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Life cycle assessment of geopolymer concrete: A Malaysian context

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Abstract. The production of Portland cement is well acknowledged as having a significant impact on the environment, accounting for 8% of global CO₂ emissions (4bn tonnes per annum). Concrete is the most widely used material in the world and therefore has vast potential to absorb high volumes of waste and by-product materials. These materials can act as partial replacements as supplementary cementitious materials or total replacements and perform as binders in geopolymer concretes. The use of Pulverised Fuel Ash (PFA) from coal-fired electricity generating stations to substitute Ordinary Portland Cement (OPC) is well established. Quantifying the potential environmental benefit of using such materials can be difficult. The life cycle assessment (LCA) methodology, internationally standardised through ISO14040 series, may be used to quantify the environmental impact of products and processes. This paper outlines the use of the LCA methodology to compare the environmental impact of OPC precast concrete products to PFA precast concrete products in a Malaysian context. The four stages of LCA are detailed and consequences of designating materials as a by-product or waste are discussed. A review of other LCA studies completed in Malaysia for the built environment are also presented so as to identify which impact assessment methods are most frequently used.

Keywords: Life cycle assessment, geopolymer concrete, environmental impact.

1. Introduction

In Malaysia in 2016, over 20 MT of cement was produced [1]. The environmental impact of cement is well acknowledged with significant emissions from three distinct areas; emissions produced as the raw materials are calcined at high temperatures to form clinker, emissions associated with fuel combustion in the cement kiln and the emissions associated with energy used to operate the cement plant [2].

The raw materials used in cement manufacture are rich in calcium carbonate and may be quarried from limestone, chalk or shale deposits. Depending on the location, the quarrying process involves the use of drilling, blasting, excavating and crushing [3]. The calcination process, which is responsible for approximately 50% of cement CO₂ emissions, requires the burning of the calcium carbonate, forming

calcium oxide and carbon dioxide. So whilst there is potential to reduce environmental emissions associated with fuel and energy use, the nature of the calcination process means that potential reduction of the environmental impact of cement is constrained.

Alkali activated concrete (AAC) or geopolymer concrete has emerged as a promising alternative to traditional Portland cement based concrete. Geopolymer is an umbrella term which refers to a range of synthetic aluminosilicate polymeric materials, often more generically termed alkali-activated binders (AAB). Geopolymer materials can be produced from a range of natural and synthetic pozzolanic solids, activated with alkaline solutions such as sodium hydroxide and sodium silicate. Geopolymers can act as “cementless” binders to replace Portland cement pastes in concrete products. One common geopolymer material is pulverised fuel ash, PFA which is generated by power stations during the production of electricity using coal as the fuel. Finely powdered (pulverized) coal is mixed with heated air and burned. The resultant ash is transported by the exhaust gases and recovered as ‘fly ash’ with fine particles. The PFA may then be used in concrete construction products or, if a surplus exists, will be stored in lagoons in close proximity to the power plants. Previous studies comparing geopolymer materials to cement have reported a reduction in CO₂ emissions of between 30[4] – 80% [5], with other studies finding values within this range [6][7].

The life cycle assessment (LCA) methodology, internationally standardised through ISO14040 [8] series, can be used to quantify the environmental impacts and compare products or processes. All products or process have various stages in their life cycle stages and during each of these stages, energy and resources are consumed and emissions to the environment and wastes are produced. In an LCA study the function of the product is taken into consideration ensuring fair and accurate comparisons. This paper provides an overview of the LCA methodology and its sets out how LCA will be used in the quantification of the environmental impact of OPC and PFA precast concrete products for a Malaysian context.

2. Life cycle assessment

Under ISO14040 [8], life cycle assessment is carried out in four stages namely:

- goal and scope definition
- inventory analysis
- impact assessment
- interpretation

2.1. Goal and scope definition

The goal definition of a life cycle assessment sets out the intended application and the purpose of conducting the study. It will also identify the intended audience and whether results are being used for internal or external purposes. The scope of an LCA sets out the product or processes which are being examined and details methodological choices, assumptions and limitations of the work. This paper provides an overview of the LCA methodology and its sets out how LCA will be used in the quantification of the environmental impact of OPC and PFA concrete for a Malaysian context.

2.1.1. Functional unit definition

Functional unit is defined as being a “quantified performance of a product or system for use as a reference unit”. For example if two shopping bags; one made of plastic and one made of cloth, were compared, the functional unit could be the number of loads of shopping that the bag could carry. An appropriate functional unit ensures a fair basis of comparison and that the quantitative and qualitative aspects of a product are considered.

