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Life cycle assessment of lightweight concrete containing recycled plastics and fly ash

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ABSTRACT

Researchers put significant effort to decrease the environmental impact of concrete by using industrial by-products as an alternative binder. However, the considerable environmental impact still exists due to the consumption of natural resources as aggregates. Natural aggregates are the most used resources by volume in the construction sector. Therefore, it is necessary to investigate by-products as an alternative to natural aggregates as well. This study presents the environmental impact of lightweight concrete (LWC) produced by replacing natural aggregates with recycled waste plastic (polyethylene) (RWP) and partially replacing Portland cement with Class F fly ash (FA). Life Cycle Assessment (LCA) was performed to compare a conventional LWC, containing pumice as natural aggregate and Portland cement as a binder, with green LWC, containing 30% RWP as pumice replacement and 20% FA as cement replacement. These scenarios were evaluated in terms of global warming potential, abiotic depletion, ozone layer depletion, terrestrial ecotoxicity, photochemical oxidation, acidification and eutrophication. LCA was coupled with mechanical tests at 7 days and 28 days. RWPs were found to be an environment-friendly replacement material for natural lightweight aggregates with an overall decrease in all CML-IA impacts except eutrophication. Tested green mix design also provided sufficient strength for nonstructural applications.

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Lightweight concrete; life cycle assessment; fly ash; recycled waste plastic

1. Introduction

Transition towards a more sustainable built environment is considered among the twenty-first century's super challenges. Implementation of new regulations motivated almost all industries to remodel their conventional activities to achieve a more environment friendly process line. For the last 20 years, significant effort was put to integrate sustainability concept into the construction sector as well. Yet, construction sector can still be considered as the least environment friendly sector (Ghisellini et al., 2018; Zutshi & Creed, 2015).

Construction sector leads the market at global scale considering the annual net materials addition to stock, which makes it also one of the greatest consumer of natural resources and the largest contributor of the global pollution (Proske et al., 2013). Buildings alone are estimated to be responsible for 40% of the global energy and material flow, and 50% of the global water use (Chel & Kaushik, 2018). Researchers reckon that 23% of the global air pollution, 30% of the greenhouse gas (GHG) emission, 40% of the global wastewater production and 40% of the global solid waste production is due to built environment (Chel & Kaushik, 2018; Herczeg et al., 2014).

Reports on the total construction material consumption in EU 27 countries reveal that the amount of concrete, aggregates and bricks used in buildings (construction, renovation, etc.) between 2006 and 2010

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corresponds to 90% (by weight) of the total (Herczeg et al., 2014). Among these construction materials, owing to its significant cement content, concrete is responsible for 5% of the anthropogenic CO_2 footprint (Barcelo et al., 2014). Besides, production of one ton of ordinary Portland cement releases about 0.8 to 0.9 tonnes of CO_2 (Flower & Sanjayan, 2007; Hanif, Kim, et al., 2017). It was reported that cement industry emitted 522 million tonnes of CO_2 in 2016 (World Business Council for Sustainable Development, 2016). Worldwide, 4.2 billion Mt of cement was produced which approximates to production of 1 m^3 concrete per person per year in 2016 (Ober, 2017). Since the production rate tends to increase in near future, researchers put significant effort on exploring alternative binders, their impact on fresh and hardened concrete properties and their environmental impact. So far, industrial by products such as fly ash (FA), blast furnace slag, silica fume and some others were successfully utilized to partially replace cement and to decrease the cement related environmental impact and carbon footprint of concrete (Gartner & Hirao, 2015).

Currently, FA is known as the world's fifth largest raw material source (Mukherjee et al., 2008). Global FA market size is valued about 4.1 Billion USD and recent reports revealed that it is growing with a 6.5% compound annual growth rate (Reports and Data, 2019). Utilization of FA in concrete dramatically increased in the last 50 years (Yahia et al., 2017). In addition to FA, fly ash cenospheres (FACs), which are hollow spherical particles constituting 1–2% of the FA (Siddique, 2010), has been utilized as a lightweight filler material for about the last 35 years (Hanif, Lu, et al., 2017). Although, spherical particles of FACs are comparatively larger in size (10–1000 μm) than FA, they both have similar chemical compositions (Żyrkowski et al., 2016). Low density, good dispersibility, good workability, high strength and thermal resistance can be listed among the superior properties of cenospheres (Ranjbar & Kuenzel, 2017). Zhou and Brooks (2019) reported that including micro-size FAC into the cementitious matrix can decrease density and thermal conductivity of lightweight concrete (LWC). Furthermore, FAC can provide barriers to hinder crack propagation due to their strong shell and small particle size (Zhou & Brooks, 2019).

