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Life Cycle Assessment of Sugarcane Bagasse Ash as Partial Cement Replacement in Concrete

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ABSTRACT

Concerns on the environmental impacts from use of concrete in the construction industry are becoming more widespread. Past and current research trends indicate that cement represents the bulk of emissions from concrete. Thus, its replacement significantly reduces negative impacts in concrete. Incorporation of industrial and agricultural waste products have shown to positively influence properties of concrete. Particularly, sugarcane bagasse ash (SCBA) has shown promising use as a cement replacement, but its environmental performance has not been thoroughly explored in the literature. This study investigates the environmental impacts of concrete with 10% cement replacement by SCBA using a life cycle assessment approach. The results were compared to normal concrete with compressive strength of 45 MPa. A school building was selected as a case study for LCA calculations. The total volume of concrete was obtained through a digital building model constructed using building information modelling (BIM) approach. The Ecoinvent database was used to construct the life cycle inventory while ReCiPe 2016 was used as the impact assessment method. Impacts were presented in the form of 17 midpoint categories. Results show that use of SCBA concrete reduced environmental impacts by an average of 5.5% in all but 3 impact categories. A small increase was observed for water use (1.6%) while significant increases in impacts were observed for ozone depletion (7.4%) and land use (58.4%). Furthermore, approximately 3% cost reductions were achieved when using SCBA concrete over normal concrete.

Keywords—life cycle assessment, sugarcane bagasse, cement replacement, sustainable building materials

1. INTRODUCTION

Environmental issues arising from construction industry are receiving more attention from the public [1]. Increased construction demand leads to higher demand for building materials especially concrete. Cement represents the main constituent of concrete and its production involves significant carbon dioxide emissions which contribute to global warming [2]. Various studies have attempted to reduce negative environmental impacts from concrete through inclusion of waste products from industrial processes such as coal fly ash, silica fume and blast furnace slag [3]. However, recent attention has been shifted to use of agricultural waste in concrete. This reduces the environmental impacts from constituent materials of concrete which are cement, sand, and gravel. In addition, use of agricultural waste avoids negative impacts which arise from their disposal.

Waste products from agriculture have shown to be viable cement replacement in concrete such as coconut shell [4], palm oil clinker [5] and rice husk ash [6]. Particularly, use of sugarcane bagasse ash (SCBA) produces satisfactory strength and durability properties in concrete [7-10]. However, studies on environmental impact of SCBA concrete in the literature are limited. Therefore, the aim of this study was to compare embodied environmental impacts of SCBA concrete with conventional concrete using life cycle assessment (LCA). Various studies in the literature have investigated environmental impacts of concrete using an LCA approach [11]. This allows a greater appreciation of concrete and its environmental impacts using a systematic and formal methodology. A school building was selected as a case study for LCA calculations which was facilitated using building information modelling (BIM).

2. SUGARCANE BAGASSE ASH

Sugarcane bagasse is a fibrous waste material from sugar production. Particularly, sugarcane bagasse is a residue from sugarcane juice extraction. Fig. 1 shows the production process which converts sugarcane to sugar. Due to its high calorific value, it is often burned to produce energy at sugar mills. The material which remains after the combustion process is known as sugarcane bagasse ash (SCBA). Sugarcane production is highest in Brazil with a yearly yield upwards of 760 million tonnes [12] followed by India and China. Global sugarcane production reaches approximately

1500 million tonnes. Although sugarcane production in Malaysia is comparatively small at only 30,000 tonnes yearly production, up to 13,500 tonnes of bagasse may be produced locally per year [13]. Thus, there is great potential for its use in various applications.

Typically, SCBA is disposed in landfills or used as fertilizer but these methods result in negative environmental impacts. More than 70% of SCBA is comprised of silica, aluminium and other metal elements which classifies it as a class F pozzolan [13]. The high amounts of silica in SCBA poses a carcinogenic risk to human health if allowed to be dispersed into the atmosphere [14]. Use of SCBA as a concrete admixture removes silica release to the biosphere through sequestration or storage in concrete. In addition, it reduces the volume of solid waste produced which mitigates burden on landfills.

