Environmental Impact Assessment Review 87 (2021) 106543

Contents lists available at ScienceDirect

Environmental Impact Assessment Review

journal homepage: www.elsevier.com/locate/eiar

Circular economy application for a Green Stadium construction towards sustainable FIFA world cup Qatar 2022™

Abathar Al-Hamrani [a], Doyoon Kim [b], Murat Kucukvar [c,*], Nuri Cihat Onat [d]

[a] Department of Civil and Architectural Engineering, Qatar University, Qatar
[b] Senior Sustainability Expert, Qatar Foundation, Doha, Qatar
[c] Mechanical and Industrial Engineering, Qatar University, Doha, Qatar
[d] Qatar Transportation and Traffic Safety Center, Qatar University, Doha, Qatar

ARTICLE INFO

Keywords:
Recycled concrete
Circular economy
Carbon footprint
Life cycle sustainability assessment
Sustainable construction
FIFA world cup 2022™

ABSTRACT

The construction industry is responsible for a significant amount of raw material consumption and environmental footprints. Therefore, sustainable construction became a hot topic, which strives to reduce material consumption, limit constructional waste disposal, and decrease contribution to climate change. In line with Qatar's commitment to organizing a sustainable FIFA World Cup in 2022, this study aims to conduct an environmental life cycle assessment (LCA) for the construction of the Education City Stadium. The work presented here provides the first empirical LCA for analyzing the environmental and economic impacts of circular economy application in a World Cup stadium. In this research, the cyclopean concrete (CYC) methodology was utilized, which incorporate the site excavated boulders with the concrete mix to cast the under-raft foundation of the stadium. This approach was compared to the conventional concrete (CC) casting approach to assess the extent to which the newly developed methodology can reduce the environmental and economic burdens. The obtained results have shown a 32% reduction in greenhouse gas emissions when adapting the CYC approach. Thus, the CYC holds a strong promise to achieve the required structural behavior with a low-cost alternative material from existing waste products in Qatar and a lower environmental impact than the CC.

1. Introduction

As the world's largest liquefied natural gas producer, Qatar has gained international recognition because of its substantial endowment in petroleum and natural gas reserves. As a result, having an opportunity to hold the FIFA World Cup Qatar 2022™ event will have a long-term positive impact on the country's legacy. As it has been witnessed in other countries that have hosted such an event before, the FIFA organization aims to cut the overall environmental impacts of FIFA World Cups (FWC) on both the hosting country as well as the surrounding regions (Death, 2011).

Over the past century, policymakers were increasingly concerned with the environmental burdens caused by mega sports events. In 1994, the Lillehammer Winter Olympic Games was the first mega-event organization that aimed to apply sustainable and environmental practices (Paradise, 2016). Afterward, the International Olympic Committee in 1996 declared to include the environmental impact assessment as a mandatory requirement throughout the life cycle of the future Olympic Games (Dolles and Söderman, 2010; Gold and Gold, 2013; Talavera et al., 2019). For FWC events, the environmental concerns were first addressed in the 2006 FWC held in Germany, which integrated the green values under five main areas: water, waste, energy, transportation, and climate change neutrality (Talavera et al., 2019). After that, the 2010 FWC in South Africa sought to launch an initiative towards mitigating

Abbreviations: FWC, FIFA World Cup; GHG, Greenhouse gases; SC, Sustainable construction; CDW, Construction and demolition waste; CE, Circular economy; SDGs, Sustainable Development Goals; LCA, Life Cycle Assessment; FA, Fly ash; SCDL, Supreme Committee for Delivery and Legacy; CC, Conventional concrete; CYC, Cyclopean concrete; ECS, Education City Stadium; EFs, Emission factors; GWP, Global warming potential; PC, Portland cement; N_2O, Nitrous oxide; CH_4, Methane; RCA, Recycled coarse aggregates; RAC, Recycled aggregate concrete; VB, Volume of excavated boulders; FE, Fuel efficiency; CFR, Consumed fuel in rock excavation; CFD, Consumed fuel in concrete discharging; CFT, Consumed fuel in transportation processes; ER, Excavation rate; CV, Concrete volume; DR, Discharging rate of concrete; D, Distance per trip; T, Time per trip; CF, Consumed fuel; C, Cost; Q, Quantity consumed; P, Unit price.

* Corresponding author.
E-mail address: mkucukvar@qu.edu.qa (M. Kucukvar).

https://doi.org/10.1016/j.eiar.2020.106543
Received 2 October 2020; Received in revised form 29 November 2020; Accepted 19 December 2020
Available online 6 January 2021
0195-9255/© 2020 The Author(s). Published by Elsevier Inc. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

the environmental impacts called "Green Goal 2010", which entails some innovative projects ranging from recycling and waste management to city beautifications and biodiversity protection (Death, 2011). However, because South Africa was a developing country that suffers from social inequalities and poverty, the organizers allocated more focus on the social and economic aspects than the environmental aspect such as job creation and national economic boost (Ermolaeva and Lind, 2020). To some extent, the 2014 FWC in Brazil had a similar experience to the 2010 FWC in South Africa due to multiple indexes of high poverty and widespread corruption (Malhado and Rothfuss, 2013). When Russia was selected to host the 2018 FWC, a comprehensive stakeholder analysis was conducted and a sustainability strategy was built since 2013 based on the triple bottom lines (TBL) namely, social, economic, and environmental (Ermolaeva and Lind, 2020). Hence, environmental sustainability is a fundamental pillar of Qatar's vision and commitment as the host country for the next FWC event.

2. Literature review

2.1. Sustainable construction and circular economy

The construction sector is among the most prominent sectors that contribute to a major share of the environmental impact (Kucukvar and Tatari, 2012, 2013; Onat et al., 2014). For example, owing to its alterable properties and versatility, concrete has been estimated to be the most used material in the construction sector (Tatari and Kucukvar, 2011, 2012; Hill and Bowen, 1997). Annually, massive amounts of concrete exceeding 6 billion metric tons are produced worldwide (Marie and Quiasrawi, 2012; Tafheem et al., 2011), which results in huge CO_2 emissions and raw materials consumption. Alhorr and Elsarrag (2015) reported that the construction and building sector is responsible for 1/3 of the total GHG emissions, and it was classified as the second largest CO_2 emitter (Ürge-Vorsatz and Novikova, 2008). Thus, this necessitates the importance of adopting environmentally friendly strategies that contribute to meet the needs of the growing population of human societies, maintain the health of the planet, and ensure the ability of future generations to grow (Onat and Kucukvar, 2020; Onat et al., 2014; Kucukvar et al., 2014b).

Nowadays, there is a worldwide progressive thrive towards the implementation of sustainable construction (SC) practices in various construction industries (Ametepey et al., 2015). Achieving the SC environment is based on an endeavor that applies the three pillars of sustainability; environmental, economic, and social; on the comprehensive construction process, starting from the extraction of raw materials, and ending with the deconstruction of the resultant waste (Kucukvar et al., 2014a; Shafii et al., 2006; Tan et al., 2011). According to Kibert (1994), the SC concept encompasses six principles under which an SC environment can be accomplished: 1) minimizing resource consumption, 2) maximizing the reuse of resources, 3) using recyclable or renewable resources, 4) protecting the natural environment, 5) creating an eco-friendly non-toxic environment, 6) keeping track of quality in the built environment.

On the other hand, the linear economy model is one of the greatest challenges worldwide, which has serious negative repercussions on the economic, social, and environmental aspects of life. This model works based on extract, manufacture, use, and dispose of waste, while the circular economy (CE) model attempts to end this cycle by replacing the "waste disposal" component with "reuse"(Geissdoerfer et al., 2017; Kirchherr et al., 2017; Korhonen et al., 2018; Smol et al., 2015). This indicates that the CE is a methodology that strives to keep a further value of a product upon reaching the end of its life, eliminating waste, and motivating the regeneration of resources (Smol et al., 2015). As an example, Assefa and Ambler (2017) stated that if 10% of the institutional and commercial buildings in Canada are to be repurposed without the need for new construction, 165 megatons of CO_2-eq emissions to the atmosphere will be prevented. Also, CE is a solution that harmonizes ambitions for environmental protection and economic growth (Lieder and Rashid, 2016).

In light of the rapid urbanization and industrialization, practical solutions are needed by the governments to convert local construction waste - which is produced from the excavation and demolition of old buildings - into usable products that can be utilized in the construction of residential, roads, and infrastructure projects. Ossa et al. (2016) studied the feasibility of construction and demolition waste (CDW) aggregates to pave the hot asphalt urban roads and reported their suitability in percentages up to 20%. Moreover, several authors (Bhattacharyya, 2011; Ceia et al., 2016; Majhi et al., 2018; Manzi et al., 2020; Nepomuceno and Vila, 2014) indicated that up to 30% replacement of natural coarse aggregates with recycled coarse aggregates, the concrete properties were hardly affected and the concrete was efficiently used.

While the safe disposal of fly ash (FA) continues to pose challenges around the world, Yu et al. (2018) has developed a green concrete methodology in which not less than 80% of cement is replaced with FA for low targeted compressive strength of 30 MPa. Their methodology revealed a 70% reduction in CO_2 emissions, a 60% reduction in the embodied energy, and a 35% reduction in the material cost. Recently, Czop and Lazniewska-Piekarczyk (2020) presented an ecological friendly construction method that was aiming at reducing the CO_2 emissions produced from the cement industry by replacing 30% of cement with the slag obtained from the municipal solid waste incineration.