Life cycle assessment (LCA) is the most commonly used tool to quantify the environmental impact as it is the most appropriate and known strategy for the evaluation of environmental impacts of concrete. In the last decade, with the increasing number of studies on determining the environmental impact of various cementitious composites, LCA became a reliable tool (Giama & Papadopoulos, 2015). The outcomes of the LCA analysis provide significant input for the Environmental Product Declaration (EPD) which is a verified document that reports the environmental data and other relevant information of a material/system based on ISO standards (Biswas et al., 2017; ISO, 2006). LCA based studies revealed that the use of FA and FA derivatives for cement replacement does not only decrease the environmental impact but also the social and the economic impacts of concrete. Considering the available FA and its widespread utilization in construction industry, the potential of China alone corresponds to 560 million tonnes of reduction in CO_2 emission (Wang et al., 2017). Tait and Cheung (2016), revealed that the overall environmental load of ordinary Portland cement (OPC) could be decreased by 26% (from 173 kPt to 130 kPt) by replacing 35% of the cement with FA. When compared to different environmental impact parameters, under normalized assessment, CO_2 emission has the highest weighted contribution to the environmental load of a product. It was also shown that replacement of cement with FA can decrease the CO_2 emission due to concrete production by 30% (Tait & Cheung, 2016). In another study, it was reported that FA could reduce the greenhouse gas (GHG) emission of concrete by around 15%. Considering the data from different studies, it can be said that replacement of cement with FA can reduce the environmental load by 10–45% (Horvath, 2004; Turk et al., 2015). Due to the aforementioned features, FA and FA by-products such as cenospheres secured their place in construction sector. Now, they should be included more in green concrete LCA studies, particularly in those investigating their combination with possible environment-friendly alternatives to natural aggregates. Such studies are essential as they do not only consider greenhouse gas emissions but also deal with the consumption of natural resources.

In volumetric scale, natural aggregates (coarse and fine) are the most used materials in construction sector. Currently, the global aggregates market size is valued about 430 billion USD, and according to the recent reports, it is growing with 6.5% compound annual growth rate which signifies that, in 2020, the annual demand of aggregates will reach up to 55 billion tonnes (Grand View Research, 2019; Kurda et al., 2018). Their mining and transportation lead to waste generation and CO_2 emission. Especially for the site-specific aggregates, CO_2 emission due to transportation of these aggregates creates significant environmental burden.

Table 1. Properties of aggregates (pumice and RWP) used in experiments.

Parameters	Fine aggregate	Coarse aggregate		
		Fraction 1	Fraction 2	RWP
Particle size (mm)	<4	4-8	8–16	4–8
Water absorption (%)	1.462	0.768	0.768	2.35
Current moisture (%)	0.075	0.296	0.395	–
Specific gravity	1.42	1.23	0.45	0.84

In LWC production, lightweight aggregates (LWA) are used. LWA can be classified into natural and artificial types (ACI (American Concrete Institute), 2003; Neville, 2012). Pumice, tuff, diatomite and volcanic cinders are well-known natural LWA types. Besides, artificial LWA can be classified into industrial wastes and processed natural materials (Aslam et al., 2016). The common industrial wastes utilized as LWAs are sintered slate, sintered pulverized fuel ash and expanded or foamed blast furnace slag. Moreover, some processed natural materials such as shale, expanded clay, slate and perlite also used as LWAs in LWC production (Shafigh et al., 2010). Owing to their low density, transportation of LWA has even higher environmental impact as they occupy greater space per weight in trucks when compared to the normal aggregates. Accordingly, natural LWA are responsible for the 13–20% of the total CO_2 emission of LWC production (Flower & Sanjayan, 2007).

Recycling waste materials as an alternative for aggregates can facilitate the integration of construction industry into industrial symbiosis and decrease the dependency of the sector on natural resources. Moreover, emissions due to transportation of site-specific aggregates can be avoided as well. Recently, strategies were developed to exploit recycled wastes such as marble dust, recycled glass, recycled plastics, recycled tire rubber and recycled wood as alternative sources of aggregates or as partial aggregate replacement (Bolden et al., 2013; Bui et al., 2018; Mohajerani et al., 2017). Bostanci (2020) studied on manufacturing of sustainable concrete by using waste marble dust (MD) and recycled glass (RGS). At 28 days, strength losses of 7% and 15% were reported for MD-5 (5% replacement with marble dust) and MD-10 (10% replacement with marble dust), respectively. Besides, MD mixes decreased greenhouse gas emissions by 0.4% and RGS-20 (20% replacement with recycled glass) provided 4.7% reduction compared to PC mix (430.2 kg CO_2/m^3) (Bostanci, 2020). The studies on recycled waste plastics (RWP) as alternative aggregates are limited when compared to other alternatives like marble fines and recycled glass. Replacement of natural aggregates with RWP can increase the resource efficiency of construction sector, as well as solving the growing plastic waste disposal problems. Although, the usefulness of recycled plastics was investigated experimentally, information about the environmental impacts of the final products is scarce. Therefore, it is necessary to clearly define the environmental impact of LWC containing waste recycled materials as partial aggregate replacement (Gu & Ozbakkaloglu, 2016). Moreover, although, there are LCA studies investigating fly ash containing green concrete, studies combining fly ash incorporation together with the replacement of natural aggregates is scarce. Therefore, considering the defined gaps in literature, this study was conducted to reveal the environmental impact of a novel green LWC that 30% of the natural LWA were replaced with RWP and 20% of the cement was replaced with FA. Environmental impact of the novel green LWC was assessed in terms of global warming potential, abiotic depletion, ozone layer depletion, terrestrial ecotoxicity, photochemical oxidation, acidification and eutrophication and the results were compared with the results of conventional LWC containing Portland cement as binder and pumice as natural aggregate.

