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Towards an eco-efficient ready mix-concrete industry: advances and opportunities. A study of the Metropolitan Region of Buenos Aires

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ABSTRACT

There is a growing demand in Latin America and the Caribbean for building materials to satisfy the need for adequate housing and infrastructure in urban areas. This paper examines the consumption of materials and environmental impact of ready-mix concrete produced in the Metropolitan Region of Buenos Aires in a certain period of time. Material flow analysis and life cycle assessment (LCA) were performed. The average composition concrete was estimated by means of surveys conducted with ready-mix concrete producers. The material efficiency (ME), CO_2 equivalent emissions (ECO_2eq), materials and energy use were used as environmental indicators. Feasible impact reduction strategies and their influence on the LCA were also explored. 7.16 Mt of materials were required to produce 2,604,862 m^3 of ready-mix concrete, within 99.1% corresponded to raw materials, while 0.9% corresponded to secondary raw materials. 5.36 Mt (~78.6%) of the extracted materials belong to aggregate production and they represent ~19.5% of the ECO_2eq. Portland cement is the largest contributor to ECO_2eq and the constituent material with the lowest ME. Using recycled aggregates is the strategy that contributes the most to the reduction of the use of raw materials (~8.9% lower use of raw material by using 20% recycled coarse aggregate), while replacing Portland cement with supplementary cementitious materials (SCM) is the one that reduce the most the ECO_2eq (the use of Portland cement without SCM would increase ECO_2eq by ~13.6%). This research provides a novel approach that quantifies the effect of modifying the concrete mix and replacing raw materials by secondary raw materials, bringing a new understanding to the sustainability of building materials.

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Keywords: ready-mix concrete; material flow analysis (MFA); life cycle assessment (LCA); material efficiency; carbon dioxide emission

List of notations

AAHE	Argentinian Ready-Mix Concrete Association
ASR	Alkali-Silica Reaction
CCA	Crushing Coarse Aggregate
CDW	Construction and Demolition Waste
CFA	Crushing Fine Aggregate
ECO_2eq	CO_2 Equivalent Emissions
FA	Fly Ash
GCCA	Global Cement and Concrete Association
GGBS	Ground Granulated Blast-Furnace Slag
GHG	Greenhouse Gas
ICE database	Inventory of Carbon and Energy database
LA&C	Latin America and the Caribbean
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LF	Limestone Filler
ME	Material Efficiency
MFA	Material Flow Analysis
MRBA	Metropolitan Region of Buenos Aires
NSS	Natural Silica Sand
OECD	Organization for Economic Co-operation and Development
OPC	Ordinary Portland Cement
SCM	Supplementary Cementitious Materials
STAN	subSTance flow ANalysis

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1. INTRODUCTION

Latin America and the Caribbean (LA&C) is a developing region characterized by high economic disparity and climate risk [1]. Worldwide, an estimated 55.3% of the population lives in urban areas, which is higher in LA&C, reaching 80.7%. Likewise, 20% of the urban population lives in megacities and large cities (>5 million inhabitants) [2].

The urban population requires services and mobility that allow people to achieve well-being and promote the sustainable development of cities. The construction of such facilities and housing and the improvement of existing infrastructure lead to a great demand for building materials [2]. According to the OECD [3,4], 82 Gt of non-metallic materials will be consumed by 2060, most of them building materials. In addition, the construction industry is responsible for ~11% of greenhouse gases (GHG), and the renovation, repair, and demolition of structures generates a large amount of waste (CDW) when not properly managed [3,5–8]. However, reducing the consumption of building materials does not currently seem viable and sustainable if access to a modern and reliable built environment is granted to the population [2,9,10]. Hence, the infrastructure to be built from now on should be designed to reduce both material consumption and CO_2 emissions per capita and ensure climate change mitigation for the entire population of the region [1].

The sustainability of the construction industry has received increasing attention from the scientific community for decades and studies have been conducted from different perspectives and employing different methodologies. Numerous research on environmental impact assessment has been carried out based on Life Cycle Assessment (LCA), addressing system boundaries from cradle to different life cycle stages. This is a valuable technique to evaluate the potential environmental impacts of a product system throughout its life cycle from, i.e., raw material acquisition to final disposal (cradle-to-grave) [11]. It provides the means to measure various environmental impacts and compare them between categories, allowing companies to formulate decisions based on the eco-design of their products, process optimization and supply chain management [12,13]. Due to the relevance of CO_2 emissions in cementitious materials, LCA studies have been mainly focused on reducing such emissions of Portland cement [14]. Furthermore, they have addressed the reduction of the environmental impact of Portland cement [4,15–18], concrete production [19–22], or structural elements and reinforced concrete structures [14,23,24].

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Nevertheless, environmental impact assessment methods based on LCA consider only metallic minerals in the "resource scarcity" category, as they consider that the availability of non-metallic minerals is unlimited [25]. This assumption is valid on a global level, yet not on a regional level, especially considering that 93.2% of the building's mass is composed of non-metallic minerals [25,26].

The material flow analysis (MFA) methodology is essential for assessing the construction's industry impact on natural resource scarcity. For this purpose, Reis et al. [10] have studied the MFA of cementitious materials in Brazil, and some studies have been published to quantify the urban stock of materials [27,28]. However, the application of each methodology at a time does not allow a fully comprehensive environmental impact assessment [8,29]. Different research groups have proposed methodologies combining LCA and MFA, especially in circular economy models and urban stock calculation [8,29–31].

For certain products the emissions from materials transportation can be of particular importance [32], Lessard et al. analyzed and optimized the supply chain for cement industry in Canada [33,34] and these analyses will be relevant for ready-mix concrete.

Few qualitative studies overview the reduction of environmental impact on the critical points in the life cycle of the ready-mix concrete in a region [35–37]. However, none of them perform a quantitative analysis to evaluate the effect of applying particular scenarios, employing the combination of LCA and MFA.

This study proposes a methodology based on performing simultaneously material flow analysis and life cycle assessment to perform quantitatively the environmental impact caused by different changes in raw materials source of the regional ready-mix concrete production. This approach can be used to analyze any region, where the necessary data on the production of ready-mix concrete production must to be known. In this work, the analysis was performed on the Metropolitan Region of Buenos Aires (MRBA) as a case study.

2. METHODS

Figure 1 shows the outline of the methodological phases proposed to evaluate the environmental impact of the ready-mix concrete industry by considering the combination of MFA and LCA methods, identifying the system's critical points and assessing quantitatively the effectiveness system of different strategies developed to reduce the environmental impact.

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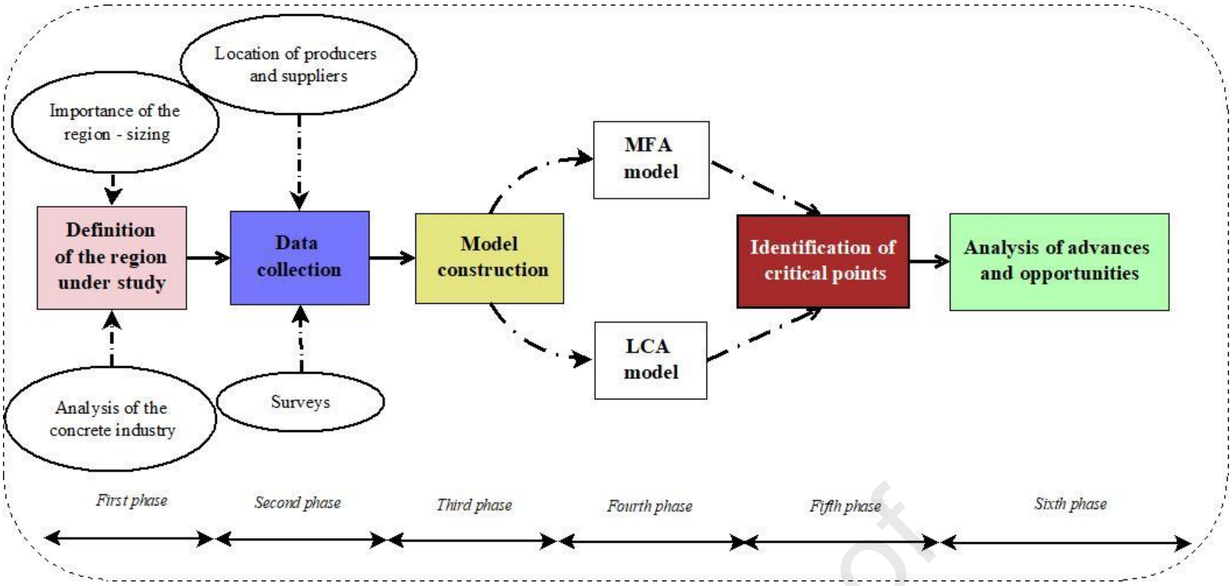

Figure 1: Proposed methodology for the environmental impact assessment of the ready-mix concrete industry.

The *first phase* comprises the definition of the system under study (Section 2.1). It is of utmost relevance for the study, as it illustrates the economic and social importance of the region and comprehends the nature of the ready-mix concrete industry.

