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Research Paper

Comparative carbon emission assessments of recycled and natural aggregate concrete: Environmental influence of cement content

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ABSTRACT

This work examines the environmental and geochemical impact of recycled aggregate concrete production with properties representative for structural applications. The environmental influence of cement content, aggregate production, transportation, and waste landfilling is analysed by undertaking a life cycle assessment and considering a life cycle inventory largely specific for the region. To obtain a detailed insight into the optimum life cycle parameters, a sensitivity study is carried out in which supplementary cementitious materials, different values of natural-to-recycled aggregate content ratio and case-specific transportation distances were considered. The results show that carbon emissions were between 323 and 332 kgCO_2e per cubic metre of cement only natural aggregate concrete. These values can be reduced by up to 17% by replacing 25% of the cement with fly ash. By contrast, carbon emissions can increase when natural coarse aggregates are replaced by recycled aggregates in proportions of 50% and 100%, and transportation is not included in analysis. However, the concrete with 50% recycled aggregate presented lower increase, only 0.3% and 3.4% for normal and high strength concrete, respectively. In some cases, the relative contribution of transportation to the total carbon emissions increased when cement was replaced by fly ash in proportions of 25%, and case-specific transportation distances were considered. In absolute values, the concrete mixes with 100% recycled aggregates and 25% fly ash had lower carbon emissions than concrete with cement and natural aggregates only. Higher environmental benefits can be obtained when the transportation distances of fly ash are relatively short (15–25 km) and the cement replacement by fly ash is equal or higher than 25%, considering that the mechanical properties are adequate for practical application. The observations from this paper show that recycled aggregate concrete with strength characteristics representative for structural members can have lower carbon emissions than conventional concrete, recommending them as an alternative to achieving global sustainability standards in construction.

1. Introduction

Construction is one of the largest consumers of natural resources generating significant levels of waste. Construction and demolition waste (CDW) accounts for about 25%–30% of all waste in Europe (EC, 2011), and about 50% of municipal solid waste in China (Ding et al., 2016). This is in the range of 500 million tonnes per year in the United States of which about 46% comes from roads and bridge infrastructure (USEPA, 2015). Moreover, 45 and 22 million tons of CDW are discarded every year in Brazil and Colombia, respectively (ABRELPE, 2015; MESD, 2017). Wide range of data is available regarding the CDW and associated environmental initiatives in developed countries, yet this is relatively scarce or non-existent for developing economies (Pomponi and Campos, 2018).

To alleviate the environmental impacts (EI) produced by conventional concrete (de Brito and Saikia, 2012), its main constituents, cement and aggregates, can be replaced with more sustainable alternatives that minimize the EI (Jiménez et al., 2015; Turk et al., 2015). Portland cement is the primary source of carbon emissions generated by typical commercially produced concrete mixes, being responsible for 74% to 81% of total emissions (Flower and Sanjayan, 2007). Cement can be partly substituted by supplementary cementitious materials (SCMs) such as ground granulated blast furnace slag and fly ash (Collins, 2010; Gursel et al., 2016; Xu et al., 2020), whilst the natural aggregates (NA)

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with recycled aggregates (RA) (Knoeri et al., 2013; Sabău and Remolina Duran, 2021). Additionally, sustainable recycled aggregate concrete (RAC) directly contribute to limiting the depletion of natural mineral resources (Knoeri et al., 2013; Tošić et al., 2015). Incorporating SCMs in NAC has the potential to reduce carbon emissions and cost of concrete, whilst partially substituting NA by RA, leads to comparable emissions but slightly increased cost for an equal design strength (Bostanci et al., 2018).

The main route to replace NA with RA is either using concrete from CDW or slag from metallurgical production (Etxeberria et al., 2007; Faleschini et al., 2014; López Gayarre et al., 2016). RA resulted from CDW have typically an irregular morphology with old mortar bonded to the rough surface of original aggregates (Kim et al., 2019) and a water absorption up to 3.5 times higher than that of NA and a reduction in unit weight with about 10% compared with NA (Evangelista and de Brito, 2007; Poon and Lam, 2008; Silva et al., 2016a). Moreover, the aggregate crushing value, which gives a relative measure of the resistance of an aggregate crushing under gradually applied compressive load is also lower for RA than for NA (Park et al., 2018). In order to obtain recycled aggregate concrete (RAC) with strength, workability, and durability properties similar to natural aggregate concrete (NAC), RAC require adjusting the water-to-cement/binder ratio by increasing the cementitious materials content and/or superplasticiser amount (Kurda et al., 2018; Nakic, 2018).

A significant number of studies focusing on the material and structural performance of RAC have been undertaken (Etxeberria et al., 2007). These include short- and long-term mechanical properties (Fonseca et al., 2011; Silva et al., 2016a; Revilla-Cuesta et al., 2020). Additional tests on slabs and beams in shear and flexure, columns in compression confirmed the feasibility of using RA in structural concrete (Ignjatović et al., 2017). Although RAC is generally an effective option to reduce the carbon emissions of conventional construction, environmental benefits may be offset due to the energy required for crushing and sorting CDW and associated transportation of RA (Ghanbari et al., 2018). Emission estimates depend on a wide range of parameters such as the local conditions at the source of raw materials, manufacturing procedures and transportation distances (Collins, 2010).

Life Cycle Assessments (LCA) are typically used as indicators for environmental effects in source separation, waste treatment and concrete recycling technologies (Van den Heede and De Belie, 2012). LCA have shown that replacing NA with RA can improve the EI of concrete production only if avoided landfilling is considered in the analysis (Tošić et al., 2015). Numerous LCA on RCA showed that the EIs are highly sensitive to transportation distances and when these are 15–25 km above, the environmental benefits of using RA become neutral or negative (Knoeri et al., 2013; Kleijer et al., 2017). Considering the transportation distances, it is recommended to use recycled aggregate only when they are locally available, otherwise their embodied carbon value can exceed that of virgin materials (The Concrete Centre, 2016; MPA, 2020). Energy savings can be achieved when recycling is carried out in fixed plants, as the fuel and electricity consumption is comparatively higher for the mobile plants (López Gayarre et al., 2016; Martinez-Arguelles et al., 2019).