2. Materials and methods

2.1. Materials

Portland cement (CEM I 42.5 R, with a specific gravity of 3.15), pumice and RWP used in experiments were obtained from Kayseri, Turkey and their physical properties and particle distribution are presented in Table 1.

The FA was obtained from Adana Sugozu, Power Plant, Turkey and the main components of FA were SiO_2 (57.34%), Al_2O_3 (22.05%) and Fe_2O_3 (7.92%) as shown in Table 2. Overall, the FA was containing $SiO_2+Al_2O_3+Fe_2O_3$ (87.31%). Based on the chemical composition, it could be classified as Class F in compliance with ASTM C618-17a (ASTM C618-17a, 2017).

Table 2. Chemical composition of FA used in concrete mixtures (Durak et al., 2018).

Name	(%)	Name	(%)
SiO_2	57.34 ± 0.10	TiO_2	1.05 ± 0.03
Al_2O_3	22.05 ± 0.10	P_2O_5	0.66 ± 0.02
Fe_2O_3	7.92 ± 0.08	SO_3	0.57 ± 0.02
K_2O	2.72 ± 0.05	SrO	0.11 ± 0.01
CaO	2.71 ± 0.05	BaO	0.10 ± 0.00
MgO	1.79 ± 0.04	MnO	0.07 ± 0.00
Na_2O	1.70 ± 0.04	ZrO_2	0.06 ± 0.00

2.2. LWC production

A traditional LWC mixture and a novel green LWC mixture were designed by considering aggregates which are in SSD (Saturated Surface Dry) conditions and the compositions of these mixtures are given in Table 3. The main difference between conventional LWC and green LWC was the substitution of raw materials that were used in the concrete mixtures. In the production of novel green LWC, 20% of the cement was replaced by FA and 30% of the coarse natural aggregates (particle size 4–16 mm) were replaced with a recycled plastic (polyethylene) material (particle size 4–8 mm).

Ingredients were measured in accordance with the mix designs represented in Table 3, and concrete mixer was used to prepare concrete. Initially, inner surfaces of the mixing machine were wetted by using a portion of the water defined in the mix design, and coarse and fine aggregates were added into the mixing drum. After mixing coarse and fine aggregates for 1 min, cement was added and dry mixing continued until all the aggregates were covered with cement which was approximately 2 min. Then, the rest of the water was added to the mixture and the concrete was mixed for another 2 min. The uniform mixture was poured into 150 × 150 × 150 mm cubic moulds. After proper compaction on a vibrating table, they were covered with a wet cloth for 24 h. Upon demoulding, specimens were immersed in water for curing until the test day.

In order to examine the compressive strength of both conventional LWC mixture and green LWC mixture, twelve 150 × 150 × 150 mm cubic specimens were prepared. All specimens were tested under compressive load after 7 days and 28 days in accordance with EN 12390-3.

2.3. LCA methodology

Different environmental impacts of two different LWC mixtures were compared and evaluated by using LCA, based on four main phases (i) goal and scope, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), (iv) interpretation and described below (ISO, 2006).

2.3.1. Goal and scope

The main goal of this study was to define and compare the LCAs of conventional LWC and green LWC made with replacing aggregates with RPW and Portland cement with class F FA. In this study, functional unit was chosen as 1 m^3 LWC. The LCAs of these two different LWC mixes (Table 3) were calculated by using SimaPro 8.4, Netherlands. The environmental impacts of concrete mixtures were assessed over seven indicators; global warming potential, abiotic depletion potential, ozone layer depletion potential, terrestrial ecotoxicity, photochemical oxidation potential, acidification potential and eutrophication potential.

2.3.2. System boundaries

The system boundaries of conventional LWC and green LWC are given in the Figures 1 and 2. Both systems included raw materials production and transportation to generate 1 m^3 LWC, which was the final output product. Since the objective was to evaluate the sustainability of LWC based on the raw materials, ‘cradle to gate’ LCA approach was selected in this study, and the other phases of life cycle such as use and demolition were excluded from the boundaries.

Table 3. Lightweight concrete mix designs (quantities are referred to 1 m^3 of lightweight concrete).