The *second phase* involves acquiring of the data needed to perform the MFA and LCA (Sections 2.2 and 3.1). Data on the ready-mix concrete composition and characteristics are gathered through surveys of different ready-mix concrete producers (the survey questionnaire is provided as supplementary data). Considering the heterogeneity of company size and market share of ready-mix concrete producers in the MRBA, it is essential to select the companies to be surveyed thoroughly.

The *third phase* covers the construction of the model for performing the MFA and LCA, based on the data collected in the surveys (materials used, processes involved, inputs, outputs, and processes with their input and output materials).

The *fourth phase* solves the model built in *phase 3* by applying the MFA and LCA methodologies (Sections 2.3, 2.4, 3.2, and 3.3). The MFA quantifies the flow of materials through the product life cycle and LCA performance is required to quantify ECO_2eq and energy use.

The *fifth phase* involves identifying the critical points of the system, by detecting the materials or processes that contribute most to the consumption of raw materials, ECO_2eq, or energy use (Sections 2.5 and 4.1). Several studies [2,4,22–24,31,36,38,10,14–20] examine different strategies to reduce the environmental

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impact, while Portland cement manufacturers and ready-mix concrete producers have introduced diverse solutions that have led to significant reductions in ECO_2eq. However, most analyses are conducted qualitatively or focus applying of one strategy at a time. It is thus imperative to quantify the effect of adopting different initiatives simultaneously and identify which one(s) generates the maximum reduction in environmental impact in raw material consumption, ECO_2eq and energy use. Hence, a comparative LCA for different yardsticks is performed, modifying the concrete component materials.

Finally, the *sixth phase* analyzes the outcome of implementing the different strategies up to date, and examines the potential of adopting the various actions set out by the Global Cement and Concrete Association (GCCA) to achieve net-zero concrete by 2050 (Section 4.3).

The different methodological phases were performed over a case study (the MRBA) to evaluate whether it meets the expected goals.

2.1. Definition of the system under study

92% of the Argentinian population lives in urban areas, and its structure is biased towards large cities [39]. The capital city of Argentina (the Autonomous City of Buenos Aires) is the third-largest city in LA&C [2]. At the same time, the MRBA, which comprises the Autonomous City of Buenos Aires and the 24 most populated districts in the surrounding area, concentrates 31% of the country’s population [39]. It is also one of the most important production and consumption centers in Latin America and concentrates 45% of the economic activity and 50% of the Gross Domestic Product of Argentina [40,41].

According to the Argentinian Ready-Mix Concrete Association (AAHE, by its Spanish acronym), about 47.5% of the ready-mix concrete produced in Argentina was delivered to the MRBA in 2019 [42], and it consumed about 29.5% of the cement dispatched in that period [43].

Therefore, due to the economic and demographic significance of the region, the MRBA was taken as the case of study.

2.2. Data collection on the ready-mix concrete industry

The AAHE is a group of ready-mix concrete producers that provides annual reports on production and industry characteristics. However, not all concrete producers are members, remaining apart some large, medium and small producers. Considering that smaller producers use more limited technology and provide

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a narrower range of concrete qualities, it was decided to survey three of the largest concrete producers in the country, whether or not they were members of the AAHE.

Strength classes of concrete typically marketed, type, amount, and source of component materials (cement, supplementary cementitious materials (SCM), coarse and fine aggregates, admixtures, and water), energy (both electrical and fuel) and the location of the main suppliers of such materials were obtained from the surveys.

Then, the average composition per m^3 of concrete and their corresponding uncertainty, the transportation distance from the component material producer to the MRBA were estimated, and the means of transportation were recorded. The average mixer load and transport distance from the ready-mix concrete plant to the placement site were deemed. Also, information on the waste generated at the plant was requested.

2.3. Material flow analysis (MFA)

MFA allows assessing flows and stocks of materials in a system with a defined time and boundaries [44,45]. The term "materials" refers to goods or substances. The current MFA considering goods, defined as economic units of matter with a positive or negative value was modeled. Air or rainwater has no economic value, with neutral value in the MFA. The system consists of flows and processes. Processes can be defined as a place where transformation by chemical reactions, transport of energy, and mass or storage activities occur. The black-box model is adopted, i.e., detailed information about what is happening inside the process is not available or considered. Only the inputs and outputs are of interest [44].

Freeware STAN (short for subSTance flow ANalysis) was used to construct the MFA. STAN is based on the Austrian Standard ÖNORM S 2096 (Material Flow Analysis - Application in Waste Management) and enables the construction of graphical models using predefined components (processes, flows, system boundaries). By entering or importing known data (mass flows, stocks, concentrations, transfer coefficients) on different layers (good, substance, energy) and periods, it is possible to compute unknown quantities, solving mass and energy balances. The unknown flows can be calculated, and their uncertainties are computed with the error propagation method. The results are presented as Sankey diagrams, then the width of the displayed arrows is proportional to their mass flow values [44].

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Figure 2 shows a simplified material flow processing for ready-mix concrete production in the MRBA. The model was built based on the "goods" layer. It covers raw material and secondary raw material inputs and system outputs from the processes of Portland cement production (CO_2 during clinkerization), stone crushing for aggregate production and ready-mixed concrete mixing (ready-mix concrete and CDW). The Portland cement manufacturing process comprises clinkering and clinker grinding as sub-processes, and includes clinker raw materials, gypsum, limestone filler, natural pozzolan, and granulated blast furnace slag as inputs, and Portland cement and CO_2 as the output of the process. The “Quarries” process covers the crushing and grinding sub-processes and involves granitic or dolomitic stones as inputs and coarse aggregates and crushing sand as outputs. In the ready-mix concrete plant, it is considered the concrete mixing itself and the storage of washing water for future recycling and reuse. In this processes, commercial Portland cements, ground granulated blast furnace slag, limestone filler, fly ash, crushing and river sand, coarse aggregates, tap and rainwater, and chemical admixtures are included as inputs, and the ready-mix concrete and CDW as outputs. The aggregate fractions resulting from quarrying that are not used for ready-mix concrete production, particulate matter, and water loss are not considered as a simplification of the model, as well as domestic and hazardous wastes. On the other hand, the raw material for clinker production is grouped under only one input and the amount of limestone, clays, iron ore and quartz are not quantified individually.

Material Efficiency (ME) is calculated as the mass ratio of the useful material to the raw materials required for its production (Equation 1) [10], where "*Product*" refers to the tons of product produced and "*Raw materials*" corresponds to the tons of raw materials required to produce the "*Product*". The amount of *product* and *raw materials* was determined considering known and calculated data from the MFA.

$$ME = \frac{Product\ (t)}{Raw\ materials\ (t)} \qquad \textit{Eq. 1}$$

Neutral values were assigned to the secondary raw materials (rainwater, fly ash, and GGBS) for the ME calculation, as they do not need treatment or are industrial by-products.

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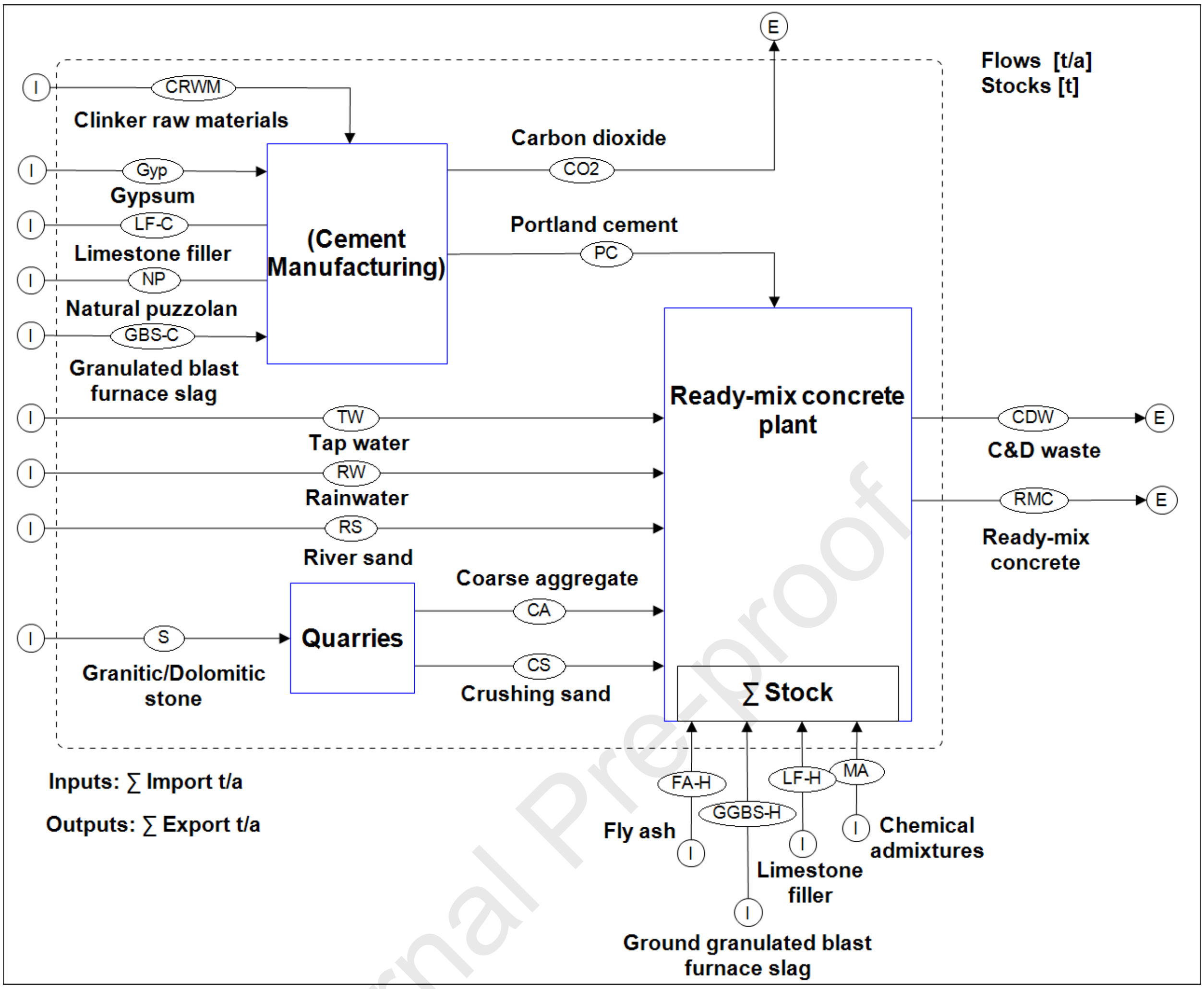

