Life Cycle Assessment on Alternatives Concretes and Cementitious Materials

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Abstract The utilization of industrial and agricultural waste materials can be an alternative as cementitious material to reduce the carbon dioxide (CO_2) emission from cement production and will lower other environmental impact. In recent years, more research has been done using life cycle assessment (LCA) on construction material production to understand the energy usage and its environmental impacts to find the possible low energy usage and green building alternatives. Several LCA studies have been reviewed in this paper that mainly are the concretes and cementitious material. Hence, this study will provide new perspectives of the methodology used in the environmental assessment by researchers in the world that compare to the International Organization for Standardization (ISO) LCA standards (ISO 14040:2006 and ISO 14044:2006). Comparing LCA studies to ISO guidelines ensures that all of the important factors in LCA are achieved, and the lack of use of these guidelines will impair the qualities of life cycle interpretation and data assessment.

Keywords Secondary cementitious material · Environmental impact · ISO guidelines

1 Introduction

The spike in the human population globally contributes to industrialization, urbanization, and economic development, which subsequently increased demand for housing and infrastructure. There are increment in global cement manufacture from 2.284 billion tons in 2005 to 4.1 billion tons in 2018 and soon 45% more cement will be

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produced by 2050 than current production [1]. Estimation about 50% of the world's carbon dioxide (CO_2) gas emissions come from the cement industrial which the manufacture of one ton of ordinary Portland cement (OPC) produces around half tons of CO_2 gas and involved other 0.39 tons of CO_2 gas in fuel emissions for raw materials processes [2]. However, despite the release of CO_2 gas as main criteria used in the assessment of environmental impacts, there are also further environmental impacts were assessed such as fresh water and marine ecotoxicity, photochemical oxidation, ozone depletion, eutrophication, acidification, and human toxicity [3–5].

To reduce the utilization of natural resources and environmental impacts in cement manufacture, any use of waste materials from other industries could be a potential alternative to cement. Some of these waste materials will display a compliant characteristic due to their chemical composition could be used in building materials manufacture [1]. Due to the huge quantity of biomass ash produced, the rising use of biomass for sustainable energy production has encouraged research into the substitution of traditional Portland cement with biomass ash by-products [6]. Some useful waste will be utilized as supplementary cementitious material (SCM) for example by recycling industrial wastes such as fly ashes (FA), blast furnace slag, and some agricultural wastes. In years, there has been extensive interest in finding to solve the difficulties of managing the industrial waste dump, construction waste, and land pollution and there are more research groups working on the application of green building materials (GBMs) in engineering construction [7]. Comparing the conventional building materials (CBMs) with the GBMs, it is more ecological, healthy, recyclable, and also high performance. Therefore, throughout its life cycle analysis including the resource used, manufacturing, operation, disposal, and recycling, the type of material that low influences towards the environment and human health can be determined [8].

Life cycle assessment (LCA) has been an important methodology and is widely used to facilitate the transition towards sustainable development by considering entirely various other potential environmental impacts related with the stages of a product life cycle respectively [9]. Basic of LCA contains three mainly phase which are the identification and evaluation of system boundary, functional unit and analysis timelines.

2 Methodology

The LCA was performed in accordance with standardization by the International Organization for Standardization (ISO), ISO 14040 and ISO 14044, which refer to the LCA of any product, whereas EN 15978:2011 is specific to construction products. Validation of data and analysis for LCA on various secondary cementitious materials can be accomplished using a variety of software and life cycle impact assessment methods. SimaPro is a software extensively used among researcher and it also uses different kind of impact assessment methods such as Eco-Indicator 99 method, ReCiPe v1.12 (H) and the Centrum voor Milieukunde Leiden (CML) methods that was recommended by EN 15978:2011. The Eco-Indicator 99 studies the 11 impact categories in three main endpoint categories; human health, ecosystem quality, and depletion of resources, and meanwhile because of to a non-specific method for the Chilean context and its global scope, ReCiPe was chose [10–13].

Another commercial LCA modelling was completed using GaBi software and the impact assessment was done using the CML 2016 method; it provides information on the environmental issues connected with the contributions and productions of any product [14]. Besides commercial software, other LCA modelling software used is EASETECH which was developed at the Technical University of Denmark (DTU) in Denmark, and the impact assessment incorporated by the European Commission's suggested the midpoint impact categories in the International Reference Life Cycle Data System (ILCD) Handbook [6].