Components	Conventional LWC (kg/m^3)	Green LWC (kg/m^3)
Portland cement	437	350
Water	287	287
Fine aggregate (<4 mm)	238	238
Coarse aggregate (4–8 mm)	205	136
Coarse aggregate (8–16 mm)	238	170
Fly ash	0	87
RWP (polyethylene)	0	136
Total	**1405**	**1404**

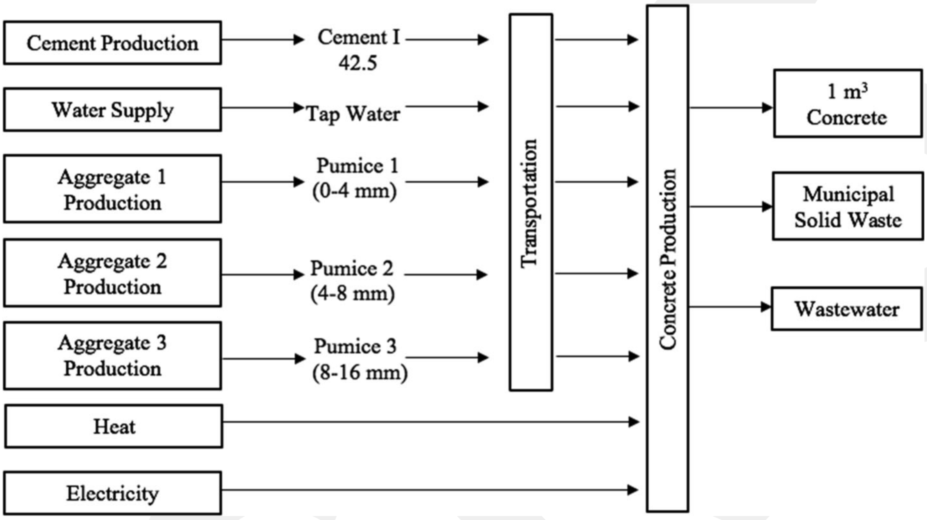

Figure 1. System boundary of the conventional LWC production (1 m^3).

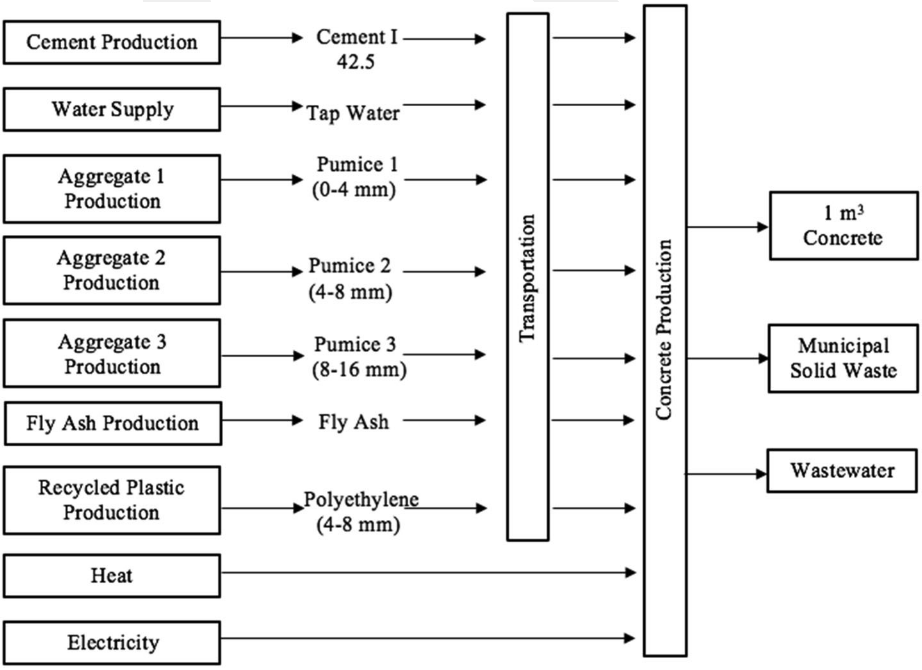

Figure 2. System boundary of the green LWC production (1 m^3).

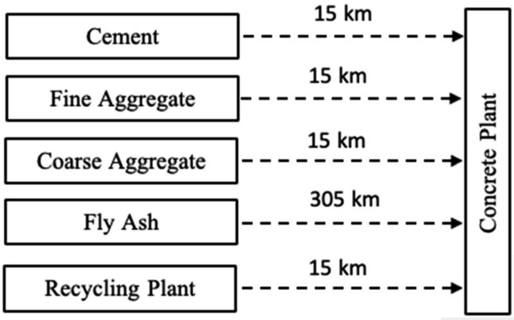

Figure 3. Transportation distances for raw materials.

The conventional LWC production system boundary consisted of production of aggregates related to their sizes, Portland cement production, water supply and relevant energy consumption, which were schematically presented (Figure 1).

