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August 3, 2022

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Abstract. *Material from waste has been researched numerously as construction material for the development of sustainable construction. An example is oil palm shell (OPS) as coarse aggregate on lightweight beam concrete. Pre-treatment with hot water (50°) positively influences the compressive strength of the OPS concrete (OPSC) laboratory scale. The result of the displacement measure with an LVDT extensometer could be applied to a two-story building, achieving the requirement of the national standard. Therefore, a life cycle analysis of OPSC was presented to assess the sustainability of the concrete with cradle-to-gate boundary. The washing and drying processes of OPS were the significant contributors to the environmental burden, along with the transport distance of the other constituents increased the results. The opportune OPS manufacture contributes to environmental burdens around one-fold higher than OPSC production stages. Meanwhile, the mathematical equations of the concrete's carbonation show a small amount of carbon dioxide uptake.*

Keywords: Lightweight beam concrete, oil palm shell, life cycle assessment, carbonation.

Introduction

The increased attention to global environmental dangers, such as climate change, non-renewable resource depletion, and water shortage, has renewed builder associations' interest in more sustainable materials. Considering those environmental challenges and a merged increase in population growth and urbanization are predicted to escalate the need for dwelling materials in developing countries. There has been a recent upsurge of interest in bio-based materials at the academic, policy, and industry levels [1]. Those green materials incorporate biomasses such as plant aggregates from agriculture waste, have they been substituted as concrete constituents only in the 20th century [2].

Aggregate is the primary constituent of concrete by mass, and combined with water and cement; it forms cement-based materials (e.g., concrete). Aggregate is commonly considered inert filler, accounting for 60 to 80 percent of the volume and 70 to 85 percent of the weight of concrete; hence, the quality of the aggregate used affects the strength of the concrete [3]. In traditional construction, concrete is produced with natural coarse and fine aggregates. Traditional concrete production accounts for annual consumption of approximately 2.28 billion tons of cement, 10–12 billion tons of natural aggregates and 1 billion tons of mixing water [4], [5]. Furthermore, the escalating demand for traditional construction materials has resulted in their depletion. Otherwise, researchers have overlooked many challenges in solving problems related to sustainable construction materials.

Oil palm shells (OPS), a palm oil solid by-product, become a potential bio-sourced material substituent. Researchers have used OPS as coarse aggregates in concrete to reduce its negative environmental impact. Numerous investigations have been demonstrated to manifest the benefits of using OPS as a lightweight aggregate (LWA) to fabricate LWA concrete (LWAC) [6], [7]. Those studied have stated that oil palm shells are technically acceptable. In the structure and material laboratory of the University of Indonesia, this aggregate has been researched as alternative material on the reinforced lightweight concrete beam. From laboratory test showed the concrete has a range of compressive strength between 20 to 25 MPa. The concrete could be applied to the two-story building based on a national standard [8], [9]. However, none of them analysed the environmental impacts of oil palm shell concrete.

OPS has the potential to create sustainability and reduce pollution in the construction sector due to reducing the requirement for coarse aggregate produced from natural resources. Thus, research is needed to prove the scientific use of oil palm shells and the environmental impact. One of the methods to calculate environmental impact is life cycle assessment (LCA). LCA is a robust methodology to estimate the environmental burden of the product life cycle. An LCA of miscanthus-lime lightweight concrete (used as wall) enables a potential low carbon retrofitting technique. The environmental performance-based analysis reveals that miscanthus blocks can capture 135 kg CO_2eq/m^3 for an assumed 100-year life period [10]. Because of the carbon capture and to prove the environmental acceptance, a cradle-to-gate study enclosed the use phase for 25 years of OPSC are assessed by life cycle assessment and accompanied by the CO_2 uptake estimation. The results of this study are expected to provide a reference for the stakeholders in improving the product/process design.