As a response to the remarkable benefits of SC and CE, Qatar has paid great attention to the use of innovative technologies for material savings and energy to reduce impacts on the natural environment. For instance, the Qatar Construction Specifications manual (Qatar Construction Specifications, 2014) has adopted the Global Sustainability Assessment System (GSAS) as part of the building code to meet the minimum environmental performance. Moreover, it considers the recycling of materials from demolished buildings and roads as of interest to Qatar. According to Zeyad Hayajneh (2017), it was mentioned that around 170,000 seats of the 2022 FWC Stadiums will be donated to countries in need of sporting infrastructure after the 2022 FWC event.

2.2. Environmental life cycle assessment

The life-cycle assessment (LCA) method is particularly used in assessing the environmental impacts associated with all stages of a product's life (Singh et al., 2011; Tatari et al., 2012). Furthermore, the LCA is a four-stage assessing tool, which begins in the first stage by identifying the purpose and scope of the work, illustrates the system boundaries, and defining the functional unit of analysis; the second stage involves data collection and establishing the energy flows for each life stage of the product; the third stage includes the categorization of environmental impacts (impact categories) and sorting the environmental problems in their relative impact categories; in the fourth stage, the quantified data are interpreted and evaluated so that the best alternative can be selected (Sen et al., 2019, 2020; Singh et al., 2011).

There is a large and growing body of literature that has employed the LCA in performance evaluation of construction practices (Bovea and Powell, 2016; Carpenter et al., 2007; Colangelo et al., 2018; De Schepper et al., 2014; Ding et al., 2016; Horvath, 2004; Ingrao et al., 2016; Knoeri et al., 2013; Singh et al., 2011; Tsai et al., 2014; Varun et al., 2012). For example, Horvath (2004) developed an LCA framework, which draws on the environmental and economic impacts of using recycled material in highway construction. A comparative LCA by Knoeri et al. (2013) was performed between partially recycled aggregate concrete (RAC) and conventional concrete (CC). The LCA results exhibited a 30% reduction in the environmental impacts, which was mainly attributed to the avoidance of CDW dumping in landfills and to the recovered steel scrap. An attempt by De Schepper et al. (2014) was carried to produce completely recyclable concrete (CRC). The environmental benefits of

CRC were then quantified through an LCA analysis, which showed a significant reduction in the total carbon footprint. Kucukvar et al. (2014) also build a hybrid LCA model to quantify all of the economy-wide supply-chain impacts of three construction waste management strategies such as recycling, landfilling, and incineration. Their findings showed that only the recycling of construction materials provided positive environmental footprint savings in terms of carbon, energy, and water footprints Ding et al. (2016) performed a closed-loop LCA on RAC in China to measure the environmental influence of aggregate production, cement content, transportation, and landfilling. The transportation activities along with the cement proportions were observed to be the top two contributors to energy consumption and CO_2 emissions.

More recently, Colangelo et al. (2018) conducted an LCA on four recycled concrete mixes, i.e., blast furnace slag, incinerator ashes, CDW, and marble sludge, and found that the blast furnace slag had the least environmental impact. Data from several resources have confirmed the fact that cement material is responsible for 6–7% of the world's total CO_2 emissions (Andrew, 2017; Karsan and Hoseini, 2015; NRMCA, 2008; Tafheem et al., 2011). Therefore, Wang et al. (2017) have studied the LCA for concrete, where cement was partially replaced with FA. Their results revealed that the use of FA has saved costs and reduced environmental and social burdens. Another holistic approach was followed by Ansah et al. (2020), who incorporated Building Information Modelling, LCA, and Life Cycle Cost to provide useful guidelines in selecting the greenest and economic façade systems for a low-cost residential building in Ghana.

2.3. Novelty and research objectives

Qatar is currently witnessing major prosperity in the field of construction, and worldwide, there is a growing trend towards SC applications. In line with this, the Supreme Committee for Delivery and Legacy (SCDL), who is responsible for planning and delivery of the 2022 FWC Qatar, decided on implementing the cyclopean concrete (CYC) methodology by embedding the site excavated boulders as concrete is deposited rather than the conventional concrete (CC) methodology to fill the under-raft foundation of the 2022 FWC Education City Stadium (ECS). Based on the available literature, no existing work has been found which exploit the site excavated boulders as a filling material for the under raft foundation of the same construction site without the need to excavate and bring boulders from remote locations. Therefore, to ensure the feasibility of the CYC method as an environmentally friendly methodology, the following objectives need to be determined as follow:

1) Performing a detailed comparative environmental LCA of CYC and CC starting from the manufacturing and transportation processes and ending with disposing of or reuse.
2) Investigating the efficiency of the developed method in reducing resource consumption, preventing unnecessary transport emissions, minimizing waste generation, and saving costs.
3) Show Qatar's commitment to organizing and building environmentally friendly facilities to host the first edition of the FWC in the Middle East and the Arab world.

3. Methods

The approach to empirical LCA research adopted for this study is summarized in a step-by-step manner in Fig. 1. More details about data collection and analysis of materials for each stage of the system life cycle are also presented in Section 3.

3.1. Case study

The ECS project is one of the FIFA 2022 WC stadiums that will host matches until the quarter-finals stage of the tournament. Before the general contractor company was awarded the design and build contract for the construction of the ECS project, the site was already excavated by another contractor. While the project's specifications for foundation and substructure preparation recommended the areas under raft slab to be backfilled up to the foundation stratum, these areas were found to be lower than anticipated due to over-excavation by the previous contractor. Hence, to fulfill this requirement, the general contractor in cooperation with SCDL has developed the CYC method, which employs the site excavated boulders as one of the concrete ingredients.

Around 45,000m^3 of soil and boulders have been excavated on the site. Boulders were then cut in specific sizes of 200 mm to 400 mm diameter to fulfill the requirements and to be used for CYC application. With the help of a wheel loader/excavator and a screening bucket, the boulders were selected by size and then washed. Moreover, point load tests were performed on the selected specimen to investigate their strength characteristics. Also, full safety control measures were applied on the site and the procedures of the approved method of statement for the application of CYC fill were carefully followed. After the completion of the whole casting of the CYC fill, load-bearing capacity and coring was performed and tested by a 3rd party approved laboratory. While the CYC methodology was adopted in the construction project of ESC stadium to reduce the environmental life cycle impact of concrete, the main question that needs an answer is does the followed method supports Qatar National Vision 2030 on the environmental and economic levels and helps to achieve an environmentally friendly FWC event with

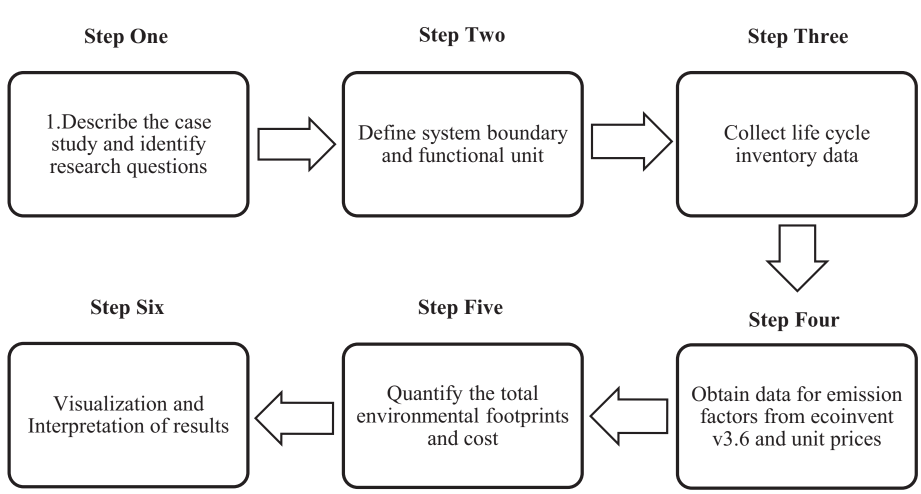

Fig. 1. Steps for conducting a comparative LCA between CYC and CC.

reduced CO_2 emissions?

3.2. System boundaries

Before data collection, the system boundaries were defined for CYC and CC as shown in Fig. 2a, and Fig. 2b, respectively. As illustrated in Fig. 2a and b, the definition of system boundaries for this LCA study begins by specifying the input parameters on which the environmental and economic performance of either type of concrete will be evaluated. These parameters included:

1) Raw materials needed for reinforced concrete production such as cement, sand, aggregates, boulders, and reinforcement.
2) Water needed for concrete mixing and for cleaning concrete mixer and concrete pump trucks.
3) Diesel to be consumed by machines on-site and for transporting construction materials.