Figure 2: Material flow diagram for concrete processing

2.4. Life cycle assessment (LCA)

LCA comprises four phases:

2.4.1.Goal and scope definition:

This study aims to determine the phases or materials associated with the most significant environmental impact and draw up feasible alternatives to reduce that impact. The functional unit is 2,604,862 m^3 of ready-mix concrete produced in MRBA in 2019. The LCA was carried out from the raw material extraction to the concrete casting site. The extraction and production phases of the different building materials, transportation from the manufacturing site to the ready-mix concrete plant, concrete loading and mixing, and distribution to the casting site were considered. The stages of casting, construction, use and deconstruction/demolition of the structure, and recycling and final

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disposal of concrete were not included. As inputs and outputs of the system, mineral materials, water, fuels, and electricity were considered. However, other materials required for plant operation (like paper and rags) were omitted.

2.4.2.Life cycle inventory (LCI):

The LCI includes energy and transportation of materials from the extraction/production site. Inputs and outputs from the model built in the *third phase* were reproduced in the *OpenLCA* software. OpenLCA is a free, professional LCA and Footprint software with a broad range of functions and available databases, created by GreenDelta. As is an open-source software, its source code is freely available and can be continuously modified.

For this study, the database was generated based on local data because the country's energy matrix differs from that of Europe and transportation is relevant for certain materials. The database was contrasted with the ICE database (Inventory of Carbon and Energy) [46] to validate the local data. In cases in which the data were not available, bibliographical data was consulted.

For this study, clinker kiln dust is not computed as an output, as it is usually returned to the cement production process.

2.4.3.Life cycle impact assessment (LCIA):

LCIA aims to understand and evaluate the magnitude and significance of the potential environmental impacts of a product system throughout its life cycle. In this phase, the most significant impact categories to be evaluated for the product system were set: (i) ECO_2eq, (ii) energy use, and (iii) use of raw materials.

The categories selected for the impact assessment were chosen based on their pertinence to the production of ready-mix concrete and its component materials. As noted, the construction industry is responsible for ~11% of GHG and many LCA studies have focused on analyzing ECO_2eq and mitigation strategies [3,5–8,14]; quantification of raw material use is essential due to the extensive use of non-metallic minerals [3,4,8,10,25,26]; and the production of certain concrete component materials are highly energy intensive [23,25], so it is crucial to quantify and identify hotspots of energy use in the study.

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A customized method for impact determination was created since traditional methods do not account for non-metallic mineral materials in the "resource scarcity" category [8,25,26].

ECO_2eq was calculated considering the Intergovernmental Panel on Climate Change (IPCC) equation [47] (Eq. 2), where CO_2eq are CO_2 equivalent emissions, CO_2, CH_4 and N_2O correspond to the amount of carbon dioxide, methane gas and nitrous oxide emitted during the process under study.

$$CO_2eq\ [kg] = CO_2[kg] + 25 * CH_4 + 298 * N_2O \qquad \text{Eq. 2}$$

The resulting emission factors are presented in Table 1.

Table 1. Emission factors of concrete compound materials

Material	**kg CO_2 e/t**
Ordinary Portland Cement (OPC)	912
Crushing coarse aggregate (CCA)	46
Crushing fine aggregate (CFA)	46
Natural silica sand (NSS)*	14
Limestone filler (LF)**	35
Granulated blast furnace slag (GBFS)**	47
Fly ash (FA)**	35
Tap water***	9
Reinforcing steel*	1990

Value taken from *[48], **[46], ***[49]

The input energy consumption database was provided as MJ or GJ per ton of material, with the exception of the fuel consumption of the mixers during transport from the ready-mix concrete plant to the placement site. Then, a factor of 1 GJ/GJ or 35.94 GJ/m^3 of diesel [50] was considered for the impact measurement in the "energy use" category.

For the "raw material" category, a value of 1 t per t of raw material and a null value (0) for secondary raw materials was adopted.

2.4.4. Life cycle interpretation:

The results of the LCIA and the impact assessment concerning the goal and scope of the study were evaluated and, the points of the product system that could be improved were established.

2.5. Yardstick definition:

Despite the large environmental impact caused by the construction industry, specific strategies have already been implemented to reduce it. Nevertheless, it is necessary to establish further measures that can be taken in the short to medium term that lead to meeting the Net Zero Concrete target by 2050. Therefore, yardsticks to quantify the environmental impact reduction due to the change in the concrete composition or materials source were established. Yardsticks were considered as facts by which the success of modifying the source of raw materials can be judged. To quantify the reduction of environmental impact, the LCA of concretes containing materials from different sources were performed. The functional unit is 1 m^3 of ready-mix concrete. The concrete proportioning was unchanged, as well as the mixing energy and the average transport distance to the casting site. Only the source of the raw materials (e.g., Portland cement with and without SCM, natural and recycled aggregates, tap and rainwater) and the transportation distance from the production site to the ready-mix concrete plant were modified. Then, the LCAs were compared and the outcome of material replacement in the different impact categories was analyzed.

3. RESULTS

The data gathered from the ready-mix concrete producer surveys and the results obtained from the MFA and the LCA are presented below.

3.1. Characterization of ready-mix concrete produced in MRBA

According to the AAHE, 2,604,862 m^3 of concrete was produced in 2019 in the MRBA [42]. The strength classes produced are between H8 to H110 (compressive strength between 8 and 110 MPa at 28 days). Structural concretes H30/H35 are the most representative (50.8%). H17/H25 and H38/H55 concretes represent 15.2 and 26.8% of the market share, respectively, while the lowest (H8/H15) and the highest (H60/H80/H110) strength classes are the least representatives (6.6 and 0.6%, respectively).

Figure 3 illustrates the map generated with the free software QGIS that shows the districts comprising the MRBA, the location of the suppliers, and the commonly used routes for material transportation. The green dots correspond to the districts that comprise the MRBA, and the blue dots to the suppliers considered for the study. The red lines represent the roadways, and the green line represents the railway.

The cement types used in 2019 were: ordinary Portland cement (similar to CEM I of EN 197-1 standard), compound Portland cement (CEM V/A), limestone Portland cement (CEM II/A-LL), and to a minor extent, blast-furnace cement (CEM III/A) and pozzolanic Portland cement (CEM IV/A) representing 47.3, 30.9, 20.0, 1.0 and 0.9% of the market, respectively. SCM are generally included in the cement, although ground granulated blast-furnace slag (GGBS), limestone filler (LF) and fly ash (FA), have been incorporated in

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concrete mixing plant to produce some special concretes. A transport distance of 236 km for the FA (the path by road from San Nicolás district to MRBA), 147 km for the GGBS (the average roadway distance from the districts of Ramallo and Campana to MRBA), and a bimodal transport for the LF (~331 km by train and ~63 km by truck) was adopted.

