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Research Article

Carbon Footprint of Recycled Aggregate Concrete

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Carbon footprint is one of the most widely used tools for assessing the environmental impacts of the production and utilization of concrete as well as of the components derived from it, representing the amount of carbon dioxide and other greenhouse gases associated with this product, expressed as CO_2 equivalents. In this paper, carbon footprint was used to compare the environmental performance in the production phase of a concrete made with both recycled and crushed virgin limestone aggregates, using a life cycle analysis methodological approach. Research outcomes revealed, as expected, that carbon dioxide equivalent emissions decreased slightly as the use of recycled aggregates increased. Emissions for concrete with 0.5 w/c were between 347 and 351 kg of CO_2-e/m^3. It was also corroborated that cement is the material with the greatest influence on greenhouse gas emission generation in the concrete's production phase, regardless of the use of recycled or virgin aggregates.

1. Introduction

The construction industry constitutes a substantial development factor for the so-called emerging economies, but at the same time, it is one of the main sources of waste generation, since in its processes many materials associated with other industrial sectors are used, such as cement, steel, stone, cardboard, glass, wood, aluminum, plastics, and ceramics, among others. Natural resource consumption to sustain that industry's growth increases steadily, contributing to environmental deterioration, for example, the rise in the atmosphere's temperature as well as that of the oceans, which has led to the well-known climate crisis of global warming [1].

Building materials, such as concrete, are increasingly being questioned for their environmental impact; because construction and demolition waste is a major component of all the waste generated by the construction industry, and to reduce the pressure on the exploitation natural resources, industry has focused on finding greener ways to produce concrete, encouraging the use of recycled materials to replace virgin materials [2].

In the last decades, a reduction of natural resource consumption in the production of aggregates through concrete debris recycling has been sought, so that new aggregates can be obtained which replace the usual aggregates coming from the crushing of virgin limestone [3], which even offers economic advantages, because when comparing costs of recycled aggregates with normal aggregates, savings of almost 4 USD (26%) per m^3 of aggregate and almost 6 USD (9%) per m^3 of concrete can be obtained [4].

However, in view of the diversity and variability of the recycled aggregates' properties, there is a lack of consensus regarding the concrete's behavior when this kind of aggregates is used, so it is necessary to evaluate the feasibility of using them from an environmental perspective, which can be achieved through the application of a life cycle assessment (LCA) methodological approach.

LCA in concrete fabrication has been used by some researchers to assess the environmental impact generated in the cement production process and in the extraction of stone material to obtain aggregates [5]. This has resulted in the search for alternate materials such as fly ash, slag, and aggregates recovered from construction and demolition waste (CDW), which has given rise to the *Green Concrete* notion [6].

An important tool to evaluate the environmental impacts generated by the concrete production and its components within the LCA methodology is the carbon footprint. The carbon footprint has its roots in the ecological footprint concept; originally, it was expressed through the area required for assimilating the CO_2 emissions generated during the life cycle of manufactured products. However, as the global warming problem became a priority on the international agenda, the concept and method of carbon footprint have changed; it no longer represents an area, but the amount of greenhouse gases (GHGs) associated with a product or service throughout its life cycle. Then, a product's carbon footprint consists of the LCA limited to the emissions that have an effect on climate change. The property often referred to as carbon footprint is the weight, in kilograms or tons, of GHG emissions per person, product, or activity, for which an emissions inventory is required [7].

Several authors around the world have reported the advantages of using recycled materials in the reduction of GHG. In Taiwan, LCA in the rehabilitation of pavements using recycled materials was evaluated. The conventional materials replaced by recycled materials were crushed stone (67%), sand (50%), and asphalt cement (70%). The results revealed GHG reductions of 16 to 23% [8]. In a study developed in Hong Kong, GHG reductions ranged from 6 to 17% in the construction of concrete buildings, using various recycled materials such as recovered stone aggregates, bricks and concrete blocks, plastics, asphalts, and galvanized steels, among others [9]. In Australia, a GHG reduction about 10% was determined when geopolymers replaced ordinary portland concrete (OPC) in the manufacture of concrete [10]. Recently, in the USA, Asutosh and Nawari [11] reported that the use of recycled materials in pavement construction reduces GHG emissions about 12%.