Materials and Methods

The environmental burden of lightweight beam concrete life cycle evaluates via Life Cycle Assessment (LCA). The LCA study followed the international ISO standards guideline and the four stages of LCA are goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation of the results [11]. The tool to analyse lightweight beam concrete environmental impacts was assessed by openLCA version 1.11, providing the open-source database and allowing the electricity production in Indonesia from Ecoinvent 3.8 database. After that, CO_2 uptake of lightweight beam concrete was estimated by mathematical equations, which could allow benefits by reabsorbing the carbon dioxside in the atmosphere. The mix design of OPSC beam shows in Table 1.

Table 1 Mix properties and mix proportion of OPSC beam

Concrete name	Cement Portland (kg/m^3)	Tap water (kg/m^3)	Steel bar (kg/m^3)	Aggregate (kg/m^3)		W/C	Density (kg/m^3)	Compressive strength at 28 days (MPa)
				Fine	Coarse			
OPSC	500	175	6165	860	273	7/20	1792	21.82

Life Cycle Assessment

The study's goal was to assess the environmental burdens of an oil palm shell lightweight concrete. The boundary system of cradle-to-gate and the functional unit (FU) was 1 m^3 of ready-to-use lightweight beam concrete. The investigated lightweight concrete is manufactured by a laboratory of structure and materials at the University of Indonesia, with a four-stage production process: sieving, washing, drying and mixing the constituents in Figure 1. The oil palm shell production yield was collected from the oil palm mill PT X in Riau and used the inside factory capacity. However, data regarding land preparation up to oil palm mill is based on Kiman (2015) [12]. The Ecoinvent 3.8 database was used for the other constituents and electricity production processes to complement the life cycle inventory. The impact assessment of construction products was conducted using the environmental impact categories: abiotic depletion (DAR-elements), abiotic depletion (fossil fuels) (DAR-fossils), acidification (Ac·P), eutrophication (Eu·P), freshwater aquatic ecotoxicity (FAETP), Global warming (GWP100a), and photochemical oxidation (Ph.O); using the CML-IA baseline.

CO_2 uptake

The equations to calculate the amount of CO_2 uptake during the concrete life cycle can be modelled according to Zhang (2019) [13]. The steps are followed by estimating the surface area of concrete exposed to the air, determining carbonation depth with the life period, and calculating the molar concentration of carbonate substances in concrete. The dimension of the OPS concrete was 15 cm in thickness, 25 cm in width, and 300 cm in length. The water and cement ratio was 7/20 [8], and the design life period of the concrete is 25 years. The value of carbonation depth is 9 mm/year$^{0.5}$ for the compressive strength concrete with the range between 20 to 23 MPa [14].
The model of CO2 uptake as follows:

$$U_{CO_2}(t) = A \times d(t) \times [CO_2] \times 44 \tag{1}$$

In which A is the exposed surface area of concrete ($A = L \times W$); $d(t)$ is the carbonation depth and calculate by Equation 5. $[CO_2]$ is the molar concentration of carbonatable substances and 44 is the molecular weight of carbon dioxide.

$$[CO_2] = \alpha_h(t) \times M \tag{2}$$

where $\alpha_h(t)$ is the degree of hydration of cement paste at t (time), M is the molar concentration of the carbonate substances, and C is cement contents.

$$\alpha_h(t) = \frac{t}{2+t} \times \frac{1.031\frac{W}{C}}{0.194+\frac{W}{C}} \quad (3)$$

$$M = 8.06 \times C\left(\frac{10^{-6}mol}{cm^3}\right) \quad (4)$$

The depth of carbonation over time calculates by the following equation.

$$d(t) = k \times t^{1/2} \quad (5)$$

k stands for the carbonation rate while t is the period time of concrete.