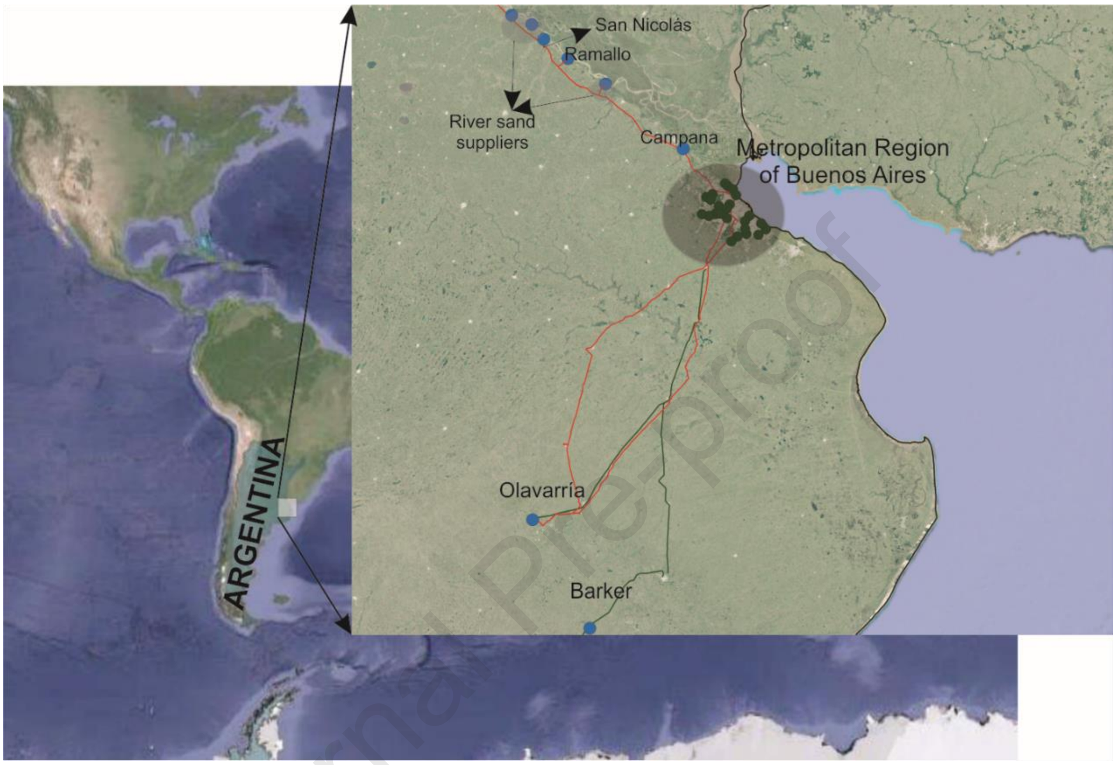

Figure 3: Map of the MRBA and location of suppliers, roadways and railway.

Natural aggregates are mainly used as coarse and fine aggregate. Granitic (82.7%) and dolomitic (17.3%) rocks are used as coarse aggregate. In the MRBA, crushing aggregates come from quarries located in the district of Olavarría, province of Buenos Aires. The transportation is mainly by truck (~355 km) and, to a lesser extent, by bimodal transport (~307 km by train and ~63 km by truck). Regarding the transportation distance of natural coarse aggregates, recycled coarse aggregates emerge as a promising alternative in the MRBA. For this reason, the use of recycled coarse aggregate has recently grown after the standardization, and it is estimated that in 2019 recycled aggregates represented 6.3% of the total coarse aggregates. The national standard IRAM 1531:2016 allows replacing up to 20% of natural aggregate with recycled aggregate, so an increase in replacement is projected for the future.

As fine aggregates, mostly river sand is used (~90.1%), with a smaller proportion of crushing sand (~9.9%). River sand generally has a low fineness modulus, completing the large particle sizes with crushing sand.

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The river sand comes from the northern area of the province of Buenos Aires or the southern area of the province of Santa Fe. Transportation is by truck, and a transport distance of 170 km was adopted. The crushing sand comes from quarries located in Olavarría. Therefore, the same means of transport as the coarse natural aggregates were adopted.

Tap water and rainwater are used for concrete mixing and washing the mixers. The washing water is recycled entirely for further use as washing/mixing water. An estimated 0.343 m^3 of water/m^3 of concrete is used in the ready-mix concrete plant. Referring to mixing water, 0.143 m^3 is required per m^3 of concrete produced and 0.200 m^3 of water per m^3 of concrete for washing the mixers [51]. About 15.8% of the water is collected from rainwater.

Different chemical admixtures are used, namely water-reducing admixtures, superplasticizers, and slump retention.

The use of 1.90 MWh/m^3 of concrete and 3.16 l of diesel/m^3 of concrete was estimated. Likewise, the average mixer load at 7.6 m^3 and the average transport distance at 11.27 km were estimated. It means about 342,745 runs and 3,861,595 km driven by the mixers in 2019.

The ready-mix concrete producers classify waste as similar to domestic, hazardous (including rags contaminated with fuel and oil), and CDW. Producers recycle the CDW themselves, and appropriate agencies collect domestic and hazardous wastes from the plants.

3.2. Material flow analysis of ready-mix concrete in MRBA

Figure 4 shows the MFA of the ready-mix concrete produced in MRBA in 2019. The production of 2,604,862 m^3 of ready-mix concrete corresponds to 6,664,434 ± 583,645 t of concrete and requires 7,156,871 ± 595,383 t of raw and secondary raw materials. Among these ~7 Mt, 6,818,281 ± 529,637 t (~95.3%) are minerals, and 410,912 ± 65,746 t (~4.7%) correspond to water. Meanwhile, ~78.6% of the minerals corresponds to aggregate production or extraction, and ~21.4% to cement and SCM production. 52,317 ± 23,990 t of CDW are generated at the ready-mix concrete plant. The 46,276 ± 88,139 t stocked in the ready-mix concrete plant corresponds to the washing water stored for recycling and subsequent reuse.

The production of 944,861 ± 109,368 t of the different types of cement required 1,338,705 ± 291,519 t of raw and secondary raw materials. 393,844 ± 68,624 t of CO_2 are released during cement production due to

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the decarbonation of limestone, i.e., the chemical reaction that occurs during clinkerization, whereby the limestone ($CaCO_3$) is decomposed into CaO and CO_2 [48].

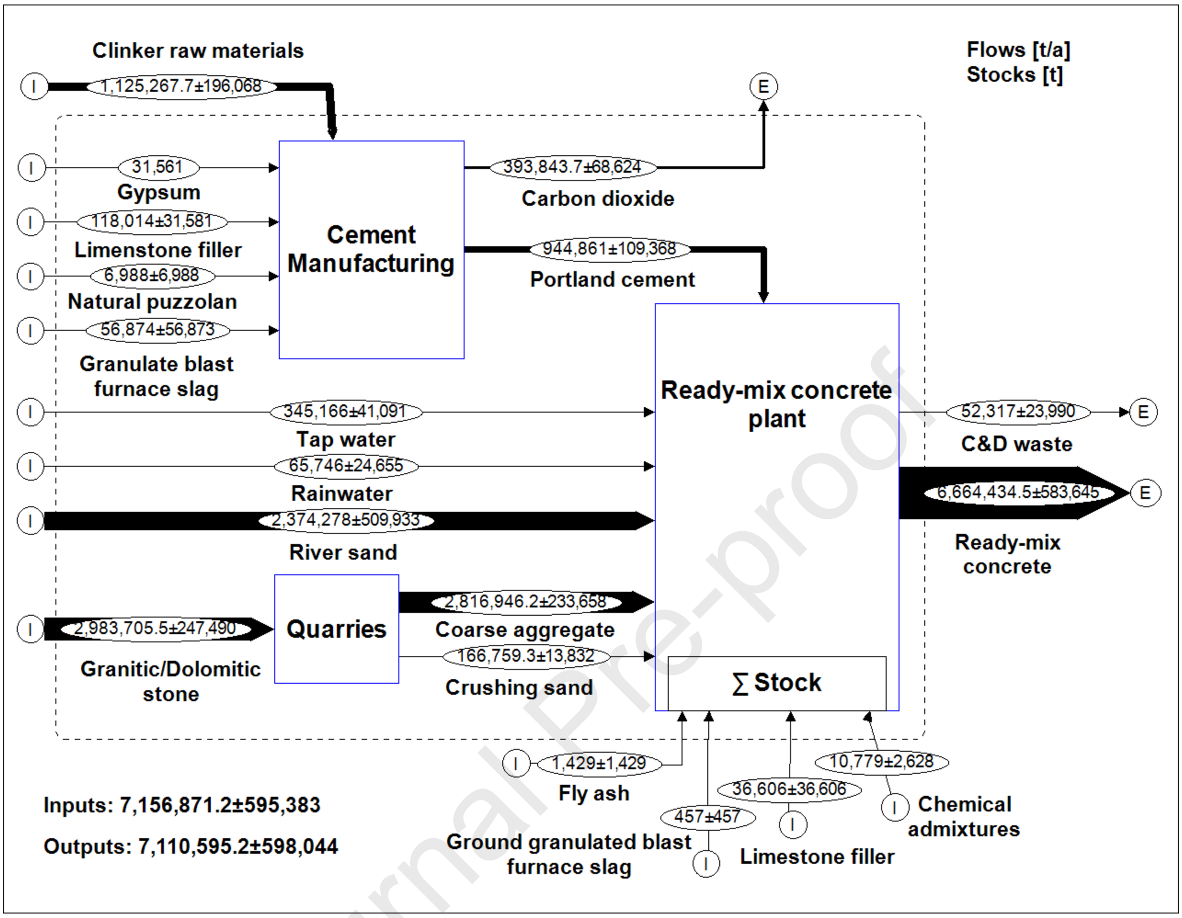

Figure 4: Material flow analysis of ready-mix concrete in MRBA

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The production of 2,604,862 m^3 of ready-mix concrete requires 2,816,946 ± 233,648 t of coarse aggregate and 166,759 ± 13,832 t of crushing sand. However, the fractions of stone that are used by other industries [52] or accumulate in the quarries as waste (i.e., dust, very fine sands, large rocks) are omitted in this study and provide a smaller value of raw material use. Based on estimations from local quarrying production, 1.35 t of stone is extracted to produce 1 t of coarse aggregate. Therefore, 3,802,877 ± 315,438 t of raw materials would be required to produce 2,816,946 ± 233,648 t of coarse aggregates, giving a difference of about 1 Mt between the use of raw material calculated in STAN (2,983,705 ± 247,490 t) and the theoretical estimation.

