodied energy and greenhouse gas emission perspective

H.W. Kua*

Department of Building, School of Design & Environment, National University of Singapore 4 Architecture Drive, S117566 Singapore, Singapore

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ABSTRACT

Steel slag is a by-product of steelmaking and is usually disposed of in landfills. Recent development in sustainable concrete saw the use of steel slag as a replacement for sand in concrete mixture. This study applied attributional and consequential life cycle assessment to deduce the net environmental impacts – measured in terms of global warming potential and embodied energy – due to replacing sand with steel slag. It was found that, considering both mass and economic allocation methods, steel slag generally has more negative life cycle environmental impacts. However, by considering three likely consequences of this material replacement (resulting in changes in international trade in sand and steel slag) and that certain sustainable steelmaking technology innovations were adopted, it was found that such a replacement may result in a net reduction in environmental impacts. To ensure that this material replacement results in lower global warming and also ensure resource security, a mathematical expression was derived that enables us to estimate how much Singapore's sand trade has to change. To apply lessons learnt from these assessments to integrated sustainability policymaking, the environmental, economic and social related challenges were discussed and possible solutions proposed.

1. Introduction: Sand, steel slag and the application of life cycle assessment

Concrete – one of the primary materials in buildings and civil engineer structures – is the second most consumed product on earth, after water [1]. One of its compositions is fine aggregate, whereby sand is the dominant choice. The heavy reliance on sand, a natural material, inherently creates an issue of sustainability as extensive mining worldwide inevitably results in global resource depletion. Due to the lack of sand quarries in Singapore, all sand used in Singapore has to be imported. The ban of sand export by Indonesia in 2007, and the subsequent bans by Cambodia and Vietnam in 2009, raised doubts about the dependability of foreign sand supply. It also directly encouraged local authorities to consider the possibility of replacing sand with more sustainable alternatives. One such replacement encouraged in early 2007 was steel slag (SS).

SS is the by-product of the steelmaking process. It is a non-metallic ceramic material formed from the reaction of flux such as calcium oxide with the inorganic non-metallic components present in the steel scrap. The possible utilization of slag as a building material was explored as early as 1873 when a paper was presented to the Royal Society of Arts in the United Kingdom on methods of casting molten slag into blocks and the production of bricks and mortar [2]. Thereafter, in-depth studies into utilizing slag as concrete aggregates were carried out by researchers, such as Gutt, Kinniburgh & Newman [3] and Everett & Gutt [4]. These studies revealed that slag concrete was stronger in both transverse and compressive strength than gravel concrete and similar to limestone concrete. However, slag concrete was found to be more vulnerable to corrosive sulphate attacks.

Using of SS has a long history in the United States. By 1918, the United States was producing 40 million tons of pig iron a year, with an estimate output of 20 million tons of slag [5]. Two main types of SS that are widely used for construction and civil engineering projects are basic oxygen furnace (BOF) SS and electric arc furnace (EAF) SS. Both types of SS are commonly blended with granulated slag, fly ash and lime to form pavement material, skid resistant asphalt aggregate and unconfined construction fill. The U.S. Department of Interior and U.S. Geological Survey estimated that about 19 million tons of iron and steel slag are sold annually for use in construction with a commercial value of USD 150 million.

* Tel.: +65 93695985.
E-mail address: bdgkuahw@nus.edu.sg

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In Japan, recent restrictions imposed on dredging of marine sand and decreasing sources of sand from overseas has prompted sales of slag as aggregates for making concrete mixture. Specifically, under the 2002 Green Purchasing Law, blast furnace slag aggregates became a widely procured building material; this trend was later seen for SS from electric arc furnace in 2005. In the building industry, these materials are highly regarded as environmental-friendly materials that help to reduce waste generation and embodied energy of buildings [6].

In Singapore, prior to 1994, SS was treated as a type of industrial waste and all SS produced were disposed in landfill sites due to its lack of use. However, the successful engineering of SS into aggregates for asphalt mix in 1994 allowed 100% of the SS generated to be fully recycled as wearing course in asphalt mix used for road resurfacing. Currently, the application of SS is mainly limited to road construction and studies are still been carried out to determine its suitability for building construction.

As SS gains popularity as an effective building material around the world, it is important to fully understand not only the environmental benefits one can reap from using SS but also its life cycle environmental impacts, as compared to the material it is used to replace. The National Slag Association of the United States engaged environmental scientists and toxicologists to conduct a human health and ecological risk assessment of slag [7]. Based on worst case exposure assumptions, it was found that iron and steel slag poses no negative threat to human health or the environment when used in a variety of residential, agricultural, industrial and construction applications. However, environmental sustainability of SS cannot be merely assessed according to these indicators. For instance, the greenhouse gas (GHG) emissions and embodied energy (EE) of SS should be examined carefully as well. Furthermore, a material that has lower environmental impact when it is being utilized may still have significant impacts during other stages of its life cycle.