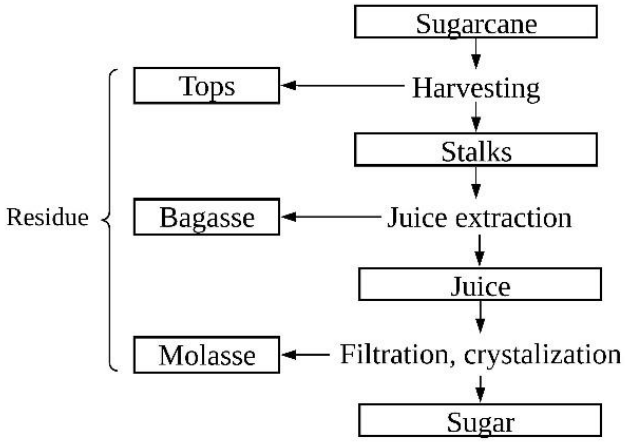

Fig. 1. Sugarcane to sugar production chain

Most studies in the literature have been directed towards exploration of SCBA use as an admixture in concrete since the late 1990s [15]. However, the utility of SCBA is widespread among various research disciplines. For example, SCBA has been used to produce glass-ceramics [16], geopolymers [17] and silica aerogels [18]. These studies represent novel approaches to agricultural waste recycling. Thus, the potential engineering value and environmental benefits associated with SCBA use are apparent.

Investigation of SCBA has found it to exhibit pozzolanic properties [7, 13]. This is indication that it may be used as cement replacement. Studies in the literature have found SCBA produced improvements to mechanical and durability properties when incorporated into concrete [13]. Additionally, incorporation of SCBA increased workability of the resulting concrete mix [8, 10]. Other studies had found that compressive strength of concrete with SCBA was comparable to conventional concrete [7, 9-10]. In terms of durability, chloride ion penetration resistance of concrete increased with increasing amounts of SCBA [10]. Furthermore, sieving of the SCBA prior to incorporation into concrete resulted in higher pozzolanic activity thus improving performance of the resulting concrete [19]. Therefore, these properties are evidence that SCBA concrete may be viable for use as direct replacement of conventional concrete.

3. METHODOLOGY

3.1. Mix Design

Table I shows the mix designs of the concrete mixes used in the study which were obtained from [20]. The number in the mix name denotes the percent replacement of cement with SCBA. The control mix (i.e. normal concrete) is designated as C0 which has compressive strength of 45 MPa at 28 days. The maximum replacement level among the mixes was 25% replacement of cement with SCBA at 5% intervals. It was observed that 10% replacement was the optimal level which achieved the highest compressive strength among the SCBA samples. Thus, mix C10 was chosen for the case study calculations involving the whole school building. This mix was selected since it presents the best alternative in terms of structural performance.

Table I. Mix design for normal and scba concrete

Mix	**Cement**[a]	**Sand**[a]	**Gravel**[a]	**SCBA**[a]	**Compressive Strength at 28 days (MPa)**
C0	330.0	693.4	1233.8	0	45.0
C5	313.5	693.4	1233.8	16.5	48.8
C10	297.0	693.4	1233.8	33.0	52.3
C15	280.5	693.4	1233.8	49.5	48.5
C20	264.0	693.4	1233.8	66.0	44.8
C25	247.5	693.4	1233.8	82.5	43.7

[a] Units are in kg/m^3

3.2. Building Information Modelling

BIM is one of the latest technologies revolutionizing the architectural, engineering and construction industry worldwide. BIM is an object-oriented design method that replaces traditional paper-based mediums through digitization of workflows [21]. BIM software simplifies the production of structural drawings and aids clash detection in the multi-disciplinary nature of construction. It goes beyond a technological advancement and represents a shift in the traditional building delivery process towards an integrated workflow. BIM shifts the attention of stakeholders towards the design phase where key decisions may be made with minimal impacts towards cost or schedule of the project.