The calculated ME for the ready-mix concrete is 0.93, for cement 0.71, and for coarse aggregate is 0.78. The low ME of cement is due to the limestone decarbonation. The relatively low ME of the crushing aggregate is due to those fractions not being used in concrete and directed to other industries. Finally, the

ME of concrete is reduced by using low ME materials, the generation of CDW, and the large amount of washing water involved.

For the production of ready-mix concrete, only 0.74% of the inputs are secondary raw materials, and 99.26% are raw materials. 41.7% of the raw materials correspond to crushing aggregate production, and 33.2% to river sand. Therefore, reducing the consumption of raw materials would be possible by replacing crushing coarse aggregates with recycled coarse aggregates from the CDW. The 20% of replacement of natural coarse aggregates by recycled aggregates allow to reduce from 99.26 to 91.31% the use of raw material for the ready-mix concrete production. For the production of the different types of cements, ~95.8% corresponds to raw materials and ~4.2% to secondary raw materials. It has been proven that replacing ordinary Portland cement (OPC) by up to 25% of ground ceramic waste and ground glass allows for obtaining concrete of equivalent performance to OPC concrete without compromising mechanical strength and durability [53,54].

Therefore, the material efficiency of concrete could be increased, and the use of raw materials could be reduced by using secondary raw materials.

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3.3. Life cycle assessment of ready-mix concrete in MRBA

Figure 5 shows the input and output flows to the system corresponding to the LCI. Transportation of materials is significant in the life cycle inventory of MRBA due to the high quantity of materials to be transported and the long transport distances from the extraction/production site to the ready-mix concrete plant.

Due to the limited information on the materials and manufacturing process of the chemical admixtures, they are only considered a concrete constituent material. Transportation from the acquisition site to the ready-mix concrete plant was not considered.

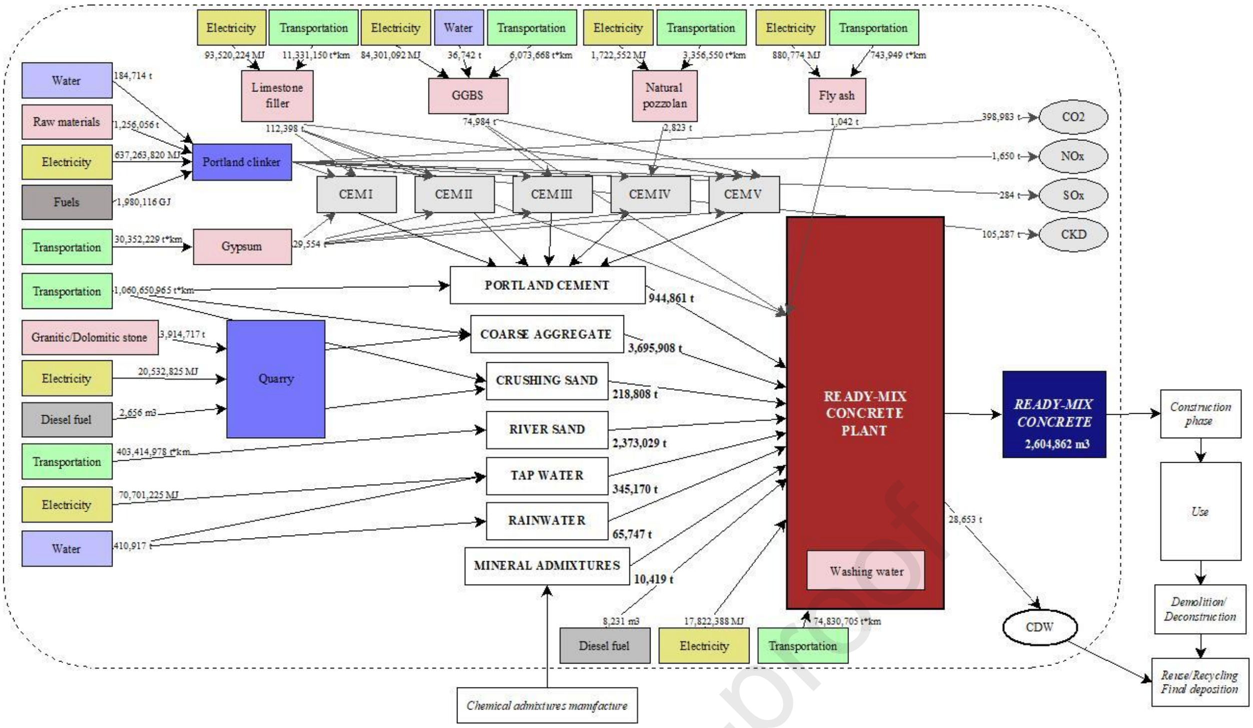

Figure 5: Life cycle inventory of the ready-mix concrete

Table 2 shows the ECO$_2$eq and the use of materials and energy of the ready-mix concrete produced in 2019 in the MRBA.

Table 2. Impact analysis of ready-mix concrete in MRBA in 2019

	ECO$_2$eq *t*	**Energy use** *GJ*	**Use of raw materials** *Mt*
Concrete mixing	22,726	17,822	-
Chemical admixtures	17,400	-	0.01
Water	3,720	89,637	0.52
Crushing aggregate	116,839	115,762	3.91
River sand	50,140	2,819	2.37
Cementitious materials	618,520	2,797,804	1.59
TOTAL	**829,346**	**3,023,845**	**8.41**

Regarding the ECO$_2$eq, 74.6% is associated with Portland cement and SCM production. Meanwhile, 64.5% of the ECO$_2$eq of cement and SCM correspond to the release of CO$_2$ from the limestone decarbonation, 29.8% to the combustion of fuels in the clinker kiln, 5.5% to the use of electricity, and 0.2% to the transportation of the material. The aggregate production/extraction represents 20.1% of the ECO$_2$eq. For crushing aggregates, 96.4% of the ECO$_2$eq is due to transportation from the quarry to the MRBA and only 3.6% to extraction, crushing, and transportation operations within the plant. For river sand, less than 1% corresponds to extraction operations, with transportation being the largest contributor to ECO$_2$eq. The

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remaining ECO_2eq are related to the concrete mixing and transportation from the ready-mix concrete plant to the casting site (2.7%), the mineral admixtures production (2.1%), and water treatment (0.4%).

The production of concrete compound materials and the concrete mixing and transport of 2,604,862 m^3 of ready-mix concrete required 3,023,845 GJ of energy. 92.5% of the energy used corresponds to Portland cement and SCM production, 3.9% to the aggregate production, 3.0% to the water treatment, and 0.6% to the concrete mixing and transport from the concrete plant to the casting site. Of the energy consumed in Portland cement production, 24.3% corresponds to electrical energy and 75.7% to the fuels burned in the kiln, which is the process with the highest energy intensity due to the high clinkerization temperature (~1450 °C).

8.41 Mt of raw material were required to produce 2,604,862 m^3 of ready-mix concrete in MRBA. 74.1% of the materials correspond to the production/extraction of aggregates (46.1% to crushing aggregates and 28.0% to river sand), and 19.7% to Portland cement and SCM production. The use of raw materials for aggregate production is predominant since it is the material that represents the largest mass of concrete [25,26]. On the other hand, to produce 962,340 t of cementitious material, 1,400,831 t of raw materials were required (Figure 5). Thus, the material efficiency was 0.69, attributed mainly to the decarbonation of limestone in the kiln. Based on this assessment, the method for estimating the use of raw materials created in OpenLCA yields values similar to those estimated in the MFA. Therefore, it would be applicable in other LCAs without the need to perform the MFA simultaneously.

