Life Cycle Assessment of Ordinary Portland Cement (OPC) using Damage Oriented (Endpoint) Approach.

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Abstract

The cement industry's environmental impact is fast becoming a significant concern with a continuous increase in population. Different studies were carried out to understand this impact and potential damage, but more concrete results are required. This study aims to verify the damage caused by a cement industry to areas of significance to life (AoSL). The tool used for this evaluation is the life cycle assessment (LCA) of Ordinary Portland cement (OPC). The evaluation outcome showed that the clinker production phase has the most significant damage to both human health and the ecosystem because of high CO_2 emissions. The resources prone to scarcity are natural gas, coal, clay, and most importantly, petroleum. With this evaluation, the life expectancy of individuals, the species loss, and economic value loss resulting from extraction because of damage caused by environmental impacts from the cement industry can be calculated annually in every country.

Keywords
Clinker production, Damage, Environmental impact, LCA, Ordinary Portland cement (OPC).

1. Introduction

With continuous changes in the globalization of the landscape, the construction sector, which deals with building the environment to accommodate these changes, has shown diverse environmental implication in its production process (Andrew, 2018; Huntzinger & Eatmon, 2009; Worrell, Price, Martin, Hendriks, & Meida, 2001). Cement is a significant material in concrete production and implication the construction sector (Feiz et al., 2015). The substantial impact seen in the production process of cement is the emission of greenhouse gas (GHG), excessive usage of resources, and energy (fossil fuel and electricity) (Stafford, Raupp-Pereira, Labrincha, & Hotza, 2016). Ordinary Portland cement (OPC) is made up of calcium, silicate, alumina, and sometimes iron. Gypsum is added to improve cement setting time (Vito Alunno Rossetti, 1995; V Alunno Rossetti & Ferraro, 2007). After crushing and pulverizing to the required texture, the mix is pre-heated and moved to a large kiln of a high temperature of 1400-1500ºC for the calcination process (Pacheco-Torgal, Cabeza, Labrincha, & De Magalhaes, 2014); which is also the clinker production phase. Several authors have opined the clinker production phase to be the highest energy-consuming and CO_2 emitting phase of the entire production phases (Barcelo, Kline, Walenta, & Gartner, 2014; Edenhofer et al., 2011). This involves the chemical decomposition of limestone to give CaO and CO_2. This process accounts for well over half of the CO_2 emitted while the remaining gas is obtained from fossil fuels/energy used during the production process (Policy & Policy, 1999). The global CO_2 emission in 2005 was about 28.3 Gt, and the cement industry generated about 6.5% of this emission. The global CO_2 emission from the cement industry by 2011 was 2.6Gt, in which more than half of this value was from the calcination process and the rest from the energy generation process (Gursel, 2014). In 2012, global cement production reached 3.6 Gt (Cembureau, 2012). Trends show that global CO_2 emissions from this industry increase for every production year, and this is forecasted to increase at a rate of 0.8-1.2% annually and has a value of 3700 and 4400 Mt by 2050 (Agency & Initiative, 2017). This is because there is a need for continuous cement production, seeing that 1 ton of cement is needed by every individual annually (Cembureau, 2012). There is a need for a massive supply of power to produce cement as the industry has heavy machines/kilns needed for grinding, pulverizing, and pre-heating (Edenhofer et al., 2011). Therefore, the cement industry accounts for an average of 12-16% of the global industrial energy and 6-8% of global CO_2 emission (Fry, 2013). Also, this industry imposes so much pressure on raw materials. About 1.5t of limestone is used to produce 1ton of cement and requires thermal energy of 2.93-6.28GJ and electrical energy of 65-141 kWh (Huntzinger & Eatmon, 2009; Madlool, Saidur, Hossain, & Rahim, 2011; Valderrama et al., 2012). In his work, Meyer opined that 1 ton of cement produced gives rise to about 1 ton of CO_2 emission (Meyer, 2009). However, this value can vary depending on the type of fuels used in the kiln, the plant/quarry location, and the avalanche of factors. Therefore, the cement industry's significant environmental impacts are high CO_2 emission, high energy, and resource consumption. Cement is fast becoming the most-produced material on earth, being the primary material for concrete production and consequently construction. There is a need to be aware of these impacts' environmental consequences with the abundance of cement and the fact that construction is becoming increasingly essential for life and sustainability (Lippiatt & Ahmad, 2004; Masanet & Price, 2005).