Using BIM, the selected case study building was constructed as a 3-dimensional digital model. This model was comprised of digital objects representing the different structural elements such as beams, columns, and slabs. These structural elements were defined according to physical drawings. BIM was able to accurately calculate the volume of concrete required for the structure using its automated quantity takeoff feature. However, architectural elements such as roof, walls and windows were not included in the model.

3.3. Case Study Structure

The selected structure is a 4-storey administrative block of a school building. This structure was selected since its mass is large enough for differences in environmental impacts to become apparent. Structural drawings were obtained from the Malaysia Public Works Department (PWD). These particular drawings represented the recently introduced Pre-Approved Plans (PAP) which greatly streamlines the building approval process.

Sekolah Menengah Kebangsaan Agama (SMKA) Jerlun in the state of Kedah was one of the first schools to be built using this particular set of PAP. The overall design of the main school building resembles a binuclear layout which divides the building into two main blocks with a rectangular courtyard in between them. A single corridor or walkway connects rooms within a floor with stairwells are located at each end of the building. A BIM methodology was employed to construct the digital model according to the physical drawings. Total volume of the structure was calculated using BIM quantity take off.

3.4. Life Cycle Assessment

LCA is a systematic method to quantify environmental impacts of a product or process throughout its life cycle. The earliest use of LCA was to compare life cycle impacts between various beverage containers in the 1970s. Since then, LCA has been applied to various sectors including the construction industry. Its usefulness lies in its ability to objectively and systematically evaluate the environmental impacts associated with every stage of construction or life cycle of building material.

The standard documents ISO14040 and ISO14044 describe the framework and technical requirements for an LCA, respectively. A typical LCA is comprised of 4 phases: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) interpretation. These phases are introduced in the following paragraphs along with their context within this study. Fig. 2 shows the framework of the LCA carried out in this study.

3.4.1 Goal and scope definition:

The first phase defines the objective or goal of the LCA. The goal of the LCA describes its intended application, justification, and audience. On the other hand, the scope describes the thoroughness of the LCA and defines the conditions required to achieve the goal. For example, an LCA may be directed towards embodied environmental impacts of a material (i.e. comparative LCA) or it may assess the energy use throughout a building use phase (i.e. whole-building LCA). Furthermore, an LCA may extend from creation of the product (i.e. cradle) to its intended use (i.e. gate) or its disposal (i.e. grave). A system boundary graphically describes the extent of LCA coverage within the life cycle of the studied product. This phase also defines the functional unit which is used as unit of comparison between different LCA studies.

a) Goal: The goal of the LCA in this study was to compare environmental impacts between SCBA concrete and conventional concrete with similar compressive strength. In this case, the target compressive strength was 45 MPa. All mixes from [20] conform to this condition except for C25 which is slightly below the threshold.

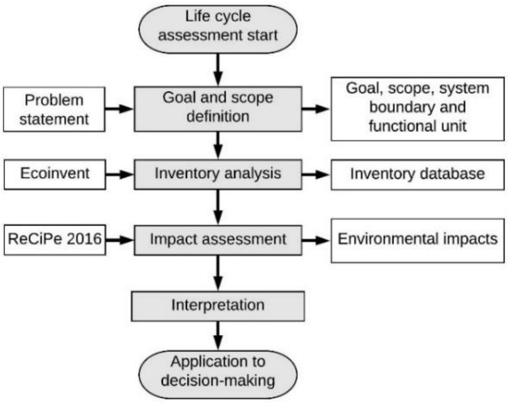

Fig. 2. Outline of the LCA in this study

b) Scope: The LCA was a cradle-to-gate study which started from production of concrete constituents up to transportation to the concrete batching plant. The constituents of concrete include cement, sand, gravel and sugarcane bagasse ash. The production process for these materials is shown in Fig. 3 which also defines the system boundary of the LCA. Impacts from construction, building maintenance and demolition were not considered since these may be considered equal between normal and SCBA concrete mixes.