4. DISCUSSION

The production of Portland clinker is the largest contributor to energy use and GHG emissions of concrete [4,8,17,55,56]. The cement industry’s leeway to reduce de ECO_2eq is limited due to the chemical nature of the clinkerization process at the cement plant, making the partial replacement of Portland clinker by SCM one of the most widespread strategies [17]. However, this approach can lead to lower mechanical strength and can affect the durability of the concrete [36]. Low mechanical strength increases the volume of concrete required and eventually generates a higher environmental impact [14,57]. The reduction in durability drives a larger use of materials for structural maintenance and repair or a higher renovations rate of the structures, increasing the environmental impact [17,58]. Consequently, the use of SCM should be studied with a

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comprehensive approach from different standpoints, since attempting only to decrease ECO_2eq per ton of material might increase the environmental impact at further stages of the structure's life cycle.

Besides that, different efforts can be made to reduce the environmental impact concerning the consumption of raw materials associated with aggregates and the ECO_2eq attending to the large transportation distance (350-400 km) to MRBA. Therefore, reducing the transportation distance or the amount of material transported would reduce the environmental impact of this constituent material. It is possible to obtain H30/35 concrete (the strength class mostly traded in the MRBA) using up to 20% of recycled aggregates, without affecting the properties of the fresh state and durability [59,60], making the use of this secondary raw material an attractive alternative for the region. However, it may also mean a higher cement content to maintain the mechanical and durable properties of the concrete [21,36], counterbalancing the positive effect of the use of recycled materials. Therefore, the LCA of concretes with recycled aggregates should be analyzed considering the constituent materials and the supply chain to avoid reducing the impact at one point in the life cycle but increasing it at further stages.

The CDW in the city of Madrid is mainly composed of ceramic materials (54% by weight) [61]. The CDW composition is similar in different cities in Argentina [62–64]. In a study carried out by the authors [65], it would be possible to obtain between 80 and 100 thousand tons of ceramic waste per year to be used as SCM in the Autonomous City of Buenos Aires. Therefore, MRBA could also provide an artificial SCM from the urban quarry, reducing concrete ECO_2eq and reducing the impact of transportation on a share of the Portland cement consumed.

4.1. Yardstick analysis

Yardsticks to quantify the environmental impact reduction due to the change in the concrete composition or materials source were established:

- *Yardstick 1 (YS1)*: no SCM are used, and the washing water is not recycled for reuse, either as mixing or washing water. 100% of the water is taken from the mains.
- *Yardstick 2 (YS2)*: no SCM are used. The washing water is 100% recycled and reused for further mixing and washing. Therefore, 0.343 m^3 of water/m^3 of concrete at the ready-mix concrete plant were estimated. 100% of the water is taken from the mains.

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- *Yardstick 3 (YS3)*: no SCM are used. The washing water is 100% recycled and reused as mixing water. 16% of the water is collected from the rains, and 84% is taken from the mains.
- *Yardstick 4 (YS4)*: this is equivalent to the current situation: clinker factor of ~0.82, 0.200 m^3 of water/m^3 of concrete at the ready-mix concrete plant, and 16% of the water collected from rainwater.
- *Yardstick 5 (YS5)*: *YS4* plus replacing 20% of natural coarse aggregate by recycled coarse aggregate.
- *Yardstick 6 (YS6)*: *YS5* plus replacing 50% of the OPC with a blended cement containing 25% ground ceramic waste as a partial replacement of Portland cement, reducing the clinker factor from ~0.82 to ~0.77.
- *Yardstick 7 (YS*7): *YS6* plus reducing the w/b ratio to 0.35.

Figure 6 shows the ready-mix concrete LCA results for each studied *yardstick*. ECO_2eq and energy use are intimately related (Fig. 6a and b). The main contributor to those impact categories is the production of the cementitious material due to the highly intensive use of energy in the clinker kiln.

For concrete without SCM (*YS1*, *YS2,* and *YS3*), the ECO_2eq would be ~13.6% higher than in the current situation (*YS4*). Meanwhile, without the implemented improvements to date, the use of raw materials (Fig. 6c) would be 5.3% higher (*YS1* vs. *YS5*). Recycling 100% of the washing water (*YS2*) only reduces ECO_2eq (Fig. 6a) by 0.4% and using 16% rainwater (*YS3*), 0.1%. However, it reduces the use of raw materials by ~3.2% (Fig. 6c). Replacing 20% of the crushing coarse aggregates with recycled coarse aggregates (*YS5*) reduces only 2.5% of the ECO_2eq (Fig. 6a), despite the significant reduction of the transport distance. Nonetheless, the most significant impact is recorded in the use of raw material, which would be about 8.9% lower than in the current situation (Fig. 6c). Replacing 50% of the OPC with a blended cement using powder ceramic waste (*YS6*) allows a further 4.0% reduction in ECO_2eq per m^3 of concrete (Fig. 6a), as it simultaneously reduces the emissions from cement production and OPC transportation to the MRBA and 1.1% of the use of raw materials (Fig. 6c). The reduction of the *w/b* ratio (*YS7*) modifies neither the ECO_2eq nor the use of raw material (Fig. 6a and 6c) since more water is used for washing than for mixing. However, varying the mix proportions could maintain the *w/b* ratio and simultaneously reduce the water and cement content of the mix, potentially having a more significant effect on this impact category.

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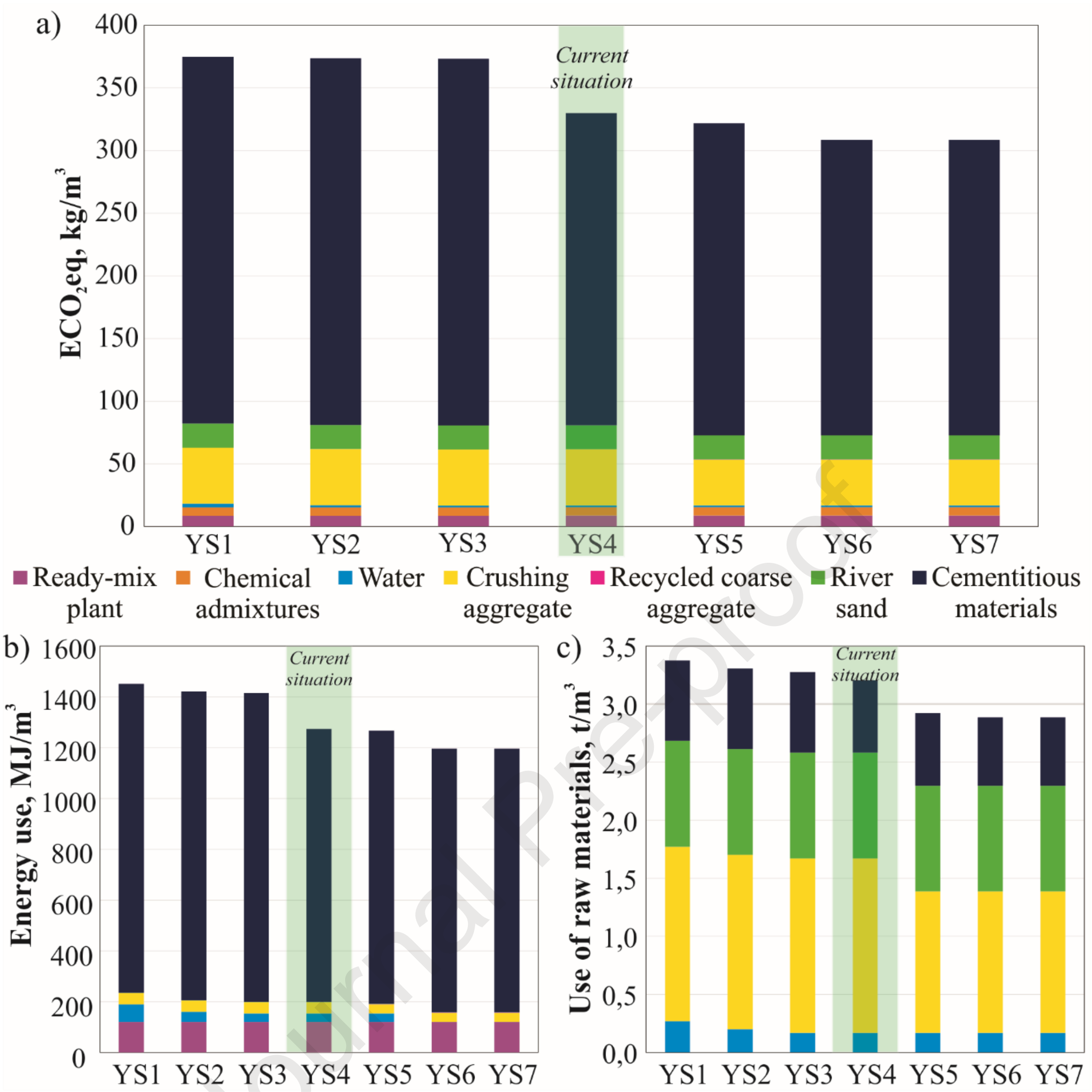

Figure 6: Life cycle impact assessment of ready-mix concrete yardsticks

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4.2. Limitations of the study

This study examines ready-mix concrete purely in terms of its composition, yet the effects of technical specification adjustments are not evaluated. In addition, the study excludes stages after the arrival of the mixer on-site (casting, use, maintenance, dismantling/demolition), thus, workability (ease of casting), finishing, durability, thermal properties, and other concrete properties are not assessed.