Then, the activities with major sources of impacts were identified, which include the production process of concrete, the transportation processes, the excavation processes, the pumping and casting of concrete, and the cleaning processes. The production phase encompasses the manufacturing processes of all concrete ingredients and their resultant impacts until they exit from the factory. The transportation processes phase considers the fuel consumed during the transportation processes of concrete from the plant to the construction site through the mixer and pump trucks. Meanwhile, the fuel consumed during the excavation and transportation of the site excavated boulders to the location of the under-raft foundation was considered in the excavation phase. The phase of casting concrete considers the fuel consumed during the discharging of concrete from the pump trucks into the recommended locations in the site. The final phase considers the amount of water consumed during the cleaning of concrete mixer and pump trucks. As can be depicted from Fig. 2a and Fig. 2b that the excavated boulders were embedded in concrete to produce CYC for the under-raft foundation, while they were disposed into landfills in the CC case. After

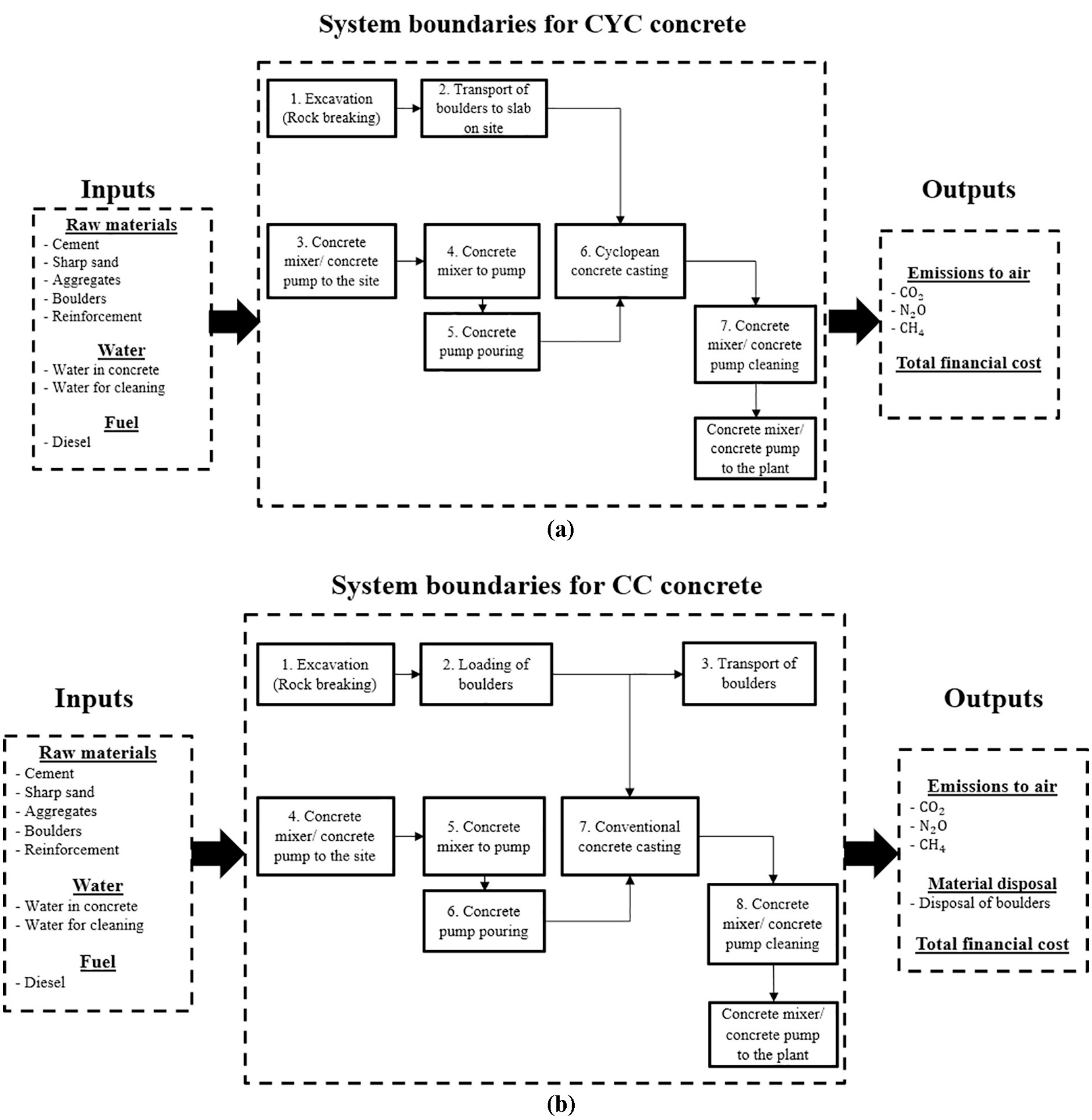

Fig. 2. System boundaries (a) Cyclopean concrete (b) Conventional concrete.

analyzing the consumed amount of the input parameters in the defined boundary system, the associated outputs were calculated based on the greenhouse gases (GHG) emissions to air (CO_2, N_2O,and CH_4), the disposed of boulders, and the total financial cost.

3.3. Functional unit

The functional unit in this study was defined as the zone under the raft foundation of the ESC FWC stadium, which constituted a total volume of 18,000 m^3. Within this study, a comparison between two concrete methodologies such as CYC and the CC will be conducted in terms of environmental and economic impacts to fill that zone. It is worth noting here that the CYC methodology differs from the CC one by the embedment of boulders to fill some of the required volumes before the addition of concrete, while there is no difference in the concrete properties used for both cases, and hence the unit price of concrete ingredients will be same.

3.4. Life cycle inventory data

After identifying the system boundaries, data regarding concrete mix proportions, and prices for both types of concrete were gathered from the contractor as shown in Table 1. The total concrete volume used for CC was 18,000m^3, while 13,637m^3 of concrete plus 6500m^3 of boulders were used for CYC. To account for CO_2 emissions released from the production of each concrete ingredients, the emission factors (EFs) for Portland cement (PC), coarse aggregates, and sharp sand were obtained from the Ecoinvent v3.6 database, which is recognized as one of the most consistent and largest life cycle inventory databases (Treyer and Bauer, 2016). Furthermore, the EF for the reinforcing bars was obtained from Qatar Steel's 7th annual sustainability report in (2017). These factors are listed in Table 2 with a measuring unit of kg CO_2-eq/kg. The CO_2-eq is referred to as CO_2 equivalents and it was used to incorporate the global warming effect of nitrous oxide (N_2O) and methane (CH_4) emitted during each production activity.

Besides, the fuel efficiency (FE) associated with different heavy machinery trucks, that were utilized in the excavation, transportation, and disposal processes were determined from the trucks located in the construction site. As shown in Table 3, the fuel efficiency was determined in terms of either liter/km or liter/h units, so that the consumed amount of diesel in liters for each truck can be calculated based on the traveled distance or the queuing time, respectively. The queuing time in this study represents the time needed for excavating rocks or discharging a unit volume of concrete. It is important to note that the distance of the site from the concrete plant and the dumping site was 40 km and 50 km, respectively. Furthermore, the time needed for the front wheel loader to transport the excavated boulders to the destination was estimated to last $\geq$12 min, whereas the cleaning time for concrete mixer and concrete pump trucks were estimated to last $\geq$5 and $\geq$ 12 min, respectively.

Table 1
Concrete mix proportions and quantities used for: i) CC concrete; ii) CYC concrete.

Ingredients	CC	CYC	Price	Reference
PC	5762 tons	4365 tons	60.42 ($/ton)	(Public Works Authority (Ashghal), 2020)
Coarse Aggregates	21,606 tons	16,366 tons	20.6 ($/ton)	(Public Works Authority (Ashghal), 2020)
Sharp sand	10,803 tons	8183 tons	9.61 ($/ton)	(Public Works Authority (Ashghal), 2020)
Water	3168.75 m^3	2400.21 m^3	5 ($/m^3$)	(Qatar General Electricity and Water Corporation, 2020)
Excavated boulders	–	6500 m^3	–	–
Total concrete volume (m^3)	18,000 m^3	13,637 m^3		

Table 2
CO_2-eq emission factors for concrete making materials.

RC ingredients	Emission factor	Unit	Reference
PC	0.8	kg CO_2-eq/kg	Ecoinvent v3.6
Coarse Aggregates	0.04	kg CO_2-eq/kg	Ecoinvent v3.6
Sharp sand	0.004	kg CO_2-eq/kg	Ecoinvent v3.6
Reinforcing bars	1.31	kg CO_2-eq/kg	Qatar Steel (2017)

Table 3
Fuel efficiency for heavy machinery in the site.

Truck type	FE
Hammer excavator	32.52 l/h
Front-wheel loader	16.43 l/h
Concrete mixer	Empty truck: 0.714 l/km Loaded truck: 0.84 l/km 11.13 l/h
Concrete pump	0.3 l/km 26.6 l/h
Tipper truck	0.368 l/km

To estimate the GHG emissions liberated by fuel consumption of the construction equipment, the EF for the consumed fuel was calculated according to Yan et al. (2010) by utilizing Eq. (1):

$$Fuel j EF = EF of CO_2 for fuel j + EF of CH_4 for fuel j \times GWP of CH_4 + EF of N_2O for fuel j \times GWP of N_2O \tag{1}$$

where GWP is referred to as global warming potential.

Hence, for diesel fuel the GHG EF is $= 2.69 + 0.0239 \times \frac{25}{1000} + 0.0074 \times \frac{298}{1000} = 2.7 kg\ CO_2 - eq/liter$ Data related to the EF of CO_2, the EFs, and GWPs of CH_4 and N_2O were obtained from (International Energy Agency, 2018). It is worth mentioning that the diesel cost per liter was 0.55$ according to WOQOD company (2019), which is the sole distributor of fuels in Qatar.

To evaluate the environmental and economic performance for CYC and CC, the detailed calculations are presented, respectively, in Table 4 and Table 5. In these tables, the main activities were listed in order, then all sub-activities were identified under them with their environmental and economic impacts. The environmental impact of each concrete type was evaluated in terms of CO_2-eq emissions that resulted during the entire life of the product. Whereas the economic impact was evaluated based on the consumed raw materials such as PC, coarse aggregates, sharp sand, reinforcing steel, diesel fuel, and water. The detailed calculations in Table 4 and Table 5 were carried as follows:

1- Calculate the CO_2-eq emissions for each concrete ingredient based on Eq. (2):

$$CO_2 - eq\ emissions = Q \times EF \tag{2}$$

where Q is the quantity of each concrete ingredient and EF is the emission factor presented in Table 2 for each material.