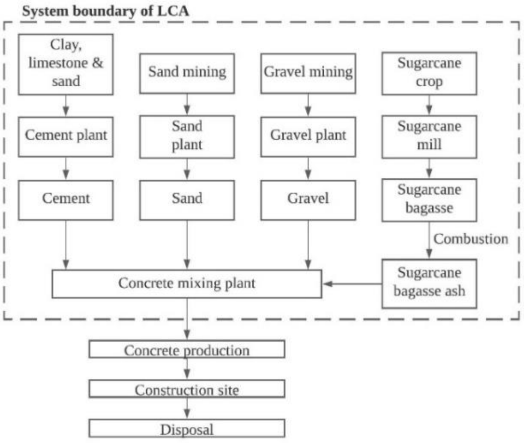

Fig. 3. System boundary of the LCA

c) Functional unit: The functional unit for the LCA was a school building which was constructed as a 3-dimensional, digital model using a BIM approach. Through the digital model, BIM software calculates the total volume of the structure to enable accurate LCA calculations to be carried out. Only structural elements such as beams, columns and slabs were modelled. Architectural elements such as walls and roofs were excluded from the model. Fig. 4 shows the completed digital model of the school.

3.4.2. Inventory analysis

The second phase constructs an inventory database of all processes in the system boundary. For this purpose, comprehensive life cycle inventory databases may be used such as GaBi and Ecoinvent. For processes not covered in any database, the LCA practitioner may construct the LCI based on primary investigation, adapt from existing processing, or literature review. The accuracy of data in this phase influences accuracy of the environmental impacts calculated in the following phase. Often, LCA practitioners encounter the most problems during this phase since defining new processes requires detailed and thorough evaluation. Additionally, this phase defines the transport distances for all materials.

a) Database: Ecoinvent (i.e. version 3.6) was used to construct the life cycle inventory (LCI) for the LCA in this study. Ecoinvent was selected due to its comprehensive collection of various processes and applicability towards different regional contexts. Among the processes included are cement production, sand/gravel extraction, sugar cane production and transportation by lorry. These processes from Ecoinvent are listed below.

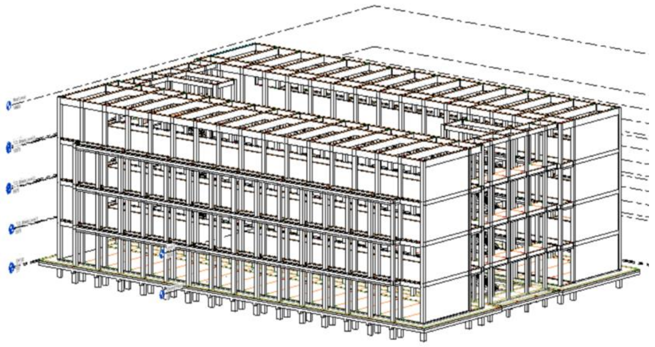

Fig. 4. Digital model of the school constructed using BIM

- Cement production, Portland, Rest of World (RoW)
- Sugarcane processing, traditional annexed plant, RoW
- Treatment of bagasse, from sugarcane, in heat and power co-generation unit, 640 kW thermal, RoW
- Silica sand production, RoW
- Gravel production, crushed, RoW
- Transport, lorry, 16-32 metric ton, EURO5, RoW

b) Transport distance: A theoretical concrete batching plant was established in the center of Kuala Lumpur, Malaysia. The nearest sources of concrete constituents were identified using a publicly available web mapping service provided by Google Inc. These locations include cement production plants, quarries and sugarcane plantations. Table II shows the transport distances used in LCA calculations. Due to privacy concerns, company names were not included in the origin and destination columns.

3.4.3. Impact assessment

The third phase of LCA is where calculations of environmental impacts are carried out based on the LCI constructed in the previous step. Various impact assessment methods may be used to calculate the environmental impacts such as Eco-Indicator 99, CML2001 and ReCiPe 2016. Additionally, environmental impacts may be presented as either midpoints or endpoints. Midpoints have more certainty but are less relevant to decision support. They are useful to identify emission targets and specific areas of environmental concern [22]. On the other hand, endpoints have more relevant to decision support at the cost of certainty. LCA results may be most suitable when presented as endpoints to the public or a non-technical audience [23].

a) Impact assessment methodology: The impact assessment method used was ReCiPe 2016 (hierarchist perspective) and included 17 impact categories [24]. Midpoints were adopted because they have stronger relation to environmental flows and their uncertainty is low. Impacts were calculated using Microsoft Excel to enable a high degree of control over data and calculations [25]. The hierarchist perspective was selected due to its balance between short- and long-term damaging effects.