It is expected that a holistic evaluation of concrete as a building material could be conducted in further research, including a broader spectrum of decision-makers. The design and optimization of the supply chain of ready-mix concrete plants is desirable to reduce the economic costs and environmental impacts associated with the material transportation, to obtain concrete of high strength and good durability

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properties with the lowest environmental impact, and it will be an important step to achieve the goal of Net Zero Concrete by 2050.

4.3. Opportunities for the construction industry to achieve Net-zero emissions

The most significant savings in emissions and energy use are obtained from a material composition standpoint by reducing the clinker factor. Nevertheless, according to the GCCA [37], to achieve Net-zero concrete emissions by 2050, only 9% can be reduced by modifying the binder composition.

Furthermore, based on this roadmap drawn up by the GCCA, it would be possible to reduce 22% of the global CO_2 associated with concrete by enhancing efficiency in design and construction, 11% by increasing efficiency in concrete production, 6% by absorbing CO_2 through carbonation of structures, 11% by improving thermal efficiency and using alternative fuels in the cement plant and 5% by decarbonizing electric power. The remaining 36% of emissions should be reduced by capturing and storing CO_2 in the cement plants [37]. The capture and storing of CO_2 lead to an increase in the cement price and reduces the prospects of a better quality life for the population of developing countries such as Argentina. On the other hand, Argentina consumes natural gas as a large fraction of the fuels burned in the clinker kilns. Hence, replacing traditional fuels with alternative ones might not necessarily reduce ECO_2 from Portland clinker production.

Depending on the intervention level, different decision-makers and stakeholders are engaged, and it is often challenging to implement diverse strategies due to the industry's fragmentation [4,66]. Considering the opportunities for the construction industry worldwide and their feasibility for the MRBA, Table 3 summarizes the potential environmental impact mitigation strategies to achieve the Sustainable Development Goals by 2050, the stakeholders involved, and the policy implementation difficulty in five central points.

In the MRBA, SCM available are limited. Electric power produced in thermal carbon plants is minimal, most of the steel is produced from scrap, and natural pozzolans (volcanic glasses or zeolites) are found in deposits too far, which discourages their use due to the costs of transporting them. However, it is possible to use other types of SCM, such as calcined common brick clays [67], powder ceramic waste [54], dolomitic filler [68], CDW fines [69] or waste glass powder [70]. Modifying the binder composition (Strategy 1 in Table 3) is expected to reduce up to 9% of the GHG associated with concrete production. The Argentinean

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code for concrete design and calculation (CIRSOC 201) allows setting a concrete age of compliance longer than 28 days. However, building designers' guidelines and tender documents usually specify the age of concrete conformity at 28 days. It may limit the use of concrete with blended cements, requiring the intervention of the policy makers to encourage the conformity age extension when the building features admit it.

By enhancing efficiency in design and construction (Strategy 2 in Table 3), it would be possible to reduce up to 22% of GHG [37]. A distinction can be made between changes in the design of the concrete component materials and the properties of the concrete. The use of non-traditional materials as concrete constituents may be considered among the design upgrades.

The use of recycled aggregates is fairly widespread in the world. Specific analysis shall be performed when using large volumes of recycled aggregates. Furthermore, policy adjustments are needed to allow for a higher percentage of replacement and foster the use of recycled aggregates.

According to the *YS7*, reducing the *w/b* ratio does not have the expected impact of reducing the use of raw materials since the water use is governed mostly by the amount of water needed for washing. A possible approach to reduce the impact of water use might be to acquire it from "non-traditional sources" (e.g., gray water, industrial wastewater). In Argentina, water is usually obtained from the public water supply system, which means that 8.5 kg of ECO_2eq/m^3 of water [49] are associated due to the treatment it receives for its suitability for human consumption. Therefore, using water from other sources could reduce ECO_2eq and the use of raw materials. However, depending on the impurities present in the "non-traditional source" water, the fresh and hardened properties may be compromised [71,72], and water quality should be regularly monitored.

By increasing the mechanical strength of concrete, the volume of the structural elements is reduced, which leads to lower environmental impact due to the reduction of the volume of materials used and the lowering of ECO_2eq. The production of higher-strength concrete usually requires a higher cement content per m^3, yet the reduction in the volume of the structural element outweighs the increased cement requirement [73,74]. Therefore, promoting the use of higher-strength concrete would contribute to reducing the environmental impact.

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Table 3. Environmental impact mitigation of the potential strategies in the MRBA construction industry

Strategy	Level of action	Stakeholder	Expected impact	Considerations
(1) Use of SCM	Cement	Cement industry, concrete manufacturer	Reduction of GHG emissions and energy usage, material efficiency improvement	⸙⸙⸙ ※※※ ~ Could be limited by the regional availability of resources ~ Could increase the volume of materials required ~ May require lengthening the age of concrete conformity
(2) Use of recycled aggregates	Concrete	Concrete manufacturer, Policy makers, Demolition companies	Reduction of GHG related to transportation and new material extraction	⸙⸙ ※※※ ~ Could be limited by the type and quality of CDW ~ May require increasing the cement content per m^3 to maintain mechanical and durability properties
(2) Non-traditional water sources	Concrete	Concrete manufacturer	Improvement of the material efficiency of concrete	⸙ ※※※ ~ May be limited by the physicochemical properties of water ~ May affect the setting time, strength and durability of concrete
(2) Reduction of *w/b* ratio	Concrete	Concrete manufacturer	Reduction of raw materials used	⸙ ※ ~ May require higher control in concrete casting
(2) Increase the compressive strength of concrete	Concrete	Building designer, Concrete manufacturer	Reduction of GHG, Reduction of new material extraction	⸙⸙⸙⸙ ※ ~ May be limited by the regional availability of materials ~ May require higher control in concrete casting and curing
(2) Improve the durability properties of concrete	Concrete	Concrete manufacturer	Increased service life of the structure, Reduction the rate of repair and renovation of structures	⸙⸙ ※ ~ May be limited by the regional availability of materials ~ May require higher control in concrete casting and curing ~ May increase the maintenance costs
(2) Improve the concrete and structure design	Concrete, Buildings	Concrete manufacturer, Building designer	Reduce the energy usage for heating and refrigeration during the service life of the structure	⸙⸙ ※※※ ~ May be limited by the regional availability of materials ~ May require more strict policies for new buildings ~ May require higher control in concrete casting and curing
(3) Promote the use of ready-mix concrete instead of “in-situ” concrete	Concrete	Policy makers	Reduction GHG by using alternative and low-energy materials	⸙⸙ ※※※※ ~ May require government investment to foster the use of ready-mix concrete ~ Requires a cultural change in the informal building sector
(4) Promote re-carbonation of concrete and cementitious materials	Concrete	Concrete manufacturer, Building designers, Demolition companies	Reduce the net-GHG of concrete industry by recapturing CO_2 due to concrete carbonation	⸙⸙⸙ ※ ~ May be reduced by the use of coatings and coverings on structures ~ May be increased in CDW, by increasing the exposed surface of concrete
(5) Change in the transportation system	Composite materials	Governments	Reduction of GHG related to transportation	⸙ ※※※※※ ~ May face resistance from a certain sector of society ~ Requires high investment by the public sector
(5) Shift in the energy matrix towards renewable energies	Composite materials, Buildings	Governments	Reduction of GHG related to building and use stages	⸙ ※※※※※ ~ Requires high investment by the public sector ~ Reduces minimally GHG associated to the manufacture of materials

⸙ Environmental impact reduction expected ※ Difficulties in implementation related to regulation

Improving the durable properties of concrete extends the service life of structures and reduces their maintenance, repair, and renovation costs [36,58]. The concrete durability improvement might be challenging to quantify in LCA performed up to the construction site gate (such as the one performed in the present study), as it involves the time extension of the building and the consequent reduction in CDW generation in the same period of time, as well as the lower amount of materials used for repair and maintenance. Therefore, to assess the impact of changing such concrete properties would require a complete LCA formulation, from cradle-to-grave/cradle-to-cradle. However, it is likely that the durability of the material has a significant influence on the environmental impact. The MRBA exposure environment is moderately aggressive since there are no sulfates or magnesium in the soil or water, nor chlorides in the environment, as the shoreline of the City of Buenos Aires is on the Río de la Plata. Consequently, the durability problems to be addressed are primarily due to carbonation and alkali-silica reaction (ASR) when reactive aggregates are used. ASR problems are shallow frequency since the reactive aggregate deposits are located in distant regions to the MRBA, using non-reactive aggregates in most cases. Thus, concrete designers shall design concrete with low capillary absorption and, when using SCM, ensure adequate curing to prevent rapid carbonation that can lead to subsequent corrosion of the reinforcing bars [75,76].

