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Evaluation of environmental impact distribution methods for supplementary cementitious materials

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ABSTRACT

As the world's most widely used construction material, the production of concrete has been recognized to lead to major environmental impacts. To promote sustainability in the concrete industry, various kinds of supplementary cementitious materials (SCMs), such as fly ash, blast furnace slag and silica fume have been used to replace cement in concrete production. The nature of these SCMs has therefore been changed from wastes to co-products or by-products. Life cycle assessment (LCA) has been increasingly adopted in the concrete industry to assess environmental sustainability. However, the choice of an appropriate method for impact distribution in the LCA of concrete incorporating SCMs is a research challenge. This study aimed to present a comprehensive review of the impact allocation approaches for assessing the environmental impacts of SCMs-incorporated concrete. Furthermore, the use of the system expansion approach was compared with the conventional mass and economic allocation approaches. A case study of concrete production using SCMs in Hong Kong was conducted using the different approaches. The results were then analyzed and it was concluded that the system expansion approach is appropriate for the assessment of the environmental impacts of SCMs-incorporated concrete.

1. Introduction

Since environmental sustainability is a paramount concern in the modern era, the production of environmentally benign products are encouraged in nearly all industrial sectors. As one of the major greenhouse gases (GHGs) emission intensive industries, the construction industry is responsible for significant environmental problems and natural resources depletion [1,2]. Consequently, the development of sustainable construction materials is highly demanded [3,4]. Life cycle assessment (LCA), a well-established technique [5,6], has been extensively used to evaluate environmental impacts and serves as a decision support tool at both the business and political levels [7].

Concrete is one of the most commonly used construction materials. The annual consumption rate of concrete is around 25 gigatonnes globally (over 3.5 tonnes per capita) [8]. The production of cement, a key component of concrete, has attracted much attention in the LCA area, due to its energy-intensive production process that produces huge amounts of GHGs [9,10]. Worldwide, the cement industry contributes to 5–10% of the total anthropogenic GHGs emissions [11], and 12–15% of total industrial energy use [12]. The environmental consequences of cement manufacturing can be local, regional or global in scale [13]. In addition to global CO_2 emissions, the cement production process generates SO_2 and NO_x which are considered to have regional environmental impacts, and dust emissions as a local impact [14]. The cement industry is also blamed for its global impacts of non-renewable resource depletion, such as fossil fuels, limestone and clay.

To date, due to increasing sustainability concerns in the construction sector and to produce more durable concrete, it has been a common practice to produce concrete with cement replacements by the so-called supplementary cementitious materials (SCMs). SCMs are originally generated as industrial wastes or by-products. The most commonly used SCMs are fly ash (FA), granulated blast furnace slag (GBFS) and silica fume (SF). They are widely used in blended cement [15–18], concrete batching [19–26] and concrete products [27,28]. When recycled and reused, they are not disposed of in landfills and their associated environmental impacts can be avoided. In addition, this can also reduce the demand for non-renewable resources of fossil fuel and limestone. As such, the status of SCMs in LCA has changed from wastes to by-products or co-products and their environmental impacts should then be accounted for and allocated in the LCA methodology [29].

Until now, three types of allocation approaches have been employed for assessing the environmental impacts of SCMs-incorporated concrete [30]: allocation by mass value, economic allocation and no allocation (considered as waste and allocation are avoided). As the status of SCMs

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Nomenclature

CLCD	Chinese life cycle database
CLP	China Light and Power
CO_2	Carbon dioxide
FA	Fly ash
FeSi	Ferrosilicon alloy
FU	Functional unit
GBFS	Granulated blast furnace slag
GHGs	Greenhouse gases
HK$	Hong Kong dollars
ISO	International Organization for Standardization
Kg	Kilogram
Km	Kilometre
LP	Limestone powder
LCA	Life cycle assessment
LCI	Life cycle inventory
MD	Mix-design
M-E	Combined mass and economic allocation
MPa	Megapascal
MPA	Mineral Products Association
N-E	Combined no and economic allocation
N-M	Combined no and mass allocation
N-M-E	Combined no (without), mass and economic allocation
NO_x	Nitrogen oxides
OPC	Ordinary Portland cement
SCMs	Supplementary cementitious materials
SO_2	Sulphur dioxide
SF	Silica fume
t	Tonne
B_i	Environmental impacts of the by-product *i*
A	Allocation coefficient (mass/economic)
x	Type of allocation
SP_i	Environmental impacts of the secondary process
Ti	Environmental impacts due to the transport
I_{mP}	Environmental impact of the main product
$Mass_i$	Mass fraction of the by-product *i*
$Mass_{mP}$	Unit mass of the main product *mP*
B_{imass}	Total environmental impacts due to mass allocation
$\O_i$	Allocation coefficient (mass)
γ_i	Allocation coefficient (economic)
$\mathcal{E}$	Fluctuation index (price)
$\$_i$	Unit price of the by-product *i*
$\$_{mP}$	Unit price of the main product
B_{iecon}	Total environmental impacts due to economic allocation
β	Binding capacity
K	Specific coefficient for each SCM
Env	Environmental impacts
CEM I	Cement type I (e.g., OPC)
X	Environmental impacts of supplementary material