Table II. Transport distances for LCA calculations

Material	**Origin**	**Destination**	**Total distance (km)**
Cement	48000, Rawang, Selangor	55200, Kuala Lumpur	36
Sand	43100, Hulu Langat, Selangor		20
Gravel			
Sugarcane bagasse ash	47000, Sungai Buloh, Slangor		27

b) Impact categories: The 17 impact categories included in the LCA cover a wide range of environmental protection areas. The most commonly reported impact category in most LCA studies is climate change which is reported in “kilograms of carbon dioxide equivalent” (kg CO_2 eq.). However, other emissions may also negatively affect the environment but are often not reported. Therefore, this study sought to be as comprehensive as possible in the coverage of impact categories. These categories and their corresponding units are listed in Table III. Calculation of the impacts is shown in Fig. 5 which outlines a simplified multiplication path. In the figure, an example for calculating the amount of “kilograms of chloroflourocarbon-11 equivalent” (kg CFC-11 eq.) which are emitted from nitrous oxide (N_20) from 1 kg of cement. Emissions of kg CFC-11 eq. from other materials such as CFC-11, CFC-12 and Halon-1301 are summed up to result in the total ozone depletion potential of cement. The steps involved in calculations for other impact categories are identical.

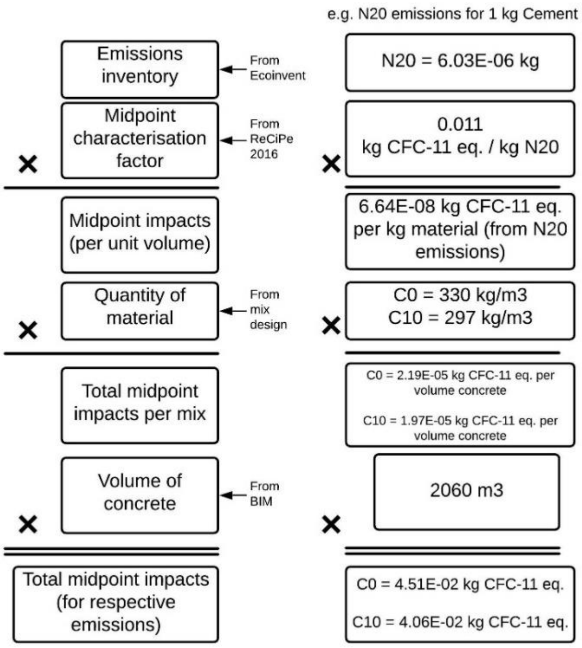

Fig. 5. Example of midpoint impact calculations

Table III. Included impact categories from ReCiPe 2016

Impact category	Units
Climate change	kg CO_2 eq.
Ozone depletion	kg CFC-11 eq.
Ionizing radiation	kBq Co-60 eq.
Fine particulate matter formation	kg $PM_{2.5}$ eq.
Photochemical oxidant formation (Human health)	kg NO_x eq.
Photochemical oxidant formation (Ecosystem quality)	kg NO_x eq.
Terrestrial acidification	kg SO_2 eq.
Freshwater eutrophication	kg P eq.
Freshwater ecotoxicity	1,4-DCB eq. emitted to freshwater
Marine ecotoxicity	1,4-DCB eq. emitted to seawater
Terrestrial ecotoxicity	1,4-DCB eq. emitted to industrial soil
Human toxicity (Cancer)	1,4-DCB eq. emitted to urban air
Human toxicity (Non-cancer)	1,4-DCB eq. emitted to urban air
Water use	m^3 water consumed
Land use	m^2 x annual crop eq.
Mineral resource scarcity	kg Cu eq.
Fossil resource scarcity	kg oil eq.