2. Literature study of life cycle applications as it applies to environmental analyses

Cement, being a globally significant product, suggests the need for critical analyses of the actual damage caused by this industry. To this end, this study is carried out. Life cycle assessment (LCA) is a vital assessment tool used to analyze the effects of a product's entire production process from the start point to the finish point of such production (Arvanitoyannis, 2008). This tool is of exquisite importance when there is a need to understand the environmental effect caused by different production stages. Also, its application in the cement industry will help cement producers optimize the production process and serve as a decision-supporting tool.
This tool gives a detailed overview of the entire cycle of a product. According to the international standard organization (ISO), there are four stages of LCA, which are: Goal and Scope definition, Life cycle inventory (LCI), Life cycle impact assessment (LCIA), and Interpretation (Van den Heede & De Belie, 2012). Where goal and scope definition deals with the assessment's jurisdiction alongside objectives and assumptions, LCI involves all the necessary input and output data needed for the product's production process under evaluation (Marinković, 2013). LCIA, on the other hand, is a multiple-face phase of the actual assessment to reveal all environmental impact categories by using the LCIA method to evaluate the provided database. The interpretation, which is the last phase, explains the LCIA phase's outcome based on the LCI (Andersson, Ohlsson, & Olsson, 1994). The remaining part of the study is divided into methods in section 2, result and discussion in section 3, and the last section concludes.

3. Methodology

LCA is an impact evaluation tool for the cycle of a product or process. It takes into consideration all potential consequences of the production process. LCIA uses different methods based on the system or product understudy to speed up analysis and simplify it. The damage-oriented approach (endpoint) is adopted in this study. This LCIA approach gives a proper understanding of the damage caused by the environmental impacts during any production process. This helps to understand why we should worry about any of the effects. It simplifies the numero us impacts into only three damage categories in the area of significance to life (AoSL): Human Health (HH), Ecosys tem (ES), and Resources (RS); presenting a relatively easy result evaluation (Dong & Ng, 2014). It helps to answer the question: why should I be perturbed about global warming or fossil resource scarcity? ReCiPe is an LCIA method that evaluates the impact category using the endpoint approach (M Goedkoop, Heijungs, De Schryver, Struijs, & Van Zelm, 2013). ReCiPe uses the disability-adjusted life years (DALY) in the human health category, which means the years of life expended or the years of damage to life as a result of environmental impacts. The ecosystem damage category uses species lost within a specified period due to emissions to the environment, waterbody, etc. damage to resources is based on economic loss due to marginal increase in costs as a result of resource extraction (Mark Goedkoop, Effting, & Collignon, 2000; M Goedkoop et al., 2013; PRé & Mark Goedkoop, January 2016). The software used for this assessment is SimaPro 9.0.49 (PRé & Mark Goedkoop, January 2016). All inventory data used for the evaluation is taken from Ecoinvent v3.5, incorporated in the software.

3. Results and Discussion

The LCA analysis was carried out for 1kg of cement with 22 environmental impact categories and three specific damage units based on their contribution. The characterization result of the impact assessment represented in Table 1 gives insight into each of the impacts in the damage category with the individual units of the impact showing what is affected. For instance, Disability-adjusted life years (DALY) have to do with the years of life spent or years of life damaged because of environmental impacts, which by implication affects humans generally. Species/yr which affects the ecosystem denotes the species lost within a specific period (the year in this case) to water bodies and the environment as a whole. USD2013 damage to resources signifies the monetary value of economic loss due to the increased resource extraction.