2- Assign each truck to the corresponding activity and select its fuel efficiency as determined in Table 3

3- Calculate the CO_2-eq emissions for each activity, excluding the emissions released during the manufacturing processes of RC ingredients, as in Eq. (3):

$$CO_2 - eq\ emissions = CF\ (liters) \times 2.7\ kg\ CO_2 - \frac{eq}{liter} \tag{3}$$

where CF is the consumed fuel.

4- Calculate the consumed fuel for transportation processes of concrete and boulders (CFT) as in Eq. (4):

Table 4
CO_2-e emissions and total cost obtained from the CYC production.

Activity	Truck type/ concrete ingredients	Amount of diesel/ concrete ingredients consumed	CO_2-eq emissions (kg CO_2-eq)
Excavation/rock breaking	Hammer excavators	Hammer Excavator fuel consumption: 32.52 l/h Breaking of Rocks: ≥ 6 m^3/h. x 6 equipment = 36 m^3/h Excavation fuel Consumption: (6500 m^3 / 36 m^3/h) x 32.52 l/ h = 5871.7 l	5871.7 l × 2.7 kg CO_2-eq/l = 15,853.59 kg CO_2-eq
Transport excavated boulders to the slab	Front-wheel loader	Front-wheel loader fuel consumption: 16.43 l/h. Trips: 6500 m^3 / (4.7 m^3 bucket capacity x 0.60 yield loss) = 2305 Duration: ≥12 min / trip = (2305 / 60 mins.) x ≥ 12 min = 461 h Transport fuel consumption: 461 h. x 16.43 l/h. = 7574.23 l	7574.23 l × 2.7 kg CO_2-eq/l = 20,450 kg CO_2-eq
Producing RC ingredients	Portland Cement (PC) Coarse aggregates Sharp sand Water Reinforcing steel	PC = 4365 tons Coarse Aggregates = 16,366 tons Sharp sand = 8183 tons Water = 2400.21 m^3 Reinforcing steel = (13,637 m^3/1000) x 115 kg/m^3 (Rafts) = 1568.26 tons	PC = 4,365,000 kg × 0.8 kg CO_2-eq/kg = 3,492,000 kg CO_2-eq Coarse aggregates = 16,366,000 × 0.04 kg CO_2-eq/kg = 654,640 kg CO_2-eq Sharp sand = 8,183,000 kg × 0.004 kg CO_2-eq/ kg = 32,732 kg CO_2-eq Reinforcing steel = 1,568,260 kg × 1.31 kg CO_2-eq/kg = 2,054,420.6 kg CO_2-eq
Concrete mixer/ pump transportation	Concrete mixer	Distance from the concrete plant: 40 km Number of Trips (loads): 13,637 m^3/ 8 m^3 (capacity) = 1705 Mixer Truck Fuel efficiency for empty truck: 0.714 l/km Mixer Truck Fuel efficiency for loaded truck: 0.84 l/km Travel & Return Trip Average fuel efficiency per trip: 0.77 l/km Mixer Truck Fuel Consumption per trip: (40 × 2 km) x (0.77 l/ km) = 61.77 l Mixer Truck Transportation: 1705 trips × 61.77 = 105,318 l	105,318 l × 2.7 kg CO_2-eq/l = 284,358.6 kg CO_2-eq
	Concrete pump	Pump Truck Fuel Efficiency: ≥30 l/100 km = 0.3 l/km Pump Truck Transportation: [(0.3 l/km x 40 km)] x (45 times × 2 way) = 1080 l	1080 l × 2.7 kg CO_2-eq/l = 2916 kg CO_2-eq
Concrete mixer to pump	Concrete mixer	Number of Trips (loads): 13,637 m^3/ 8 m^3 (capacity) = 1705 Discharging Rate (concrete): ≥2 m^3/ min Queuing Time: 8m^3 / 2m^3 = 4 × 1705 = 6820 min Mixer truck fuel consumption: 11.13 l/ h Queuing Total Fuel Consumption: = [(6820 mins / 60 mins.] x 11.13 = 1265 l	1265 l × 2.7 kg CO_2-eq/l = 3415.5 kg CO_2-eq
Concrete pouring	Concrete pump	Concrete pump truck discharge rate: 38 m^3/ h Concrete pump truck fuel consumption: 0.7 l/m^3 (26.6 l per hour) Concrete pouring duration: 13,637 / 38 = 359 h Number of Casting (Pouring): 359 h. / 8 h. operation = 45 Pouring of Concrete Fuel Consumption: (45 × 26.6) x 8 h = 9576 l	9576 l × 2.7 kg CO_2-eq/l = 25,855.2 kg CO_2-eq
Cleaning	Concrete mixer	Mixer Truck Cleaning time: ≥5 min = 1705 × 5 = 8525 min Mixer truck fuel consumption: 11.13 l/ h Cleaning Fuel Consumption = 8525 min/60 min × 11.13 l/h = 1581.3 l Water consumption (liters): Concrete Mixer: ≥200 l × 1705 = 341,000 l	1581.3 l × 2.7 kg CO_2-eq/l = 4269.51 kg CO_2-eq
	Concrete pump	Concrete pump truck cleaning time: ≥10 min Cleaning Fuel Consumption = [(45 × 10 min) / 60 mins] x 26.6 l/h = 199.5 l Water consumption (liters): Concrete Pump Truck: ≥250 l × 45 = 11,250 l	199.5 l × 2.7 kg CO_2-eq/l = 538.65 kg CO_2-eq
		Costs: Diesel cost = 0.55 $/liter x 132,465.73 l = 72,856.15 $ PC cost = 4365 tons × 60.42 $/ton = 263,733.3 $ Coarse aggregate cost = 16,366 tons × 20.6 $/ton = 337,139.6 $ Sharp sand cost =	Total emissions: 6,591,449.65 kg CO_2-eq

(continued on next page)

Table 4 (*continued*)

Activity	Truck type/ concrete ingredients	Amount of diesel/ concrete ingredients consumed	CO_2-eq emissions (kg CO_2-eq)
		8183 tons × 9.61 \$/ton = 78,638.63 \$ Reinforcing steel cost = 1568.26 tons × 587.75 \$/ton = 921,744.82 \$	

$$\text{CFT} = \text{No.of trips} \times \text{D}\left(\frac{\text{km}}{\text{trip}}\right) \times \text{FE}\left(\frac{\text{liter}}{\text{km}}\right) \tag{4}$$

where D is the distance per trip and FE is fuel efficiency.

5- Calculate the consumed fuel for rocks excavation (CFR) and the consumed fuel for concrete discharging (CFD) processes according to Eq. (5) and Eq. (6), respectively:

$$\text{CFR} = \frac{\text{VB}(\text{m}^3)}{\text{ER}\left(\frac{\text{m}^3}{\text{hour}}\right)} \times \text{FE}\left(\frac{\text{liter}}{\text{hour}}\right) \tag{5}$$

$$\text{CFD} = \frac{\text{CV}(\text{m}^3)}{\text{DR}\left(\frac{\text{m}^3}{\text{hour}}\right)} \times \text{FE}\left(\frac{\text{liter}}{\text{hour}}\right) \tag{6}$$

where VB is the volume of excavated boulders, ER is the excavation rate, CV is the concrete volume, and DR is the discharging rate of concrete.

6- Calculate the cost (C) of each raw material based on Eq. (7):

$$\text{C} = \text{Q} \times \text{P} \tag{7}$$

where Q is the quantity of each concrete ingredient and P is the unit price of materials presented in Table 1.

4. Results and discussion

Fig. 3 and Fig. 4 are showing the percentage contribution of different activities to the overall fuel consumption and CO_2-eq emissions, respectively. In general, Fig. 3a and Fig. 3b clearly show that both concrete types are following the same trend in terms of the highest environmental impact activity. Around 80% of the consumed diesel fuel was due to the transportation processes of concrete mixers and concrete pump trucks from the plant to the construction site. This major contribution may be explained by the fact that the distance from the concrete plant to the construction site was 40 km, and that the CYC and the CC with quantities of 13,637 m^3 and 18,000 m^3, respectively were transported through an 8 m^3 concrete mixer truck, which requires 1705 and 2251 trips to completely transport the required amount of concrete as illustrated in the detailed calculations of Table 4 and Table 5. This was followed by 7% of fuel consumption assigned to the pump truck during the pouring of concrete activity. While the excavation and loading of boulders to trucks activities in combination constituted around 6% and 11% of the consumed fuel in the CC and CYC cases, respectively, the rest of the activities including concrete transfer from concrete mixer truck to pump truck and the subsequent cleaning activity of both trucks represented the least contribution with 2% of fuel consumption for both cases.

The most interesting finding was that the activity of transporting the excavated boulders for disposal into landfills contributed to the total consumed fuel in the CC case by 6%, while it has no contribution in the CYC case since such activity was avoided. As calculated in Table 5, this has prevented additional transport distance of tipper trucks, which comprises 296 trips to the dumping site that is 50 km away from the construction site, and as a result, 10,881.95 l and 29,381.27 kg of fuel

Table 5
CO_2-e emissions and total cost obtained from the CC production.