As a reference, previous environmental assessments on wide databases of NAC and RAC have shown that the equivalent carbon emissions vary between 214 and 387 $kgCO_2e$, depending on the proportions of the concrete constituents (Braga et al., 2017). For example, a C8/10 NAC has 273 $kgCO_2e$, whilst a C50/60 NAC has 350 $kgCO_2e$. On the other hand, a C8/10 RAC has around 214 $kgCO_2e$, whilst a C50/60 NAC has 387 $kgCO_2e$. These values are with ranges indicated in established assessment guides (Hammond and Jones, 2011). As noted above, reductions in $kgCO_2e$ can be achieved by replacement of cement by SCM, yet this would affect the early concrete strength. For example, replacement of cement by fly ash in proportions of 20%, 35%, 55% can lead to reductions in $kgCO_2e$ by 19.4%, 45.8%, 53.7%, respectively (Jones et al., 2011).

In many countries in which the construction is growing, RAC can be a reliable alternative to NAC, contributing to reusing CDW and to achieving the wider sustainability goals. Although some strategies to minimise carbon emissions associated with the construction sector exist in Latin America, EI studies of various aspects related to CDW and construction sector in Colombia are still limited (Martinez-Arguelles et al., 2019). Environmental evaluation studies of RAC exist, but their general application may be limited as they are strongly dependent on the system boundaries and regional characteristics. As concrete recycling is significantly different compared to Europe or the United States, where most of the studies were undertaken, there is a need to carry out LCA in the regional context.

To this end, this study is the first to evaluate the EIs of RAC for application in structural members of buildings and infrastructure in Colombia. As a result, this study is a regional analysis, but its results are expected to be directly applicable to other countries with similar levels of development. The environmental influence of cement content, aggregate production, transportation, and waste landfilling is analysed using the LCA framework and an associated Life Cycle Inventory (LCI) largely specific for the region. To obtain a detailed insight in the optimum LCA parameters, a sensitivity study is carried out in which SCM, different ratios of natural-to-recycled aggregates and various transportation distances were considered.

2. Materials and methods

2.1. Goal and scope

The overarching goals of this paper are to: (i) quantify comparatively the EI of RAC and NAC through LCA approach, according to ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b), (ii) collate a database of transportation distances characteristic for the region, (iii) interpret the results and provide recommendations. The LCA framework is considered a reliable tool to assess the EIs of a functional unit (FU) over its life cycle within determined system boundaries (Van den Heede and De Belie, 2012; Faleschini et al., 2014).

The EI assessments in this paper were undertaken by employing the IPCC 2013 approach (IPCC, 2014). As the main measure used by the construction industry to characterise the EI of various construction materials and systems is $kgCO_2e$, the global warming potential (GWP) impact category was considered. GWP considers the effects of various greenhouse gas (GHG) on the climate. Although the main measure is CO_2, the effects of other GHG (e.g. methane, nitrogen dioxide) to climate change is represented by a CO_2 equivalence (Horvath, 2005).

Amongst the available impact categories, GWP is the most representative for the production of concrete (Tošić et al., 2015; Ding et al., 2016; Gursel et al., 2016; Nakic, 2018). The analysis presented in this paper covers all life cycle stages encountered in the production of concrete including production and transportation of main constituents such as cement, SCM, NA, RA, and admixtures. The background environmental data were taken from the Ecoinvent database version 3.6. The EIs of the concrete mixes assessed in this study are materials with application in load-bearing structures such as buildings and bridges as well as subgrade applications such as pavements. The cylindrical compressive strength obtained from tests corresponds to concrete grades ranging between C12/15 to C25/30 according to BS EN 1992-1-1 (BSI, 2004).

2.2. System description

The system boundaries of the LCA methodology of this study are illustrated in Fig. 1a, b and further described in Section 2.5. As shown, the system boundaries employed in this study are representative for a 'cradle-to-gate' approach (stages A1–A3), in which A1 stage refers to the extraction and production of raw materials required for concrete mixes, stage A2 involves assessing the EI of transportation, and stage A3 is related to the concrete production process at the plant. This approach does not include the EI associated with the concrete casting (application), maintenance (user stage), and end-of-life (demolition). Although compressive strength and associated mechanical properties are more related to the user stage (beyond A1–A3) (Jiménez et al., 2015), they are precursory for ensuring the quality of monolithically cast-in-situ reinforced concrete structures. Also, having concrete materials of