Table 1: Impact Assessment of 1kg Portland Cement

S/N	IMPACT CATEGORY	UNIT	PORTLAND CEMENT
1.	Global warming, Human health	DALY	8.45E-7
2.	Stratospheric ozone depletion	DALY	4.16E-11
3.	Ionizing radiation	DALY	1.08E-11
4.	Global warming, Human health	DALY	1.3E-9
5.	Ozone formation Human health	DALY	3.62E-7
6.	Fine particulate Formation	DALY	4.02E-9
7.	Human carcinogenic toxicity	DALY	3.24E-9
8.	Human non-carcinogenic toxicity	DALY	2.69E-9
9.	Global warming, Terrestrial ecosystems	Species/yr	2.55E-9
10.	Global warming, Freshwater ecosystems	Species/yr	6.97E-14
11.	Ozone formation Terrestrial ecosystems	Species/yr	1.89E-10
12.	Terrestrial acidification	Species/yr	2.96E-10
13.	Freshwater Eutrophication	Species/yr	7.74E-12
14.	Marine Eutrophication	Species/yr	6.05E-16
15.	Terrestrial ecotoxicity	Species/yr	4.99E-12
16.	Freshwater ecotoxicity	Species/yr	6.88E-14
17.	Marine ecotoxicity	Species/yr	4.02E-14
18.	Land use	Species/yr	3.24E-11
19.	Water consumption, Terrestrial ecosystems	Species/yr	1.72E-11
20.	Water consumption, Aquatic ecosystems	Species/yr	1.17E-11
21.	Mineral Resource scarcity	USD2013	0.00107
22.	Fuel resource scarcity	USD2013	0.022

The impact categories in Table 1 are further grouped into their respective damage categories: human health (HH), ecosystem (ES), and resources (RS), with the damage assessment presented in Table 2. The HH having a value of 1.22E-6 DALY implies that for every 1kg of OPC, 1.22 E-6 human life is damaged, an ES of 3.1E-9 species/yr indicates that for every 1kg of OPC produced, 3.1E-9 species are lost every year, and RS of 0.0231 USD2013 implies that for every 1kg of OPC, 0.0231 USD is lost on resources (Table 2).

Table 2: Damage Assessment of 1kg Portland Cement.

S/N	DAMAGE CATEGORY	UNIT	PORTLAND CEMENT
1	Human health	DALY	1.22E-6
2	Ecosystem	Species/yr	3.1E-9
3	Resources	USD2013	0.0231

These damage categories are further analyzed to know the substance and the production process causing damage to human health, Ecosystem, and Resources.

Table 3: STP of HH

S/N	PROCESS	PORTLAND CEMENT (%)
	Total of all processes	100
	Remaining processes	4.38
1	Clinker	70.1
2	Diesel burned in building machine	4.02
3	Electricity, high voltage	11.1
4	Hard coal mine operation	4.9
5	Heat, district, or industrial	4.5
6	Transport freight	1

Table 4: STS of HH.

S/N	SUBSTANCE	PORTLAND CEMENT (%)
	Total of all compartment	100
	Remaining substances	2.99
1	Carbon dioxide, fossil	67.3
2	Nitrogen Oxides	8.23
3	Particulates, <2.5µm	9.01
4	Sulfur dioxide	12.2
5	Water	2.5

Table 3 represents the analysis specific to the process (STP) causing damage to human health. The study reveals that 70.1% of the damage to human health resulted from the clinker production process. Others are from energy generation: diesel (4.02%), electricity (11.1%), hard coal (4.9%), and heat (4.5%) results in the emission of primary gases such as CO_2, SO_2, NO_2, and 1% is from transportation with the rest being negligible. The analysis specific to the substance (STS) causing damage to Human health given in Table 4 shows that 67.3% of the damage results from CO_2 emission, with other substances such as Nitrogen oxides (8.23%), Sulfur dioxide (12.2%), particulate matter (9.01%) and the rest being negligible. Nitrogen oxides are emitted during fuel combustion in the calcination process. Sulfur dioxide emission is one of the major gases emitted during the sulfur content reaction in the raw material with the coal in the clinker. These emissions were majorly released into the air and water.