In spite of this evidence, great care must be taken in the development of this kind of studies, since small variations in the goals and objectives definition, data gathering from inventories, and the election of the impact analysis methodology may cause important differences in the environmental qualification obtained during the interpretation of results phase. According to all of the above, the main objective of the present work was to evaluate the environmental sustainability of a concrete produced with both virgin and recycled aggregates through the comparison of its carbon footprint, expecting that CO_2 emissions decrease when the amount of recycled coarse aggregate in the mix increases during the concrete manufacturing process.

2. Materials and Methods

In the present study, the concrete's carbon footprint involved the quantification of the GHG released throughout the manufacturing process, including material supply. The GHGs were mainly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which have impact on global warming. In this work, the environmental impact was calculated from field data and from the data obtained in different inventories, following the internationally recognized standard ISO 14064-1 [12]. In this way, it was possible to know the carbon dioxide equivalent mass (CO_2-e) originated during the concrete manufacturing process. The study was performed according to the framework shown in Figure 1.

Objectives and scope included both the exact definition of the system under study and the depth of the study. Inventory analysis consisted in the data collection to quantify material and energy inputs and outputs of the studied system. Impact and damage assessment was related to the identification, characterization, and quantification of the effects of the studied system on the environment. In the interpretation of results phase, significant points were identified based on the outcomes from the previous phases, corroborating their integrity, sensitivity, and coherence, sustaining the conclusions and recommendations of the study on the base of the inherent limitations of the work.

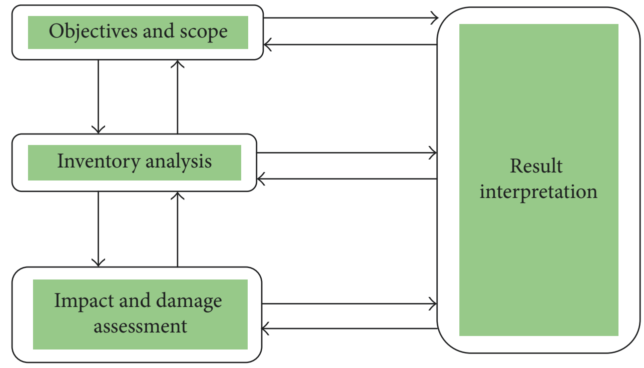

Figure 1: Framework for carbon footprint assessment.

2.1. Scope and System Limits. The analysis was focused on the aggregate production for the concrete manufacture: fine and coarse aggregate, coming from crushed virgin limestone, and recycled coarse aggregate, obtained from the trituration and classification of concrete debris. Limestone is the most common in the study region (Yucatán México). Five concrete mixes were produced with a water/cement ratio (w/c) of 0.5 and other five mixes with a w/c of 0.7. Five replacement rates of virgin coarse aggregate by recycled coarse aggregate (%R) were used: 0, 25, 50, 75, and 100%. OPC was used in all mixtures, and its production process was considered independently from the rest of the materials.

The material was collected selectively in CDW landfills, leaving it free of undesirable residues such as steel and plastics, among others. CDW composition is very diverse from one place to another and depends on the construction processes, available materials, and population customs. The most common components of CDW are concrete and mortar, masonry, ceramic floors, wood, plastics, and metals. Different authors, in several parts of the world, agree that the first three predominate, which are the main raw material for recycling processes, reaching between 30% and 40% of total waste [13, 14].

In this research, only debris from structural elements such as slabs, beams, and columns was selected. Subsequently, reinforcement steel, wires, ducts, and other electric material were dismantled, and the material was brushed to clean impurities such as earth and vegetable remains. The extracted raw material was taken to an impact mill plant for grinding so that coarse recycled aggregate could be obtained. In the same plant, the virgin material coming from a bank was crushed to obtain the fine and coarse aggregates, and then, the tests were carried out. In Tables 1 and 2, aggregate properties and mixture design are indicated.

Table 1: Aggregate properties.

Property	Normal coarse	Recycled coarse	Fine
Loose unit weight (kg/m^3)	1187	1102	1146
Compact unit weight (kg/m^3)	1401	1235	—
Specific gravity	2.33	2.31	2.38
Absorption (%)	6.7	7.2	—
Fineness modulus	—	—	2.4

Table 2: Mixture design (kg/m^3).