3.4.4. Interpretation

The fourth phase of LCA interprets the results obtained from impact assessment. This phase is not strictly defined compared to previous phases. This allows the practitioner to apply findings from the LCA to various disciplines or situations. The interpretation phase concludes the results and provides recommendations towards decision-making. Additionally, other analyses may be conducted in the interpretation phase such as cost analysis. The main purpose of an LCA is to inform the decision-maker [26]. Therefore, the interpretation phase should not directly draw conclusions based on LCA results alone but consider values of the practitioner and stakeholders.

4. RESULTS AND DISCUSSION

4.1. LCA impact assessment

The results for LCA of the whole building are shown in Fig. 6. Reductions were observed in all impact categories except for the significant increases in ozone depletion (OD) and land use (LU) which are 7.4% and 58.4% respectively. A relatively small increase was observed in water use (WU) of approximately 1.6%. An average reduction of approximately 5.5% was observed in all but the 3 impact categories. It was observed that the environmental impacts were generally proportional to the amount of cement replaced with SCBA.

The results show that midpoint results allowed a deeper insight into the trade-offs of using alternative building materials. For example, through midpoint impacts, decision-makers would have been able to identify significant LU and OD impacts. Such findings would not be obvious if endpoints or a single impact category (i.e. climate change only) were used.

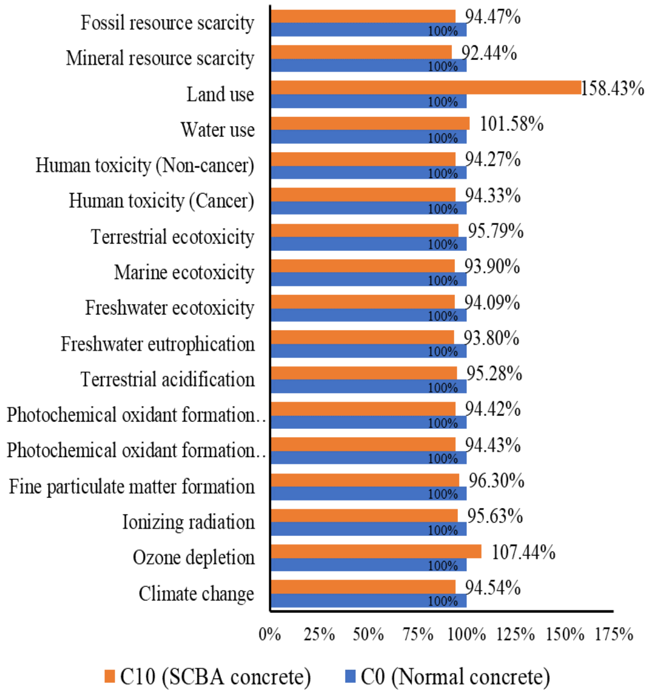

Fig. 6. Percent change in impacts between normal and SCBA concrete for the whole building

4.2. Ozone depletion (OD)

OD for normal concrete is 0.121 kg CFC-11 eq. while that for SCBA concrete is 0.130 kg CFC-11 eq. This indicates an increase of approximately 7.4% impacts in OD from normal concrete to SCBA concrete. It is inferred that the production and denitrification of nitrogen fertilizers are sources of nitrous oxide which contribute to the degradation of stratospheric ozone [27]. Thus, the cultivation of sugarcane may contribute to the increased impacts in OD. Exploration of alternative fertilizers may help reduce OD impacts.

4.3. Land use (LU)

LU will cause the loss of habitat for certain animal species. The impacts of land transformation, land occupation and land relaxation were included in the results. The impact was measured in units of m^2 × annual crop equivalents. LU in normal concrete production is 54,015 m^2 × annual crop eq. whereas the LU in SCBA concrete production with 10% replacement level is 85,577 m^2 × annual crop eq. This implies an increase of approximately 58.4% in LU for SCBA concrete compared to normal concrete. Sugarcane plantations are believed to contribute to a large portion of land use in SCBA concrete production. The transformation and occupation of land causes damage to the ecosystem through loss of habitat. However, the LCA in this study did not include the effects of avoided impacts due to removal of SCBA from waste disposal cycle. This may further reduce impacts in LU but further investigation is required to determine this as LCI data on bagasse ash disposal are lacking in the literature.