Activity	Truck type	Amount of fuel consumed (Liters)	kg CO_2-eq
Excavation/ rock breaking	Hammer excavators	Hammer Excavator fuel consumption: 32.52 l/h Breaking of Rocks: ≥ 6 m^3/h. x 6 equipment = 36 m^3/h Excavation fuel Consumption: (6500 m^3 / 36 m^3/h) x 32.52 l/ h = 5871.7 l	5871.7 l × 2.7 kg CO_2-eq/l = 15,853.59 kg CO_2-eq
Loading of excavated boulders to trucks	Excavator	Excavator Truck Fuel Consumption: 32.52 l per hour Bucket capacity: 1.68 m^3 (40% for yield loss consideration) Number of buckets: 6500 m^3 / (1.68 m^3/ bucket x 0.40) = 9673 buckets Loading duration: (≥1-min (per bucket) x 9673) / 60 min = 161.22 h Loading Fuel Consumption: 161.22 × 32.52 = 5242.90 l	5242.90 l × 2.7 kg CO_2-eq/l = 14,155.83 kg CO_2-eq
Truck trip for boulders disposal	Tipper truck	Tipper Truck Capacity: 22 m^3 Number of Trips: 6500 m^3 / 22 m^3 = 296 trips Distance from dumping site: 50 km Tipper Truck Fuel efficiency (Km per liter): 2.7201 Disposal Fuel Consumption: [(50 km × 2)/(2.7201 km/ l)] x 296 = 10,881.95 l	10,881.95 l × 2.7 kg CO_2-eq/l = 29,381.27 kg CO_2-eq
Producing RC ingredients	Portland Cement (PC) Coarse aggregates Sharp sand Reinforcing steel	PC = 5762 tons Coarse Aggregates = 21,606 tons Sharp sand = 10,803 tons Water = 3168.75 m^3 Reinforcing steel = (18,000 m^3/1000) x 115 kg/m^3 (Rafts) = 2070.6 tons	PC = 5,762,000 kg × 0.8 kg CO_2-eq/kg = 4,609,600 kg CO_2-eq Coarse aggregates = 21,606,000 kg × 0.04 kg CO_2-eq/kg = 864,240 kg CO_2-eq Sharp sand = 10,803,000 kg × 0.004 kg CO_2-eq/kg = 43,212 kg CO_2-eq Reinforcing steel = 2,070,600 kg × 1.31 kg CO_2-eq/kg = 2,712,486 kg CO_2-eq
Concrete mixer/ pump transportation	Concrete mixer	Distance from the concrete plant: 40 km Mixer Truck Fuel efficiency for empty truck (Km per liter): 1.40 Mixer Truck Fuel efficiency for loaded truck (Km per liter): 1.19 Travel & Return Trip Average fuel efficiency per trip (Km per liter): 1.295	139,044 l × 2.7 kg CO_2-eq/l = 375,418.8 kg CO_2-eq

(continued on next page)

Table 5 (*continued*)

Activity	Truck type	Amount of fuel consumed (Liters)	kg CO_2-eq
		Mixer Truck Fuel Consumption per trip: (40 × 2) / 1.295 = 61.77 l Number of Trips (loads): 18,000 m^3/ 8 m^3 (capacity) = 2251 Mixer Truck Transportation: 2251 trips × 61.77 = 139,044 l	
	Concrete pump	Pump Truck Fuel Efficiency: ≥30 l/100 km =0.3 l/km Pump Truck Transportation: [(0.3 l/km x 40 km)] x (59 trips × 2 way) = 1416 l	1416 l × 2.7 kg CO_2-eq/l = 3823.2 kg CO_2-eq
Concrete mixer to pump	Concrete mixer	Discharging Rate (concrete): ≥ 2m^3/ min Queuing Time: 8m^3 / 2m^3 = 4 × 2251 = 9004 min Mixer truck fuel consumption: 11.13 l/ h Queuing Total Fuel Consumption: = [(9004 mins / 60 mins.] x 11.13 = 1670.24 l	1670.24 l × 2.7 kg CO_2-eq/l = 4509.65 kg CO_2-eq
Concrete pouring	Concrete pump truck	Concrete pump truck discharge rate: 38 m^3/ h Concrete pump truck fuel consumption: 0.7 l/m^3 (26.6 l per hour) Concrete pouring duration: 18,005 / 38 = 473.82 h Number of Casting (Pouring): 473.52 h. / 8 h. operation = 59 Pouring of Concrete Fuel Consumption: (59 × 26.6) x 8 h = 12,555.2 l	12,555.2 l × 2.7 kg CO_2-eq/l = 33,899.04 kg CO_2-eq
Cleaning	Concrete mixer	Mixer Truck Cleaning time: ≥5 min × 2251 = 11,255 min Cleaning Fuel Consumption = (11,255 min / 60 min) X 11.12911 l/h = 2087.636 Water consumption (liters): Concrete Mixer: ≥200 l × 2251 = 450,200 l	2087.64 l × 2.7 kg CO_2-eq/l = 5636.63 kg CO_2-eq
	Concrete pump	Concrete pump truck cleaning time: ≥10 min Cleaning Fuel Consumption = [(59 × 10) / 60 mins] x 26.6 = 261.6 l Water consumption (liters): Concrete Pump Truck: ≥250 l × 59 = 14,750 l Costs: Diesel cost = 0.55	261.6 l × 2.7 kg CO_2-eq/l = 706.32 kg CO_2-eq
		$/liter x 173,159.40 l = 95,237.67 $ PC cost = 5762 tons × 60.42 $/ton = 348,140.04 $ Coarse aggregate cost = 21,606 tons × 20.6 $/ton = 445,083 $ Sharp sand cost = 10,803 tons × 9.61 $/ton = 103,816.83 $ Reinforcing steel cost = 2070.6 tons × 587.75 $/ton = 1,216,995.15 $	Total emissions: 8,712,922.33 kg CO_2-eq

consumption and CO_2-eq emissions were saved, respectively.

Looking at Fig. 4 from an overall perspective, it can be concluded that most CO_2-eq emissions were emitted in the stage of manufacturing reinforced concrete ingredients, which corresponds to 94.45% and 94.57% for the CC and CYC cases, respectively. Closer inspection of Table 4 and Table 5 highlighted that around 53% of the total emissions were attributed exclusively to PC production, while around 41.6% of emissions were attributed to the rest of the ingredients. Yazdanbakhsh et al. (2018) also reported that most of the climate change potency was due to the production of cement. The significant emissions released from PC production are associated with the high energy consumed in the cement kiln, wherein raw materials are melted at high temperatures between 1400 and 1650 °C to transfer them into cement clinker (Mamlouk and Zaniewski, 2011). Besides, these significant emissions are associated with the limestone decomposition process, which decomposes $CaCO_3$ into CaO + CO_2 (Andrew, 2017). According to Flower and Sanjayan (2007), 0.5 tons of CO_2 is released in this process for each ton of CaO. On the other hand, the transportation processes of concrete and boulders revealed a much lower contribution to the total emission with approximately 5%, whereas rock breaking, boulders disposal, concrete pouring, and truck cleaning activities have shown very minor emissions within 1% of the total CO_2-eq emissions.

A similar finding was also reported by Yan et al. (2010) and the researchers concluded that the 82–87% of total carbon footprints were due to the embodied GHG emissions resulted from the construction of building materials, while only 6–8% and 6–9% of emissions have resulted from the transportation processes of building materials and the energy consumed by the construction equipment, respectively.

Fig. 5 provides an overview comparison between the two concrete types and illustrates the savings induced by applying the CYC methodology. In this section, the analyzed results will be discussed based on raw materials consumption, fuel consumption, water consumption, CO_2-eq emissions, and total cost. What stands out from Fig. 5 is that the CYC construction method has presented several striking benefits over the CC one. Firstly, as shown in Fig. 5a, there is a clear trend of decreasing raw materials consumption, where the PC, sharp sand, coarse aggregates, and reinforcing bar consumption was reduced by 1397 tons, 2620 tons, 5240 tons, and 502 tons, respectively. This reduction in raw materials is related to the addition of 6500 m^3 of boulders while adopting the CYC method, which has filled part of the zone under-raft foundation. Secondly, the disposal of 6500 m^3 of the site excavated boulders into landfills was avoided, and hence this methodology has created a cleaner environment and has removed part of the environmental burden that would be incurred while adopting the CC construction method. Thirdly, the single most striking observation to emerge from the data comparison in Fig. 5b is the 40,695 l savings of diesel fuel, which corresponds to 110 tons of CO_2-eq.