The process of conducting an LCA consists of few steps and the initially step is the goal of study; objectives of the study (intended application) and targeted audiences. Then, the scope of study consists of functional unit, system boundary, the justification of the system boundary, and distribution procedures. Next, life cycle inventory includes data assessment such as location coverage, raw material sources, relation data to functional unit, data quality, data uncertainty, and data disaggregation. Then, life cycle impact assessment and lastly life cycle interpretation provides restriction and recommendation of the study [15, 16]

3 Comparison Results and Analysis

Table 1 shown an overview of origin and research product that has been reviewed and the research papers selected mainly are concrete and cementitious related materials.

The checklist of LCA procedure according to the ISO standard has been retrieved from previous research paper [15]. Table 2 shown the results comparison of all these ten LCA for cement and concrete to ISO standard guidelines.

3.1 Goal

Definition of the goal of study must be defined in early stage of the study and clearly state. A research without clear definition goal of study will influence the methods and its impact assessment [16]. All of the research paper reviewed clearly state the goal of study and the main goal of LCA study is to evaluate the potential environmental benefits and material sustainability due to alteration or substitution materials in the cement mixture. The impact of biomass secondary cementitious material or ecological aggregates added in the cement mixture to produce concrete were caught the researcher's interest besides the impact of waste management (resource) and human health.

Table 1 Overview of LCA studies

Origin	Product	References
Campania, South Italy	Concrete mixtures using recycle aggregate i.e., marble sludge, incinerator ashes, blast furnace slag, and construction and demolition waste (CDW)	[11]
Qatar	Cement mortar (waste carbon black, WCB)	[14]
Western Europe	Portland cement	[10]
Chile	Supplementary cementitious material (copper treated tailings, TT)	[17]
Brazil	Wood bio-concrete	[12]
Ontario, Canada	Concrete mixture, supplementary cementitious materials (i.e., slag, silica fume and metakaolin)	[18]
Netherlands	Cement mortars, secondary cementitious material (biomass fly ash)	[6]
Malaysia	Concrete (Mixture of Granulated Blast-Furnace Slag, GBFS and fly ash, FA)	[19]
United State (11 western state)	Mixed mortar (containing the 13 different blended binders)	[20]
United Kingdom	Concrete mix designs: 100% PC and various ratio of CEM II and CEM III with FA and GBFS	[21]

Intended audiences was neglected by most of researchers, only few papers clearly address the intended audiences that will provide them new insights from these environment assessment reports. The targeted audiences included are policymakers, concrete manufacturers, the construction industry and academics, future developer and building designer will benefits on the environmental implications of replacing conventional material [12, 18].

3.2 Scope

Generally, the scope of study consists of functional unit, system boundaries and assumption or scenario to rationale the system boundaries. Functional unit and system boundaries have been identified in all paper research, but the rationale for the system boundary is not clearly stated in most papers. The functional unit is known as the reference to which inputs and outputs are related and ensure the reliability of LCA results for alternative projects. Meanwhile, the system boundaries limits which unit processes should be included within the LCA, cut-off criteria, application reliability and the hypothesis made [5]. LCA is increasingly being used to analyse the potential implications of various waste and residue treatment methods [22].

Table 2 Results comparison between 10 LCA research papers to ISO standard guidelines

ISO standard guidelines	10 LCA research papers		
	State unambiguously	State but not clear	Not defined
Goal			
Objectives of the study	10		
Targeted audiences	2		8
Scope			
Functional unit	7		3
System boundary	8	1	1
Rationale of system boundaries	5	4	1
Explicit allocation procedures	2		8
Life cycle inventory			
Time-related, technology coverage, geographical	6	4	
Sources of data inventory; *Primary sources* *Secondary sources*	8 6	4	2
Uncertainty of data/information	4		6
Relation of data—functional unit	3	2	5
Quality data assessment; *Completeness analysis* *Consistency analysis* *Sensitivity analysis*	3	1 1	9 10 6
Data disaggregation	1	9	
Life cycle impact assessment			
Impact models (indicators, categories, and characterization)	9	1	
Classification of LCI results	8	1	1
Characterization of category indicator results (calculation)	9	1	
Life cycle interpretation			
Identification of the significant issues (LCI or LCA results)	7	2	1
Conclusion	9	1	
Limitation	5	3	2
Recommendation	6	2	2

3.2.1 Functional Unit

Functional unit quantifies the primary function by providing a basis of comparison to the input and output data. This reference is particularly important when comparing different systems to approve that such evaluations are made on a constant basis [16].

In cement and concrete studies, the functional units are commonly compared on a volume basis as 1 cubic meter (1 m^3) and material properties such as compressive strength, mechanical strength, workability, and durability [18]. There are some hypothesis or assumption being made to ensure the comparisons unit valid such as the cement content and the functional performance of the concrete were constant [11], biomass enter to the systems with zero burden assumption [6] and concretes were sold in volumetric basis [21].