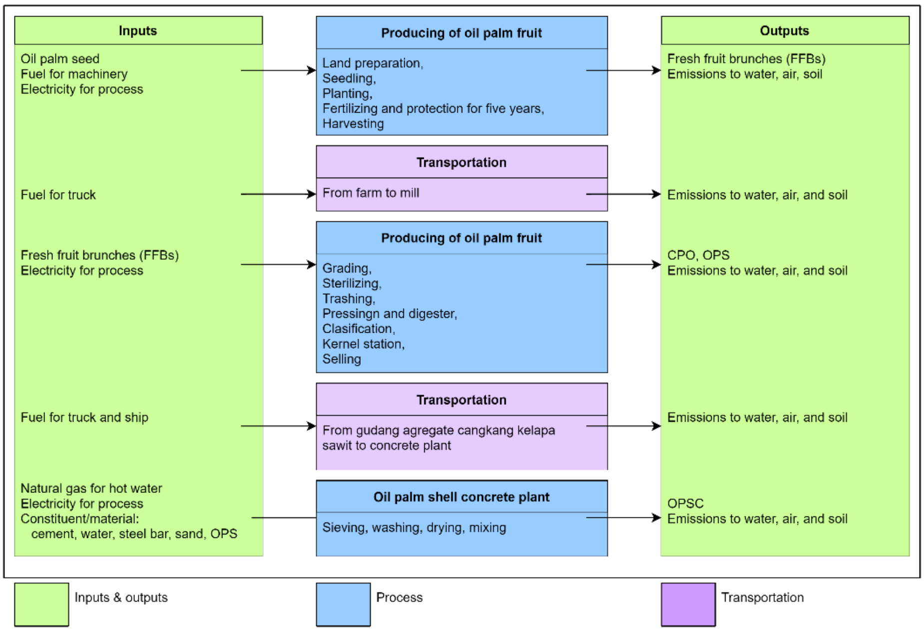

Figure 1: The cradle-to-gate system boundary for the production of OPS lightweight concrete beam.

Results and Discussion

Following the equations (1 - 5) for the OPSC beam, the reabsorbed CO2 during the design age is 9,5 grams. The 1 m^3 beam concrete can reabsorb carbon dioxide 106 grams through normalization. The results also show that this two-story strength concrete in an indoor environment can absorb up to 25% of the CO_2-eq emitted during manufacture from the atmosphere during in-service conditions. However, it should be noted that the CO_2 uptake by photosynthetic during plant growth is not calculated in this study. Furthermore, the inventory analysis results with the normalization of the OPSC beam are presented in Table 2, and the transport distance of each constituent is presented in Table 3.

The cradle-to-gate boundary starts with land preparation (A), where ready-to-use land is planted with oil palm seed up to produce fresh fruit bunch (B), then harvested and transported to the palm oil mill (C). Meanwhile, the production process of oil palm shells in palm oil mills is denoted as D. An oil palm shell yield of 8 tons/ha was considered. The mass outputs considered were: 22% empty fruit bunches, 20% crude palm oil, fiber 14%, oil palm shell 6%, and kernel 5%, while an economic allocation among co-products was not considered. The pre-treatment of palm shells in the laboratory (E), The laboratory test of the hot wastewater consists of volatile fatty acid, phosphate and nitrate was 195.8, 279.3, and 23 mg/litter, respectively. According to the same sample, ammonium and chloride is 2.6 and 17 mg/litter, respectively. F is the manufacture of reinforced lightweight concrete beams.

The impact categories on the CML-IA baseline perform on the Table 4. Oil palm shell manufacture contributes around one-fold higher than lightweight beam concrete production. Fresh water aquatic ecotoxicity, for example, on the opportune oil palm shell stage contributes 2,65 ton 1,4-DBeq, higher than other OPS manufacture stages. The primary emitter for this impact category was the presence of beryllium and hydrogen fluoride in the urea production and electricity generation process. Another major contributor to environmental impacts was diesel consumption, represented as transportation stages marked by the high value of abiotic depletion (fossil fuels). A diesel consumption of the machinery used in the fresh oil palm fruit (palm oil cultivation) and urea production were responsible for the depletion of abiotic fossil resources, due to the usage of natural gas, coal and crude oil on those process. In addition, eutrophication from the opportune oil palm shell process significantly increases from other previous stages, up to 10 times due to phosphate produced from the OPS wastewater.