In the case of concrete products, environmental impacts have been reported on a volumetric per m³ basis or on a unit size basis. However it is noteworthy that these volumetric units do not accurately

reflect the predominant function of the material as a structural element. Therefore a unit which includes the compressive strength and volume is preferable eg m^3 of 50MPa or the load carrying capacity of the material kN m^2 [11].

2.1.2. System boundary

The system boundary outlines which stages of the product or process life cycle will be included in calculating the environmental impact. There are three commonly accepted system boundaries; cradle to gate, cradle to site and cradle to grave.

- Cradle to gate: includes all impacts from extraction of raw materials, processing and manufacturing into the end product, as shown in Figure 1.
- Cradle to site: includes all cradle to gate impacts and the transport of the product to the site of its use.
- Cradle to grave: includes all cradle to site impacts as well as impacts associated with the operating life such as maintenance/repairs, energy consumed and end-of-life scenarios, such as how the item will be disposed/reused/recycled.

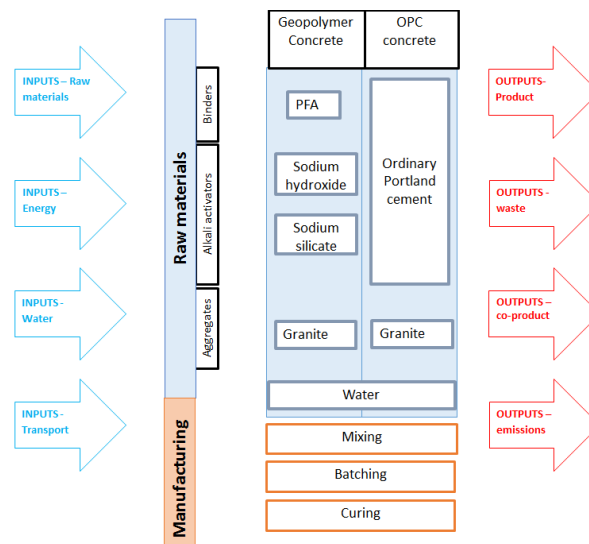


Figure 1. Example of cradle to gate system boundary for geopolymer and OPC precast products

There are many processes in which more than one product is produced. For example a timber mill may produce wooden planks and sawdust from the same process. In circumstances where there are multiple products, the proportioning of environmental impact is carried out through a process called allocation. According to ISO14044, allocation should be avoided where possible by either of the following:

- 1) expanding the system boundaries to include the additional functions associated with all products or by
- 2) dividing the process into sub-process and measuring the inputs and outputs of these sub-processes.

In circumstances where allocation simply cannot be avoided it is recommended to partition based on the physical relationship between products, by weight or mass for example, or by the economic value. Using the previous example of the timber mill for example, on a mass basis the environmental impact could be allocated 10% to the saw dust and 90% to the wooden planks, this relationship would not change. In the case of economic allocation, the current market price for the planks versus the saw dust would be used. As the planks have a much higher economic value they would be allocated perhaps 99% of the impact versus 1% for the sawdust. If however there was a change to markets, where for

some reason saw dust became a highly sought after commodity this allocation basis would change. As such, allocation procedures must be used with caution. Economic allocation is subject to is high variability due to price instability [2], [12], whilst mass allocation allows for greater stability, but is sometimes less appropriate.

The quantification of the environmental impacts of multiple substances produced during a single process depends on whether they are formally designated as being a “waste” or a “by-product”. As discussed by Chen *et al.*, (2010) the only environmental impact of producing a waste is in its disposal. However, when productive uses for waste materials have been discovered, their economic value increases and as a result they are no longer considered as waste materials, and are instead considered as valuable by-products of the initial process. In this case, some of the environmental impacts of their production processes should be attributed to them [8]. Under the most recent Waste Framework Directive [13] in Europe, a waste may be reclassified as a by-product if the following criteria are met:

- 1) there is certainty that the substance will be used;
- 2) the substance can be used without any further processing;
- 3) the substance is produced as integral part of the production process and
- 4) further use of the substance is lawful, without impact on the environment or human health as per Article 5 of Directive 2008/98/EC 2008.

Under these criteria, PFA in the EU would no longer be considered a waste product but is instead considered to be a by-product, and therefore allocation would apply. Mass allocation attributes a much higher environmental impact to PFA than economic valuation, with reported values of 2.44 kgCO₂/kg and 0.196 kgCO₂/kg respectively [2], [12], as the ratio by mass between primary product and by-product is must higher than the ratio of their economic values. These values cited in Table 1 are commonly used in LCA studies in the UK and Europe.