Table 5: STP of ES

S/N	PROCESS	PORTLAND CEMENT (%)
	Total of all processes	100
	Remaining processes	5.09
1	Clinker	77.8
2	Diesel burned in building machine	1.81
3	Electricity, high voltage	7.7
4	Hard coal mine operation	2.8
5	Heat (Natural gas)	2.6
6	Transport, freight	2.2

Table 6: STS of ES

S/N	SUBSTANCE	PORTLAND CEMENT (%)
	Total of all compartment	100
	Remaining substances	1.72
1	Carbon dioxide, fossil	79.9
2	Nitrogen Oxides	9.48
3	Sulfur dioxide	5.6
4	Methane	2.1
5	Water	1.2

The Specification analysis of the process of the damage to the ecosystem summarized in Table 5 showed that 77.8% of damage originated from the clinker production process. As observed in the case of human health, a large portion of the remaining percentage is from energy generation (Diesel is 1.81%, electricity 7.7%, hard coal 2.8%, heat 2.6%) during which primary gases (CO_2, SO_2, NO_2) are emitted; 2.2 % is from transportation, and the rest is negligible.
The Specification analysis of substance (STS) damage to the ecosystem is as seen in Table 6. The 79.9% is because of CO_2 emission, and other substances constitute the rest of the percentage while other substances such as Nitrogen oxides, which are 9.48%, Sulfur dioxide is 5.6%, methane 2.1%, water 1.2%, and the rest are negligible. These emissions are often emitted into the water body and the environment.

Table 7: STP of RS

S/N	PROCESS	PORTLAND CEMENT (%)
	Total of all processes	100
	Remaining processes	9.95
1	Clay	4.18
2	Hard coal	8.8
3	Natural gas,	11.3
4	Petroleum production, on-shore	65.8

Table 8: STS of RS

S/N	SUBSTANCE	PORTLAND CEMENT (%)
	Total of all compartment	100
	Remaining substances	0.473
1	Clay	4.19
2	Coal, hard	11.4
3	Gas, natural/m^3	16
4	Oil, crude	67.9

Table 7 represents the analysis of the Specification to process of the damage to Resources. This shows that the major resource depletion is from petroleum (65.8%), natural gas (11.3%), hard coal (8.8%), clay (4.2%), and the same is also seen in the analysis of the Specification to the substance of the damage to Resources in Table 8: crude oil (67.9%). natural gas (16%), hard coal (11.4%), clay (4.19%).

4. Conclusion

This evaluation was carried out on 1kg of ordinary Portland cement. The endpoint approach applied in this study presents 22 different environmental impact categories classified into three damage categories of AoSL. Clinker production contributes 70.1% to HH and 77.8% to ES, affecting humans and species' health because of the amount of CO_2 emitted at this production stage. In both damage categories, 67.3% and 79.9% CO_2 were emitted, respectively. This is in line with what is in literature but now with an exact percentage. CO_2 emission causes global warming which brings about climate change that affects both humans and the ecosystem. In the two damage categories, other primary emissions such as NO_2, SO_2, CH_4, particulate matter were emitted into air and water though minimal compared to CO2 gas. Using RS such as natural gas, coal, clay, and petroleum in OPC production can lead to scarcity, especially petroleum (crude oil). Therefore, this study concludes that the clinker production pro cess emits the highest CO_2 gas and, thus, the most hazardous production stage to both human health and the ecosyste m. On average, about 0.74kg of CO_2 gas was obtained for every 1kg of OPC produced. It also concludes that cement' s continuous production can lead to the scarcity of resources such as petroleum, natural gas, coal, and clay. As seen above, ReCiPe makes use of DALY, Species/yr, and USD2013 as units of HH, ES, and RS damage categories, respectively. Disability-adjusted life years (DALY) have to do with the years of life spent or years of life damaged because of environmental impacts. Hence, with this evaluation, we can easily determine the years of damage to people's lives in an entire based on the production output of such a country.
Furthermore, the evaluation has shown that whatever affects species affects human beings seeing that almost all the primary emissions affecting human health jeopardize the ecosystem. Also, humans feed on some of them and are also part of their environment. Species/yr denotes the species lost within a specific period (the year in this case) to water bodies and the environment as a whole; this can also be evaluated for a nation per year. Also, damage to resources is based on the monetary value of economic loss due to the increase in costs because of extraction.

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