Furthermore, using materials with better thermal and acoustic insulation properties would improve the livability of buildings, reducing energy use for heating, ventilation, and refrigeration [58,77]. Bio-inspired construction could boost the benefits, decreasing the energy use during the life-cycle of the building. It is an active strategy that covers different levels, from materials to the whole building. Its principles aim to increase *adaptability*, *multi-ability*, and *evolvability* of buildings, being inspired by nature [77].

On the other hand, in Argentina, most cement is traded in bags (68.9% in bags vs. 31.1% in bulk [43]). This indicates that only a small share of the concrete produced for construction is manufactured in ready-mix concrete plants, whereas the vast majority is produced on-site. On-site concrete production hinders the transfer of knowledge for the use of low-energy/low-emission and recycled materials since specialized batching and chemical admixtures are often needed, demanding the employment of advanced know-how that is not generally accessible to small construction sites. It also increases the amount of waste produced, reducing material efficiency and increasing environmental impact. There is also a cultural factor of a reluctance of masons to use non-traditional materials, which hampers their application. Therefore,

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advancing towards net-zero emission concrete and reducing small-scale concrete production can only be accomplished after public policies that foster ready-mix concrete use (Strategy 3 in Table 3).

According to available research, it is estimated that about 6% of the CO_2 emitted by the construction industry could be reduced by the re-carbonation of cementitious materials (Strategy 4 in Table 3) [37,78]. To reach this target and favor the carbonation process, it is necessary to consider increasing the surface area of exposed concrete and exposed cement/lime mortars without painting or coating. Otherwise, a reduced carbonation situation occurs [78]. Additionally, fair-faced concrete also allows optimizing the thermal performance of the concrete, which can considerably decrease energy in the use stage [58]. However, care must be taken to prevent corrosion of steel bars when reinforced concrete is used, as it could damage and reduce the useful life of the structures, thus counteracting the positive effect of CO_2 capture in the cement paste.

Government involvement would be needed to reduce emissions due to transportation and electric power use (Strategy 5 in Table 3). The transportation of materials in Argentina has a major impact since it is mostly done by truck and to a small extent by train, and long distances transportation required. In addition, cement and natural coarse aggregate are relatively distant and without quality aggregate quarries from which material can be obtained at a shorter distance. However, governmental action is imperative to modify the transport network scheme. More extensive and inclusive rail networks are required, which involves a large investment for the construction of new lines and the rehabilitation of existing ones that are no longer operational. Meanwhile, the feasibility of waterway shipping could be explored. Finally, the Argentinian energy matrix is fairly low-emission due to the fact that most of the electricity production is generated by using natural gas, hydroelectric, and nuclear power plants, and the share produced by petrol or coal is smaller [79]. However, emissions from electric power can be further reduced, requiring the active encouragement of using renewable energy sources (i.e., solar, wind) by means of public policies.

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5. FINAL REMARKS

The methodology proposed for this work proved to be a useful tool to quantify the environmental impact of the ready-mix concrete production for a particular region, constituting a deeper understanding of the current knowledge of the construction industry.

The results show that, for the production of 2,604,862 m^3 of ready-mix concrete in the Metropolitan Region of Buenos Aires in 2019, 7.16 Mt of materials were required. 99.1% corresponded to raw materials, while 0.9% corresponded to secondary raw materials.

5.36 Mt (~78.6%) of the extracted materials belong to aggregate production, as they cover the largest volume of concrete. In contrast, they represent less than 19.5% of the ECO_2eq from the ready-mix concrete production. About 96.4% of the ECO_2eq of aggregates is due to transportation from the quarries to the ready-mix concrete plants. Aggregates production itself has a low ECO_2eq since electric energy is mainly used during crushing and classification, and Argentina has a relatively clean energy matrix.

Portland cement is the largest contributor to ECO_2eq and the constituent material with the lowest material efficiency, attributable to the decomposition of limestone in the clinkerization process. Even more, Portland cement production is the most energy-intensive process due to the high temperatures that must be reached in the clinker kiln.

Within the possible strategies for which the potential impacts on the life cycle assessment were measured, using recycled aggregates is the approach that contributes the most to the reduction of the use of raw materials. Furthermore, as the production of recycled aggregates might be located close to the construction site or the ready-mix concrete plant, it would significantly reduce the ECO_2eq of the aggregates.

Regarding the ECO_2eq of concrete, the approach that contributes the most to their mitigation is the replacement of Portland cement with supplementary cementitious materials (SCM). Additionally, the use of SCM contributes to increasing the material efficiency of concrete and reducing the use of raw materials.

Finally, the construction industry has already introduced several initiatives that mitigate the environmental impact of materials production and housing and infrastructure construction. Nevertheless, to achieve the goal of Net Zero Concrete by 2050, the consolidation of diverse actions must be enforced to boost material efficiency, dematerialize the construction industry, and reduce CO_2 equivalent emissions. This requires the

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broader engagement of stakeholders, not only cement and concrete producers, and further studies such as holistic life-cycle analysis and supply chain optimization.

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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Strategy	Level of action	Stakeholder	Expected impact	Considerations
(1) Use of SCM	Cement	Cement industry, concrete manufacturer	Reduction of GHG emissions and energy usage, material efficiency improvement	⸙⸙⸙ ※※※ ~ Could be limited by the regional availability of resources ~ Could increase the volume of materials required ~ May require lengthening the age of concrete conformity
(2) Use of recycled aggregates	Concrete	Concrete manufacturer, Policy makers, Demolition companies	Reduction of GHG related to transportation and new material extraction	⸙⸙ ※※※ ~ Could be limited by the type and quality of CDW ~ May require increasing the cement content per m^3 to maintain mechanical and durability properties
(2) Non-traditional water sources	Concrete	Concrete manufacturer	Improvement of the material efficiency of concrete	⸙ ※※※ ~ May be limited by the physicochemical properties of water ~ May affect the setting time, strength and durability of concrete
(2) Reduction of *w/b* ratio	Concrete	Concrete manufacturer	Reduction of raw materials used	⸙ ※ ~ May require higher control in concrete casting
(2) Increase the compressive strength of concrete	Concrete	Building designer, Concrete manufacturer	Reduction of GHG, Reduction of new material extraction	⸙⸙⸙⸙ ※ ~ May be limited by the regional availability of materials ~ May require higher control in concrete casting and curing
(2) Improve the durability properties of concrete	Concrete	Concrete manufacturer	Increased service life of the structure, Reduction the rate of repair and renovation of structures	⸙⸙ ※ ~ May be limited by the regional availability of materials ~ May require higher control in concrete casting and curing ~ May increase the maintenance costs
(2) Improve the concrete and structure design	Concrete, Buildings	Concrete manufacturer, Building designer	Reduce the energy usage for heating and refrigeration during the service life of the structure	⸙⸙ ※※※ ˘ May be limited by the regional availability of materials ˘ May require more strict policies for new buildings ˘ May require higher control in concrete casting and curing
(3) Promote the use of ready-mix concrete instead of "in-situ" concrete	Concrete	Policy makers	Reduction GHG by using alternative and low-energy materials	⸙⸙ ※※※※ ~ May require government investment to foster the use of ready-mix concrete ~ Requires a cultural change in the informal building sector
(4) Promote re-carbonation of concrete and cementitious materials	Concrete	Concrete manufacturer, Building designers, Demolition companies	Reduce the net-GHG of concrete industry by recapturing CO_2 due to concrete carbonation	⸙⸙⸙ ※ ~ May be reduced by the use of coatings and coverings on structures ~ May be increased in CDW, by increasing the exposed surface of concrete
(5) Change in the transportation system	Composite materials	Governments	Reduction of GHG related to transportation	⸙ ※※※※※ ~ May face resistance from a certain sector of society ~ Requires high investment by the public sector
(5) Shift in the energy matrix towards renewable energies	Composite materials, Buildings	Governments	Reduction of GHG related to building and use stages	⸙ ※※※※※ ~ Requires high investment by the public sector ~ Reduces minimally GHG associated to the manufacture of materials

⸙ Environmental impact reduction expected

※ Difficulties in implementation related to regulation

HIGHLIGHTS

- 7.16 Mt of materials were required to produce 2,604,862 m^3 of ready-mix concrete
- 99.1% of materials required corresponded to raw materials
- 0.9% of the materials required corresponded to secondary raw materials
- ~78.6% of the extracted materials belong to aggregate production
- ~74.6% of the CO_2 equivalent emissions are from Portlan cement production

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CRediT

Gisela Cordoba: Conceptualization, Methodology, Sofware, Formal analyze, Investigation, Data curation, Writing - Original Draft, Visualization, Funding. **Cecilia Inés Paulo**: Methodology, Software, Validation, Writing – Review & Editing, Visualization, Supervision. **Edgardo Fabián Irassar**: Conceptualization, Validation, Resources, Writing – Review & Editing, Supervision, Project administration, Funding.

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Declaration of interests

☐ 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.

☒ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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