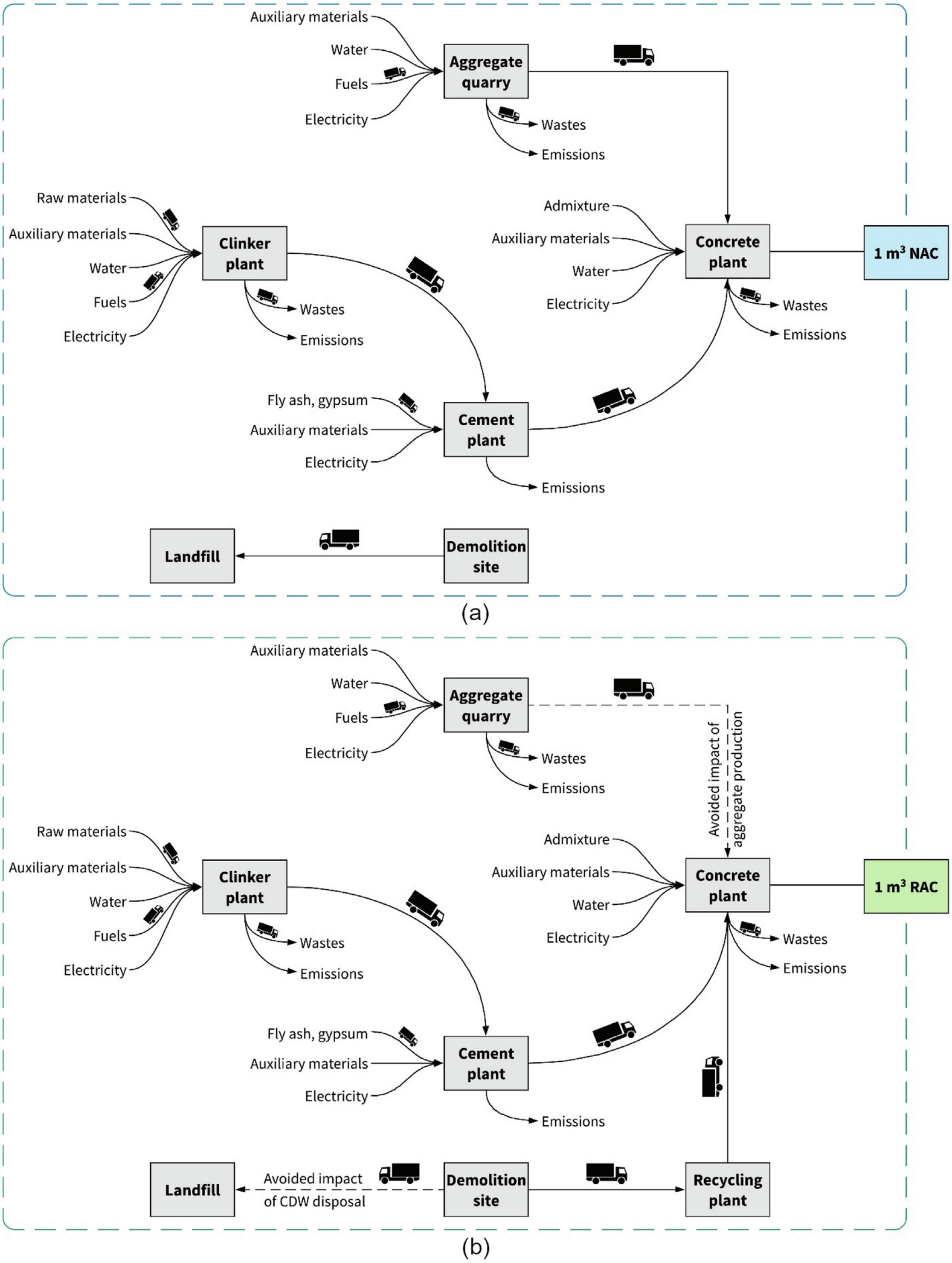

Fig. 1. System boundaries for production of (a) Normal aggregate concrete, (b) Recycled aggregate concrete.

the same mechanical properties and workability would provide similar EIs from the construction and demolition phase (Tošić et al., 2015).

With regard to the production and transportation of RA, the cut-off rule was applied. Through this approach, the EI resulted from demolition and recycling of the parent NAC are allocated to the RA production. It is worth noting that the EIs related to moving the demolition waste within the recycling site and associated emissions are not considered as they are generally insignificant (Kurda et al., 2018), but benefits from avoiding landfills are accounted for (Ding et al., 2016).

2.3. Functional unit

The data flows are calculated for an FU equal with the unit volume of concrete (1 m^3) and all comparisons undertaken in this paper use this as a reference value. The inputs consider resources, production, energy, processes operations, and transportation. The outputs include waste from material processing, emissions and the use of machines (e.g. waste rubber, waste mineral oil). To enable reliable comparisons for the FU, concrete mixes having the same basic mechanical properties and have similar functional requirements, are investigated. This is practically achieved by increasing the amount of water while maintaining the water-to-binder content constant. (Marinković et al., 2010; Tošić et al., 2015). Additional superplasticizer would be required for acquiring similar workability (Ding et al., 2016). However, the influence of chemical admixtures emissions to the total amount of emissions per cubic meter of concrete is rather small, and a significant increase in their quantities would largely keep the output emissions similar (Jiménez et al., 2015). Note that, in this study it is considered that the concrete is used in a non-aggressive environment and both NAC and RAC have similar durability performance.

The analysis in this paper deals with comparing the EI of concrete mixes only with NA, and 50% and 100% replacement of NA with recycled coarse aggregates (RA). These mixes are either investigated previously and described briefly below (Sabău and Remolina Duran, 2021), or from literature (Jau et al., 2004; Reda Taha et al., 2008; Aiello and Leuzzi, 2010; Kim et al., 2015; Dimitriou et al., 2018). Besides the RA content, the EI of concrete mixes in which the cement was replaced partly by SCM while maintaining the concrete strength fixed, was also investigated.

2.4. Concrete mixes

In this paper, two distinct assessments are undertaken considering two reference concrete materials with compressive strengths typically used in flexural members such as slabs and beams (31.5 MPa) (Sabău and Remolina Duran, 2021), and in members primarily subjected to compression such as columns (51.3 MPa) (Dimitriou et al., 2018). The first mix is based on a previous experimental study that focused on the mechanical behaviour of RAC incorporating RA from pavement demolition (Sabău and Remolina Duran, 2021). The full details of the concrete mixes and concrete strength are shown in Table 1. For a replacement of 50% of NA with RA, the compressive strength was reduced by about 10%, whilst for a full replacement (100%) of NA with RA, the compressive strength was about 28% lower than of its reference. Additional flexural tests on prismatic members showed a reduction in strength with an increase in RA content, whilst the density was slightly reduced. In this paper, these three mixes are used as a reference for EI assessments.

The concrete mixes names from Table 1 adopt the format *Caa-Sbb-RAccc-d-Fee* (*Caa* is the amount of cement from the total binder in percentage, *Sbb* represents the quantity of SCM, *RAccc* represents the RA content, *d* is for reference concrete strength, and *Fee* represents the concrete strength). For example, C75-S25-RA50-H-F36 corresponds to a concrete with 75% cement, 25% SCM, 50% RA, the reference concrete is of relatively high strength (f_c = 51.3 MPa) and the compressive strength of RAC is around 36 MPa). Note that all strengths refer to experimental values obtained from tests on cylinders ($f_{c,cyl}$) at 28 days. For cases in which only cubic strengths ($f_{c,cube}$) were available a conversion factor of $f_{c,cyl}/f_{c,cube}$ = 0.8 was considered, as recommended by current provisions (BSI, 2004).

Based on the cement manufacturer datasheets used in C75-S25-RA0-L, the material already included 25% of SCM, implicitly having a reduced EI compared with a cement-only based concrete. Note that cement-only refers to Type I Portland cement or CEM I 52.5 which has a minimum of 95% clinker, whilst the remaining 5% contains other constituents such as gypsum. To determine the effect of SCMs, cement-only concrete materials with NA or RA of the same strength as those obtained from experiments, were considered from literature (Jau et al., 2004; Reda Taha et al., 2008; Kim et al., 2015). This approach allows determining the EI of both SCM and aggregate type (NA versus RA) whilst the strength properties are relatively the same. It is worth noting that some variation exists in terms of strength for concrete with similar strengths and different constituents, but this is within expected experimental ranges. As shown in Table 1, the concrete mix C75-S25-RA50-L-F29 had a f_c = 28.2 MPa, which is similar to C75-S25-RA0-L-F29 (f_c = 29.7 MPa) and C100-S0-RA0-L-F29 (f_c = 29.3 MPa). The same comment is valid for the comparative assessment in which the reference concrete is of higher strength (C75-S25-RA0-H-Ref).