The green LWC production system boundary consisted of production of RPW, production of aggregates related to their sizes, Portland cement production, water supply, relevant energy consumption and FA production which were schematically presented in the diagram of system boundaries (Figure 2). The recycled plastic was produced from packaged plastic waste as a secondary material according to the weight ratio given in Table 3. Recycling process of the plastic waste consists of five stages, namely, washing, sorting, shredding, extrusion and palletization. The overall energy (heat and electricity) used for the recycling process is considered while conducting the LCA in this study.

2.3.3. Inventory data

Primary data concerning the amount of raw materials (pumice, recycled plastics), energy consumption, land use and water use were gathered from local manufacturers. The rest of the data for production of portland cement, fly ash and the transportation of the raw materials were implemented into the analyses by using the database available in SimaPro 8.4 LCA software.

2.3.4. Recycling energy data for waste plastic

Recycling process of the waste polyethylene plastic materials that were used in this study uses electricity from the local electrical grid. Therefore, the energy consumption for the overall recycling process could be calculated as 0.32 kWh/kg by using the electricity consumption data obtained from the company.

2.3.5. Waste scenarios

Since LCA was conducted using cradle to gate approach, only the solid waste and wastewater generated in concrete production phase were considered by using the wastewater and solid waste quantities available in SimaPro 8.4 databases.

2.3.6. Transportation scenarios

The raw materials of conventional LWC were obtained from local industries in Kayseri, Turkey. The distance for the transportation of aggregates (cement, recycled plastics, pumice, etc.) to the concrete production plant was defined as 15 km (Figure 3), since pumice is a natural aggregate that is locally available in Turkey and LWC production plants are located in a 15 km perimeter in that zone. In order to exclusively distinguish the environmental impacts of using pumice or RWP via LCA, transportation distances of aggregates were standardized as 15 km, based on the farthest possible transportation distance of natural aggregates. For the green LWC, as mentioned above, the recycled plastic and FA were utilized in concrete mixture. The distance of FA transport from Sugozu, Adana, Turkey to concrete production plant was taken as 305 km by using Google Maps.

Table 4. Compressive strength values of LWC mixtures.

	Compressive strength (MPa)	
Mix	7 days	28 days
Conventional LWC	9.3 ± 0.3	12.0 ± 0.4
Green LWC	7.0 ± 0.1	9.3 ± 0.3

2.4. LCIA methodology

The CML-IA baseline methodology was used for the impact assessment of conventional and green LWC by applying the problem-oriented (midpoint) approach (O'Born, 2018). The CML-IA baseline methodology is created by the University of Leiden in Holland. The CML-IA baseline methodology provides the environmental impacts of a product or a system according to the effects of base line impact categories (Evangelista & de Brito, 2007). The base line impact categories that are considered in this methodology are as follows: depletion of abiotic resources, land competition, climate change, stratospheric ozone depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photo-oxidant formation, acidification and eutrophication. Characterization is based on global and European average values. The regional validity of the CML methodology impact categories was global, except for acidification and photo-oxidant formation, which were based on average European values (Menoufi, 2011). Global and European database values available in SimaPro 8.4 were used to characterize and normalize the environmental impacts of the products.

In addition to LCA analysis with CML-IA methodology, LCA results of conventional and green LWC mixtures were also evaluated by using IMPACT 2002+ method. IMPACT 2002+ method provides a proper implementation of a combination of midpoint and damage approach by linking several midpoint categories to several damage categories. IMPACT 2002+ methodology considers 14 different impact categories and combines midpoint and endpoint categories. The methodology incorporates the following midpoint impact categories; human toxicity, respiratory effects, ionizing radiation, ozone depletion, photochemical oxidant formation, aquatic ecotoxicity, terrestrial ecotoxicity, aquatic eutrophication, terrestrial eutrophication and acidification, land occupation, global warming, nonrenewable energy and mineral extraction. Through the midpoint categories, the inventory results are linked to four endpoint damage categories, which in this case are also the environmental areas of protection; human health, eco-system quality, climate change and resources. Characterization factors are adapted from other methodologies such as Impact 2002, Eco indicator 99 and CML. The methodology has a European regional validity; certain issues are of a global concern such as ozone layer depletion and resources (Menoufi, 2011). The reason why CML-IA method has been chosen as a main method of consideration was that it is the most commonly used method for LCA of construction materials (Marinković et al., 2017).

3. Results and discussion

3.1. Compressive strength

The results of the compressive strength tests at 7 and 28 days for the conventional LWC and green LWC mixtures were presented as mean values and standard deviations in Table 4. At the end of 7 days, the average compressive strength values were 9.3 MPa and 7.0 MPa for conventional LWC mixture and green LWC mixture, respectively. At the end of 28 days, the strength values increased about 22% and reached to 12.0 MPa and 9.3 MPa for conventional and green LWC concrete, respectively.