Therefore, adding this benefit to the reduced consumption of raw

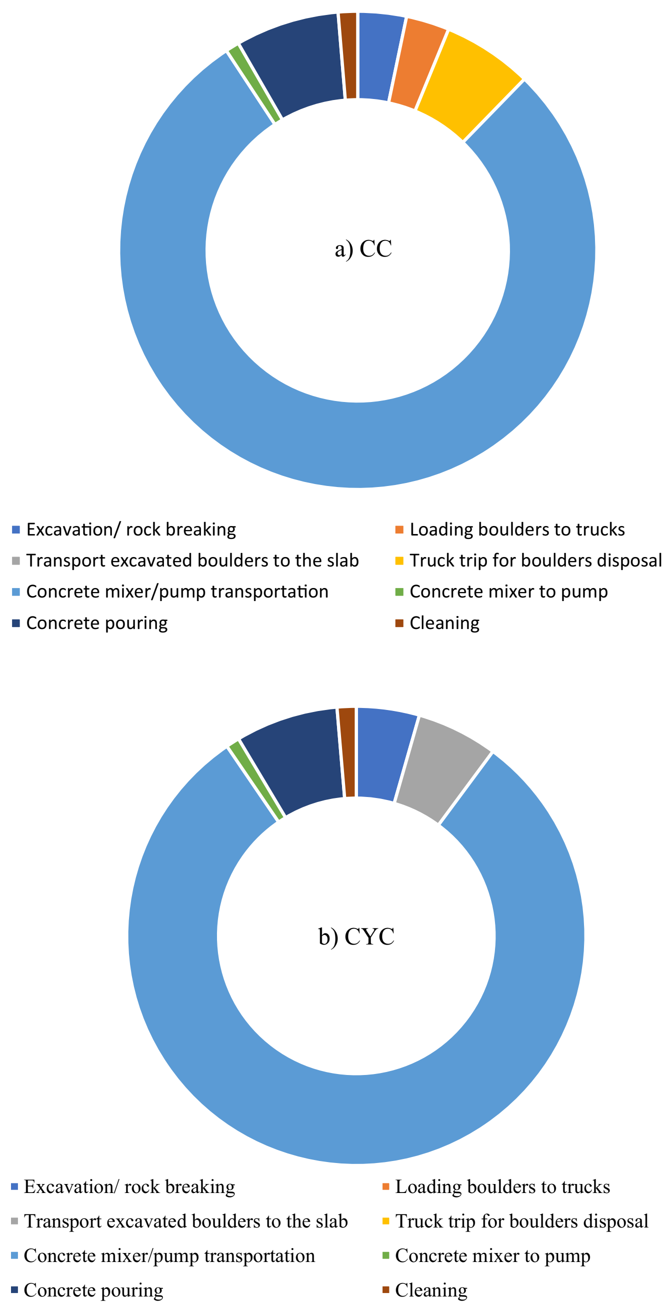

Fig. 3. Percentage contribution to fuel consumption by activity (%) a) CC b) CYC.

materials has significantly reduced the CO_2-eq emissions by 32.2%, which accounts for 2122 tons of CO_2-eq as shown in Fig. 5c. Fourthly, from the reported data in Fig. 5d, it is apparent that the total amount of water used for cleaning concrete mixer and pump trucks and producing the concrete mix has dropped by 43% and 32%, respectively. Based on the above analysis, it was noticed that adopting the CYC method has saved 53,5159 $ which is equivalent to a 32% reduction in the total cost (Fig. 5e). Overall, these results indicate that the CYC approach will allow the research community in Qatar to take active roles in this emerging research topic, and importantly will partially solve a significant environmental concern from land-filling the large quantities of waste construction materials produced every year.

5. Conclusions and recommendations

The present study aimed to evaluate the environmental and economic benefits of utilizing the site excavated boulders in CYC. This research presented the first empirical LCA for environmental analysis of the green stadium constructed for the 2022 FIFA World Cup in Qatar. Qatar is committed to developing a World Cup event with reduced CO_2-eq emissions and therefore the SCDL aims to design, construct, and sustainably operate its stadiums. This research provided a holistic approach by revealing the environmental, resource utilization, and cost benefits of green design construction for Qatar which demonstrated the following outcomes:

- The CYC approach has shown a substantial payoff to the Qatari construction sector and contributes to make Qatar a front-runner in applying the research results for constructing sustainable concrete structures. Also, it would advance knowledge in terms of relevance and importance of the projected results to the problems in the area of sustainable construction and eco-friendly practices using site excavated boulders.
- Based on the LCA results, the highest CO_2-eq emissions were due to concrete ingredients production, which accounts for 94% of the total emissions for both approaches the CYC and the CC, wherein 53% of them were due to cement production and 41.6% were for the rest of the ingredients. This was followed by approximately 5% of emissions that emerged from the transportation process and only 1% of emissions emerged from excavating, pouring, and cleaning processes.
- With the CYC approach, the raw materials consumption was significantly reduced, and the 6500m^3 excavated boulders were efficiently utilized in constructing the under-raft foundation of the stadium. As a result, this action has prevented their disposal into landfills and prevented landfilling areas from expansion. The CYC methodology reported outstanding environmental and economic benefits over the CC methodology, where 3122 tons of CO_2-eq were reduced and 53,5159 $ were saved, respectively.
- The CYC will generate a research culture in Qatar at many different levels. The CYC holds a strong promise to improve knowledge on the structural behavior of concrete made with a low-cost alternative recycled material from existing industrial waste products in Qatar. Besides, it will improve accepting of the concept of sustainable concrete structures for the next generations of civil engineers. This will lead to the development of local advanced expertise in this important field and thus provides the local industry with the requisite technical skills.

The CYC shall consist of concrete containing large embedded stones. The total volume of stones shall not be greater than 40% of the total volume of the zone in which it is placed (United Nations Developing Programme, 2015). The CYC shall be used only in heavy footings, massive piers, gravity walls, and gravity abutments. To avoid any damage to the form of the partially set adjacent concrete, the large stones shall be carefully placed-not dropped. Also, when embedded in concrete, each stone shall be surrounded by at least 150 mm of concrete (Japan International Cooperation Agency, 2010). Although the CYC methodology is applied, the contractors should also be cautious about their uses. In CYC, the rubble stones should only be selected if they are of suitable quality, durable and sound, and free from cracks, seams, and other structural defects. It shall be free from weathered, worn, or rounded surfaces. If a stone was found to be weathered, then it should be rejected. The stone shall be kept free from oil, or dirt that may cause improper adhesion of the surrounding mortar. Besides, the rubble stones must be uniformly distributed along the foundation and not concentrated at one side so that no weak zones exist which are filled with mortar only (Japan International Cooperation Agency, 2010).

Another possible environmentally friendly methodology is to partially replace the natural coarse aggregates with recycled coarse

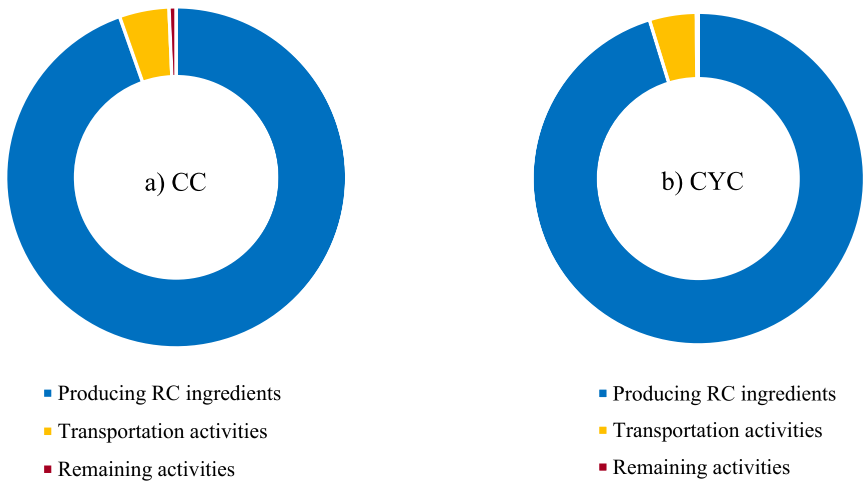

Fig. 4. Percentage contribution to total carbon footprints by activity (%) a) CC b) CYC.

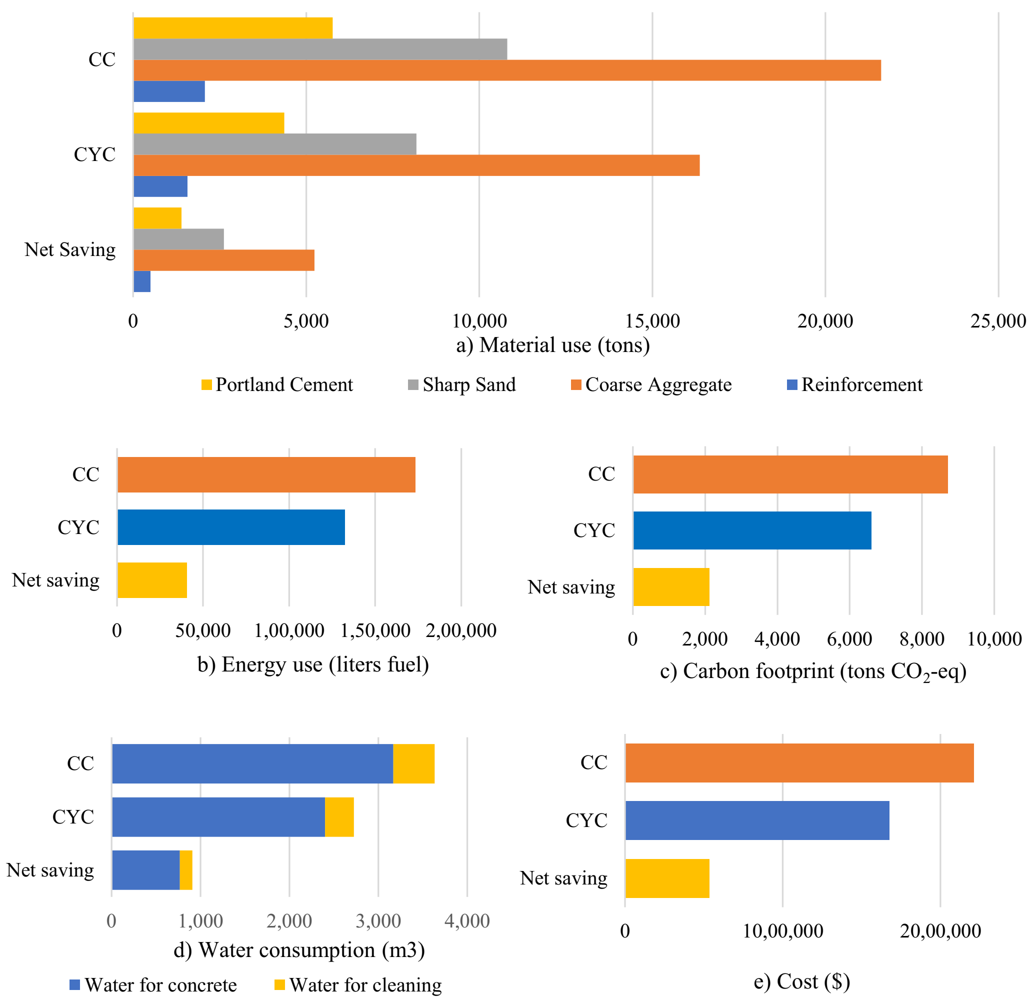

Fig. 5. Conventional Concrete vs. Cyclopean Concrete performance (a) material use (tons) (b) energy use (liters of fuel) (c) carbon footprint (tons CO_2-eq) (d) water consumption (m^3) (e) cost ($).

aggregates from demolished buildings. Moreover, the Portland cement could be partially replaced with industrial by-products such as fly ash to reduce cement consumption and as a result, mitigate the massive CO_2-eq emissions released during the production process of Portland cement.