2.5. Life cycle inventory

As can be seen in Fig. 1, the inventory flows considered for clinker production were as follows: raw materials (72% limestone, 15% clays, 11% calcareous marl, and 2% iron oxide), auxiliary materials (infrastructure and lubricating oil), water, fuels (95% primary fuels and 5% secondary fuels), electricity (81 kWh per ton of clinker), and transportation of raw materials and fuels to the clinker plant. All the water used for clinker and cement production was included in the clinker production. All the fuels used for clinker, cement and concrete production were allocated to clinker production. The inventory flows for cement production were as follows: raw materials (75% clinker and 25% fly ash), auxiliary materials, electricity (37 kWh per ton of cement), and transportation of raw materials to the cement plant. The inventory flows for aggregate production were as follows: auxiliary materials, water, fuels, electricity (2.74 kWh per ton of aggregates), and transportation of fuels to the aggregate quarry. The inventory flows for concrete production were as follows: raw materials (cement, aggregates, and admixture), auxiliary materials (infrastructure, lubricating oil, and wearing parts), water, electricity (2.38 kWh per ton of concrete), and transportation of raw materials to the concrete plant.

Appendix A (Supplementary Data) depicts the source of data for the concrete production. As shown in the table, these are based on available Ecoinvent database with reference to a detailed report of regional LCIs for Colombia and Peru (Gmünder et al., 2018). In Colombia, cement production conforms with the NTC 121 (ICONTEC, 2011) provision that is largely based on the ASTM C1157 standard specification for hydraulic cement (ASTM C1157/C1157M-20, 2011). From the two available cement data sheets, general use (GU) and high early strength (HE or ART), the later was used in the experiments described in Section 2.4 (Sabău and Remolina Duran, 2021). This cement (ART) is finer and has a higher clinker content than the type GU and incorporates 25% SCMs with high pozzolanic reactivity (Gmünder et al., 2018). The energy associated with cement and concrete production is based on sustainability reports issued by main cement manufacturers in Colombia and updated based on communications with local experts

Table 1
Concrete mix properties.

Mix ID	Authors	Binder total (kg/m^3)	Clinker (kg/m^3)	SCM (kg/m^3)	Fine NA (kg/m^3)	Coarse NA (kg/m^3)	RCA (kg/m^3)	Water (l/m^3)	Admix-tures (kg/m^3)	w/b ratio	*fc* (MPa)
C75-S25-RA0-L-Ref	(Sabău and Remolina Duran, 2021)	396.0	297.0	99.0	804.0	965.0	0	225.7	0	0.57	31.5
C75-S25-RA50-L-F29	(Sabău and Remolina Duran, 2021)	396.0	297.0	99.0	670.0	504.0	504.0	233.6	0	0.59	28.2
C75-S25-RA100-L-F22	(Sabău and Remolina Duran, 2021)	396.0	297.0	99.0	508.0	0	1050	249.5	0	0.63	22.5
C75-S25-RA0-L-F29	Jau et al. (2004)	380.0	285.0	85.0	862.0	852.0	0	204.0	4.9	0.54	29.7
C75-S25-RA0-L-F22	Jau et al. (2004)	350.0	262.5	87.5	875.0	865.0	0	205.5	4.6	0.59	21.7
C100-S0-RA0-L-F29	Kim et al. (2015)	347.0	329.7	17.4	827.0	937.0	0	177.0	2.4	0.51	29.3
C100-S0-RA0-L-F22	Reda Taha et al. (2008)	350.0	332.5	17.5	630.0	1160	0	200.0	0	0.57	21.0
C75-S25-R0-H-Ref*	Dimitriou et al. (2018)	400.0	300.0	100.0	667.0	919.0	0	192.0	3.0	0.48	51.3
C75-S25-R50-H-F36*	Dimitriou et al. (2018)	400.0	300.0	100.0	667.0	459.5	459.5	192.0	4.5	0.48	36.5
C75-S25-RA100-H-F29	Dimitriou et al. (2018)	400.0	300.0	100.0	667.0	0	919.0	192.0	5.9	0.48	28.5
C75-S25-R0-H-F36	Jau et al. (2004)	380.0	285.0	95.0	887.0	877.0	0	184.7	5.3	0.49	36.3
C75-S25-R0-H-F29	Jau et al. (2004)	380.0	285.0	95.0	862.0	852.0	0	204.0	4.9	0.54	29.7
C100-S0-RA0-H-F36	Aiello and Leuzzi (2010)	335.0	318.3	16.7	1116.0	744.0	0	174.0	3.4	0.52	36.6
C100-S0-RA0-H-F29	Kim et al. (2015)	347.0	329.7	17.3	827.0	937.0	0	177.0	2.4	0.51	29.3

Notes: * the concrete mixes were obtained from linear interpolation from the mixes from the same paper and available literature.

(Gmünder et al., 2018). The LCI model is based on the Product Category Rules (PCR) for cement and concrete (IEPDS, 2010), as well as on the LCA core model of the WBCSD-CSI EPD tool (Dauriat et al., 2018).

In a lack of specific regional data, the aggregate production was obtained from LCI of NA and RA from Brazil (Rosado et al., 2017; Silva et al., 2018), and employed in literature for assessing the EI of NAC and RAC for pavements in Colombia (Martinez-Arguelles et al., 2019). It is expected that the technologies, production conditions, input energy and output emissions for NA and RA would be similar for Colombia and Brazil due to comparable characteristics of the construction industry. The avoided impacts of CDW disposal were accounted for in the analysis, while scrap iron recovery from steel reinforcement was not considered. For electricity production, data were taken from the Ecoinvent database for Colombia (Suppen et al., 2018).

The water production was also obtained from a regionalised inventory for Colombia (Gmünder et al., 2019). The remaining required inputs were either representative for the rest of the world (RoW) or global (GLO) (Appendix A), and were chosen against specific data for Europe and United States as they are more representative of the study from this paper. The impacts of concrete plant construction (building, machines, land-use) and wearing of parts and their production (metal and non-metal) were considered in the analysis. The treatment of wastes (scrap steel, waste concrete, waste mineral oil, waste rubber, wastewater) was also accounted for (Hischier, 2007; Kellenberger et al., 2007; Classen et al., 2009; Doka, 2009; Boesch and Hellweg, 2010).