Mixture		Water	Cement	Normal coarse	Recycled coarse	Fine
w/c	%*R*					
0.5	0	205	410	987	0	527
0.5	25	205	410	719	240	556
0.5	50	205	410	465	465	580
0.5	75	205	410	226	677	609
0.5	100	205	410	0	874	635
0.7	0	205	293	987	0	615
0.7	25	205	293	719	240	644
0.7	50	205	293	465	465	669
0.7	75	205	293	226	677	698
0.7	100	205	293	0	874	723

Figure 2 shows the CO_2-*e* emission system for the production of 1 m^3 of concrete (both regular and recycled). Raw material refers to limestone and water. The difference between both concrete types is that, in order to produce the recycled aggregate mix, concrete debris extracted from CDW is also used.

2.2. Inventory Analysis. This phase involved data collection and calculation procedures to quantify the system's inputs and outputs. Data collection was classified into two levels.

2.2.1. Level 1. In this level, energy consumption and other resources are obtained from the operating facilities' processing logs, which include yields and resource consumption rates at the time of the facility's operation activities. They are typically derived from the use of a fossil fuel (diesel) for the raw material transport. In this case, it refers to vehicle fuel consumption for the transportation of the materials, as well as the limestone's exploitation rates and volumes, use of explosives, and water that generate CO_2-*e* emissions.

2.2.2. Level 2. In this level, CO_2-*e* emission factors for material production were determined. They are induced indirectly by the activity under analysis, not emitted in the place where the activity was carried out, since they were derived from sources not directly controlled. In this case, these were associated with cement production, energy consumption, and utilization rates of materials for the manufacture of concrete. They were collected from different databases, as indicated in Table 3.

Table 3 shows an average emission factor of 745 kg CO_2-*e*/ton for OPC average [15]. The value of 612 kg CO_2-*e*/ton, reported in 2013 by the main cement producer in Mexico [19], was rejected because, in that report, the company does not indicate the methodology used for the emission factor calculation, and on the contrary, it differs markedly from what is reported in other countries with a higher degree of industrialization and technological progress, where the estimated emission factor ranges from 800 to 850 kg CO_2-*e*/ton of cement, as in Germany, France, Denmark, and other European Union countries [20–23]. Total amount of CO_2-*e*/m^3 emissions of concrete corresponded to the sum of the emissions from cement production, aggregates, water, casting, and concrete placement. These components required the use of limestone, water, electricity, diesel fuel, and explosives. The latter refers to a mixture of low-density explosive agents and other additional elements such as fulminant and wicks used during blasting work.

3. Results and Discussion

Carbon footprint assessment for each concrete mix, expressed in kg CO_2-*e*/m^3, is summarized in Table 4, which includes total cement, aggregates, and other nonsignificant emissions such as the use of water, and explosive agents.

Calculations were made from the following equation:

$$CO_2\text{-}e = \sum (Q_1F_1 + Q_2F_2 + \cdots + Q_nF_n), \tag{1}$$

where *Q* corresponds to the material quantity or input used and *F* represents the emission factor for the production of 1 m^3 of concrete. Also in Table 4, the results of compressive strength (Fc) for each concrete mixture, expressed in MPa, have been included to show their relationship with CO_2-*e* emissions.

In the *Partial* column of Table 2, the sum of emissions is registered, excluding the cement contribution, since this material generates most of the total emissions when compared to the rest of the elements, with more than 80% (Figure 3), similar to what was reported by Marincović et al. [24].

On the contrary, the influence of fine and coarse aggregates has been compared in Figure 4, where it can be appreciated that recycled coarse aggregate has a slight lower contribution than virgin gravel with a difference of 3%.

As expected, because of the difference in the cement content, the carbon footprint of the mix with 0.5 w/c was 25% higher than that of the mix with 0.7 w/c. The carbon footprint of all the analyzed mixes decreased to a small extent as the coarse aggregate %*R* increased. For the case of the concrete with 0.5 w/c, the values fluctuated between 347 and 351 kg of CO_2-*e*/m^3, slightly lower than that reported by Turner and Collins [10] under similar conditions (354 kg of CO_2-*e*/m^3 for a 0.6 w/c) and than that reported by Kim et al. (356 kg of CO_2-*e*/m^3 for a concrete with compressive strength of 30 MPa) [25].