Table 2 Inventory data of 1 m^3 OPSC

	Sieving	Amount	Washing	Amount	Drying	Amount	Mixing	Amount
Input	OPS	1820 kg	OPS (4.75-12.5 mm)	273 kg	Clean OPS	455 kg	Cement Portland	500 kg
			Hot and tap water	16380 L	Electricity	26,21 kWh	Tap water	175 L
			Natural gas	25,12 kg			Reinforcing steel	138,89 kg
							Fine aggregate	860 kg
							Dry clean OPS	273 kg
							Electricity	2,78 kWh
Output	OPS (4.75-12.5 mm)	273 kg	Clean OPS	455 kg	Dry clean OPS	273 kg	OPSC beam	1 m^3
	Residue	1365 kg	Wastewater	16198 L	Steam	182 kg		

Table 3 Transport scenarios

Constituents	Amount (kg)	Distance (km)	(kg*km)	Dataset
OPS (Rokan Hulu – Depok)	273,00	1429	390117	Transport, freight, lorry 3.5-7.5 metric ton, EURO2 | transport, freight, lorry 3.5-7.5 metric ton, EURO2
		30,6	8354	Transport, freight, sea, container ship | transport, freight, sea, container ship
Fine aggregate (Belitung Timur – Depok)	860,00	466	400760	Transport, freight, lorry 3.5-7.5 metric ton, EURO2 | transport, freight, lorry 3.5-7.5 metric ton, EURO2
		54	46440	Transport, freight, sea, container ship | transport, freight, sea, container ship
Reinforced stell (Jakarta Timur – Depok)	138,89	30	4167	Transport, freight, lorry 3.5-7.5 metric ton, EURO2 | transport, freight, lorry 3.5-7.5 metric ton, EURO2
Cement Portland (Banyumas – Depok)	500,00	22	11000	Transport, freight, lorry 3.5-7.5 metric ton, EURO2 | transport, freight, lorry 3.5-7.5 metric ton, EURO2

Table 4 The comparison of the environmental impacts of opportune OPS manufactures and OPS concrete

Impacts	Reference unit	A	B	C	D	E	F
(DAR-elements)	kg Sb eq	8,54E-07	6,36E-04	1,22E-02	1,22E-02	8,14E-02	8,44E-02
(DAR-fossils)	MJ	1,01E+00	2,93E+02	9,78E+03	1,02E+04	6,98E+04	7,45E+04
(Ac·P)	kg SO_2 eq	5,08E-04	1,40E-01	2,88E+00	3,04E+00	2,04E+01	2,23E+01
(Eu·P)	kg PO^{4-} eq	1,41E-04	4,88E-02	9,40E-01	1,14E+00	1,22E+01	1,30E+01
(FAETP)	kg 1,4-DB eq	4,21E-02	1,67E+01	3,63E+02	3,96E+02	2,65E+03	3,32E+03
(GWP100a)	kg CO_2 eq	7,91E-02	2,37E+01	5,89E+02	6,24E+02	4,19E+03	4,90E+03
(Ph.O)	kg C_2H_4 eq	2,05E-05	5,18E-03	1,27E-01	1,32E-01	8,91E-01	1,06E+00

Conclusions

The environmental performances of oil palm shell concrete show that the manufacture of oil palm shells has significantly contributed to environmental impacts due to fertilizer usage for five years. Meanwhile, concrete carbonation offers more benefits for carbon sinks in small quantities in this study. Further studies need to analyse the more actual amount by experimental testing and include it during the end-of-life phase. The absence of a national standard regulating the environmental impact of construction products cannot be used as a reference for comparing commonly used results.

Acknowledgments

This research was supported by the members of Laboratory Structure and Material; and Laboratory Health and Environmental Engineering, University of Indonesia.

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