Modelling was carried out using Open LCA program employing the system boundaries and FU described above as well as the inherent limits imposed by the information available in the Ecoinvent database. It is worth noting that due to possible variations between region-specific data and that available in existing databases for RoW and GLO, some uncertainty may exist in the EI values obtained from the analysis.

2.6. Aggregate production

The production of coarse NA involves the extraction of limestone in quarries, crushing and sieving, lorry loading, and transportation to the concrete plant. This is the typical process employed in coarse NA production in Colombia (Martinez-Arguelles et al., 2019). The fine NA follow a similar procedure except for extraction that is typically from riverbeds and depending on the size of the particle, crushing may not be required. Production of RA involves four steps. In the first step, the concrete waste resulted from demolition is collected by an excavator and placed in a crushing machine. Crushing is typically a two-phase process including the removal of impurities and embedded reinforcing steel (Tošić et al., 2015). The removal of steel is generally made by electromagnets. Crushing is followed by sieving to obtain RA of required granulometry. This is a typical production process of RA and employed by most recyclers in Colombia (Silva et al., 2016b; Martinez-Arguelles et al., 2019).

Due to relatively inferior quality of RA in comparison to NA, RA was typically used previously in sub-grade applications such as road pavements (Martinez-Arguelles et al., 2019). Procedures to improve the surface properties of RA exist and RAC can achieve similar properties to NAC without modifying the mix proportions, yet these procedures are relatively energy-intensive (Fan et al., 2014). However, based on the concrete compressive strengths depicted in Table 1, RAC mixes studied in this paper are feasible for structural applications such as beams, slabs, and columns in buildings. It is worth noting that, although some studies used fine RA (Braga et al., 2017), these were not considered in the concrete mixes investigated here as their application is typically not recommended in structural members (Tošić et al., 2015).

2.7. Transportation

The main transportation processes (stage A2) in the production of concrete are those related to the transportation of raw materials to the concrete plant. The transportation distances are variable and process-characteristic dependent. In this paper, the location of the main suppliers of concrete constituents was identified (Appendix B, Supplementary Data) and used to perform four case studies. These case studies can be regarded as a parametric investigation that offer information regarding the threshold distance at which the environmental benefits of the RAC are offset. For each of the concrete mixes from Table 1, four distinct case studies in which characteristic transportation distances for four Departments of Colombia were considered: (i) Case study A— Cundinamarca with capital at Bogotá, (ii) Case study B — Antioquia with capital at Medellín, (iii) Case study C - Valle del Cauca with capital at Cali and (iv) Case study D — Atlántico with capital at Barranquilla (Fig. 2 and Appendices B and C). These are the regions with the

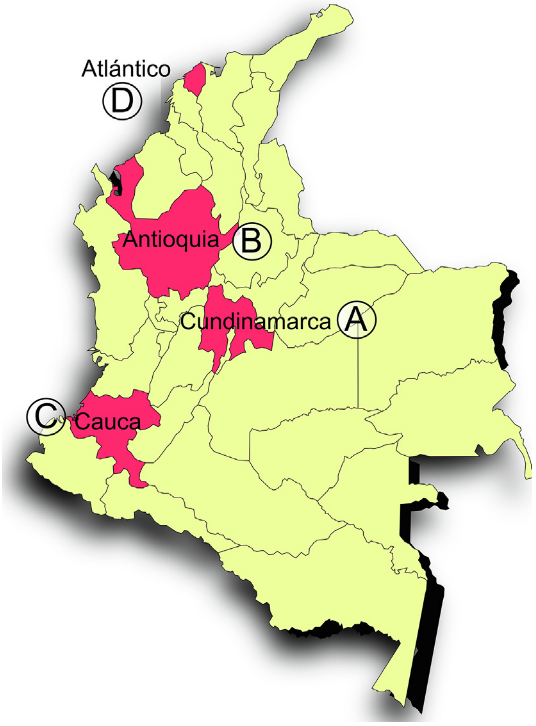

Fig. 2. Map of the regions accounted for the LCA (Case study A – Cundinamarca, Case study B – Antioquia, Case study C – Cauca, Case study D - Atlántico).

highest population density and degree of urbanisation, and implicitly have the highest level of construction waste (MESD, 2017).

To undertake these investigations a database with available production plants for main concrete binders (cement, fly ash, ground granulated blast furnace slag, limestone), aggregate quarries, recycling plants, landfill locations and concrete production plants was collated (Appendices B and C). Each case study considered the transportation of raw materials to a concrete plant, as well as transportation of the demolition waste from the city centre to recycling plant or landfill as described below. Mobile recycling units located within the concrete plants were considered in the assessments, except for Case study A, where a fixed recycled unit exists about 17.1 km from the concrete plant.

These distances are illustrated in Fig. 3. The transportation of NA and RA to the concrete plant was considered that is made by 16–32 metric ton lorries, as they are representative for most construction works in Colombia (Spielmann et al., 2007). Larger lorries of >32 metric tonnes were considered for the transportation of cement and SCM from production plant to the concrete plant, in agreement with region-specific practice and literature (Kurda et al., 2018). Note that the influence of waste transportation within the recycling plant were not accounted for in the analysis.

After all constituents are transported to the concrete plant, the last stage (A3) of the "cradle-to-gate" approach involves assessing the impacts related to the production of concrete such as mixing materials (binders, aggregates, water, admixtures) and associated use of energy (e.g. electricity and fuel). Impacts associated with the production stage were determined using the data described in Section 2.5.