Table 1. Environmental impacts of PFA (per kg) from literature sources – considering both no allocation and mass and economic allocation

	Industry estimates No allocation [14] (UK)	No allocation [15] (EU)	Economic Allocation [15] (EU)	Mass allocation [2](EU)	Economic allocation [12] (EU)
Units	kgCO ₂ /kg	kgCO _{2e} /kg *	kgCO _{2e} /kg *	kgCO ₂ / kg	kgCO ₂ /kg
PFA	0.004	0.0048	0.190	2.44	0.196

* The CO₂eq indicator represents the Kyoto ‘basket of 6’ greenhouse gases, converting methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride to an equivalent CO₂ value using different multiplication factors.

In Malaysia the definition of a waste is stated in the Environmental Quality Act 1974 as including: “...any matter prescribed to be scheduled wastes, or any matter whether in a solid, semi-solid or liquid form, or in the form of gas or vapor which is emitted, discharged or deposited in the environment in such volume, composition or manner as to cause pollution.”

Malaysia Environmental Legislation does not include a formal definition for by-products, and as such waste materials cannot be formally designated as by-products in Malaysia, however given that PFA has an economic value in Malaysia, best practise in LCA would dictate that it should be treated as a by-product with allocation of relevant environmental impacts.

2.2. Inventory analysis

Inventory analysis identifies and quantifies all the inputs (energy, material resources etc.) and outputs (emissions, wastes etc.) of a system. Where possible, information should be gathered from the process being examined (primary data) such as energy being consumed in mixing, batching and curing the

concrete products. Quantities of the raw materials such as aggregates, water, binders should be measured and transport mode and mileage should be recorded.

When data is gathered from secondary sources in the inventory analysis there are a number of data quality rules about the information gathered which are as follows:

- The information is time-sensitive - past 5 years preferable
- The information is geographically appropriate – is it from the same or similar location
- The technology being used is the same or similar as the process in question
- The data is representative - reflects population of interest.
- The data has consistency - matches the procedures and processes being examined
- The information is reproducible - another person could find it and use it to come to the same solution.

For example the MY-LCID (Malaysia Life Cycle Inventory Database) has data for over 150 products and processes and can be used in circumstances where primary data is not available [16].

2.3. Impact assessment

The data from the inventory stage is collated and the potential impact to the environment is calculated during this stage. According to ISO14040, life cycle impact assessment consists of two mandatory procedures - selection of impact categories and classification and characterisation – and two optional procedures - normalisation and weighting. All environmental damages can be classified into impact categories at midpoint or endpoint level. The process in which an emission becomes an environmental impact is referred to as an environmental mechanism [17]. A midpoint impact occurs at some point along the environmental mechanism and represents the direct negative effect on the environment, such as eutrophication and climate change. Endpoint impact is taken at the end of the mechanism and uses damage-orientated indicators corresponding to damage to human health or ecosystem [18]. Using multiple midpoint impact categories allows for greater detail on the environmental damage, but endpoint damage-orientated indicators may be aggregated into single scores, which are easier for non-experts to interpret and understand. A simplified representation and example of the pathway of an emission through the life-cycle impact assessment stage is shown in Figure 2.

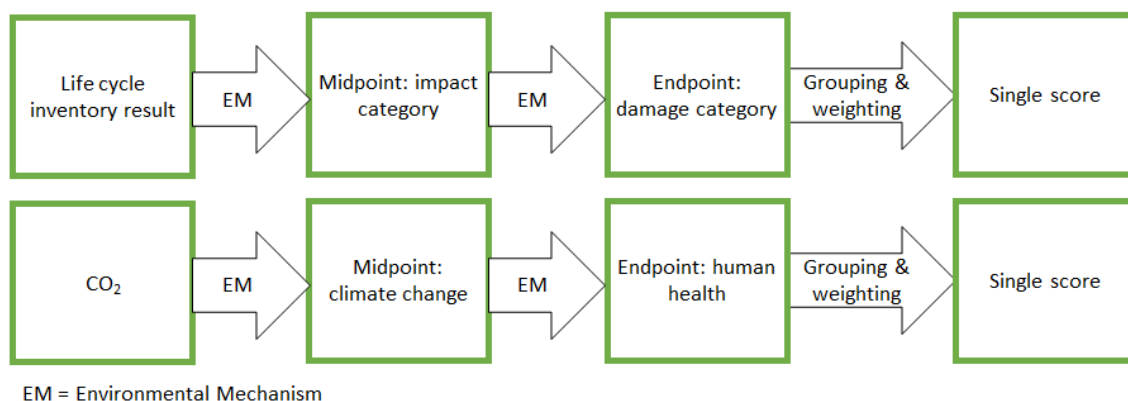


Figure 2. Relationship between life cycle inventory results, midpoint, endpoint and single score

There are many impact assessment midpoint and endpoint methods available, such as CML, Impact 2002+, TRACI and Eco-indicator 99. A gathering of LCA experts in the year 2000 concluded with a consensus, that a common framework of impact assessment that presented results at midpoint and endpoint level was required. The resulting method, ReCiPe, was developed, building on the Eco-indicator 99 and CML methods; it harmonises modelling principles and choices [18].