This research presented the first empirical LCA method for understanding the environmental impacts of a circular economy application in the FIFA World Cup Stadium construction in Qatar. The proposed method can provide vital insights for decision-makers towards achieving an environmentally friendly event using circularity principles in design and construction. For future work, the researchers also propose to conduct a detailed LCA on the 2022 FIFA World Cup Ras Abu Aboud Stadium, which is a container stadium and will be entirely dismantled and reused after 2022. Conducting such a study on this unprecedented stadium in the history of World Cups would reveal the potential benefits of CE from a modular construction perspective.

Furthermore, the authors propose to extend the existing LCA model using the advanced life cycle sustainability assessment framework in which social, economic, and environmental impacts of green stadiums can be analyzed. For future work, the authors strongly recommend the inclusion of the triple bottom line aspects of sustainability using a global, multiregional hybrid LCA method in which regional and global life cycle sustainability impacts of construction projects can be estimated (Onat et al., 2019, 2020). In this way, the policymakers will be able to assess not only the carbon footprint reduction potential of circular economy applications in construction but also other benefits such as life cycle cost minimization, job creation, increased economic value-added, and reduced human health impacts and work-related injuries/fatalities. Integration of social LCA into the process-based LCA will also help decision-makers to evaluate the socioeconomic benefits of circularity in construction management. Recent applications of using hybrid life cycle environmental and social sustainability models in sustainable construction are available in the literature (Dong and Ng, 2016; Onat et al., 2014; Zheng et al., 2019).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Open Access funding provided by the Qatar National Library

References

Alhorr, Y., Elsarrag, E., 2015. Climate change mitigation through energy benchmarking in the GCC green buildings codes. Buildings 5 (2), 700–714. https://doi.org/10.3390/buildings5020700.

Ametepey, O., Aigbavboa, C., Ansah, K., 2015. Barriers to successful implementation of sustainable construction in the Ghanaian construction industry. Proc. Manuf. 3, 1682–1689. https://doi.org/10.1016/j.promfg.2015.07.988.

Andrew, R.M., 2017. Global CO2 emissions from cement production. Earth Syst. Sci. Data Discussions 195–217. https://doi.org/10.5194/essd-2017-77.

Ansah, M.K., Chen, X., Yang, H., Lu, L., Lam, P.T.I., 2020. An integrated life cycle assessment of different façade systems for a typical residential building in Ghana. Sustain. Cities Soc. 53 (June 2019), 101974. https://doi.org/10.1016/j.scs.2019.101974.

Assefa, G., Ambler, C., 2017. To demolish or not to demolish: life cycle consideration of repurposing buildings. Sustain. Cities Soc. 28, 146–153. https://doi.org/10.1016/j.scs.2016.09.011.

Bhattacharyya, M.C.R.S.K., 2011. Influence of field recycled coarse aggregate on properties of concrete Bureau of Indian Standards. Mater. Struct. 205–220. https://doi.org/10.1617/s11527-010-9620-x.

Bovea, M.D., Powell, J.C., 2016. Developments in life cycle assessment applied to evaluate the environmental performance of construction and demolition wastes. Waste Manag. 50, 151–172. https://doi.org/10.1016/j.wasman.2016.01.036.

Carpenter, A.C., Gardner, K.H., Fopiano, J., Benson, C.H., Edil, T.B., 2007. Life cycle based risk assessment of recycled materials in roadway construction. Waste Manag. 27 (10), 1458–1464. https://doi.org/10.1016/j.wasman.2007.03.007.

Ceia, F., Raposo, J., Guerra, M., Júlio, E., Brito, J.De., 2016. Shear strength of recycled aggregate concrete to natural aggregate concrete interfaces. Constr. Build. Mater. 109, 139–145. https://doi.org/10.1016/j.conbuildmat.2016.02.002.

Colangelo, F., Forcina, A., Farina, I., Petrillo, A., 2018. Life cycle assessment (LCA) of different kinds of concrete containing waste for sustainable construction. Buildings 8 (5). https://doi.org/10.3390/buildings8050070.

Czop, M., Lazniewska-Piekarczyk, B., 2020. Use of slag from the combustion of solid municipal waste as a partial replacement of cement in mortar and concrete. Materials 13 (7), 1–20. https://doi.org/10.3390/ma13071593.

De Schepper, M., Van den Heede, P., Van Driessche, I., De Belie, N., 2014. Life cycle assessment of completely recyclable concrete. Materials 7 (8), 6010–6027. https://doi.org/10.3390/ma7086010.

Death, C., 2011. "Greening" the 2010 FIFA world cup: environmental sustainability and the mega-event in South Africa. J. Environ. Policy Plan. 13 (2), 99–117. https://doi.org/10.1080/1523908X.2011.572656.

Ding, T., Xiao, J., Tam, V.W.Y., 2016. A closed-loop life cycle assessment of recycled aggregate concrete utilization in China. Waste Manag. 56, 367–375. https://doi.org/10.1016/j.wasman.2016.05.031.

Dolles, H., Söderman, S., 2010. Addressing ecology and sustainability in mega-sporting events: the 2006 football world cup in Germany. J. Manag. Organ. 16 (4), 587–600. https://doi.org/10.5172/jmo.2010.16.4.587.

Dong, Y.H., Ng, S.T., 2016. A modeling framework to evaluate sustainability of building construction based on LCSA. Int. J. Life Cycle Sust. Assessm. 555–568. https://doi.org/10.1007/s11367-016-1044-6.

Ermolaeva, P., Lind, A., 2020. Mega-event simulacrum: critical reflections on the sustainability legacies of the world cup 2018 for the Russian host cities. Probl. Post-Communism 00 (00), 1–11. https://doi.org/10.1080/10758216.2020.1791185.

Flower, D.J.M., Sanjayan, J.G., 2007. Green house gas emissions due to concrete manufacture. Int. J. Life Cycle Assess. 12 (5), 282–288. https://doi.org/10.1007/s11367-007-0327-3.

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The circular economy – a new sustainability paradigm? J. Clean. Prod. 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048.

Gold, J.R., Gold, M.M., 2013. "Bring it under the legacy umbrella": Olympic host cities and the changing fortunes of the sustainability agenda. Sustainability (Switzerland) 5 (8), 3526–3542. https://doi.org/10.3390/su5083526.

Hill, R.C., Bowen, P.A., 1997. Sustainable construction: principles and a framework for attainment. Constr. Manag. Econ. 15 (3), 223–239. https://doi.org/10.1080/014461997372971.

Horvath, A., 2004. A life-cycle analysis model and decision-support tool for selecting recycled versus virgin materials for highway applications. In: University of California at Berkeley (issue 23). http://www.rmrc.unh.edu/Research/past/P23/P23Final.pdf.

Ingrao, C., Scrucca, F., Tricase, C., Asdrubali, F., 2016. A comparative life cycle assessment of external wall-compositions for cleaner construction solutions in buildings. J. Clean. Prod. 124, 283–298. https://doi.org/10.1016/j.jclepro.2016.02.112.

International Energy Agency, 2018. Emission Factors Greenhouse Gas Invent. 40 (6), 590–615.

Japan International Cooperation Agency, 2010. Concrete Works-Rubble or Cyclopean Concrete. JICA. https://openjicareport.jica.go.jp/pdf/11600046_03.pdf.

Karsan, K.R., Hoseini, A.G., 2015. Investigating the effectiveness of using green concrete towards promotion of sustainable built. Universiti Putra Malaysia 8 (3), 49–59. http://www.frsb.upm.edu.my/dokumen/FKRSE1_49-59.pdf.

Kibert, C.J., 1994. Establishing principles and a model for sustainable construction. In: Proceedings of First International Conference of CIB TG 16 on Sustainable Construction (issue table I, pp. 3–12).

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127 (April), 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.

Knoeri, C., Sanyé-Mengual, E., Althaus, H.J., 2013. Comparative LCA of recycled and conventional concrete for structural applications. Int. J. Life Cycle Assess. 18 (5), 909–918. https://doi.org/10.1007/s11367-012-0544-2.

Korhonen, J., Nuur, C., Feldmann, A., Birkie, S.E., 2018. Circular economy as an essentially contested concept. J. Clean. Prod. 175, 544–552. https://doi.org/10.1016/j.jclepro.2017.12.111.