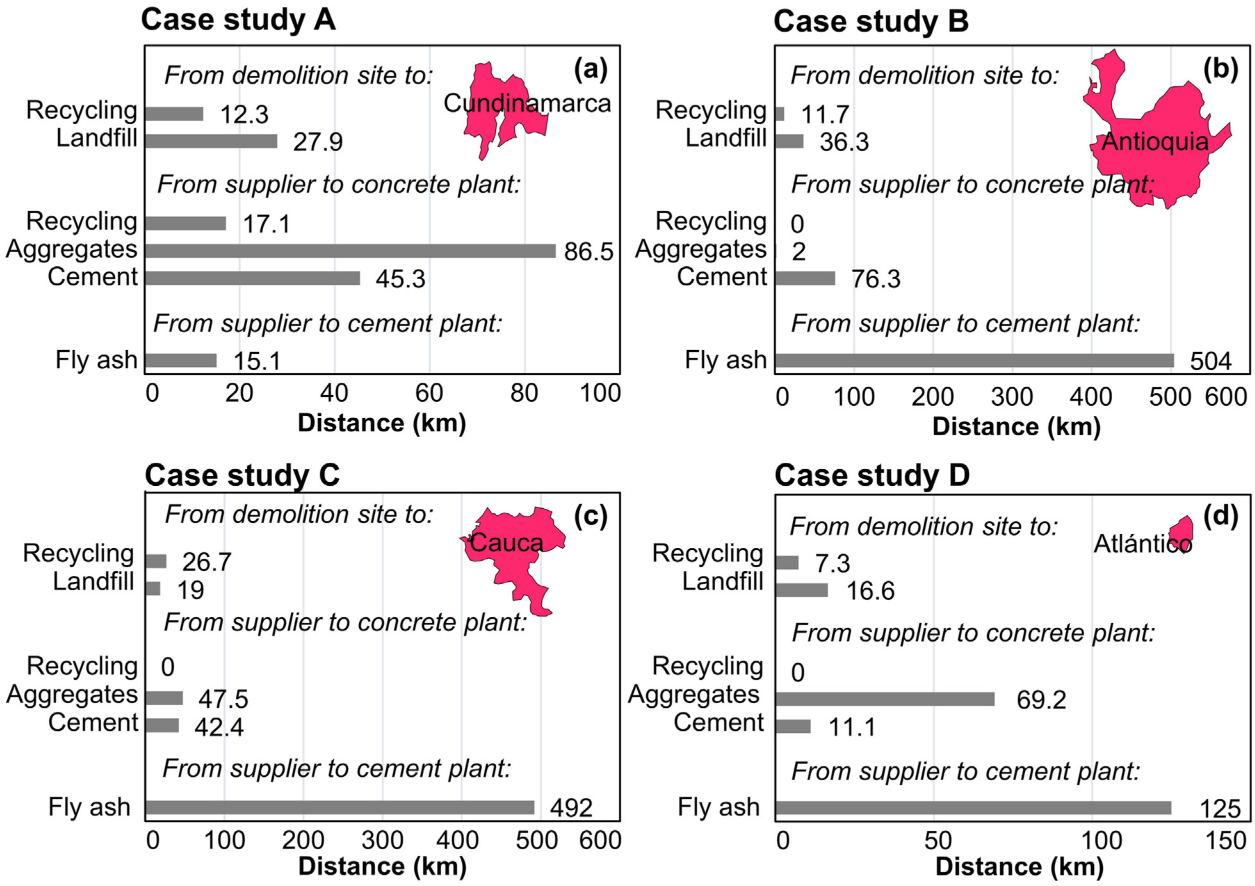

Fig. 3. Transportation distances from suppliers to production plants for (a) Case study A – Cundinamarca; (b) Case study B – Antioquia; (c) Case study C – Cauca; (d) Case study D – Atlántico.

3. Results and discussion

3.1. Concrete constituents

As noted before, the EI assessments in this paper are based on the mix proportions depicted in Table 1. In the first stage, an initial LCA covering stages A1 and A2 was carried out. This assessment focused on the influence of binder and aggregate type on the GWP. Fig. 4a-d illustrates the GWP values obtained for the concrete mixes from Table 1. It is shown that materials incorporating cement only, without any other SCM and incorporating NA have a GWP between 323 and 332 $kgCO_2e$ (mixes C100-S0-RA0). Replacement of 25% of cement with fly ash showed reductions in GWP between 8% and 17%. These reduction ratios are largely similar to other results from literature which indicated that GWP is mainly affected by cement content and that it significantly decreases with the incorporation ratio of fly ash (Tošić et al., 2015; Braga et al., 2017). These differences can be increased when transportation is accounted for (Kurda et al., 2018).

Based on the analysis from this study, the replacement of NA with RA in proportions of 50% and 100% generally increased the carbon emissions ($kgCO_2e$). For 50% replacement of NA for a reference concrete with a relatively high strength, the increase in GWP was around 3.4% (C75-S25-RA0-H-F36 versus C75-S25-RA50-H-F36), whilst for a reference concrete with relatively low strength, this increase was around 0.7% (C75-S25-RA0-L-F29 versus C75-S25-RA50-L-F29). On another note, for 100% replacement of NA with RA, the increase is around 3.7% (C75-S25-RA0-H-F29 versus C75-S25-RA100-H-F29), and 7.3%, respectively (C75-S25-RA0-L-F22 versus C75-S25-RA100-L-F22). As observed, a higher increase in carbon emissions occurs when the replacement ratio for NA by RA is 100% compared with the case of 50% replacement. As mentioned before, RA have an inherent higher water absorption ratio compared with NA. Hence, a concrete mix with higher proportions of RA but the same strength of a corresponding NAC would require a higher amount of water and implicitly cement, or quantity of superplasticiser (González-Fonteboa and Martínez-Abella, 2008). Both the cement and superplasticisers increase EIs (López Gayarre et al., 2016; Nakic, 2018).

3.2. Transportation distances

Case-by-case specific transportation distances of raw materials to a concrete plant, and of the CDW from the city centre to the recycling plant or landfill, were considered herein (Appendix C, Supplementary Data). It is worth noting that the transportation distances between the city centre to landfill and recycling plant were in the same range for all case studies (i.e. city centre to landfill 16.6–36.3 km, and city centre to recycling plant 7.3–26.7 km). Transportation distances for cement and fly ash were highly variable, 11.1–76.3 km, and 15.1–504 km respectively. From the collected database of available suppliers in each region, the supplier located at the shortest distance to the concrete plant was considered. The results in Figs. 5–8, illustrate the GWP in $kgCO_2e$ of the concrete mixes in Table 1 accounting for the distances depicted in Fig. 3.