4.4. Water use

There was a small increase in WU for SCBA concrete compared to normal concrete. This may be attributed to the water used during sugarcane cultivation as agricultural products inherently require water to produce biomass [28]. However, the increase in WU was comparatively small. This may be due to high quantity of water required for cement production and aggregate washing as well.

Table IV. Cost breakdown for normal and SCBA concrete

Mix	Cement[a]	SCBA[a]	Sand[a]	Gravel[a]	Total cost of structure (MYR)
C0	66.06	0.00	25.19	44.79	280,232.74
C10	59.45	2.15	25.19	44.79	271,060.88

[a] Prices are in Malaysian Ringgit (MYR) per cubic metre of concrete

4.5. Cost analysis

In addition to environmental impacts, the total cost of building material was calculated for each concrete mix. It was assumed that the volume of concrete needed for both types of concrete mixes is constant. Quantity take off from the BIM software revealed that the total concrete volume for the school structure is 2060 m^3. The cost of transportation was excluded from the cost estimation. The price of cement, fine aggregate and coarse aggregate used in this cost estimation was based on the Building Material Price 2019 from the Malaysian Construction Industry Development Board (CIDB). Meanwhile, the cost of sugarcane bagasse was obtained from Chandel et al. [29]. The total cost of normal concrete obtained is RM 280,000 while the total cost of SCBA concrete is RM 271,000. The results show that there is approximately 3.2% financial saving from using SCBA concrete over normal concrete. Table IV shows a breakdown of cost for the individual concrete constituents for each mix.

4.6. Comparison with other LCA studies

It was useful to compare the results of normal concrete in this study with the literature. This verifies that the LCA calculations were carried out accurately. The impact values from the climate change impact category for normal concrete mixes were used as the main point of comparison. The climate change impacts for 1 m^3 of C0 in this study was calculated to be 346.6 kg CO_2 eq. Table V summarizes the climate change impact values for normal concrete in various LCA studies. From the table, the climate change impact value for C0 was found to fall within the range of values indicated in the literature. Therefore, it is inferred that the LCA calculations in this study were carried out correctly.

Table V. Summary of climate change impacts for normal concrete in the literature

Cement content (kg/m^3)	Compressive strength (MPa)	Climate change impact value (kg CO_2 eq.)	Reference
315	39.2	307	[30]
384	41.5	340	[31]
380	32-40	339	[32]
350	30-37	317	[33]
380	50	379	[34]

5. CONCLUSIONS

Results of the LCA show that use of SCBA concrete over normal concrete resulted in reductions in all but 3 impact categories. The reduction in environmental impacts was approximately proportional to the replacement level of cement with SCBA. However, the high impacts in land use and ozone depletion should not be ignored. Solutions should be sought to address land use change impacts from sugarcane cultivation and ozone depletion from nitrogen fertilizer application. Furthermore, the impact values of normal concrete in this study were found to be consistent with values from the literature. On the other hand, cost for SCBA concrete was found to be lower due to reduction in cement use for the concrete mix.

LCA results are proof that the sustainable alternatives to conventional concrete may be feasible. Notably, use of LCA to study SCBA in concrete has been identified as lacking in the literature. Thus, this research is believed to contribute towards this research gap and subsequently inspire similar research in the future. Future research in this knowledge domain may focus on establishing a life cycle inventory database for all agricultural residues used in construction. This may facilitate future LCA studies on sustainable concrete and encourage their use in the construction industry.

This study focused on embodied environmental impacts since this aspect was lacking for BIM on its own. For example, out-of-the-box BIM software is typically able to carry out lighting and heating simulations to estimate operational impacts. However, calculation of embodied impacts requires a distinct methodology to fully account for all potential impact pathways which BIM may not be able to perform. When paired with the information-rich models created using BIM, the application of LCA may be fully realized.

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