Since the carbon footprint itself is an intermediate assessment point, the impacts were converted to damage to human health. This was determined considering that 1 kg CO_2-*e* represents 2.1×10^{-7} DALY (disability-adjusted life

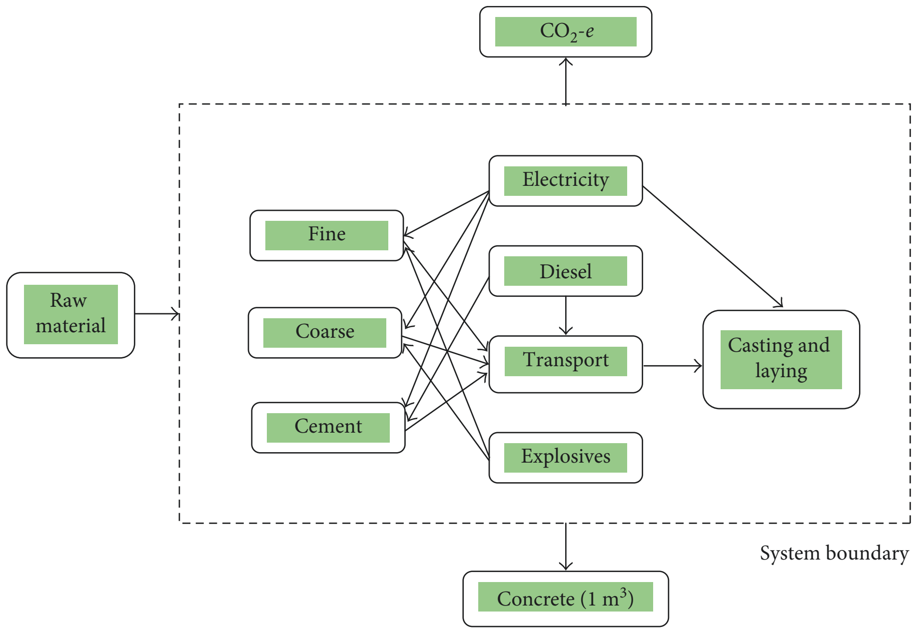

FIGURE 2: CO_2-*e* emission system for the concrete production.

TABLE 3: Inventory of CO_2-*e*, energy, and materials.

Input	Factor	Unit	Context	Reference
Cement	0.745	kg CO_2-*e*/kg	Mexico, 2004	[15]
Explosives				
Yield	0.465	kg product/m^3	Mexico, 2014	[16]
Emission	0.440	kg CO_2-*e*/kg	Australia, 2013	[10]
Diesel				
Yield	3.000	km/L	Mexico, 2014	[16]
Emission	2.680	kg CO_2-*e*/L	Australia, 2013	[10]
Coarse				
Yield for normal	1.320	m^3 stone/1000 kg	Mexico, 2014	[16]
Yield for recycled	0.002	m^3 debris/kg	Mexico, 2014	[16]
Emission	0.041	kg CO_2-*e*/kg	Australia, 2013	[10]
Fine				
Yield	1.120	m^3 stone/1000 kg	Mexico, 2014	[16]
Emission	0.014	kg CO_2-*e*/kg	Australia, 2013	[10]
Electricity	0.458	kg CO_2-*e*/KWH	Mexico, 2015	[17]
Water	0.540	KWH/m^3	Mexico, 2011	[18]
Concrete				
Casting and laying	0.012	kg CO_2-*e*/kg	Australia, 2013	[10]

year), which expresses the number of years lost as a result of lack of health, disability, or premature death [26]. Applying this conversion factor, the obtained DALY values ranged from 7.29 to 7.36×10^{-5} (about 38.5 minutes) for 0.5 w/c and from 5.49 to 5.56×10^{-5} (about 29 minutes) for 0.7 w/c.

These results may seem insignificant at the global level, as they would need to be standardized and weighted considering other impact categories such as eutrophication, acidification, and land use change, which is beyond the scope of this research.