3.2.2 System Boundaries

The system boundaries is the interface between the product and the environment system and also define the processes and life cycle stages [23]. It defines which activities will be included in the product system and is usually clearly illustrated. For concrete and cement production, the processes in the system boundary include energy, environmental discharges, and flows of material (inputs and outputs) [10]. Commonly researcher choose cradle-to-gate model system [17]. Six of the research papers illustrated the system boundaries and one research paper refer system boundaries as reference scenario.

3.3 Life-Cycle Inventory (LCI)

The LCI step includes producing an inventory of flows from and to nature for a product system and all system boundary's unit processes are quantified [16]. Inventory tables usually are extensive and it begin with the contributions and productions throughout the life cycle will be compiled and quantify, and then feed data into the software. This should include all of the materials and processes that were defined in the system boundary. Finally, after the various processes, the calculation of tabulated numerical values of the inputs and outputs will be displayed related to the concern of the environmental impact [21].

LCI information generally derived from two sources: primary data and secondary data and researcher can be used one or two sources for LCA and must be related to functional unit [15]. Most of researcher conducted the LCI primary data in laboratory, Environmental Product Declaration (EPD), during inspection to the manufacturing and recycling sites. If the primary data unavailable, the researcher were opted to use database such as Ecoinvent from SimaPro and database of GaBi software.

Sensitivity analysis has been done for data quality assessment because several assumptions were made during research. To assess the influence of these assumption, the most sensitive parameter must be identified. Four of the research papers completed the sensitivity analysis including of these parameters; transportation distance [17], constrained SCMs [18], leaching from second life, density leaching from landfill, infiltration rate, layer, production of additional OPC [6], various fuels used in the calcination and allocation processes of biomass [12]. Another data quality assessments are consistency analysis and completeness analysis, none of researchers done the consistency analysis and only one researcher done completeness analysis which provide information is sufficient to reach conclusions. A good quality of dataset should provide all three types analysis for data quality assessment.

3.4 Life-Cycle Impact Assessment (LCIA)

The LCIA assesses the impact of operations on the environment, resources, and human health by categorization and characterization of LCI results. The significance of the potential impacts can be understood and evaluated throughout its life cycle and completed in four steps; classification, characterization, normalization and weighting [11]. This will aid in determining the significance of data and its association with various impact categories. The impact mostly considered by researcher are on environmental categories such as Global Warming Potential (GWP_{100}), Potential of Photochemical Oxidation (POCP), Ozone Depletion Potential (ODP), Eutrophication Potential (EP), Acidification Potential (AP), Abiotic Depletion of Elements (ADP-e), and Abiotic Depletion of Fossil Fuels (ADP-ff) [12]. Some researchers were evaluated the impact of greenhouse gas (GhG) emission, cost and energy saving but the most popular impact is Global Warming Potential (GWP_{100}) with 7 out of 10 research papers. The impact assessment categories by all research papers were responded to the goal of the studies which related to environmental impacts.

3.5 Life Cycle Interpretation

Life cycle interpretation conclude the understanding of result accuracy and ensure the goal of the study achieved. This systematic technique can be accomplished by categorising the data elements that contribute significantly to each impact category, assessing the sensitivity of these significant data, evaluating the completeness and consistency of the study, drawing conclusions and recommendations based on the LCIA results were developed [16].

Identification of LCIA results in accordance with the goal and scope definition determine the significant issues raised in the study. There are few issues that being state in the research papers such as lack information on region context [17], uncertainty of leaching data from uncontaminated biomass ash [6], technical and economical aspect [11]. Next, the researchers will evaluate the issue, conclude the LCA findings and released the recommendation for the intended audiences. The research on LCA has a great implication into concretes and cementitious materials studies since majority agreed with the LCIA results showed low environmental impacts with alteration/ substitution materials on OPC.

4 Conclusions

In this article, the LCA studies on cementitious material and concrete have been comparing to ISO guidelines to ensure the information obtained for the LCA study is appropriate. In all studies, the waste used on construction materials has been shown promising potential and proven to reduce environmental consequences. Although the target audience has been disregarding in their studies, most researchers are clear about the goal of the LCA study since it is critical to set the objectives before starting the analyses. All the potential findings will be impractical in the real world due to the lack of a targeted audience indicated in the research papers. Global warming and other environmental impacts can also be reduced if the potential results and solutions can reach the right audience. Another incomplete issue by researchers is data quality assessment; the researchers failed to disclose the completeness, consistency, and sensitivity analyses in their studies. In the future, researchers are advising to complete these analyses to improve the data assessment quality and fulfilled all the ISO guidelines.

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