The lower strength of green LWC compared to conventional LWC could be attributed to both the lower strength of the plastic aggregates and the weaker bonding of plastic aggregates in the interfacial transition zone when compared to pumice aggregates (Farahani et al., 2017). RWP have a smooth surface and thus little affinity to hold water which further reduces the hydration efficiency in the RPW/cementitious matrix interfacial transition zone (Saikia & De Brito, 2014). At the end of 28 days, the strength loss in this study was recorded as 22% with respect to the reference specimen. This observation was significantly lower than the previously reported strength reductions due to replacement of aggregates with various plastics. For instance, upon replacement of 15% of the natural coarse aggregates with plastic waste, Saikia and De Brito (2014) reported strength reduction up to 60%. Bostanci (2020) reported strength loss similar to our findings when marble dust was used for replacing Portland cement and

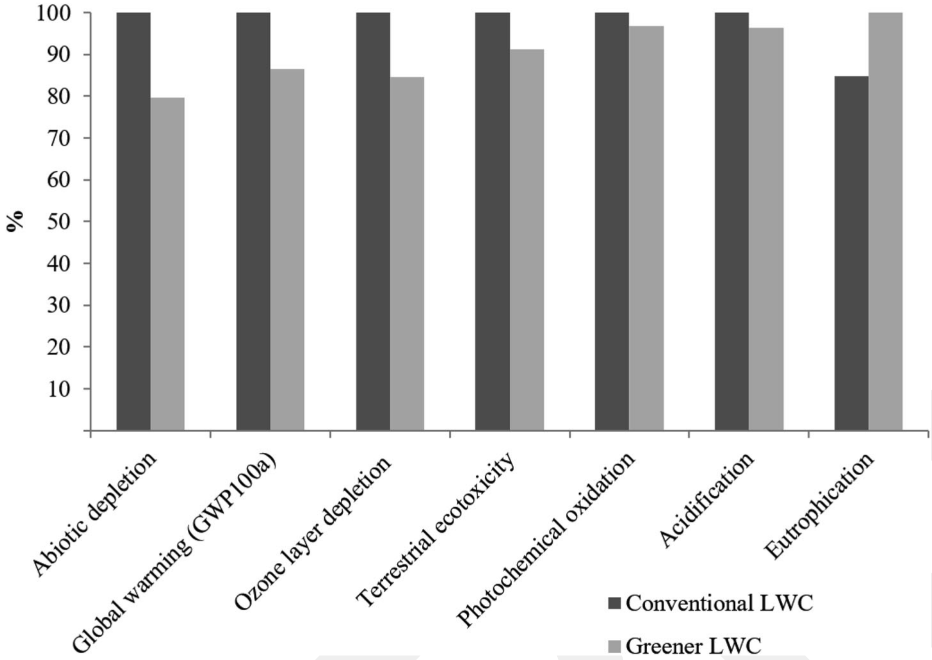

Figure 4. The environmental impacts comparison of conventional LWC and green LWC based on CML-IA method: CML-IA baseline V3.04/EU25/Characterization.

recycled glass was used to replace natural sand. Compared to a reference specimen, the compressive strength on Day 7 was reported to be 9% and 19% lower for MD-5 (5% marble dust replacement) and MD-10 (10% marble dust replacement), respectively. On the one hand, these similar findings indicated that the strength loss can occur due to the partial replacement of concrete constituents with recycled waste materials. On the other hand, in our study, strength development between day 7 and 28 was quite similar for both conventional LWC and green LWC which indicated that, although, 30% replacement of natural aggregates with RWP decrease the overall strength, it did not interfere with the hydration reactions of green LWC concrete. Therefore, the decrease in strength was mainly attributed to the completely different nature of RWP and pumice and hence their varying interfacial transition zone properties. Yet, the precise influence of such replacement on pozzolanic reactions still remains unknown and should be noted for further investigations. Nonetheless, obtained strength values and strength development of green LWC were adequate for conventional nonstructural applications, which generally requires compressive strengths in the range of lower than 20 MPa (ACI (American Concrete Institute), 2003). Since, the novel green LWC has acceptable strength value, it is worth quantifying the environmental impact of the novel green LWC.

3.2. Decrease in environmental impact of concrete containing RWP and FA

Environmental impacts of conventional LWC mixtures and green LWC mixtures were studied by using SimaPro 8.4 software and CML-IA baseline methodology. As mentioned in the goal and scope, the LCA analysis involves the comparison of environmental impacts of conventional LWC and green LWC mixtures. LCA analysis consists of seven impact categories calculated in CML-IA method and compared for conventional LWC and green LWC mixtures and the results were shown in Figure 4. First, abiotic depletion of conventional LWC was found as 1.87×10^{-7} kg Sb eq and 1.49×10^{-9} kg Sb eq for green LWC, respectively, since natural LWA were partially replaced with recycled plastic material in green LWC production (Table 5). Like abiotic depletion values, global warming, ozone layer depletion, terrestrial eco-toxicity, photochemical oxidation and acidification values of green LWC were lower than the conventional LWC.

Table 5. Impact category values of conventional LWC and green LWC mixtures (CML-IA Method).