Kucukvar, M., Gumus, S., Egilmez, G., Tatari, O., 2014a. Ranking the sustainability performance of pavements: An intuitionistic fuzzy decision making method. Automation in Construction 40, 33–43.

Kucukvar, M., Noori, M., Egilmez, G., Tatari, O., 2014b. Stochastic decision modeling for sustainable pavement designs. The International Journal of Life Cycle Assessment 19 (6), 1185–1199.

Kucukvar, M., Tatari, O., 2012. Ecologically based hybrid life cycle analysis of continuously reinforced concrete;. Transportation Research Part D: Transport and Environment 17 (1), 86–90.

Kucukvar, M., Tatari, O., 2013. Towards a triple bottom-line sustainability assessment of the US construction industry. The International Journal of Life Cycle Assessment 18 (5), 958–972.

Lieder, M., Rashid, A., 2016. Towards circular economy implementation: a comprehensive review in context of manufacturing industry. J. Clean. Prod. 115, 36–51. https://doi.org/10.1016/j.jclepro.2015.12.042.

Majhi, R.K., Nayak, A.N., Mukharjee, B.B., 2018. Development of sustainable concrete using recycled coarse aggregate and ground granulated blast furnace slag. Constr. Build. Mater. 159, 417–430. https://doi.org/10.1016/j.conbuildmat.2017.10.118.

Malhado, A.C.M., Rothfuss, R., 2013. Transporting 2014 FIFA world cup to sustainability: exploring residents' and tourists' attitudes and behaviours. J. Policy Res. Tourism Leisure Events 5 (3), 252–269. https://doi.org/10.1080/19407963.2013.801159.

Mamlouk, M.S., Zaniewski, J.P., 2011. Materials for Civil and Construction Engineers.

Manzi, S., Mazzotti, C., Bignozzi, M.C., 2020. Self-compacting concrete with recycled concrete aggregate : study of the long-term properties. Constr. Build. Mater. 157 (2017), 582–590. https://doi.org/10.1016/j.conbuildmat.2017.09.129.

Marie, I., Quiasrawi, H., 2012. Closed-loop recycling of recycled concrete aggregates. J. Clean. Prod. 37, 243–248. https://doi.org/10.1016/j.jclepro.2012.07.020.

Nepomuceno, M.C.S., Vila, M.F.C., 2014. Permeability properties of self-compacting concrete with coarse recycled aggregates. Constr. Build. Mater. 51, 113–120. https://doi.org/10.1016/j.conbuildmat.2013.10.061.

NRMCA, 2008. Concrete CO 2 fact sheet. In: National Ready Mixed Concrete Association, 2. https://doi.org/10.1016/j.ejso.2010.10.007.

Onat, N.C., Aboushaqrah, N.N., Kucukvar, M., Tarlochan, F., Hamouda, A.M., 2020. From sustainability assessment to sustainability management for policy development: The case for electric vehicles. Energy Conversion and Management 216, 112937.

Onat, N.C., Kucukvar, M., 2020. Carbon footprint of construction industry: A global review and supply chain analysis. Renewable and Sustainable Energy Reviews 124, 109783.

Onat, N.C., Kucukvar, M., Aboushaqrah, N.N., Jabbar, R., 2019. How sustainable is electric mobility? A comprehensive sustainability assessment approach for the case of Qatar. Applied Energy 250, 461–477.

Onat, N.C., Kucukvar, M., Tatari, O., 2014. Integrating triple bottom line input-output analysis into life cycle sustainability assessment framework: the case for US buildings. Int. J. Life Cycle Assess. 19 (8), 1488–1505. https://doi.org/10.1007/s11367-014-0753-y.

Ossa, A., García, J.L., Botero, E., 2016. Use of recycled construction and demolition waste (CDW) aggregates: a sustainable alternative for the pavement construction industry. J. Clean. Prod. 135, 379–386. https://doi.org/10.1016/j.jclepro.2016.06.088.

Paradise, S., 2016. Lillehammer 1994 Set The Standard For Sustainable Winter Games (1). https://nieveyalgomas.blogspot.com/2014/05/lillehammer-1994-set-standard-for.html#:~:text=When. Lillehammer was awarded the, Green Games%22 by President Samaranch.&text=NOCs%3A 67.

Public Works Authority(Ashghal), 2020. http://www.ashghal.gov.qa/ar/Services/Pages/PriceList.aspx?category=2.

Qatar Construction Specifications, 2014. Concrete Structures Requirements. QCS.

Qatar General Electricity & Water Corporation, 2020. https://www.km.qa/Pages/default.aspx.

Sen, B., Kucukvar, M., Onat, N.C., Tatari, O., 2020. Life cycle sustainability assessment of autonomous heavy-duty trucks. Journal of Industrial Ecology 24 (1), 149–164.

Sen, B., Onat, N.C., Kucukvar, M., Tatari, O., 2019. Material footprint of electric vehicles: A multiregional life cycle assessment. Journal of Cleaner Production 209, 1033–1043.

Shafii, F., Arman Ali, Z., Othman, M.Z., 2006. Achieving sustainable construction in the developing countries southeast asia. Proc. 6th Asia-Pacific Struct. Eng. Construct. Conf. (APSEC 2006) 1 (September 2006), 5–6.

Singh, A., Berghorn, G., Joshi, S., Syal, M., 2011. Review of life-cycle assessment applications in building construction. J. Archit. Eng. 17 (1), 15–23. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000026.

Smol, M., Kulczycka, J., Henclik, A., Gorazda, K., Wzorek, Z., 2015. The possible use of sewage sludge ash (SSA) in the construction industry as a way towards a circular economy. J. Clean. Prod. 95, 45–54. https://doi.org/10.1016/j.jclepro.2015.02.051.

Tafheem, Z., Khusru, S., Nasrin, S., 2011. Environmental Impact of Green Concrete in Practice ICMERE2011-PI-069 (December).

Talavera, A.M., Al-Ghamdi, S.G., Koç, M., 2019. Sustainability in mega-events: beyond Qatar 2022. Sustainability (Switzerland) 11 (22). https://doi.org/10.3390/su11226407.

Tan, Y., Shen, L., Yao, H., 2011. Sustainable construction practice and contractors' competitiveness: a preliminary study. Habitat Int. 35 (2), 225–230. https://doi.org/10.1016/j.habitatint.2010.09.008.

Tatari, O., Kucukvar, M., 2012. Eco-efficiency of construction materials: data envelopment analysis. Journal of Construction Engineering and Management 138 (6), 733–741.

Tatari, O., Kucukvar, M., 2011. Cost premium prediction of certified green buildings: A neural network approach. Building and Environment 46 (5), 1081–1086.

Treyer, K., Bauer, C., 2016. Life cycle inventories of electricity generation and power supply in version 3 of the ecoinvent database—part I: electricity generation. The International Journal of Life Cycle Assessment 21 (9), 1236–1254.

Tsai, W.H., Yang, C.H., Chang, J.C., Lee, H.L., 2014. An activity-based costing decision model for life cycle assessment in green building projects. Eur. J. Oper. Res. 238 (2), 607–619. https://doi.org/10.1016/j.ejor.2014.03.024.

United Nations Developing Programme, 2015. Provision of Civil Works for the Installation of Water Networks in KAMED EL Loz-LEB/CO ITB/190/15. UNDP, pp. 1–52. https://www.ungm.org/Public/Notice/39356.

Ürge-Vorsatz, D., Novikova, A., 2008. Potentials and costs of carbon dioxide mitigation in the world's buildings. Energy Policy 36 (2), 642–661. https://doi.org/10.1016/j.enpol.2007.10.009.

Varun, Sharma, A., Shree, V., Nautiyal, H., 2012. Life cycle environmental assessment of an educational building in northern India: a case study. Sustain. Cities Soc. 4 (1), 22–28. https://doi.org/10.1016/j.scs.2012.03.002.

Wang, J., Wang, Y., Sun, Y., Tingley, D.D., Zhang, Y., 2017. Life cycle sustainability assessment of fly ash concrete structures. Renew. Sust. Energ. Rev. 80 (May), 1162–1174. https://doi.org/10.1016/j.rser.2017.05.232.

Yan, H., Shen, Q., Fan, L.C.H., Wang, Y., Zhang, L., 2010. Greenhouse gas emissions in building construction: a case study of one Peking in Hong Kong. Build. Environ. 45 (4), 949–955. https://doi.org/10.1016/j.buildenv.2009.09.014.

Yazdanbakhsh, A., Bank, L. C, Baez, T., Wernick, I., 2018. Comparative LCA of concrete with natural and recycled coarse aggregate in the new York City area. Int. J. Life Cycle Assess. 1163–1173. https://doi.org/10.1007/s11367-017-1360-5.

Yu, J., Mishra, D.K., Leung, C.K.Y., 2018. Very high volume fly ash green concrete for applications in India. Waste Manag. Res. 36 (6), 520–526. https://doi.org/10.1177/0734242X18770241.

Zeyad Hayajneh, A., 2017. Football and sustainability in the desert, Qatar 2022 green world Cup's stadiums: legal perspective. Eur. J. Soc. Sci. 55 (1450–2267), 475–493.

Zheng, X., Easa, S.M., Yang, Z., Ji, T., Jiang, Z., 2019. Life-cycle sustainability assessment of pavement maintenance alternatives: methodology and case study. J. Clean. Prod. 213, 659–672. https://doi.org/10.1016/j.jclepro.2018.12.227.