In the first Case study (A), the transportation distance for NA was 86.5 km, for cement 45.3 km and for fly ash 15.1 km. Results show that for the concrete with cement only and NA (C100-S0-RA0), the increase in GWP due to transportation was on average 10% compared to the case without transportation. The increase in emissions were by 2.7%, 5.8% and 7.4% for Case study B, C and D, respectively. This corresponds to transportation distance for NA of 2 km, 47.5 km and 69.2 km, respectively. Key observations from

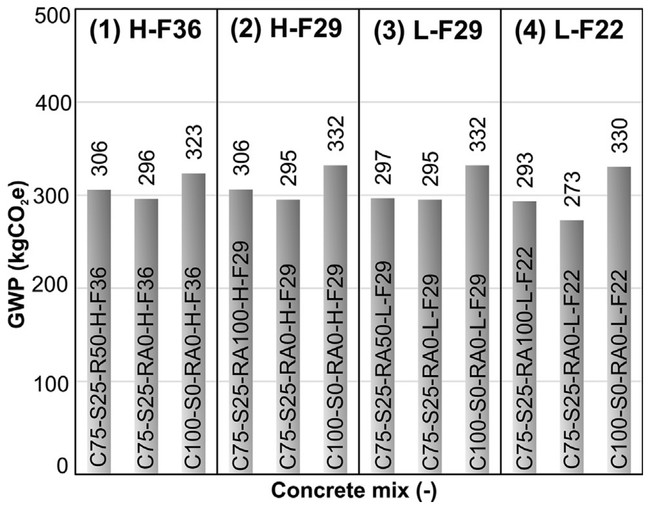

Fig. 4. GWP for investigated mixes without accounting for transportation.

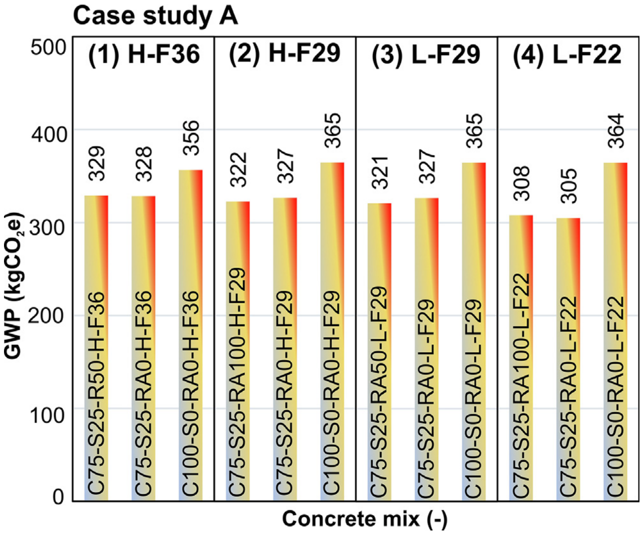

Fig. 5. GWP for Case study A.

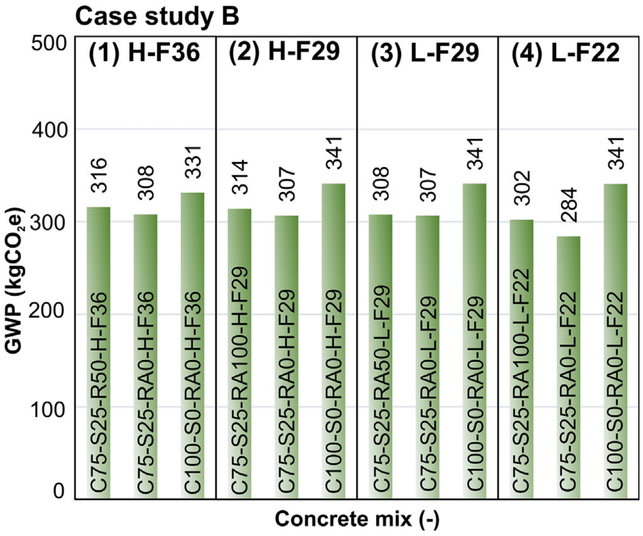

Fig. 6. GWP for Case study B.

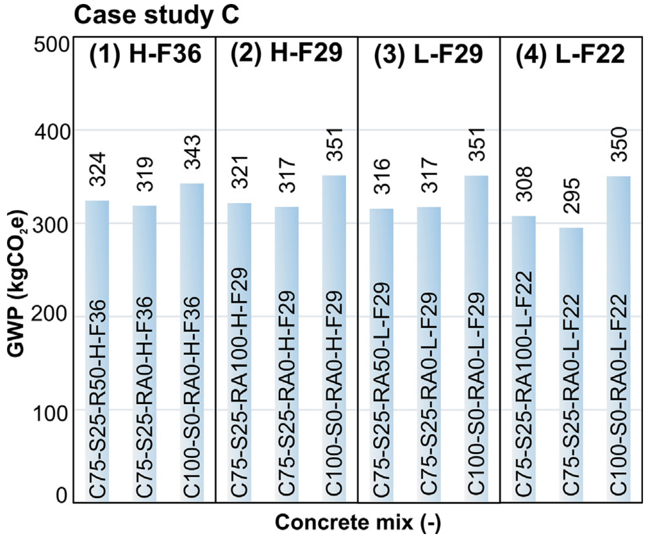

Fig. 7. GWP for Case study C.

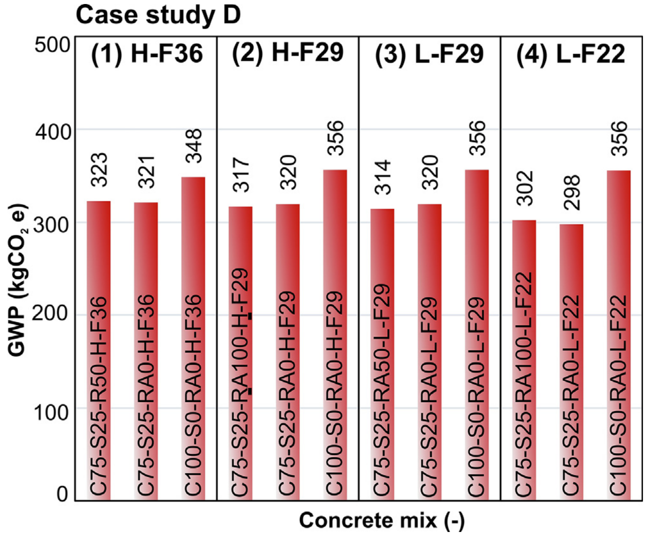

Fig. 8. GWP for Case study D.

this comparison show that there is a proportional increase in GWP with transportation distance of NA.