Impact category	Unit	Conventional LWC	Green LWC
Abiotic depletion	kg Sb eq	1.87E-04	1.49E-04
Global warming	kg CO_2 eq	423	366
Ozone layer depletion	kg CFC-11 eq	1.352E-05	1.143E-05
Terrestrial ecotoxicity	kg 1,4-DB eq	0.525	0.479
Photochemical oxidation	kg C_2H_4 eq	0.038	0.037
Acidification	kg SO_2 eq	0.957	0.923
Eutrophication	kg PO_4— eq	0.226	0.266

With regard to the LCA of both LWC, the results reveal that the green LWC (use of FA and recycled plastic aggregate) showed significantly lower environmental impacts with respect to EPD criteria. Our green LWC design revealed significantly better performance particularly in terms of abiotic depletion potential, ozone layer depletion potential and global warming potential. The decrease in the latter was 14% which was the highest reduction among the evaluated parameters. Replacing cement and pumice with FA and RWP is a promising way to achieve a sustainable and environment-friendly building material. The proposed approach is a promising way to deal with accumulation of waste plastics.

Table 5 presented the environmental impact values of conventional LWC and green LWC mixtures for each category of CML-IA method. Replacing 20% of the Portland cement with FA and 30% of the pumice with RWP decreased global warming potential (kg CO_2 eq.) of LWC by 13% when compared to conventional LWC. The decrease in global warming potential was attributed to the lower Portland cement content of green LWC, which is the main responsible for the CO_2 emission in production of conventional concrete (Di Filippo et al., 2019).

Observed difference between the environmental impacts of the analyzed LWCs was due to fly ash incorporation. In green LWC, 20% of the cement was replaced with FA which resulted in a decrease in the environmental burden appearing due to cement content of the mix. The observed impact of 20% cement replacement was slightly lower than the previously reported values (Seto et al., 2017; Tosun-Felekoğlu et al., 2017; Turk et al., 2015), that the difference was attributed to the incorporation of RWP aggregates. On the one hand, although, the use of RWP aggregates avoided the use of natural aggregates, owing to the energy intensive plastic recycling process, RWP caused a slight increase in the environmental impact that in return made the overall environmental impact of the green LWC less recognizable compared to previously reported mixes where FA was the only replacement. On the other hand, plastics are still commonly used in different industries which make plastics an indispensable waste product (Plastics Europe and EPRO, 2016) and their disposal still remains as a problem. Therefore, the proposed approach revealed a possible way of dealing with waste plastics and created an alternative end-use option that when incorporated into concrete together with FA, RWP can create a green LWC with a strength value similar to a conventional nonstructural LWC.

Moreover, one should note that the recycling process of RWP plays a significant role on the environmental impact of RWP and even virgin plastics can be more environmentally friendly sometimes due to the environmental burden created during plastic recycling process (Gu et al., 2017). It was reported that the extrusion process in plastic recycling procedure has the highest environmental impact, particularly on terrestrial eco-toxicity and eutrophication, followed by pelletization process due to the energy consumption and persistent organic pollutants containing wastewater generation (Gu et al., 2017). The RWP used in this study were obtained through the aforementioned procedure (washing, sorting, shredding, extrusion, pelletization) which was included in the LCA of the green LWC. Considering the findings in this study and the available literature, it can be claimed that by using RWP aggregates obtained through a centralized recycling practices, the negative impact of RWP can be avoided and the overall environmental impact could be decreased further which would be a promising way to produce a green LWC. Moreover, owing to its huge production capacity, construction materials sector can stimulate centralized plastic recycling by creating local and regional end-users with high demand.

Findings in this study indicated that RWP can be applied together with FA without interfering with the strength development. Since cement replacement with FA enabled obtaining a green LWC with lower environmental impact, FACs can also be considered to decrease the environmental impact even further. Recently, Zhou and Brooks (2019) applied FACs in structural LWC and reported that FACs are compatible with natural LWA, and their incorporation may improve the micromechanical properties of concrete. It was also reported that using FACs as fine LWA in lightweight mortar specimens drastically improved

Table 6. Impact category values of two different methods for conventional LWC.

Conventional LWC	CML-IA	IMPACT 2002
Global warming	423 kg CO_2 eq	415 kg CO_2 eq
Ozone layer depletion	1.30 E-05 kg CFC-11 eq	1.35E-05 kg CFC-11 eq
Aquatic acidification	0.957 kg SO_2 eq	1.02 kg SO_2 eq

mechanical and thermal properties of the cementitious composites and strength values as high as 20 MPa could be achieved (Hanif et al., 2016). As mentioned previously, the green LWC obtained in this study revealed a slightly lower strength when compared to the traditional LWC (Table 4). Considering the compatibility of FA and RWP, this handicap of the proposed green LWC may be overcome by partial replacement of the fine LWA with FACs. Such composition may pave the way for application of the proposed green LWC even for structural applications.