Finally, the construction industry generates a large amount of waste, either by the construction process itself or by demolition; in fact, it is the largest source of industrial waste in developed countries, which have been estimated in a range of 520 and 760 kg/person/year, without taking into account wars or natural disasters [4]; of this large volume, concrete is the most abundant, since it represents 67% by weight. If we consider an average of 640 kg/person/year and the Yucatan Peninsula population of 4.17 million inhabitants by the year 2010 [27], the Mexican region in which most of the limestone aggregates in the country are produced, a total concrete waste is 1.79 million tons per year, that is, around 744,751 cubic meters per year. If such quantity were recycled, this would imply that approximately 22,343 tons of CO_2-*e* would cease to be emitted per year in this region.

Table 4: CO_2-e emissions.

Mixture w/c	Mixture %R	Fc	Cement	Aggregates	Others	Partial	Total
0.5	0	32.5	305.5	44.6	0.61	45.2	350.7
0.5	25	31.6	305.5	43.9	0.55	44.4	349.9
0.5	50	30.8	305.5	43.1	0.49	43.6	349.0
0.5	75	29.8	305.5	42.3	0.44	42.7	348.2
0.5	100	29.8	305.5	41.6	0.38	42.0	347.4
0.7	0	23.7	218.3	45.8	0.63	46.4	264.7
0.7	25	23.1	218.3	45.0	0.57	45.6	263.9
0.7	50	22.5	218.3	44.2	0.51	44.7	263.0
0.7	75	21.0	218.3	43.5	0.46	44.0	262.2
0.7	100	19.0	218.3	42.7	0.41	43.1	261.4

Others: water, casting, and placement of concrete, and use of explosive agents in blasting works.

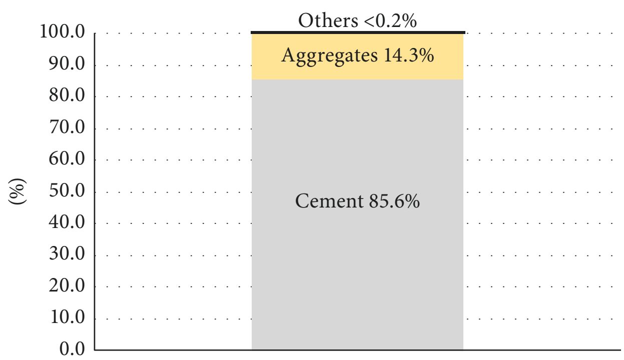

Figure 3: CO_2-e by material type.

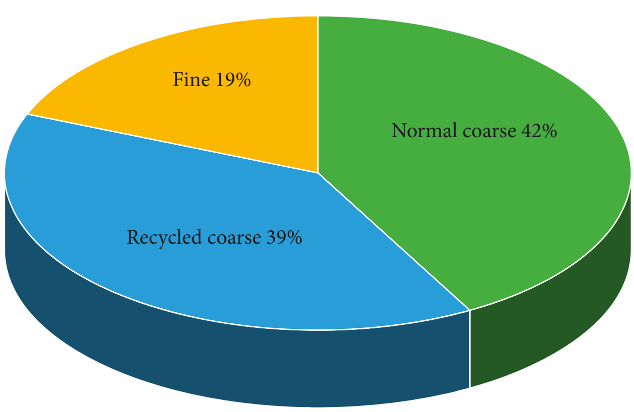

Figure 4: CO_2-e by aggregate type.

4. Conclusions

Specific conclusions of the present work are drawn based upon the experimental results:

(i) It was determined that CO_2-e emissions decrease slightly by increasing the percentage of recycled coarse aggregates in the concrete mixtures, indicating that the use of this material has little influence on the reduction of the carbon footprint in the concrete manufacturing process.

(ii) It was also confirmed that cement is the material with the greatest influence on greenhouse gas emissions in the production of concrete.

(iii) If we consider the per capita generation average of concrete waste from the construction industry and the population of the region where most of the limestone aggregates in Mexico are produced, the recycling of concrete waste would imply that approximately 22,343 tons of CO_2-e would cease to be emitted annually in this region.

(iv) Regarding the use of recycled aggregates in concrete production, although the progress has been made in the study of the physical, mechanical, and durability properties of the material, there is still a large area of opportunity in the research of the environmental impacts involved. Future research avenues should consider the contributions of other cementitious materials within a broader LCA framework, including both the use stage and the final disposal of buildings, besides the construction stage.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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