Whilst no specific papers related to the LCA of concrete products in Malaysia were identified, Table 2 details the completed studies that are relevant to the built environment and outlines the life cycle impact assessment methodology that was used in each case.

Table 2. Summary of LCA studies conducted in Malaysia

Ref	Paper title	Research Topic	Impact assessment method and indicators examined	Additional notes
[19]	Life Cycle Assessment of Sodium Hydroxide	Functional unit of 1kg of sodium hydroxide. Based on 3 years of data gathered from Malay producer.	LIME method (Endpoint) Global Warming Potential, Human Toxicity Potential (Carcinogenicity) Aquatic Ecotoxicity Potential Eutrophication Potential Acidification Potential Fossil Energy Resource Consumption	JEMAI LCA Pro Due to lack of LCIA software in Malaysia impact assessment found using LIME method an Endpoint method developed in Japan
[10]	Environmental Impact Analysis on Residential Building in Malaysia Using Life Cycle Assessment Ahmad	Semi-detached residential building. Construction, operation and end-of-life (EOL) included.	CML 2001 (Midpoint) Acidification, eutrophication, global warming potential (GWP), and ozone layer depletion (ODP)	Malaysia Life Cycle Inventory Database (MYLCID) used. 50 year life span assumed. Cradle to grave study.
[20]	Strategies for reducing greenhouse gas emissions from residential sector by proposing new building structures in hot and humid climatic conditions	Study of residential building constructed using 6 Industrialised building system (IBS) construction methods, block-work, precast, steel frame, timber prefabricated, glued laminated veneer, laminated veneer lumber.	IPCC (20,100,500) (Midpoint) Greenhouse gas emissions kgCO _{2eq}	SimaPro 8 software used. Assumed life span of buildings 50 years. Cradle to grave study. Malaysia Life Cycle Inventory Database (MYLCID) used.
[9]	Assessment of embodied energy and global warming potential of building construction using life cycle analysis approach: Case studies of residential buildings in Iskandar Malaysia	Comparing IBS with cast-in-situ using two residential buildings in Malaysia. Functional unit 1m ² .	CML2002-2010 (Midpoint) GWP 100 years (kg CO _{2eq}) Embodied energy (MJ) (method not stated)	GaBI software used to conduct analysis. Sensitivity analysis to test assumptions conducted.
[21]	Life cycle assessment and life cycle costing toward eco-efficiency concrete waste	Seven high rise construction projects, examining construction waste	IPCC (100) (Midpoint) Greenhouse gas emissions	Models 4 end-of-life scenarios: 1) landfilling, 2) recycling to road

management in Malaysia	at end-of-life only. Functional unit per ton of waste material.	kgCO _{2eq}	construction, 3) recycling to concrete batching 4) recycling to road construction and concrete batching.
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Of the Malaysian LCA studies identified, there is a mix of both midpoint and endpoint results LCIA methods used. CML and IPCC are the most common midpoint methods. As mentioned previously the CML and Eco-indicator 99 methods have been amalgamated to form the ReCiPe method. There has been no study identified in Malaysia that aggregates these results into a single score; however these are all academic studies intended to communicate with expert audiences.

2.4. Interpretation

In the final phase of the LCA, results, assumptions and choices made throughout are examined and evaluated in terms of soundness and robustness by the undertaking of sensitivity and uncertainty analysis. Following evaluation overall conclusions are drawn and recommendations made with a summary of key issues, limitations and justification of conclusions based on the findings of the LCA process [17]. On completion of the life cycle impact assessment stage all results will be reviewed and key findings presented.

3. Conclusions

This paper outlines how the LCA methodology may be used for assessing the environmental impact of geopolymer and concrete products. The review of previous literature highlights the importance of designating a material as a waste or a by-product and how allocation on a mass or economic basis can significantly alter the calculated environmental impact. The types of data that is required by the life cycle inventory phase and the data quality rules were also outlined. Examining previous construction related LCA studies from Malaysia has shown that both mid-point and end-point life cycle impact assessment indicators have been used, with the CML and IPCC impact methods identified as the most common.

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