In addition to LCA analysis with CML-IA methodology, LCA results of conventional and green LWC mixtures were also evaluated by using IMPACT 2002+ method and the comparison of two methods in terms of different categories were given in Tables 6 and 7. Impact categories differ in each method related to different aspects. CML-IA method considers 10 different impact categories. IMPACT 2002+ method considers 14 different impact categories, unlike CML-IA method. The reason why CML-IA method was chosen as a main method of consideration is it is used most common method for construction materials.

The differences in two methods differences were identified as follow:

- Global warming potential values obtained via CML-IA method for both products (conventional and green LWC) were approximately 2% higher than the value obtained via IMPACT 2002.
- Ozone layer depletion values obtained via CML-IA method for both products (conventional and green LWC) were approximately 4% lower than the value obtained via IMPACT 2002.
- Aquatic acidification potential values obtained via CML-IA method for both products (conventional and green LWC) were approximately 7% lower than the value obtained via IMPACT 2002.

These differences in impact category values of CML-IA and IMPACT 2002 are mainly based on differences of data, assumption, evaluation methods used. However, the results indicated that regardless of the used method, green LWC reveals more environment-friendly performance than conventional LWC.

Final part of the LCA analysis consisted of calculation and comparison of greenhouse gas emissions and cumulative energy for both conventional and green LWC and the results were shown in Tables 8 and 9.

The total greenhouse emissions of conventional and green LWC were 433 kg CO_2 eq and 376 kg CO_2eq, respectively. Greenhouse emissions for green LWC were approximately %13 lower than greenhouse emissions for conventional LWC. These results are comparable to a recent study conducted by Bostanci where CO_2eq emissions as 428.6 kg CO_2/m^3 and 409.9 kg CO_2/m^3 were reported for MD-5 (5% replacement of cement by marble dust) and MD-10 mixtures, respectively (Bostanci, 2020). When compared to a control mixture (430.2 kg CO_2/m^3), reported emissions corresponded to 0.4% and 4.7% reductions in CO_2eq emissions, respectively. Our findings reveal that CO_2eq emissions can be decreased even more by partially replacing the natural aggregates with recycled plastics instead of recycled glass. Moreover, cumulative energy of conventional and green LWC was found as 2048 MJ and 2047 MJ, respectively (Table 9). Such comparable cumulative energy results indicate that, although, plastic recycling is considered as an energy intensive process (Gu et al., 2017), replacement of natural aggregates with RPW does not require additional energy when compared to the traditional concrete production. As energy requirements are similar, the significantly lower greenhouse gas emissions of green LWC can directly be attributed to the partial replacement of cement and pumice with FA and recycled plastic, respectively.

4. Conclusions

In the present study, the environmental impacts of two different types of LWC either made with natural aggregates (conventional LWC) or made with FA and RWP (green LWC), have been evaluated by using an LCA approach. Cradle to gate approach has been performed to compare a conventional LWC with green

Table 7. Impact categories values of two different methods for green LWC.

Green LWC	CML-IA	IMPACT 2002
Global warming	366 kg CO_2 eq	359 kg CO_2 eq
Ozone layer depletion	1.14E-05 kg CFC-11 eq	1.14E-05 kg CFC-11 eq
Aquatic acidification	0.923 kg SO_2 eq	0.965 kg SO_2 eq

Table 8. Greenhouse gas emissions for conventional LWC and green LWC.

Impact category	Unit	Conventional LWC	Green LWC
Fossil CO_2 eq	kg CO_2 eq	423	366
Biogenic CO_2 eq	kg CO_2 eq	8	7
CO_2 uptake	kg CO_2eq	2	3
Total	**kg CO_2 eq**	**433**	**376**

Table 9. Cumulative energy values of conventional LWC and green LWC.

Energy	Unit	Conventional LWC	Green LWC
Nonrenewable, fossil	MJ	1889	1861
Nonrenewable, nuclear	MJ	56	45
Nonrenewable, biomass	MJ	0.164	0.132
Renewable, biomass	MJ	27	29
Renewable, wind, solar, geoth.	MJ	5	8
Renewable, water	MJ	71	104
Cumulative energy	**MJ**	**2048**	**2047**

LWC containing 30% RWP as pumice replacement and 20% FA as cement replacement. These two LWC types have been evaluated in terms of eight environmental impact categories by using two different methods (CML-IA and IMPACT 2002).

It was found that greenhouse emissions for green LWC were approximately %13 lower than greenhouse emissions for conventional LWC. RWPs are environment-friendly replacement materials for natural LWA with an overall decrease in all CML-IA impacts except eutrophication. Although, a decrease in compressive strength was observed due to the replacement of pumice aggregates, the novel green LWC reached acceptable strength values for nonstructural applications.

Findings indicated that RWP can be used in combination with FA without hindering the strength development. Overall, this study paves the way for further investigation of RWP for development of nonstructural LWC with a significantly lower environmental impact.

Disclosure statement

No potential conflict of interest was reported by the authors.

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