is no longer wastes, the first two allocation approaches should be adopted in the LCA of SCMs-incorporated concrete. Unfortunately, these allocation approaches are not used in the current LCA practices. This is because the environmental impacts of concrete or concrete products incorporating SCMs are much higher than the normal concrete or concrete products using only conventional Portland cement as the binder [29,31]. Therefore, conflicts between practitioners and researchers in terms of choice of allocation approach occur as it is impractical and unreasonable for practitioners to declare that their SCMs-incorporated concrete yields higher environmental impacts.

In order to fulfil the research gap and facilitate the application of LCA in the concrete industry, this paper presents a comprehensive review of the current situation of selecting different LCA approaches for SCMs-incorporated concrete. This is followed by analyzing the appropriateness of using multi-functional modelling approaches of SCMs. Furthermore, the use of the system expansion approach was compared with the conventional mass and economic allocation approaches. A case study on assessing SCMs and concrete in Hong Kong is presented to corroborate the assessment.

2. Literature review

In LCA, allocation means the partitioning of input or output flows of a process to the product system, or simply, the partition of the environmental impacts according to the ratio of mass or economic value between the product and the by-product(s). The environmental impacts distribution procedure in LCA is described by the ISO 14044 standard as follows: (i) allocation should be avoided by dividing the unit process into sub-processes or system expansion, if possible, or (ii) allocation should be partitioned based on the physical relationship (by mass or energetic value) among the products and co-products, or their economic functions or values [6]. On the basis of the above, two allocation procedures have been proposed including allocation by mass value (called mass allocation), and allocation by economic value (called economic allocation) [29,30]. Allocation by mass refers to the division of environmental impacts according to the mass ratio of the main product and by-products, whereas the partition of the environmental impacts based on the economic value is called economic allocation. Besides the above two approaches, no allocated impacts of SCMs have been used by some researchers since SCMs are recycled and reused in cement or concrete as constituents to replace natural materials [19,32].

However, according to the Directive of the European Union, a substance or object can be regarded as a co-product or by-product (rather than waste), if it fulfils the following conditions: (i) its further use is certain, (ii) it can be used directly without any further processing other than normal industrial practices, (iii) it is produced as an integral production process, and (iv) it will not lead to adverse environmental or human health impacts [33]. As SCMs (e.g. FA, GBFS and SF) fulfil the conditions indicated above, SCMs should belong to by-products and the environmental impacts from producing the main products should be allocated to SCMs when these SCMs are used in concrete or concrete products. However, according to ISO [6], allocation should be avoided by applying the system expansion approach. In the literature, several LCA studies on environmental impact assessment have been conducted on concrete or concrete product production using SCMs. Table 1 lists the existing LCA studies using different approaches and Table 2 presents the details of the methodological aspects of these LCA studies.

Pushkar and Verbitsky [54] reported the environmental impacts of producing different concrete mixtures using blended cement (e.g. cement produced with FA, GBFS and limestone powder). Different allocation approaches were adopted to show the variation of the results, and they found that SCM concretes had about 15–55%, depending on the types of SCMs used, higher environmental loads than ordinary Portland cement (OPC) concrete. Hossain et al. [31] assessed the environmental impacts of concrete paving block production using recycled aggregates, FA and cement, and found that SCMs-incorporated concrete block had about 60% higher respiratory effects, 30% higher GHGs emission, and 38% higher non-renewable energy consumption when mass allocation was adopted.

Chen et al. [29] conducted a comparative study on environmental impacts between SCMs (FA and GBFS) and Portland cement using different application approaches. When mass allocation was selected, it was found that when compared to OPC, about a 165% and 495% higher global warming effect was associated with the use of GBFS and FA, respectively. The corresponding energy consumption was 346% and 744%, respectively for GBFS and FA. Similar results were found for