Based on the analysis from Fig. 4, a 25% replacement of cement by fly ash reduces the GWP by 12.5% on average. Although fly ash and other SCMs have a lower EI than cement, large transportation distances for fly ash (up to 504 km) offset the environmental benefits of using SCMs. Considering the transportation distances from Fig. 3, the increase in GWP values, referring to the relative contribution of transportation to GWP, were sometimes higher for concrete mixes with 25% SCM and NA (C75-S25-RA0), than for the cement only and NAC (C100-S0-RA0). For example, C100-S0-RA0-H-F36 had a GWP of 323 $kgCO_2e$ for the case without transportation and 343 $kgCO_2e$ when the transportation distances for Case study C were considered (the difference is 19 $kgCO_2e$). On the other hand, C75-S25-RA0-H-F36 had 296 $kgCO_2e$ without transportation and 319 $kgCO_2e$ for Case study C transportation distances (the relative contribution of transportation is then 23 $kgCO_2e$). The increase in GWP was 11.0%, 3.9%, 7.7% and 8.5% for Case study A, B, C and D, respectively. These values correspond to fly ash transportation distances of 15.1 km, 504 km, 492 km and 125 km, respectively.

As shown above, the high weight of aggregates requiring transportation compared to other dry concrete constituents has a negative effect on the influence of transportation to GWP. However, when 50% of NA are replaced by RA, the increase in carbon emissions due to transportation, as a relative contribution to the total GWP, is generally lower than when only NA are used. For example, the increase in GWP due to transportation of NA and RA for concrete mixes with 25% SCM (C75-S25-RA50) was 7.8%, 3.5%, 6.2% and 5.7%, for Case study A, B, C and D, respectively. This is lower by 0.4–3.1% than for C75-S25-R0 concrete mixes with NA only. For example, the GWP of C75-S25-RA0-H-F36 was 296 $kgCO_2e$ when transportation distances were not accounted for and 319 kgCO2e for Case study C with transportation distances (23 $kgCO_2e$ difference due to transportation). On the other hand, C75-S25-R50-H-F36 had 306 kgCO2e without transportation and 324 $kgCO_2e$ with transportation for the same case study. Hence, the relative contribution of transportation was 19 $kgCO_2e$. As observed, these relative differences are relatively low and within similar ranges.

As indicated by Figs. 5–8, the environmental benefits of using full replacement of NA with RA in proportions of 100% is higher than for 50% replacement. The increase in GWP due to transportation for C75-S25-RA100 concrete mixes is only by 5.1%, 2.7%, 4.9% and 3.2%, for Case study A, B, C and D, respectively, in comparison to the case without transportation. This is the lowest increase in GWP when transportation of concrete constituents is considered in the analysis. Depending on the transportation distances further optimisations can be made and using RA and SCMs can completely offset the carbon associated with transportation.

The analysis in this paper indicated that 25% replacement of cement by fly ash showed reductions in GWP by 12.5%, on average, in comparison to cement only concrete. This agrees with other studies from the literature that showed that the carbon emissions could be reduced between 17% and 27% (Jiménez et al., 2015; Turk et al., 2015) when cement contains up to 25% fly ash or slag. Even lower emissions can be obtained for higher replacement ratios, yet these are associated with significant reductions in mechanical properties. Due to the relatively high volume that is taken by aggregates in a cubic metre of concrete, this study showed that emissions of RAC are lower than that of NAC, particularly for RA ratios approaching 100%. This is in agreement with other sources from the literature, noting that RAC with 50% RA or above are optimal (Tošić et al., 2015; López Gayarre et al., 2016). The environmental benefits can be enhanced when benefits from recovering the steel from CDW as well as other associated avoided impacts are considered (Knoeri et al., 2013).

In Colombia, the use of CDW to produce RA is still limited and RAC was used for sub-grade applications only (Martinez-Arguelles et al., 2019). The results in this paper, however, show that concrete incorporating RA with strengths required in structural members exist and, they show lower EIs in comparison with conventional concrete. Such materials can be used in civil engineering structures, whilst actively contributing wider sustainability standards, minimise environmental damage, and promote more sustainable waste management.

4. Concluding remarks

This study assessed the environmental impacts (EI)s of recycled aggregate concrete (RAC) and natural aggregate concrete (NAC) for structural applications through life-cycle assessments (LCA). The environmental influence of cement content, aggregate production, transportation, and waste landfilling was analysed using the LCA framework and an associated life-cycle inventory (LCI) largely specific for the region. To obtain a detailed insight in the optimum LCA parameters, a sensitivity study was carried out in which supplementary cementitious materials (SCM), different values of natural-to-recycled aggregate (NA-to-RA) content ratios and case-specific transportation distances, were considered. Based on the results obtained, the following conclusions are drawn.

Carbon emissions, used here as a reference for the global warming potential (GWP) impact category, were between 323 and 332 kgCO_2e for the concrete materials incorporating NA and cement without fly ash. These values can be reduced by up to 17% by replacing 25% of the cement with fly ash. Increased carbon emissions were found when replacing NA with RA in proportions of 50% and 100%, when transportation distances were not considered. However, the concrete with 50% RA shows lower increase, only 0.3% and 3.4% for normal and high strength, respectively.

Moreover, it was shown that relatively large transportation distances of fly ash can potentially offset the environmental benefits of using SCM. The relative contribution of transportation to the total carbon emissions was found to increase in some cases when cement was replaced by fly ash in proportions of 25%, and case-specific transportation distances were considered. It is suggested that higher environmental benefits are obtained when the transportation distances of SCMs would be relatively short and the replacement ratios of the cement by fly ash would be higher than 25%, considering that the obtained material strengths are adequate for practical application In absolute values, the concrete mixes with 100% RA and 25% fly ash had lower carbon emissions than concrete with cement and NA only, but in some cases higher emissions than counterparts with NA and 25% fly ash.

The results in this paper show that RAC with strengths required in structural members can have lower carbon emissions than conventional NAC. In broader terms, the observations presented herein can be used by decision-makers and stakeholders on how the regional construction industry can improve waste management and reduce the pressure on natural resources, while actively contributing to achieving the wider sustainability standards. Note that the observations and results from this paper are limited to the system boundaries considered in the study and associated databases. Further studies would be needed to account for extended system boundaries to investigate the EIs of RAC in reinforced concrete members and structures.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsf.2021.101235.

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