Life cycle assessment (LCA) is a tool widely used to consider a product's environmental performance throughout its entire life cycle [8]. There are two main types of LCA—Attributional and Consequential LCA. Attributional LCA (ALCA) focuses on describing the environmentally relevant physical flows to and from a product or process, while consequential LCA (CLCA) describes how relevant environmental flows will change in response to possible decisions. In other words, CLCA enables one to understand the *net* environmental impacts from, for example, material substitutions by expanding the system boundaries of the materials studied; one example of such an expansion is considering the change in demand or/and supply of the material that has been replaced in the global market. For this study, both ALCA and CLCA were utilized for the purpose of a more in-depth assessment of the environmental impacts of replacing sand with SS for making concrete, and comparison between the results of ALCA and CLCA.

The available literature on LCA for SS is limited. Among those found, most are based on partial ALCA and there was no available literature on the application of CLCA on evaluating the environmental impacts of SS. For example, Norgate et al. [9] explained that the limited availability of suitable data for a full 'cradle-to-grave' approach, together with time constraints for sourcing such data, were their reasons for conducting a partial 'cradle-to-gate' ALCA which excluded the raw material acquisition, use and end of life stages. Iosif et al. [10] a did 'gate-to-gate' ALCA with system boundaries that focus solely on the steelmaking process. Although the environmental impacts such as the carbon dioxide emissions of inputs, intermediate products, by-products, and product were quantified in a detailed manner, the research focused solely on life cycle inventory (LCI) analysis and life cycle impact assessment (LCIA) was not done.

To date, applications of CLCA to assess the environmental impacts of building materials by extending their system boundaries have been rare. Emerging CLCA studies on recycled building materials include those on copper slag (see [11,12]). More recently, CLCA has also been applied to study possible consequential impact of replacing concrete with clays bricks [13] and replacing concrete with secondary steel [14]. These studies, to some extent, highlight the usefulness of doing ALCA and CLCA concurrently to give a fuller picture on the possible environmental consequences that will help policymakers design effective sustainable material policy strategies to tackle specific problems.

However, to date, no CLCA has been done on the replacement of sand with SS. This paper aims to fill this second knowledge gap in the literature, by focusing on the evaluation of EE (measured in MJ per kilogram (kg) of material) and GHG emissions (measured in terms of global warming potential, GWP, with the unit of $kg_{CO_{2-eq}}$ per kg of material). The results also serve as an important guide for industry leaders and policymaking authorities with regards to selecting SS as a building material and on how to promote it as a more sustainable material choice.

2. Research methodology

Although the geographical scope of this study is Singapore, the approach and methodology we employed can certainly be applied to another scope. The functional unit considered is 1 kg of sand. It is important to note that the replacement of 1 kg of sand by SS is not based on a one-to-one ratio in mass but in volume. The density of SS in Singapore is about 1950 kg/m^3. On the other hand, the density of sand is much lower at around 1650 kg/m^3. Taking into account the material densities, the ratio of replacement was taken as 1:1.18; that is, 1.18 kg of SS is required to replace 1 kg of sand.

In the step of LCIA, the characterization factors for various inputs were taken from Guinée et al. [15].

2.1. System boundary of steel slag

The system boundaries for both the ALCA for both SS and sand included all the life cycle stages from raw material acquisition to the point before the material is ready to be transported onsite for use in construction projects. For completeness, additional life cycle stages were also described below but only the main and significant ones were studied for the final results.

Each of the main life cycle stages within the system boundary considered for SS was described as follow:

(i) *Secondary steelmaking process (and extraction of SS):* While small amount of SS is imported into Singapore, it is not utilized as a building material due to the level of contaminations. Therefore, in this study, only SS produced from manufacturing of secondary steel is considered. All the scrap iron needed for making secondary steel is either imported or obtained locally. For SS, the acquisition of scrap is taken as the "raw material" acquisition stage. SS is produced during the separation of the molten steel from impurities in the EAF. As SS only constitutes part of the output produced by the steelmaking process, there is a need to allocate the life cycle environmental impacts to SS proportionately.

As a form of sensitivity analysis, we used both the mass- and economic-based allocation technique. In mass-based allocation, since we know that for every kilogram (kg) of steel produced, about 90 grams (g) of SS is obtained, we allocate 9% of the environmental impact of steel to SS [16]. In economic-based allocation, we allocate the environmental impacts of SS according to its "proportion" of price compared to secondary